GROWTH AND PRODUCTIVITY AS FUNCTION OF SITE QUALITY AND AGE IN TEAK PLANTATIONS OF NILAMBUR, KERALA

By
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THESIS

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DECLARATION

I, hereby declare that this thesis entitled **"Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or society.

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Certified that this thesis entitled **"Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala"** is a record of research work done independently by Mr. Sankar Thampuran M V (2019-17-001) under my guidance and supervision and it has not previously formed the basis for the award to me of any degree, diploma, associateship or fellowship to him.

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We, the undersigned members of advisory committee of Mr. Sankar Thampuran M V (2019-17-001) a candidate for the degree of Master of Science in Forestry with major in Silviculture and Agroforestry, agree that this thesis entitled **"Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala"** may be submitted by him in partial fulfilment of the requirement for the degree.

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Introduction

I. INTRODUCTION

Teak has been one among the principal timber species widely used across the world due to its matchless combination of qualities. India, especially Kerala has a long history of using teak wood as a raw material for diverse purposes ranging from furniture making to construction. Teak is found naturally in south and south east Asia. The commercial planting of teak started around the year 1700 in Malaysia, in the year 1842 in India and in 1906 in Thailand (Krishnapillay, 2000). Today the global estimates of planted teak forests lie between 4.35 and 6.89 million ha making it the most cultivated superior furniture grade tropical hardwood species. Ever since the historical attempts by H V Connolly, then Collector of Malabar to raise teak in Nilambur, Kerala during 1841, teak has been extensively cultivated throughout Kerala. Presently Kerala has 76,710 ha of pure teak plantations and 14,440 ha of teak with softwood plantation making up 49.08 and 9.24 per cent respectively of the total plantation area in the state (KFD, 2019).

National demand for teak is primarily met from its plantations, from small holder farms and through imports. With a reported area of 1.667 million ha under teak, India shares 44 percent of global teak plantations (Palanisamy et al., 2009). Despite having the largest share of plantations under teak, India is one of the largest consumer of teak wood consuming 74 percent of total traded volume (Kollert and Kleine, 2017) Interestingly, wood balance studies in Kerala have shown that the major chunk of wood demand in Kerala is met from homesteads, farm lands and rubber plantations while forest plantations contribute only 1.6% of total state wood demand (Krishnankutty and Chundamannil, 2012). In conjunction with this, it is worthy to note that the productivity of our teak plantations including the acclaimed plantations of Nilambur, are on the decline.

In countries like Indonesia, the Mean Annual Increment (MAI) of teak is as high as 17.6 m^3 ha^{-1} yr^{-1} (Jayaraman and Zeide, 2007) while in Kerala, the overall average MAI reported is 2.49 m^3 $ha^{-1}yr^{-1}$ (Chundamannil, 1997). Apart from the poor adherence to scientific management practices and the associated disproportionate accrual of growth and biomass production with advancement in age, lack of understanding on the productive potential of the site for teak growth may also play significant role in regulating the overall productivity of teak plantations. Considering the poor productivity of teak, the Kerala Forest Department is seriously scrutinizing options to revert the low productive teak plantations back to natural forests.

Low or declining productivity in forest plantations is often attributed to the 'harvest related nutrient export' from the plantation sites (Fernández-Moya *et al.*, 2014). Often, this decline in nutritional status is beyond the natural capacity of replenishment through weathering in short timescale. With increase in rotations the potential of the site to support biomass decline substantially leading to poor productivity. With much of the plantations in Nilambur in their second or successive rotations, there is a probable chance that these plantations might be exhibiting second rotation productivity decline. Furthermore, congenial biophysical environment existed in the Nilambur valley for luxuriant teak growth, has been shattered heavily on account of multitude of factors including recurring floods and landslides and uncontrolled damages caused by wild animals especially wild elephants. However, our understanding on the teak growth and productivity in the various plantations in Nilambur forests under the existing levels of environmental, ecological and economic constraints are very much limited.

Site quality is often considered as strongest indicator of the productive potential of woody vegetation. It is the totality of all the biophysical resources available in a site and the potential of the site to convert the resources into biomass. Considering the large-scale variability in species preference for the site resources for optimal growth, the site quality may vary considerably with species and their edaphoclimatic preferences. Often the dominant height of the existing trees is considered as the prudent estimate of the site quality primarily on account of its insensitivity to age and management conditions (Lanner, 1985; Ahmadi *et al.*,) Earlier observations in Nilambur forests identified teak growing regions belonging to all the four site quality (SQ) classes (SQ I, SQ-II, SQ-III and SQ-IV) exists in the Nilambur valley. However, in the existing constraints of declining productivity of teak in the Nilambur forests, it is high time to revisit the teak plantations in the existing site quality regimes and to relate their present productivity with the recorded site quality. The site quality also may influence the age and growth relationships. The age for transition from one size class to another may considerably vary with site quality. Such relationships of site quality and age on the growth of the teak is seldom attempted in Nilambur forests.

In this backdrop, a field study was designed to investigate the changes in growth and productivity of teak as a function of age and site quality for teak growing regions in Nilambur, Kerala. The locations identified for the study include teak plantations belonging to Nilambur North and South divisions. The study was proposed to explore the major drivers contributing to productivity decline in teak plantation of Nilambur and help to suggest possible strategies that enhance the teak productivity in Kerala and Nilambur in particular.

The study was designed with the following specific objectives:

i. To assess the growth and productivity of teak plantations as a function of age and site quality.

ii. To investigate the soil characteristics in teak plantations as function of site quality

Review of Literature

II. REVIEW OF LITERATURE

Teak is privy to a superior status among tropical timber species, owing to it having a combination of number of exceptional qualities. Its ability to meet human demand for wood for furniture making to ship building has made it a desired tree in managed tropical forests across the world. The practice of plantation culture in teak started when the British regime in India faced extensive dwindling in natural availability due to massive extraction. For the past 150 years, teak plantations have been managed by more or less the same techniques developed by then. However, in the recent decades, there is mounting concerns of massive decline in productivity of managed teak plantations, the reasons of which are mostly unclear which are often understudied with scientific temper. The reasons for the productivity decline remain largely elusive. The present investigation attempts to study how the productivity of teak varies between different site qualities across age groups in Nilambur, Kerala. This would give an insight into the potential factors that contribute to the recent decline of teak productivity. This chapter reviews the pertinent role of diverse biophysical factors on the productivity of teak and its understanding.

2.1. Plantation productivity decline

The term productivity refers to the amount of biomass or wood that can be grown or accumulated in a unit area of a plantation during a specific period of time (usually a year). The productivity of any plantation can vary with species, age, management, edaphic conditions, climatic and topological characters. A higher productivity ensures better economic returns and success of plantation and therefore its estimation and understanding are of high importance. When we look at the case of teak, Pandey (1996) identified annual rainfall and relative humidity as the two most influential factors influencing its productivity. Across the state of Kerala, there are variations in the productivity of teak from one area to other due to changes in different endemic characters (Jayaraman and Rugmini, 1993). Different estimates of productivity are available with respect to tropical plantation trees. The estimates of productivity of *Switenia macrophylla*, a tree grown in similar ecological regions as of teak varies from 7.7 to 19.3 $m^3h^{-1}yr^{-1}$ (Krisnawati *et al.,* 2011).

When we see the case of teak productivity, estimates portray a clear picture of declined of teak in India. The global overview of teak plantations states the productivity of teak in India at 12.3 m^3 ha^{-1} yr^{-1} in the best sistes, 7.9 in average sites and 2.7 m^3 ha^{-1} yr^{-1} in poor sites (Ball *et al.*,1999). The poor availability of productivity data of plantations in India suggest their underperformance. Enters and Nair (2000) reported the Mean Annual Increment (MAI) of teak in India at 12.3 m^3 ha^{-1} yr^{-1} which is comparatively lower to the productivity of teak in Indonesia, Myanmar and Nigeria which were 21.0, 17.3 and 23.8 m^3 ha^{-1} yr^{-1} respectively. But the questions of whether these plantations are always performing up to these ideal expectations are prevalent. Ball *et al.,* (1999) report the productivity of 70-year rotation teak plantations managed by Perum Peruhtani in Indonesia at 3 $m^3ha^{-1}yr^{-1}$. When we look at the case of Kerala the productivity again falls down, the MAI of teak at a mean rotation of 58 years was observed to be 2.49 m^3 ha^{-1} yr^{-1} (Chundamannil, 1997). In case of Nilambur, the celebrated land of teak, The MAI was a low 2.85 m^3 ha^{-1} yr^{-1} for a rotation of 53 years despite it being renowned as the best teak growing area of Kerala (Chundamannil, 1998).

There are number of examples on the growing concern over the decline in forest plantation productivity along successive rotations. Studies in Sitka spruce (*P. sitchensis* (Bong.) Carr.) plantations in North Wales show a decline in DBH by 10.3% between first and second rotation, following whole tree harvesting. Hardiyanto and Nambiar (2014) report a 21 % decline in merchantable wood production in *Acacia mangium* in South Sumatra after whole tree harvest of the previous rotation. In longer rotation species like teak, the availability of such clear estimates of productivity decline in scientific literature is limited or lacking primarily due to the time period that elapse between successive rotations.

2.2. Teak plantations of Nilambur

Historically Nilambur enjoy prominent place in the legacy of teak as home to the first man made teak plantation and as the source of highest quality teak. Nilambur teak is often regarded as the first forest based product to get a Geographical Indication status in the country (GOI, 2017). Studies have shown Nilambur teak to be unique in its genetic makeup and different from other clusters (Nair *et al.,* 2016). In Nilambur the planting of teak is carried out at a spacing of 2m*2m and is later opened through thinning operations. The yield estimates are made based on yield table published by FRI (Anonymous 1970). Nilambur teak shows an average MAI of 2.85 m^3 ha^{-1} yr^{-1} for a rotation of 53 years. Within this, site quality I was found to have a productivity of 8.21 m^3 ha^{-1} yr^{-1} and site quality IV showed a lower productivity of 1.78 m^3 ha^{-1} yr^{-1} (Chundamannil, 1997). The author also notes based on KFD records that, within Kerala the productivity of other forest divisions like Wynand, Konni and Kozhikode were lower than Nilambur and ranged between 1.23 to 2.5 m^3 ha^{-1} yr^{-1}.

2.3. Site quality

Site is an abstract concept that combine the totality of environmental variables that influence vegetation growth and development. In managed forests and plantations, the term site quality indicates the innate potential of the site to produce timber of desired quality. The credit for the earliest recorded observations of tree growth goes to Theophrastus (370-285 B.C.) who recorded phenological changes and growth rate of trees belonging to different moisture regimes (Makkonen, 1968). Cato (234-139 B.C.) developed a subjective classification of land, primarily estates in Rome (Makkonen, 1968). For long, these historical classifications were subjective in the sense that they relied on visual observations of vegetation (Tesch, 1980). More scientific approaches towards forest or site classifications emerged by 18^{th} century. In 1795 Hartig opined foresters should be content with fewer classes like poor medium and good. In contrast to this Cotta in 1804 recommended a set of 100 site classes (Cajander, 1926; Tesch, 1980). Soil still remains a major criteria in site classification. Quichimbo *et al,.* (2017) used soil properties to classify plantations of pine in Southern Andean region of Ecuador. Another early yet widely used criterion of the site potential is the accompanying ground vegetation observed in situ. Cajander (1926) and Lewis *et al.* (1976) advice the use of vegetation to classify site. Though it gives an idea of suitability of site for plantation establishment, vegetation-based classifications may not give a clear idea of growth performance of the tree species as no direct measures of tree growth is considered in them.

Attempts at use of crop statistics in determination of site quality started in 18^{th} century. Spath in 1797 developed the first yield table plotting volume at different ages (Fernow. 1911). These developments followed the use of standing volume for determining site indices (von Wimpfen, 1836; Pressler, 1870). Heyer (1841) and Baur (1881) can be considered as pioneers to propose arguments for choosing height as an index of site productivity. The relationship between mean height and age was observed to be similar to the volume productivity and age relationship (Gyldenfeldt, 1883). Site quality gives an idea of the productive potential of an area designated for tree stand establishment. Site quality distinguishes and classifies plantation sites, thereby aiding in selection based on site species compatibility and in developing better silvicultural prescriptions (Farrelly, 2009). By the start of 1900s, the early attempts evolved into scientific classification of site based on productivity (Tesch, 1980). Graves (1906) in his book Forest Mensuration gives guidelines for volume table-based site classification. The evolution of site classification based on height is a result of at least a century long experience with yield tables based on different factors. German foresters suggested the use of stand height as criteria for site classification (Skovsgaard and Vanclay, 2008).

When we see today, it is a long-established fact that the height growth of any forest stand is independent of spacing but is an inherent function of the site at which it is grown (Lanner, 1985; Sjolte-Jorgensen. 1967). Though tree morphology is widely influenced by spacing effects, height growth often remain independent of the competition owing to the physiological fact that the apical meristem of the leading stem remains a stronger sink of carbohydrates in comparison to the cambial meristem responsible for radial growth (Lanner, 1985). The three major direct methods of direct estimation of site quality viz. site index curve method, site index comparison method and the growth intercept method depends on height measurement for their estimation (Carmean, 1975). The other methods of site quality estimation (indirect methods) include mensuration methods like volume or form based site quality estimation (Ahmadi,*et al.*, 2017), plant indicator based site quality (Westveld, 1965), physiographic site classification (Carmean, 1996), synecological classification (Wilson *et al.*, 2001) and soil based site quality classification (Knoepp *et al.*, 2000). Height based site index or quality classes have been developed for various forestry species like pine (Dunning and Reineke, 1933; Meyer, 1938) and fir (Schumacher, 1926; King, 1966).

Site index curves have been developed for teak for localities across the globe like Columbia (Torres *et al.,* 2012), Nigeria (Akindele, 1991) and Puerto Rico (Friday, 1987). Based on which site quality of teak growing localities are being estimated. Most commonly top height of the plantation has been the most common factor upon which site index of teak have been devised. To quote an example, the teak growing areas of Chittagong and Sylhet forest divisions of Bangladesh has been divided into two site qualities based on the height growth potential at the sites (Mollick *et al.*, 2005). Soil properties can be used along with growth parameters to determine the performance potential of a site. Katsutoshi, *et al.* (2002) used soil characteristic study to differentiate teak plantations managed by Forest Industry Organisation of in Thailand to evaluate their site quality index.

2.4. Factors influencing productivity of plantations

Productivity of tree plantations can vary with management, site, stand, and biological limitations that influence dry matter assimilation in harvestable form (Vance *et al.* , 2010). Various studies have investigated the different factors that influence the productivity of tree plantations. As productivity is generally limited by climatic, site/soil, genetic and management/silvicultural factors, the best opportunities for a silviculturist to achieve better productivity lies in achieving the best genetic and silvicultural interventions in plantation forestry (Mead, 2005).

2.4.1 Topography and physical properties of soil

Kusbach *et al.* (2021) in their six-year growth study on site specific performance of teak in Nicaraguan dry tropics observed that site topography and soil moisture had an influence of the growth performance of teak i.e., concave topography with moderately drained soil showed better productivity. It has been reported that high slope percentage can cause soil erosion especially at younger stages to the magnitude of more than 34 t ha^{-1} (Tangtham, 1992). Steep slopes and poor understory can result in larger magnitudes of erosion and thereby lower productivity. In a study by Zech and Drechsel in 1991 comparing the growth performance of teak with nutrition and site factors in rainforest areas of Liberia, it was seen that a better growth of 1.2 to 1.8 m yr^{-1} increase in height was observed in the mid slope areas with better hydromorphic properties compared to the high or low elevation sites. Soil erosion can also be seen in plantation with soils having poor hydraulic conductivity (Fernández-Moya *et al.*, 2014).

In a number of studies that where soil horizon layers under teak are studied, It has been observed that the pH and bulk density of the 20 to 40 cm deep layer has a significant impact on the diameter increment of trees (Akinsanmi, 1985; Salifu, 2001; Rugmini *et al.*, 2007). Rugmini *et al.*, (2007) based on their study in teak plantations of Kerala reported that this phenomenon can be seen more prominent in younger plantations, being responsible for nearly 33% of variation in diameter increment.

2.4.2. Soil chemistry

In a study from tropical Northern Australia, it was reported that establishment and early growth of teak was promoted by carbon content in soil. C immobilised Al in soil and thereby C rich soil had higher Al saturation. While C and Al had a positive impact on teak growth, Mn toxicity and high Mg content had a negative impact. In the study it was also found that pH and Ca content did not have a significant effect on the establishment and early growth over first 18 months after planting (Wehr *et al.,* 2017). In contradiction to this, there has been studies which show a clear relationship between pH and teak growth (Zech and Drechsel, 1991; Rugmini *et al.,* 2007; Zhou *et al.*, 2017). Soil pH can be an indicator of potential nutrient limitation or excess (Schoenholtz *et al.*, 2000). A lower pH can make Al and Fe soluble and at toxic concentrations for plants (Rahman *et al.*, 2018). Zhou, *et al.* (2017) reports Al concentrations to be negatively corelated to growth and development of teak in South China. Teak is a calciphyte with the percentage Ca content in foliage as high as 3.6% (Bhatia, 1954). Calcium rich soils are relevant for teak establishment. Alexander *et al.*, (1981) repoted te organic carbon content of teak plantations of Nilambur to be between 0.77 to 2.14 % at a depth of 0 to 20 cm.

2.4.3. Changes in soil properties under plantations

Various studies have shown that in long rotation forest plantations like that of teak, though the soil properties may deteriorate on initial silvicultural activities, the soil will recuperate in its properties with the passing of time. Page (1968) based on his studies in temperate ecosystems reported that provided no significant damage or deterioration occur, the soil under pines would return to the original state as the tree reaches 25- 30 m height. Soils under *Larix principis-rupprechtii* plantations of Northern China took 39 years after planting to regain its physical and chemical properties (Zhao *et al.*, 2019). Similar reports can be found in the case of teak. Jose and Koshy (1972) based on their studies in Nilambur reports the soils under teak to be recuperating as the rotation is progressing. Alexander *et al.*, (1981) arrived at an analogous conclusion in comparing first and second rotation teak soils in

Petinthomuzhi and Begur in India for properties like particle-size separates, pH, organic carbon and CEC. The term recuperation itself is indicative of the fact that soil will be adversely affected on harvest of standing crop. Many a times the harvest related nutrient loss might be of a magnitude that cannot be compensated by the ecosystem over time. In contrary to the above said reports, there are a number of studies which establishes a strong connection between teak monoculture and soil deterioration (Aborisade and Aweto, 1990; Amponsah and Meyer, 2000; Healey and Gara, 2003; Abdullah *et al.,* 2018). Amponsah and Meyer, (2000) analysed the soil nutrient variation between natural semi deciduous forests and teak plantations of similar ecological conditions in Offinso and Juaso Forest Districts of Ghana. The results showed a negative variation in status of soil nutrients like organic matter content (13 to 11%), calcium (17.0 to 12.4 cmol(+) kg-1), available phosphorus (4.2 to 1.2 mg kg-1), and total nitrogen (0.3 to 0.2 %) between top soils (0-20cm) of natural forest and teak plantations.

2.4.4. Initial planting density

Initial densities of sawn timber plantations of teak are high and very much similar to those of pulpwood plantations, i.e. from 1100 to upto 3000 trees per ha (Ladrach, 2009; Pachas *et al.*, 2019 a). These initial high densities help to compete out weed growth. In case of taungya or agroforestry teak the spacing can be wider upto 6m between trees (Ladrach, 2009) A spacing configuration of 6 x 2 m i.e. 833 trees per ha can be advised to provide spacing for intercropping (Ugalde Arias, 2013). Following successive thinning interventions during its growth, the final stocking of teak can vary from place to place. on an average, there can be 2- 4 thinning interventions, resulting in an average final density of 230 trees (range 87 to 500) ha $^{-1}$ (Pachas *et al.*, 2019 a).

Regulation of Initial spacing and stand densities are important management strategies that help maximise the productive potential of forest plantations. These aspects have been scientifically investigated for number of species including teak. Eversole (1955) based on his spacing tests in douglas fir (*Pseudotsuga menziesii)*, concluded that average diameter of trees increased with wide spacing but had little effect on total stem cubic volume in the first 27 years. Reukema (1979) reported similar findings comparing 4 to 12 feet initial spacing regimes that a wider spacing performs better in douglas fir plantation of 250 trees per ha (12ft) was 60% taller and 755 larger in dbh compared to the closest spaced stand (4 ft). This is not the case for all species, In Slash pine (*Pinus elliottii*) plantations of Georgia a higher density of 500-550 stems per acre resulted in better diameter increment at an age of 7 years (Bennett, 1960). There is an established relationship between the stand density and average basal area of trees. Based on place of application and local perspectives of management across the world, a number of indices or measures of stand occupancy including Basal area, Canopy Closure, Stand density Index (Reineke, 1933), Predominant Height and Age of plantation can be used to determine the timing and intensity of thinning in even aged stands teak plantations (Kanninen *et al.*, 2004; Pérez and Kanninen, 2005b; Pachas *et al.*, 2019 b).

Based on the relationship between stand density and basal area, plantations can be managed with the aid of Density Management Diagrams (Long and Smith, 1984). Density management diagrams have been used to regulate thinning and thereby spacing in forest plantations (Drew and Flewelling, 1979; Long and Shaw, 2005). In the case of teak, density management diagram for teak was developed for plantations in Kerala in 1995 (Kumar *et al.,* 1995). Based on the DMD of teak, the authors suggested thinning intervention aimed on production of poles and larger diameter logs should be taken up when the stand density index reaches 420 and by thinning this should be reduced to 20% of the maximum stand density index.

2.4.5. Thinning regimes

Various tinning regimes are practiced in teak plantations around the world to suit the local conditions and the associated requirement of planting densities at different stages of stand development. When yield table based thinning regimes are followed, the stocking status at any stage of growth can be determined as basal area per ha as expected in the yield table of teak (Anonymous, 1970).

Kanninen *et al.*, (2004) carried out a thinning trial on 4-year-old teak plantation with initial density of 1600 trees per ha, with treatments of light (25%), moderate (40%) and heavy (60%) thinning being applied at 4 and 6 years of age (a 25% thinning was done the following year after light thinning at 4 years age). The result showed that at 8 years of age, the 60% thinning intensity applied at 4th year, and the two consecutive 25% removal at 4^{th} and 5^{th} years gave the best individual tree growth. Pachas *et al.* (2019 b) based on their studies with respect to initial spacing of teak in northern Lao PDR, reports that an initial spacing of 600 to 1000 trees per ha can achieve a maximised growth and commercial value. A higher stocking density would require thinning at an age of 5 years and a lower stocking can result in lower height development. It is noteworthy that the stands of high densities that were left un-thinned exhibited a lower growth and productivity in comparison to plantations of lower densities. Also, the authors prepose teak woodlots with taungya or agroforestry in the initial 2 years as a better management strategy as it prevents weed growth. Similarly, Zahabu *et al.* (2015) studied the effect of different spacing regimes in Longuza Forest Plantation of Tanzania. The study showed that the mean total height of teak trees at 14 years of age were significantly lower in spacing regime of 2 × 2 m compared to spacing regimes of 3 × 3 m and 4 × 4 m. Also at 14 year age the MAI was higher in 3 x 3 spacing than 4 x 4 or 2 x 2 as the spacing regime of 4 x 4 m despite being a better performer in terms og stand height is not at an optimal spacing for better resource utilization. Jayaraman and Zeide, (2007) in their modelling study for optimizing stand density in teak plantations had concluded that the optimum density that maximizes the productivity is 950 trees per ha and the long-term optimal density to be 475 trees per ha. The authors also noted that miscellaneous growth can be a detrimental factor in plantation growth, there can be a 20 and 30 % enhancement in mean diameter and MAI of teak at 50 years age if miscellaneous growth is controlled.

Jayaraman (1998) in his study on the structural dynamics of teak plantations in Kerala, observed that on considering the basal area of teak trees present in the plantations as criteria, only 19% of teak plantations were fully stocked. 36 % and 45% of the teak plantations were understocked and overstocked respectively. It is also noteworthy that the overstocking in most cases was not a resultant of vigorous growth but an after effect of lack of application of prescribed thinning operations. Jayaraman and Zeide (2007) in their study using practical process models for optimizing density for teak noted that the long-term optimal density index for teak plantations in Kerala is 475. They suggested that by bringing up or down the densities of under or overstocked stands, we can get a 42% increase in productivity.

2.4.6. Rotation (types of rotations- rotation length)

Teak is managed under various roatations according to the local conditions and to suit the management objectives. This duration of rotation varies between 25 to 80 years (Pandey, 1996). Conventionally, the average rotation age of teak falls around 50 years of age (Ball *et al.,* 1999). Intensively managed teak has a lower rotation period compared to traditional teak growing methods, like 20 to 25 years in Costa Rica (De Camino, 2002), and 20 years in Panama (Kraenzel *et al.*, 2003), The optimal rotation age in teak has been highly debated and we can find that literature favouring both long and short rotations. The property of wood extracted from teak stands vary with age of extraction. In a comparison study for wood properties between short (7 to 10) and long rotation (40 to 60) teak, done in Indonesia, the results showed that long rotation teak have higher heartwood: sapwood ratio, hemicellulose, holocellulose and cellulose but lower lignin content. Long rotation teak had higher density and dimensional stability with lower swelling coefficient. In contrast to these findings, (Wanneng *et al.,*2014) based on their study comparing wood harvested at different ages varying from 10 to 30 reports that there is no significant variation between the ages in wood properties and there is no apparent relationship between age and wood properties. Jha (2016) recommends longer rotations for teak as it would enable better carbon sequestration and would not deplete the soil nutrients.

2.4.7. Weeding

Weeding activity removes the unwanted undergrowth from tree plantations, thereby eliminating competitive suppression of tree seedling. Weeding is essential especially in the early stages of stand development. When other competitors are removed, the trees can take up maximum resources and thereby have better growth and development. Powers and Ferrell (1996) in their study was carried out in *Pinus ponderosa* plantations of California to understand the interactions among different management operations (insect, nutrient, and weed control treatments), reported that there was a synergistic effect of nutrient and weed control treatment being applied on the stand irrespective of the site quality. There was up to a 265% increase in volume in poor sites when weed control was done. Overall, there was a 666% increase in volume compared to control when the treatments were applied together. Similarly, Zutter *et al.* (1987) base on their five year observations that sweet gum *Liquidambar styraciflua* L. and green ash *Fraxinus pennsylvanica* L. noted that plantations exhibited better growth and development following weed control using herbicides and cultivation as the two treatments, in combination and otherwise, with the combination of the two being more effective.

Kadambi (1972) suggests weeding as a management practice to improve productivity of teak plantations. Anoop *et al.,* (1994) in their study on efficacy of different weed control treatments for young teak, observed that in radial growth, weed removal by paraquet showed a basal stem diameter of 7.84 cm at 22 months followed by manual weeding (7.58) and glyphosate (7.37). these values were significantly higher than ring weeding and weedy check. Taungya systems can also be taken up to ensure weed control in the early stages of teak development (Pachas *et al.*, 2019 b).

2.4.8. Pruning

Pruning activity ensure the production of clear, knot free timber. Knots are often regarded as the most detrimental of the defects that affect timber quality and its avoidance is there for essential in managed stands. The general recommendation followed is to prune upto 50% of total height at the first thinning of teak (Pérez and Kanninen 2005b; Ugalde Arias 2013). Pérez *et al.* (2003*)* based on their studies in teak plantations in Costa Rica recommended the first pruning to be done to 2-3 m when stand height is 4-5 m, the second pruning of 4-5 m height when stand height is 9-10 m and a pruning up to 7 m when stand height is around 12 m. Pruning can result in better stem shape, clearer and cylindrical bole and more knot free timber. Young plantations are reported to show better response to pruning interventions (Budiadi *et al.,* 2017). Víquez and Pérez (2005) from their studies in Costa Rica observed that different pruning treatments at ages of 3.2, 5.2, and 6.1 years of age showed significant differences in DBH and total height while the same treatments failed to bring significant changes at age of 7.1 years. In the study, the authors also reported that under intensive pruning regime, teak of rotation of 20 years produced more than 40% knot free timber out of total wood production.

An anomaly in teak is that after thinning and pruning, the excess light that reach the boles can trigger adventitious buds and epicormic branch growth (Ladrach, 2009). Based on their pruning trials in 8 to 10 year old teak plantation in Puerto Rico, Brisco and Nobles (1966) reported that In the plantation boundaries and adjacent to road clearances, 40 per cent of the trees showed epicormic branching while this fraction reduced inside the plantation to 28%. Also, they noted that the epicormic branching also varied with time of pruning ie, those pruned in August showed less branching compared to those pruned in May which branched less than those pruned in February.

2.4.9. Nutrition

Teak prefer deep fertile alluvium for its growth (Tewari 1992; Kumar 2005). Nitrogen nutrition, root penetration and precipitation were reported to be the most relevant factors that affect teak growth in west Africa (Drechsel and Zech, 1994). Teak being a calcicole is favour calcium rich soils (Rugmini *et al.,* 2007) Zech and Drechsel (1991) noted that in Liberia, poor teak sites with lower Ca content showed pH values below 4.3 and soils with a pH above 4.7 had better Ca ($CaCl_2$) content and therefore showed better growth of teak. It has been reported that there is an increase in volume and height of teak with increased foliar concentrations of N, P, K and Ca (Zech and Drechsel, 1991; Glaser and Drechsel, 1992). Negi *et al*., (1995) reported that maximum storage of N and P occur in boles while Ca content is higher in bark and roots. Jha (2014) studied the temporal storage patterns of N and P in 1- to 30-year-old teak plantations in moist deciduous tracts of India and reported that retranslocated amounts for N and P were 8.7 to 48.0 kg ha^{-1} for N and 0.1 to 3.5 kg ha^{-1} for P. The nutrient uptake varied from 28.2 to 125.2 kg ha^{-1} for N and 3.3 to 20.2 kg ha^{-1} for P. Comparing across age, it was observed that the magnitudes of retranslocation and nutrient uptake peaked in 11year old plantation and the minimum was in first year plantation.

In moist deciduous forests of Kerala, the litter nutrient content has been estimated at 0.65 to 1.6% for nitrogen, 0.034 to 0.077% for phosphorus and 9.25 to 0.62% for potassium (Kumar and Deepu 1992). Rajagopal *et al.* (2005) based on their studies on 5-year-old teak plantation with density of 2500 trees per ha reported a total litter production of 4574 kg/ha of which the nutrient return to soil were N 46kg/ha; P- 3 kg/ha; K 39kg/ha; Ca 86kg/ha; and Mg 21kg/ha. Under undisturbed conditions, the litter recycling can give upto 70% of nitrogen requirement of the stand and occurrence of fire or burning of litter can reduce this (Drechsel and Zech, 1994). Vigulu *et al.* (2019) have observed that in early stages of plantations, C and N return to the soil is density depended with higher densities producing more litter. In 10 to 15 yar old teak taungyas of Western Nigeria, the leaf litter contained 90.9 kg ha^{-1} N, 10 kg ha^{-1} P, 71 kg ha^{-1} K, 188 kg ha^{-1} Ca, 21.6 kg ha^{-1} Mg and 2.1 kg ha^{-1} Na of which 90% were concentrated in leafy matter. It was also reported that the litter decomposition happened in within a time of 6 months (Egunjobi, 1974).

2.5. Harvest related productivity loss

Harvesting operations affect plantation or forest soil in number of ways including soil compaction, soil erosion and loss of soil carbon and nutrient pool (Picchio *et al.,* 2020). Harvest related productivity decline or productivity loss has been reported in various studies from around the globe. This can be attributed to nutrient export, displacement and loss from the plantation site as a resultant of harvest and associated activities (Kimmins, 1976; Thompson *et al.*, 1986). Plantation soil degradation can be due to varied reasons from soil erosion (Fernández-Moya *et al.*, 2014) to negative nutrient budget that results from repetitive timber harvest (De Oliveira *et al.,* 2018). Harvesting multiple rotations of crop from the same site leads to depleting soil fertility. Whole tree harvesting results in what can be termed as “nutrient export” and thereby reduce tree growth (Boyle *et al.*, 1973). Fernández-Moya *et al.*, (2014) based on their work in Central America noted that nutrients are carried ex situ as a result of timber harvest in teak plantations. The nutrients Ca N, K and Mg were the most exported based on their estimated magnitudes that was 281, 220, 88 and 63 Kg ha^{-1}, respectively at 19 years of age. In a study to understand the of seasonal translocation and resorption of nutrient between woody biomass and foliage in teak plantations of Costa Rica, and the possible changes in nutrient export that can be brought about by changing harvest seasons, it was reported that a shift of harvest period from dry period (January-March) to wet period (August – October) can reduce the N, P, K exported by 24, 29 and 43%, respectively this is due to nutrients being translocated to foliage which shall be left over as slash in timber harvest (Fernández-Moya *et al.,* 2015). It has been reported that, whole tree harvest of teak can lead to an export of N and P in the magnitude of 462.4 and 167.9 kg·ha^{-1} from above ground at an age of 30 years (Jha, 2014). Burning slash after harvest in timber harvesting for site preparation for next planting leads to a short-lived peak in nutrient availability which will decline in a few months due to leaching. Nadel (2005) reported a 78- 99 % loss of N, P and K from the slash after it was burned in *Eucalyptus grandis* plantations in South Africa.

Higher magnitudes of nutrient loss from the stand area due to harvest are beyond the limit of natural fertility recuperation. This results in soils becoming impoverished after each rotation that may lead to a decline in tree growth and productivity in successive rotations. To quote an example, “second rotation productivity decline” has been observed to be up to 7% in blue gum (Battaglia *et al.*, 2015). Jha, (2016) advocates for better management practices with longer rotation and possible nutrient inputs for sustainable teak productivity at any given site.

2.6. Genetic improvement on teak

Genetic improvement in trees attempt to bring together the desired characters into select individuals and then propagate the superior individuals. Clonal forestry allows full use of non-additive gene effects like dominance, epistasis, over dominance and full or half sib progeny trials allows the use of additive gene effects (Zobel and Talbert, 1984). The genetic improvement programs in teak are aimed at developing resistance to pests, and improving the rate of growth and stem form so that grater length and volume of straight bole can be obtained in shortest possible time (Kedharnath, 1984). Teak genetic improvement in India was started in 1962 by Forest Research Institute. Works on genetic improvement for resistance have identified teak clones that are resistant to *Hyblaea puera* Cram and *Eutectona machaeralis* Walker (Ahmad, 1987; Roychoudhury *et al.*, 2016). Bhat and Priya (2004) studied the provenance variation in wood properties of teak along the western ghats to identify superior provenances for teak selection. Their results showed increasing mechanical strength as associated with a greater cell wall percentage on moving from 9° to 15° S. Under the teak improvement program of KFRI, Clonal Seed Orchard was established in Nilambur in 1979 (Venkatesh *et al.*, 1986). An international provenance trial was coordinated by the DANIDA Forest Seed Centre in 1970s and the initial evaluation was done for 21 trials in 1980s at 9-10 years (Keiding *et al.,* 1986). The second evaluation of the trials at 17 years found significant differences between the provenances with respect to various properties (Kjaer *et al.,* 1995)

2.7. Planting material in teak plantations

Teak can be propagated by direct seeding, stump planting, through root container grown seedlings, and also by coppice after felling. Stump planting has been the conventional planting method of teak as direct sowing needs protection which is difficult to provide at larger scales (Chareonmit, 1960). Stump planting has the advantages of minimum labour requirement and easy transport of planting material. It has been the major accepted method for teak plantation establishment for over the last century.

Being in practice since 1990s in India (Khedkar and Subramanian, 1996) root trainer nursery technology now getting more familiar and getting practiced more owing to its biological advantages over stump planting. Root trainer raised seedlings would have better development of biologically desirable lateral roots, hence they show better vigour and collar diameter increment compared to stump raised seedlings (Khedkar and Subramanian, 1997). The development of multiple tap roots in root trainer teak exhibited better diameter growth in comparison to stump planting (Khedkar, 1999). George *et al.* (2019) based on comparative performance study of root trainer and stump grown teak plantations of age 6 years reported that root trainer grown teak performed better in tree or bole height, basal area and crop volume.

Coppicing can also be used as a method of reforesting teak stands after harvesting (Kwame *et al.,* 2014). Teak coppice shoots have been reported to perform well in the earlier stages of growth but the development in the later stages of a 60 year rotation can be lower (Bailey and Harjanto, 2005). Auykim, *et al.* (2017) compared the growth of stump and coppice teak in Thailand and noted that coppice showed better CAI till first 8 years of growth and later declined from the 9^{th} year. Another problem with coppice might be the fact that coppice shoots develop at the edge of the tree stump, far from the centre, which might adversely affect the wood quality of the bottom part (Bailey and Harjanto, 2005).

2.7.1. Other types of propagation

Teak is grown traditionally through seedlings or stump planting. But often times large scale propagation of teak is limited due to the disadvantages of producing large amount of planting material in short periods of time and lack of superior quality seeds from quality assured sources. The conventional methods of propagation cannot be employed to fulfil the largescale propagation of superior genotypes. Clonal propagation of teak have been achieved through auxin treatment. Palanisamy and Subramanian (2001) achieved rhizogenesis in cuttings from coppice shoots of 63 year old trees and 1 to 2 year old stumps. The study found that the coppice cuttings showed 74 to 91% rooting on treatment with 2000 ppm IBA and stump shoots gave 79 to 100% with 1000 ppm IBA.

For large scale multiplication of superior genotypes, tissue culture in teak have been proposed (Apavatjrut *et. al.,* 1988). Monteuuis et.al, (1998) studied the commercial level micropropagation strategies for teak and reported that cultures can be initiated from 1 to 2 cm long mononodal portions from actively growing portions. Yashodha *et al*. (2005) developed improved micropropagation technology for teak in which seeds from clonal seed orchards were germinated in vitro and the seedings used for culturing. For this with mononodal cuttings were taken from 65 to 75-day old seedlings. Studies from Malaysia show that true to type cloning is possible in teak through tissue culture and the seedlings showed growth comparable to the superior mother trees (Chila, 2003).

2.8. Teak growing systems

Historically, before the first plantations of teak were established, it was extracted from natural forests by selection felling of superior trees. The earlier plantations were monocultures of teak that would be clear felled and this still remains the major teak management system. Taungya cultivation were initiated around 1956 in Myanmar (Ball *et al.,* 1999). Teak has an ability to grow along with other associated species like *Terminalia chebula*, *T tomentosa, T paniculata*, *Haldina cordifolia, Dalbergia latifolia, Mitragyna parviflora, Schleichera olesa* and *Gmelina arborea* (Singh *et al.,* 2010). This innate character makes teak a potential candidate for mixed species silviculture. One of the possible combination of species mixing in teak is mixing it with nitrogen fixers. (Kumar et al. 1998) based on studies in central humid Kerala reported that a 33: 67% mixture intercropping of teak and Leucaena showed 41% and 71% higher values for height and diameter at breast height for teak compared with monoculture stands during the first 44 months of growth. In a study to compare teak intercropping with *Albizia procera*, *Leucaena leucocephala* and *Acacia auriculiformis,* showed that diameter growth of teak is affected by species mixing. It was also noted that nitrogen fixing was highest in the case of Albizia mixture (Sein and MeAung, 2016).

Though in a large chunk of the literature available, we see teak as a plantation tree. Teak is a major component of smallholder multispecies agroforestry systems in many tropical countries (Kumar et al.1994; Roshetko *et al.*, 2013a; Roshetko *et al.*, 2013b) Teak smallholder systems provide 40% of household income via timber and agriculture in rural Indonesia (Roshetko *et al.*, 2013b).

Materials and Methods

III. MATERIALS AND METHODS

The present study aimed at studying the growth and productivity of teak with respect to site quality and age was carried out at Nilambur North and Nilambur south forest divisions during the period of 2019-2021. Based on information acquired through preliminary reconnaissance survey in the two administrative territorial divisions, representative teak stands belonging to five representative age classes (10-20, 20-30, 30-40, 40-50 and above 50) and four site qualities (SQI, SQII, SQIII and SQIV) together constituting a total of 20 teak plantations for the study. Consistent with this, soil sampling was done in the selected mature plantation (40-50 years) and their corresponding open contiguous areas in all four site qualities.

3.1 Location

The study was done in teak plantations in 20 plantations distributed across the 5 territorial forest ranges that falls in Nilambur South and North Forest divisions. The ranges were Karulai and Kalikavu from Nilambur South and Edavanna, Vazhikkadavu and Nilambur from Nilambur North. Nilambur falls to the eastern part of Malappuram district of Kerala along the banks of Chaliyar river and have the ranges and spur of western ghats. The centre of Nilambur falls at an elevation of 400m from mean sea level. Nilambur experiences fairly high rainfall of above 2500 mm annually and have average daily temperature ranging between 19 to 30 C^{o}. Nilambur has several small tributaries of the river Chaliyar, following among the hills of the western ghats. The soil in the hills is generally loamy in nature and the riverbeds have rich alluvial deposition. With a high precipitation, there is sufficient moisture throughout the year. The plantations selected for study based on their site quality and age class are listed in Table 1.

Table 1. Plantations selected for the study based on site quality and age class from the Nilambur South and Nilambur North Forest divisions, Kerala.

Site Quality	Age Class	Plantation Name	Year	Age	Division
I	10 to 20	Old Amarambalam CSO	2000	20	N S
	20 to 30	Emangadu	1997	23	N S
	30 to 40	Erampadam	1984	36	N N
	40 to 50	Kariem-Muriem Bit 2	1977	43	N N
	50+	Nedumgayam	1909	111	N S
II	10 to 20	Old amarambalam palamala	2004	16	N S
	20 to 30	Elancheeri Bit II	1994	26	N N
	30 to 40	Nedumgayam	1985	35	N S
	40 to 50	Elancheeri	1975	45	N N
	50+	Ex-Manjerikovilakom	1956	64	N N
III	10 to 20	Old Amarambalam SSO	2000	20	N S
	20 to 30	Elancheeri Bit I	1994	26	N N
	30 to 40	Elancheeri	1983	37	N N
	40 to 50	Paramankunnu	1979	41	N N
	50+	Mundakkadavu	1962	58	N S
IV	10 to 20	Old Amarambalam	2000	20	N S
	20 to 30	Kanjirakkadavu	1997	23	N S
	30 to 40	Churulippotti bit 2	1983	37	N S
	40 to 50	Mooleppadam	1977	43	N N
	50+	Edacode	1963	57	N N

Figure 1.Map showing the location of the 20 plantations that were selected for study in Nilambur north and Nilambur south forest divisions

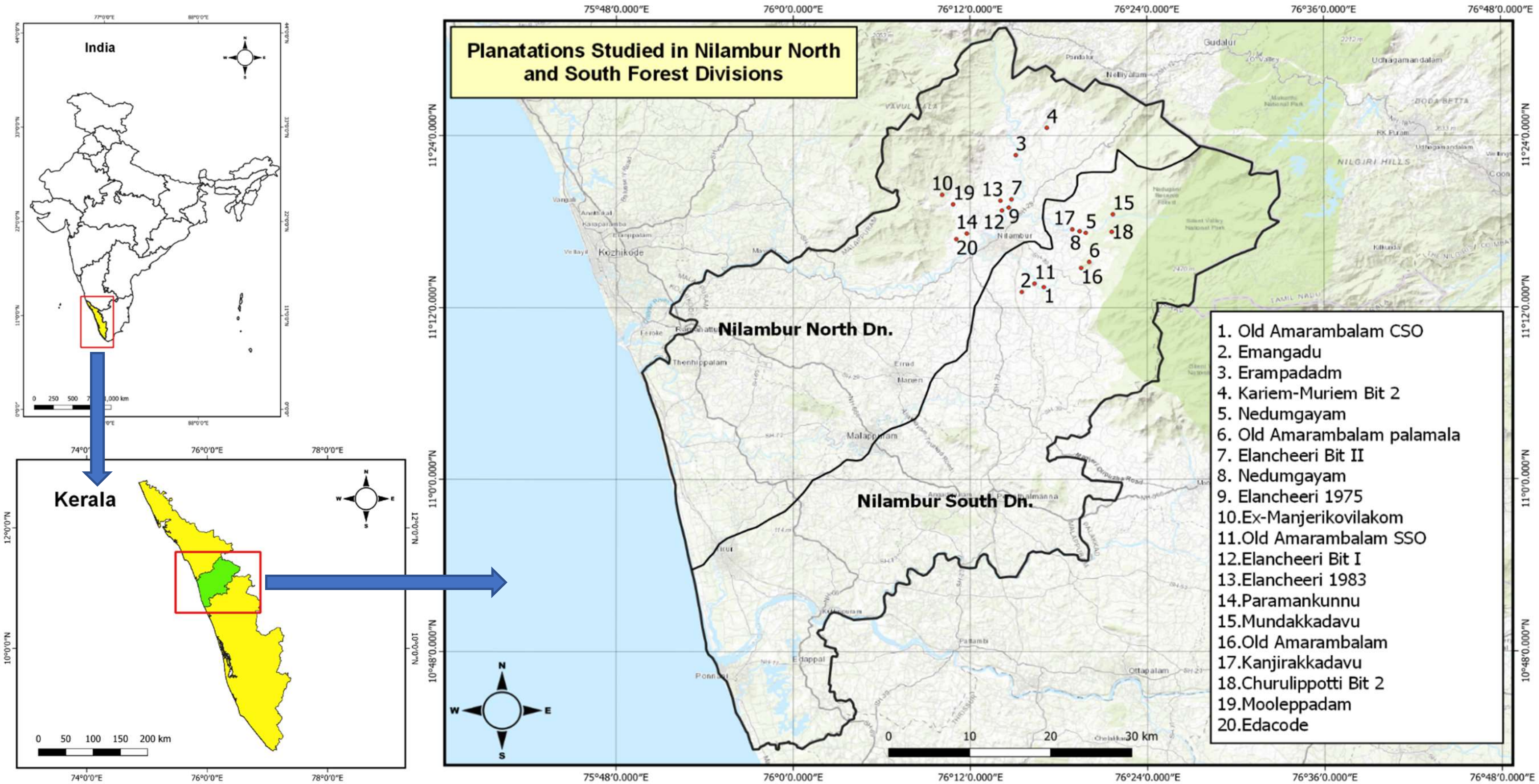

Table 2. Short description of the selected plantations, the range in which they are located and other site descriptions.

Description of the 20 plantations studied			
Site Quality	**Age**	**Plantation**	**Description**
SQ I	**10-20**	Old Amarambalam CSO	Located in Kalikavu range Established with clonal material of superior trees Management: Well managed with thinning being done as per schedule Adjacent to river Superior growth of trees
	20-30	Emangadu 1997	Located in Kalikavu range Growth of thick shrubby undergrowth present Lianas like Calicopteris floribunda growing on trees
	30-40	Erambadam	Located in Nilambur range Adjacent to Chaliyar river Silt deposition in areas adjacent to river Trees show good growth nearer to river Lianas and miscellaneous trees have invaded the areas farther from river.
	40-50	Kariem Muriem	Located in Vazhikkadavu range Soil erosion evident in the terrain Presence of Elephants in the plantation when the study was being done

	50+	Nedungayam	Located in Karulai range Part of the plantation used as timber depot Old and large trees Frequented by elephants Adjacent to Pandipuzha river
SQ II	**10-20**	Old Amarambalam-Palamala	Located in Kalikavu range Thich growth of understory shrubs and lianas Presence of wind fallen trees Hilly terrain and therefor erosion happening
	20-30	Elencheri	Located in Edavanna range Presence of miscellaneous trees Lianas like Calicopteris floribunda growing on trees
	30-40	Nedungayam	Located in Karulai range Adjacent to river Frequented by elephants Elephant damage to trees making them crooked and forked
	40-50	Elencheri	Located in Edavanna range Fairly well managed plantation No liana growth on trees Shrub removal has been done in the plantation
	50+	Ex-Manjerikovilakom	Located in Edavanna range Resembles a natural forest

			Varied species of miscellaneous trees are present The microclimate is moist with ephemeral steams flowing through the plantation.
SQ III	**10-20**	Old Amarambalam SSO	Located in Kalikavu range Established with Seedlings of superior trees to be managed as a seed orchard Well maintained with timely management interventions Adjacent to river
	20-30	Elencheri	Located in Edavanna range Presence of miscellaneous trees Trees have liana infestation
	30-40	Elencheri	Located in Edavanna range Fairly good growth of teak No shrub and liana infestation in the plantation Presence of top broken trees observed
	40-50	Paramankunnu	Located in Edavanna range Resembles natural forest Miscellaneous trees and lianas present Soil erosion in slopy areas The plantation is divided into two bits, The first bit has fairly good growth of teak while the second is comparatively low in growth performance.

	50+	Mundakkadavu	Located in Karulai range Adjacent to Chaliyar river Silt deposited in the plantation due to floods Presence of elephants in the plantation The younger adjacent plantations failed to establish due to elephant damage
SQ IV	**10-20**	Old Amarambalam	Located in Kalikavu range High density of 2m x2 m Absence of thinning operation being done Presence of lianas and shrubby undergrowth Terminalia paniculata is the major miscellaneous tree present
	20-30	Kanjirakkadavu	Located in Karulai range Sloppy terrain Presence of elephants in the plantation Elephant damage to trees Shrubby undergrowth present
	30-40	Churulippotti	Locate in Karulai range Plantation resembles a moist deciduous forest Trees like Terminalia paniculata, Macaranga peltata, Ptreospermum reticulatum are present Heavily infested with lianas.

	40-50	Muleppadam	Located in Edavanna range Hilly terrain, trees are having good growth at lower elevations of the hill but trees in higher elevations were smaller Presence of miscellaneous trees and lianas
	50+	Edacode	Located in Edavanna range Hilly terrain with good growth in lower elevations Trees are smaller towards hill top Thick bamboo regeneration was observed as undergrowth.

3.2 Methods

Plot layout

Five Representative plots of size 24m x 24m were selected from each plantation except the smallest plantation of size 0.4 ha, for measuring the growth attributes using random sampling method. With the help of forest staff, the plots were selected and demarcated in a manner that they represent the whole area of each plantation.

After laying out the plots, all teak trees in each plot were measured for height, diameter at breast height, bole height, upper bole diameter and canopy width. In mature plantations of each site quality (40- 50 years of age) a soil sampling pit of 1m was dug and triplicate samples were taken from each of the 20 cm depth classes viz. 0-20, 20-40, 40-60, 60-80, 80-100 cm. The soils were analysed for all the prominent physio-chemical attributes.

Plate 1: Measurement of growth parameters of teak in Nilambur, Kerala

Plate 2: Growth of Miscellaneous trees in teak plantations of Nilambur, Kerala

3.2.1 Growth observation of trees

From each demarcated plot, growth parameters such as height, diameter at breast height, bole height, upper bole diameter and canopy width were measured.

3.2.1.1 Height and diameter measurement

The teak enumeration plots were laid with tape and ropes and growth attributes were measured. For enumeration of plots, 24m ropes were run at right angles to form a square plot of size 24mx24m and the weed and shrub undergrowth was cleared for easy commute for tree measurement.

Height measurement: Height measurement was done using Suunto Clinometer with 0.1 cm precision (Suunto, Japan). The total height of individual trees and the bole height was estimated by looking at the scale of the clinometer while aligning it to the top point and the crown point of the tree, from a horizontal distance of 15m.

Diameter measurement: Diameter at Breast height (DBH) was measured using Mantex Laser Tree Calliper with 0.5 cm precision (Mantex, Hagloff, Sweden). Two perpendicular axes of DBH were measured by direct contact of instrument and averaged. Upper stem diameter at top of the clear bole was measured using the laser pointers of the tree calliper by pointing it at 2 ridges of top point of the bole.

3.2.1.2 Crown width/ Canopy width

Measurement of Individual tree canopy width was done by projecting the crown to the ground. Two measurements in perpendicular directions were taken and then averaged to give the crown diameter

3.2.1.3 Basal area and volume

Basal area

The basal area of individual trees was calculated from the DBH values using the formula BA= $\pi d^2/4$.

Where d= Diameter at Breast Height (DBH)

The basal area values were used to calculate the average individual basal area and total basal area per hectare of the plantations

Volume

The total volume of individual trees was calculated using the equation

$$V = BA \times h \times f$$

Where,

V=Volume

BA= Basal area

h = tree height

f = form factor

Volume of Bole

Volume of bole was calculated using the formula

$$\text{Volume,} \quad V = L\,\frac{Ab + At + \sqrt{AbAt}}{3}$$

Where,

L= length of bole

Ab= Basal area at breast height

At= Basal area at top point off bole

From the tree and bole volumes calculated, average individual volumes and total volume per hectare values were calculated for each of the 20 plantations

3.2.2 Soil analysis

For soil analysis, one-meter-deep soil pits were dug using pickaxe and spade in the selected plantations of age class 40-50 and adjacent open contiguous areas. From each depth, sampling was done in triplicates.

The soil samples were collected from the field in polyethylene bags, tagged and brought to the soil analysis lab at Dept. of Silviculture and Agroforestry, college of Forestry for estimation of physio chemical attributes. The soil samples were then spread for drying in trays. The clods of soil in the dried samples were broken with a pestle and mortar following which the samples were sieved and re-bagged in polyethylene bags and labelled. The samples were then used for different physical and chemical property estimations.

3.2.2.1 Soil physical properties

Physical properties of soil including Bulk density and soil texture were analysed across different depths in the soil pits made inside and outside the mature age class plantations in each site quality.

Bulk density

For measuring Bulk density, soil core was extracted from each depth class with specially designed steel cylinder. Undisturbed soil cores were taken gently so that the insertion of the core sampler shall not disturb the soil and cause compaction. The soil samples were oven dried at 105 ^{0}C for 48 hours and till constant weights are attained. The volume of the soil was measured by measuring the internal volume of the cylinder.

Bulk density was calculated as

$$\text{Bulk density}(g/cm^3) = \text{Oven dry weight}(g) / \text{Volume of soil}(cm^3)$$

Plate 3. Sampling of soil for analysis

Plate 4. Soil Chemical Analysis

Soil texture

For analysing the texture of soil samples, particle size analysis and separation of particles was done according to the International Pipette Method (Olmstead *et al.*, 1930). For this, 20g of soil sample was weighed and taken in a 500 ml beaker to which 50ml of 30% H_20_2 was added. The sample was stirred thoroughly so as to prevent frothing over. Additional volume of H_20_2 was added along with heat by placing the beaker with sample on a hot plate to promote complete oxidation of organic matter and disaggregation of soil particles. This was done till no more frothing was observed. The sample was then allowed to cool and 20 ml of 2N HCL was added to remove any of the carbonates that are present and the mixture was kept overnight. Following this, the mixture was filtered using Whatman No.42 filter paper. The filtrate was then washed from the filter paper into 500 ml beaker. To the washed filtrate, 8 ml of 1N NaOH was added. Then it was sieved into a 1 litre measuring cylinder through a 0.2mm sieve to remove the coarse sand particles. The coarse sand was transferred to a pre-weighed China dish and kept in oven. The volume of the suspension in the measuring cylinder was made up to 1 litre and a mark was made over the measuring cylinder at 10 cm from the top level. The temperature of the suspension was recorded using a thermometer and base on settling time of different sized particles at 10 cm depth, 20 ml was pipetted out from 10 cm depth at specific time after freely suspending the particles in water. Silt+ Clay fraction was first pipetted out into pre-weighed China dish and the volume was again made to 1 litre; later clay alone was pipetted out. After this the bulk of the suspension was poured off so that only the settled fine sand remains. This was then moved to a 500ml beaker and the fine sand was washed repeatedly so that the colour of the supernatant was that of the water added after settling of sand. The fine sand also was then kept for drying in a pre-weighed China dish in oven. The dry weight of each of the separates kept in oven was recorded for further calculation.

Based on the dry weight recorded, the percentage of each soil sperate was calculated as:

Coarse sand percentage = dry weight of coarse sand x 100/20

Fine sand percentage= dry weight of fine sand x 100/20

(Silt + clay) % = dry weight (silt + clay) x 100/20

Clay percentage = dry weight of clay x 100/20

Silt percentage= (Silt + clay) % - Clay %

3.2.2.2 Soil chemical properties

Chemical properties of soil like soil pH, organic carbon content, total nitrogen, available phosphorus and exchangeable potassium were estimated using standard analytical methods as discussed below.

Soil pH

Soil pH was estimated from an aqueous suspension of soil and water in the ratio 1:2.5 using a pH meter (Eutech, Singapore).

Soil organic carbon

Total organic carbon content was determined by wet digestion method (Walkley and Black, 1934). The soil sample was dried and finely powdered using mortar and pestle and then sieved using 0.2mm sieve. One gram of sieved sample was taken in a 500 ml conical flask and 10ml 1N $K_2Cr_2O_7$ was added and well mixed. To this mixture, 20 ml con.H_2SO_4 was added and kept for 30 min to undergo oxidation. After 30 minutes time, 200 ml distilled water was added so as to stop the reaction. 4-5 drops of ferroin indicator were added to the final mixture and was then titrated with 0.5N $FeSO_4$ taken in a burette.

The soil organic carbon was estimated as:

$$\text{Soil organic carbon (\%)} = \frac{(\text{Blank value} - \text{Titre value}) \times 10 \times 0.003 \times 100}{\text{Blank Value} \times \text{Weight of soil (g)}}$$

$$\text{Carbon stock, } (\text{Mgha}^{-1}) = \text{C(\%)} \times \text{Bulk Density} \times 10 \times 2.24$$

Soil total Nitrogen

Total nitrogen content in the soil was determined by Microkjeldahl digestion and distillation method (Jackson, 1958). One gram of soil sample was taken in a digestion tube and mixed with 10 ml Conc. H_2SO_4, digestion mixture (K_2SO_4:$CuSO_4$, 10:1 ratio) and Selenium powder. This was kept overnight for pre digestion and then transferred to a digestion chamber. The digested sample was taken and diluted to 100 ml, from the aliquot 10 ml was transferred into an auto distillation kjeldahl unit and inflamed wit 40% NaOH, the liberated ammonia was collected in 4% Boric acid. The solution was then titrated with 0.1 N HCL with a blank run simultaneously. The nitrogen content in soil was calculated as.

Percentage of N in the sample $= V \times 0.01 \times 0.014 \times 100/10 \times 100/W$

Where V= sample titer value- blank titer value; W= weight of soil taken

$$\text{Nitrogen stock, } (\text{Mgha}^{-1}) = \text{N(\%)} \times \text{Bulk Density} \times 10 \times 2.24$$

Soil available Phosphorus

Available Phosphorus in the soil samples were extracted using Bray No.1 reagent and estimated calorimetrically by Molybdate-ascorbic acid blue colour method (Watanabe and Olsen, 1965) using spectrophotometer (Thermo scientific, USA).

$$\text{Available P(ppm)} = R \times 50/5 \times 25/5$$

$$\text{Available P } (\text{Kgha}^{-1}) = \text{P(ppm)} \times 2.24$$

Where R= reading from spectrophotometer

Soil exchangeable Potassium

Available Potassium in the samples was extracted using neutral normal Ammonium acetate solution and thereafter estimated through flame photometry (Jackson, 1958).

$$\text{Available K in soil (ppm)} = R \times 25/5$$

$$\text{Available K (Kgha}^{-1}) = \text{K(ppm)} \times 2.24$$

Where R = flame photometer reading

3.2.3 Statistical analysis:

The data collected was analysed using SPSS version 2.0 and Microsoft Excel (Office 2019). A univariate ANOVA was done for different parameters across different plantations in each age class. Independent t-test was done to analyse the variation between soils within plantation and in open contiguous areas in each site quality to understand the effect of tree growth in the soil profile. Univariate ANOVA was done for soil characters across site qualities to understand the variation in soil properties between the sites that were subjected to soil study.

Results

IV. RESULTS

In the present study attempted to evaluate the growth and productivity attributes of teak in Nilambur North and South Forest divisions, Kerala. This involved analysis of the growth and productivity attributes of teak belonging to four site qualities and under five age classes for each site quality (age class 10-20, 20-30, 30-40, 40-50 and 50 above). Attempts were also made to assess the changes in soil physio-chemical attributes as function of site quality and age (age limiting to 40-50 cm). This was done by taking one-meter-deep soil profile and sampling from five depth intervals of 20 cm thickness. The salient results observed are summarised below.

4.1 GROWTH PARAMERTERS

Growth parameters such as total tree height, bole height, diameter at breast height, canopy width, diameter at crown point, taper and basal area were measured and estimated for trees belonging to various age classes and site qualities.

4.1.1 Total tree height

Tree height is often considered as the best indicator of the potential of a site. The average total tree height of each of the planation was calculated from the individual tree heights of all sampled trees from representative plots

The average height of trees in the selected plantations are shown in Table 3. The tallest among the 20 plantations studied was the 50+ age class plantation belonging to SQ I with an average tree height of 42.01 m and the shortest was the one falling in 10-20 age class of SQ IV having an average tree height of 10.19 m. There was no perceptible trend in height increment between plantations either across SQ or age class. Yet another observation was the consistent decline in height in the lower age class (10-20) with reduction in site quality from SQ I to IV. A similar decreasing trend in height from SQ I to IV can be seen in the plantations of 20-30 years of age. However, higher aged plantations (30-40 and 40-50) showed characteristic levelling off height with in a range of 20 to 25m.

Plate 5. Elephant damage in teak plantations of Nilambur

Plate 6: Liana infestation in teak plantations of Nilambur.

Table 3. Mean tree total height for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Average height of trees (m)					
Site Quality	Age Class				
	10-20	20-30	30-40	40-50	50+
SQ I	17.14^{a}	19.03^{a}	25.43^{a}	18.30^{b}	42.01^{a}
SQ II	11.13^{b}	16.89^{b}	25.43^{a}	21.83^{a}	30.91^{b}
SQ III	14.98^{c}	16.98^{b}	20.12^{b}	20.17^{ab}	26.10^{c}
SQ IV	10.19^{d}	15.71^{b}	22.86^{ab}	23.63^{a}	25.54^{c}
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.145	0.187	0.330	0.25	0.59

Means with same superscripts do not differ significantly.
Comparisons made across site qualities alone.

The height of trees did not show the expected results for their site quality. For instance, the height of a SQ I plantation should be at 28.04 – 33.8 m at the age of 40 years based on the all-India yield table for teak. However, the present study reveals that as per the observed tree height (18.30m), the SQ I plantation of the age class 40-50 falls actually in SQ III (Table 3). Similarly, for a SQ IV plantation, the expected top height is between 10.16- 16.15m as per All India site quality table. However, the average tree heights for the designated SQIV at the age class 40-50 is considerably higher (23.63m) suggesting that the plantation designated as SQ IV by the forest department may actually fall in a higher site quality.

4.1.2 Average Bole Height

The variation in average bole height for teak as influenced by site quality and stand age are presented in Table 4. The average bole height varied from 4.18 to 20.75 m among the studied teak plantations. The lowest value was for the SQ IV plantation of age class 20-30 and the highest in the SQ I plantation of age class 50+.

Table 4. Mean tree bole height for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Mean Bole Height in meters					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	12.70^{a}	12.31^{a}	12.40^{a}	8.11^{c}	20.75^{a}
SQ II	7.47^{b}	9.62^{b}	7.10^{c}	11.72^{b}	18.85^{a}
SQ III	9.16^{a}	9.67^{b}	10.38^{b}	11.34^{b}	9.82^{c}
SQ IV	7.76^{b}	4.18^{c}	8.84^{c}	12.29^{a}	15.47^{b}
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.124	0.219	0.240	0.309	0.275

Means with same superscripts do not differ significantly.
Comparisons are done only across site qualities.

In general, the best site quality regime (SQ1) showed higher bole height for all the age classes except for 40-50 age class which incidentally recorded the lowest value. Interestingly, this age class recorded the highest bole height associated with the poor site quality (SQ4). In general, the variation in bole height across age classes and site quality regimes give trends with lesser predictions though many showed statistically significant values. For instance, the age classes 10-20, 20-30 and 30-40 showed a general decline in bole height with modest variations. However, the trends were variable at higher age classes.

4.1.3 Diameter at Breast Height (DBH)

Diameter at Breast Height is often considered the best measure of the growth of a tree. In the present study the DBH of individual trees in the sample plots within the selected plantations was recorded and averaged to obtain the mean DBH of each teak plantation (Table 5). In general, site quality I recorded higher DBH for all age classes as compared to other site qualities. There was a general decline in DBH with decrease in site quality (SQ1 to SQ4) in each of the age classes.

For instance, the plantations of age class 10-20 showed the highest DBH of 28.86 cm for SQ1 while the DBH declined to 12.92 cm at SQ IV. Similar was the case with age class 20-30 where the highest DBH was for SQ I (29.40cm) and the lowest was for SQ IV (19.25 cm). However, with increase in stand age, the effect on site quality on the DBH seems to be levelling off. For instance, for the age class 30-40 cm, the variation in DBH across site qualities (SQ2 and SQ3, SQ4) was very minimal. Similar was the trend for age class 40-50 with insignificant variation among top site qualities (SQ1 and SQ2, SQ3). Obviously, an increase in DBH with increase is age class is evident for the teak trees in all site qualities.

Table 5.Mean Diameter at Breast Height for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Diameter at Breast Height (cm)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	28.86^{a}	29.40^{a}	35.50^{a}	31.71^{a}	77.50^{a}
SQ II	13.90^{c}	24.86^{b}	25.84^{b}	32.80^{a}	42.23^{b}
SQ III	23.55^{b}	20.37^{c}	25.41^{b}	32.03^{a}	34.07^{c}
SQ IV	12.92^{c}	19.25^{c}	25.60^{b}	23.84^{b}	36.56^{bc}
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.323	0.406	0.535	0.574	1.60

Means with same superscripts do not differ significantly.
Comparisons done across site qualities only

4.1.4 Diameter at Crown point (DCP)

The average diameter at crown point of the plantations varied from 8.99 cm to 53.29 cm among the 20 plantations under study. The plantation above 50 years age and belonging to top site quality (SQ-I) showed the highest DCP (53.29 cm) while the lowest DCP was recorded for younger plantation (10-20) at poor site quality (8.99 cm; SQ IV).

Table 6. Mean Diameter at Crown Point for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Diameter at crown point (cm)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	17.63[a]	18.99[a]	22.71[a]	22.95[a]	53.29[a]
SQ II	9.77[c]	16.74[b]	17.30[b]	22.18[a]	27.36[b]
SQ III	15.67[b]	12.56[c]	17.34[b]	21.90[a]	24.54[b]
SQ IV	8.99[d]	13.77[c]	18.98[b]	16.49[b]	23.75[b]
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.214	0.291	0.399	0.400	1.11

Means with same superscripts do not differ significantly.
Comparisons done only across site qualities

Domination in DCP growth was exhibited by plantations of all age classes belonging to the highest site quality of SQ1. Also, the changes in DCP values in SQ1V were considerably lower as compared to SQ I. However, the changes in DCP across the lower site qualities where not following predictable patters despite the overall decline in DCP observed the site qualities. For instance, in the age group 10-20, the SQ I plantation showed an average DCP of 17.63 cm and the other 3 plantations (SQII, SQIII and SQIV) showed values less than this, with SQ III incidentally showing a DCP value of 15.63 cm which is higher than the value of 9.77 recorded in the SQ II plantation. Also, for age classes 30-40, 40-50 and 50 above, the corresponding site qualities (II, III and IV) showed DCP values that were not significantly different from one another with only SQ I plantations showing a significantly higher value of DCP (Table 6).

4.1.5 Basal Area

Table 7 and Table 8 illustrates the changes in BA for teak grown at variable sites qualities and age classes. Basal area being a strong determinant of tree growth and productivity, it assumes considerable importance. As evident from the table, the top site quality (SQ1) had distinctively higher BA for all age classes as compared with all the other site qualities.

Table 7.Mean individual Tree Basal area for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Mean tree basal area (m^2)					
Site Quality	Age Class				
	10-20	20-30	30-40	40-50	50+
SQ I	0.065^{a}	0.068^{a}	0.099^{a}	0.079^{a}	0.471^{a}
SQ II	0.015^{c}	0.049^{b}	0.052^{b}	0.084^{a}	0.140^{b}
SQ III	0.044^{b}	0.033^{c}	0.051^{b}	0.081^{a}	0.091^{c}
SQ IV	0.013^{c}	0.029^{c}	0.051^{b}	0.045^{b}	0.105^{bc}
p value	<0.001	<0.001	<0.001	<0.005	<0.001
SEM	0.001	0.002	0.003	0.003	0.014

Means with same superscripts do not differ significantly.
Comparisons done only across site qualities

The mean tree basal area in the various teak plantations under study varied from 0.013 to 0.471 m^2. Among the various site quality and age class combinations the lowest mean tree BA was reported by younger plantations (10-20 years) in the lowest site quality (SQ4). Similarly, the largest mean basal area was recorded for the SQ I plantation for age class 50 above. In general, increase in BA with increase in site quality and age is discernible in the study. However, the trends are often fluctuating especially for younger age class across sites qualities. For instance, the 10-20 age classes showed sharp decline in mean tree BA across site qualities despite a fluctuation in SQ3. Yet another prominent observation was that the teak stands response to site quality reduced with increasing age. There were only modest changes in BA among intermediate site qualities (SQ2, SQ3) for the age class 30-40 and 40-50. For example, the mean tree basal area of the SQ II, III and IV plantations were 0.052, 0.051 and 0.051 m^2 respectively for age class 30-40 and similarly, the mean BA values for the SQ I, II and III plantations were 0.079, 0.084 and 0.081 m^2 respectively (Table 7).

Table 8. Basal Area Per Hectare (BAPH) for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Total Basal Area of plantation (m^2 ha^{-1})					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	19.98	17.01	12.33	20.03	35.37
SQ II	6.11	22.37	12.29	16.17	16.08
SQ III	12.84	6.96	14.52	13.08	12.44
SQ IV	11.06	6.72	3.57	8.65	14.79

From Table 8, it is interesting to observe considerable variation in BAPH for teak from the general trend observed for all growth variables. Obviously, the SQ1 represented higher BAPH for most of the age classes with the highest value corresponding to 50 plus age class (35.37 m^2 ha^{-1}). However, the decline in basal area with lowering of site quality was not proportional. For instance, the BAPH for SQ1 at 10-20 age class was 19.98 m^2 ha^{-1} which declined sharply to 6.11 at SQ2 and further increased twice the value in SQ3 and SQ4. A similar increase in BAPH was observed from SQ1 (17.01 m^2 ha^{-1}) to SQ2 (22.37 m^2 ha^{-1}) at age class 20-30 which were deviation from the expected lines. The lowest productivity in terms of BAPH was reported by SQ IV plantation of age 30-40 (3.57 $m^2 ha^{-1}$; Table 8).

4.1.6 Tree volume in plantations

Average bole volume, Average tree volume, total bole volume per hectare and total tree volume per hectare was calculated for the plantations studied. The observed values are represented in Table 9 to Table 12.

Table 9.Mean bole volume for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Average individual bole volume (m3)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	0.58^{a}	0.62^{a}	0.96^{a}	0.53^{c}	7.32^{a}
SQ II	0.09^{c}	0.37^{b}	0.34^{bc}	0.72^{a}	2.27^{b}
SQ III	0.30^{b}	0.23^{c}	0.41^{b}	0.71^{a}	0.73^{d}
SQ IV	0.08^{c}	0.11^{d}	0.27^{c}	0.59^{b}	1.30^{c}
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.0097	0.016	0.027	0.030	0.245

Means with same superscripts do not differ significantly.
Comparisons done across site qualities only.

The average bole volume of the plantations varied from 0.08 m^3 to 7.32m^3. the lowest value was recorded for the SQ IV plantation of age class 10-20 and the highest was the SQ I plantation of age class 50+. Generally, the SQ I planation showed the highest average bole volume, across age groups except in age class 40-50 where it showed the least value. Though there was no trend that could explain the change in bole volume across all the plantations, there was a general decline in mean bole volume as we move from SQI to SQ IV within an age group. For instance, in the age group 30-40, the SQ I plantation had a mean bole volume of 0.96 m^3 which reduced to 0.27 m^3 in the SQ IV plantation (Table 9).

Table 10. Total bole volume for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Total bole volume per hectare ($m^3\ ha^{-1}$)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	174.05	149.54	113.15	130.00	533.64
SQ II	33.16	158.94	73.81	136.77	252.12
SQ III	86.72	47.20	111.93	108.04	94.07
SQ IV	65.83	22.01	20.59	88.68	162.30

Table 11. Mean tree volume for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Average individual tree volume in cubic meter (m3)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	0.76^{a}	0.89^{a}	1.78^{a}	1.02^{a}	13.52^{a}
SQ II	0.12^{c}	0.59^{b}	1.01^{a}	1.22^{a}	2.93^{b}
SQ III	0.45^{b}	0.38^{c}	0.70^{b}	1.15^{a}	1.70^{c}
SQ IV	0.09^{c}	0.46^{bc}	0.69^{b}	0.95^{a}	2.06^{c}
p value	<0.001	<0.001	<0.001	NS	<0.001
SEM	0.0129	0.023	0.052	0.048	0.433

Means with same superscripts do not differ significantly.
Comparisons done across site quality alone

The total bole volume per hectare of the plantations studied varied from 20.59 to 533.64 $m^3\ ha^{-1}$. The lowest value of 20.59 $m^3\ ha^{-1}$ was incidentally observed in the 30-40 age classed plantation belonging to SQ IV and not the young plantation of the lowest age class. Interestingly, the SQIV showed much higher stand level bole volume at age class 10-20 (65.83 $m^3\ ha^{-1}$).

The average individual tree volume (mean tree volume) of teak among the plantation studied varied from 0.09 to 13.52 m^3. Interestingly, it can be observed that in the age class 40-50, the plantations belonging to different site qualities had their mean tree volume values not significantly different from each other. Also, in the age class 30-40, the plantations fell into two levels in terms of mean tree volume with SQ I and II forming one group where the values are at par and those of SQ III and IV forming another group which also were statistically at par (Table 11).

Table 12.Total volume per hectare for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Total volume per hectare of each plantation in cubic meter per hectare (m3ha-1)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	225.88	216.34	210.17	248.57	985.86
SQ II	44.85	256.28	221.68	232.77	325.21
SQ III	127.45	79.53	193.37	175.29	218.85
SQ IV	76.54	90.40	52.99	140.87	258.10

Table 12 shows that the variations in total volume per hectare of all the 20 plantations studied. The values of total volume per hectare varied from 52.99 m^3ha^{-1} in the SQ IV plantation of age class 30-40 to o 985.86 m^3ha-^{1} in SQ I plantation of age class 50 above. It is interesting to note that the lowest per hectare volume in a plantation was observed for a plantation falling in age class 30-40. The age class 40-50 showed a decline in total volume per hectare value from SQ I to SQ IV. In rest of the age classes, there was no such observable trend between the site qualities from SQ I to IV.

4.1.7 Average form factor of bole

Based on the upper and lower diameters and the bole height, Form factor of the bole was calculated for the individual trees and averaged to obtain the average form factor of bole for each of the individual plantations.

Table 13. Average Form Factor of boles for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Average form factor of bole					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	0.69^{d}	0.69^{b}	0.73^{b}	0.75	0.72^{ab}
SQ II	0.74^{a}	0.71^{b}	0.77^{a}	0.72	0.70^{b}
SQ III	0.70^{c}	0.69^{b}	0.72^{b}	0.72	0.74^{a}
SQ IV	0.73^{b}	0.78^{a}	0.75^{ab}	0.73	0.71^{b}
p value	>0.001	>0.001	>0.001	NS	<0.005
SEM	0.012	0.005	0.003	0.004	0.006

Means with same letter are not significantly different
NS: Non-Significant
Comparisons done across site quality only

Table 13 shows the average bole form factor for each of the plantations. The form factor varied from 0.69 to 0.78 between the teak plantations at variable site qualities and age classes (20 plantations). The teak plantations at lower age class showed marginal lower values which increased with age. However, the trends are not conspicuous. Incidentally all the site qualities under the age class 30-40 showed fairly high form factor (0.72 to 0.77). The overaged teak stands showed no appreciable change in form factor across the site quality regimes.

In the Age classes 10-20 and 20-30, the SQ I plantation showed the lowest value for form factor. The highest form factor value of 0.78 was recorded for the SQ IV plantation of age class 20-30. It is interesting to note that the plantations of age class 40-50 showed no significant difference between one another in terms of form factor. Even in the age class 50 above, the plantations of SQ I, II and IV were not significantly different from one another and the plantation of SQ III was not significantly different from SQ I plantation.

4.1.8 Crown diameter

The average crown diameter or canopy width varied between 3.53 m to 12.84m between the 20 plantations. The lowest value of canopy width was seen in SQ II plantation of age class 10-20 and the highest value for the SQ I plantation of the last age class. In the age classes 10-20, 30-40 and 50+, the SQ I plantation had the broadest canopy. In the remaining 2 age classes, i.e., 20-30 and 40-50, the SQ II plantations had the greatest canopy width. In the age classes 40-50 and 50 above, we can see that except for those plantations that are having the broadest canopies, the other three in both age classes have no significant difference between them (Table 14).

Table 14..Average Canopy Width of trees in teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala

Average Canopy Width (m)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	7.45^{a}	5.02^{a}	9.17^{a}	6.72^{b}	12.84^{a}
SQ II	3.53^{c}	5.23^{a}	5.01^{c}	9.39^{a}	6.48^{b}
SQ III	5.32^{b}	4.93^{ab}	7.39^{b}	6.47^{b}	7.45^{b}
SQ IV	3.93^{c}	4.13^{b}	7.61^{b}	6.44^{b}	6.97^{b}
p value	<0.001	<0.001	<0.001	<0.001	<0.001
SEM	0.075	0.068	0.155	0.147	0.258

Means with same letter are not significantly different
Comparisons done across site quality only

4.1.9 Mean Annual Increment (MAI)

The mean annual increment in basal area, individual tre volume and volume was calculated for the 20 plantations. The estimated values are represented in .

Table 15.

Table 15. Mean Annual Increment in Basal Area for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Mean Annual Increment in Basal area of plantations ($m^2ha^{-1}yr^{-1}$)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	0.999	0.740	0.342	0.466	0.319
SQ II	0.382	0.860	0.351	0.359	0.251
SQ III	0.642	0.268	0.392	0.319	0.214
SQ IV	0.553	0.260	0.096	0.201	0.259

From .

Table 15, it can be seen that the MAI $_{(basal\ area)}$ varied from 0.201 to 0.999 $m^2ha^{-1}yr^{-1}$ between the 20 plantations that were studied. The highest value of 0.999 $m^2ha^{-1}yr^{-1}$ was observed in the SQ I plantation of age class 10-20. Expect in the case of SQ II, in all the other 3 site qualities, the plantation belonging to age class 19-20 showed the largest mean annual increment in basal area. Also, it was observed that except for SQ IV, in the other 3 site qualities the 50 above aged plantations showed the lowest values for mean annual increment in basal area. Among SQ IV plantations the 40-50 aged plantation showed the least value of MAI.

Table 16. Mean Annual Increment in timber volume for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Mean Annual Increment in volume of plantations ($m^3ha^{-1}yr^{-1}$)					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ 1	8.70	6.50	3.14	3.02	4.81
SQ 2	2.07	6.11	3.11	3.84	3.94
SQ 3	4.34	1.82	3.03	2.64	1.62
SQ 4	3.29	0.92	0.56	2.06	2.85

The MAI in volume varied between 0.56 to 8.70 $m^3ha^{-1}yr^{-1}$ between the studied plantations. Generally, the SQ I plantations exhibited the best MAI accrual in each age class. $MAI_{(v)}$ declined in the lower site qualities from SQ II to SQ IV with minor variations in the trend. The maximum value of $MAI_{(v)}$ was estimated for the SQ I plantation of Age class 10-20 (8.70 $m^3ha^{-1}yr^{-1}$) and the least value for the SQ IV plantation of age class 30-40 (0.56 $m^3ha^{-1}yr^{-1}$). Across age, there was no perceptible trend of variation in the estimated values of $MAI_{(v)}$. (Table 16). The individual tree MAI in volume ranged from 0.0038 m^3yr^{-1} to 0.0633 m^3yr^{-1}. Obviously, SQ I plantations showed higher mean tree MAI across all age groups. The subsequent site qualities showed a general decline from SQ I to IV with few exceptions. The trend was clearly visible in the age classes 20-30 and 30-40 (Table 17).

Table 17. Mean Annual Increment in Volume for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Mean Annual Increment in individual tree Volume (m^3yr^{-1})					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ 1	0.0212	0.0208	0.0211	0.0112	0.0633
SQ 2	0.0049	0.0154	0.0088	0.0137	0.0283
SQ 3	0.0099	0.0044	0.0086	0.0123	0.0097
SQ 4	0.0036	0.0038	0.0060	0.0087	0.0205

4.1.10 Density of teak trees in plantations

The number of trees in each sampled plots were counted and the stocking density was calculated as number of trees per hectare.

Table 18. Density of teak trees for teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Density of teak in the plantations (number of trees ha^{-1})					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	410	313	149	269	76
SQ II	424	398	240	222	139
SQ III	438	417	354	215	167
SQ IV	917	243	94	236	139

The number of trees per hectare varied between 94 to 917 among the 20 plantations studied. There is difference in number of trees per hectare between the plantations within an age group across site qualities. In the age group 10-20, the

SQ IV plantation is having a high density of 917 trees ha^{-1} while those of SQ I, II and III had a little over 400 trees per hectare. Among the plantations of age class 20-30, The SQ III plantation have a high density of 417 trees ha^{-1} and the SQ IV plantation at Churulipotti has a low density of 243 trees^{-1}. In the age class 30-40, the plantations belonging to SQ I and IV had lower stand density compared to the other two site qualities. plantations had more or less similar number of trees in per hectare area, falling between 215 in SQ III and 269 in SQ I for the age class 40-50, the. Interestingly, in the age class 50 above, both the plantations of SQ II and IV had same number of trees per hectare (Table 18). Miscellaneous tree growth was prominent in a number of plantations that were studied. The highest density of miscellaneous trees was recorded for the SQ I plantation of age class 30-40, present at Erambadam, Nilambur. The SQ I and III plantations of age class 10-20 were well managed without presence of any miscellaneous trees inside the planation (Table 19).

Table 19. Density of miscellaneous trees in teak plantations at variable site quality and age class regimes at Nilambur forests, Kerala.

Density of miscellaneous trees in the plantations (number of trees ha^{-1})					
Site Quality	**Age Class**				
	10-20	**20-30**	**30-40**	**40-50**	**50+**
SQ I	0	108	694	32	12
SQ II	94	87	42	14	236
SQ III	0	103	23	146	24
SQ IV	215	72	358	197	145

4.2 Soil Chemical and Physical Properties.

The physio-chemical attributes of the soil in the selected teak plantations in Nilambur forest divisions were studied in detail. Soil factors such as pH, total Nitrogen, percentage Carbon, available Phosphorus, exchangeable Potassium, Bulk Density and Texture were analysed. The observed results are presented below.

4.2.1 Soil pH:

Tables 20 to 23 represent the pH values of soil from the 4 plantations at different site qualities and their respective adjacent contiguous treeless open areas. There is variation in pH values between plantations and their respective contiguous open areas. It can be seen that the pH values of the SQ I plantation was lower than that of the respective contiguous open area up to a soil depth of 80cm (Table 20). In the depth layer of 80-100, both the soil from plantation as well as open area showed similar value for pH. Interestingly, a reverse trend was discernible for the other site qualities with higher pH value for teak plots as compared to the adjacent treeless plots. For example, teak plantation soil in the SQII recorded higher pH than contiguous open area at all depth (Table 21). Similar trend was repeated for teak plantation soil in the SQ III and SQ IV (Table 22). In general, there were weak relation existing in pH value with increasing soil depth. An appreciable trend in pH was observed only for the SQI teak plantations where the pH of soil was found to be increasing with soil depth (Table 23). Across the site qualities the SQ III plantation had the highest pH values while the SQ I plantation showed the lowest (Table 24). Also, it was interesting to note that the pH of SQ I plantation increased with depth.

Table 20. Variation in soil pH in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality 1 at Kariem Muriem, Nilambur, Kerala.

Soil pH of SQ I Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	5.49	5.17	0.002
20-40	5.31	5.22	0.105
40-60	5.48	5.26	0.001
60-80	5.38	5.3	0.018
80-100	5.43	5.43	0.915

Table 21. Variation in soil pH in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality II at Elencheri, Nilambur, Kerala.

Soil pH of SQ II Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	5.49	5.72	0.070
20-40	5.28	5.81	0.000
40-60	5.27	5.44	0.016
60-80	5.34	5.66	0.001
80-100	5.37	5.83	0.020

Table 22. Variation in soil pH in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality III at Paramankunnu, Nilambur, Kerala.

Soil pH of SQ III Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	5.12	5.94	0.002
20-40	4.94	5.8	0.001
40-60	5.03	5.98	0.000
60-80	5.18	5.85	0.000
80-100	5.1	5.66	0.002

Table 23. Variation in soil pH in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality IV at Muleppadam, Nilambur, Kerala.

Soil pH of SQ IV Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	5.59	5.18	0.001
20-40	5.53	5.42	0.010
40-60	5.41	5.28	0.069
60-80	5.59	5.52	0.209
80-100	5.37	5.23	0.016

Table 24. Variation in soil pH in teak plantation of age class 40-50 belonging to different site qualities at Muleppadam, Nilambur, Kerala.

pH of the soils in different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	5.17^{b}	5.72^{a}	5.94^{a}	5.18^{a}	0.000
20-40	5.22^{b}	5.81^{a}	5.8^{a}	5.42^{b}	0.000
40-60	5.26^{c}	5.44^{b}	5.98^{a}	5.28^{cb}	0.000
60-80	5.30^{c}	5.66^{ab}	5.85^{a}	5.59^{bc}	0.000
80-100	5.43^{b}	5.83^{a}	5.66^{ab}	5.23^{b}	0.000

4.2.2 Soil Carbon

Tables 25,26,27 and 28 depict the variation in soil organic carbon between the teak plantations and their contiguous treeless open areas. Table 25 shows that there was a higher concentration of organic carbon in the plantation when compared to the contiguous open area. For instance, the carbon content in the top layer (0-20 cm) was 1.79% in the plantation while it was only 1.50% in the open area. In the 20-40 cm layer, there was no significant difference in C content between the two soil pits.

Yet another observation is that there was consistent reduction in soil carbon content with increase in soil depth. However, the rate of reduction was more for the treeless open soil as compared to the tree bearing plots. For example, the plantation soil in SQ I plantation maintained fairly high soil Carbon even at a depth of 80-100cm (1.24%) while the contiguous open soil had only 0.95% for this soil depth.

In the teak plantation at SQ II, there was a higher concentration of carbon in the top layer of soil inside the plantation (1.70%) compared to the contiguous tree less area (1.48 %). However, a reverse trend was discernible for the successive soil layers both for plantation and open soil. Incidentally the soil carbon content was higher in the tree less area compared to the plantation (Table 26). Similarly, soils in the teak plots in SQIII also exhibited lower carbon values in the top (0-20) and bottom (80-100) as compared to their corresponding open soil (Table 27). In the other 3 layers viz. 20-40, 40-60 and 60-80 cm, there was no significant difference between the two soils in terms of percentage C content. In the plantation belonging to SQ IV, the carbon content of the soil of the contiguous open area was significantly higher than the plantation soil at all 5 soil depth intervals (Table 28). Comparing the soil carbon content across the site qualities revealed significant difference in soil C concentrations between the plantations (Table 29). There is a general trend of declining carbon content with increasing soil depth and highest soil carbon content was always associated with the top soil for all site qualities. Yet another characteristic observation with the SQI soil is that it maintained fair amount of carbon in all the soil depth including the farthest depth of 80-100 cm (1.24%). However, considerable decline in soil carbon was observed with increase in soil depth for all the remaining site qualities. For example, the top soil in SQIV teak stand reported high C content to the tune of 2.07% which however declined drastically across soil depths reaching upto 0.59% in the deepest soil (80-100 cm).

The changes in soil carbon content for different site qualities within the same age class showed significant observations. In general, modest reduction in SOC is discernible while moving from higher to lower site qualities (SQI to SQ IV). This trend is partially visible in the top soil (0-20 cm) with moderate changes in SOC across site qualities. However, the changes are much pronounced at higher depth intervals. Interestingly, the highest SOC was observed in the top soil corresponding to SQIV.

Changes in soil carbon stocks in the teak plantations managed at variable site qualities and age classes are presented in Table 30. The highest total soil carbon stock in the one-meter-deep soil profile was for site quality I (160.61 Mg ha^{-1}) followed by SQIV (143.60 Mg ha^{-1}) and the lowest was for SQII (112.02 Mg ha^{-1}). Barring the higher SOC observed in the top soil of SQ IV, the SQ I maintained higher soil carbon stocks in all the depth intervals. Also, this soil maintained fairly uniform carbon stock in all the soil depths. However, such a trend was not discernible for other site qualities where the decline in soil carbon stocks with increasing soil depth was considerably higher.

Table 25. Variation in soil carbon in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality I at Kariem Muriem, Nilambur, Kerala.

Percentage Carbon content in soil of SQ I Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	1.5	1.79	0.024
20-40	1.46	1.49	0.559
40-60	1.09	1.47	0.000
60-80	0.98	1.23	0.014
80-100	0.95	1.24	0.008

Table 26. Variation in soil carbon in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality II at Elencheri, Nilambur, Kerala.

Percentage Carbon content in soil of SQ II Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	1.48	1.7	0.021
20-40	1.1	1.23	0.025
40-60	1.03	0.9	0.067
60-80	1.08	0.77	0.003
80-100	1.07	0.58	0.001

Table 27. Variation in soil carbon in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality III at Paramankunnu, Nilambur, Kerala.

Percentage Carbon content in soil of SQ III Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	2.74	1.76	0.000
20-40	1.36	1.38	0.509
40-60	1.06	1.3	0.055
60-80	0.88	0.78	0.224
80-100	0.78	0.68	0.052

Table 28. Variation in soil carbon in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality IV at Muleppadam, Nilambur, Kerala.

Percentage Carbon content in soil of SQ IV Plantation at various depths			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	2.65	2.07	0.001
20-40	1.8	1.19	0.002
40-60	1.18	1.23	0.01
60-80	1.5	0.89	0.001
80-100	1.32	0.59	0.002

Table 29. Variation in soil carbon in teak plantation of age class 40-50 belonging to 4 different site qualities.

C (%) in the soils of different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	1.79^{b}	1.70^{b}	1.76^{b}	2.07^{a}	0.001
20-40	1.49^{a}	1.00^{b}	1.38^{a}	1.19^{c}	0.000
40-60	1.47^{a}	0.90^{c}	1.30^{ab}	1.23^{b}	0.000
60-80	1.23^{a}	0.77^{b}	0.78^{b}	0.89^{b}	0.000
80-100	1.24^{a}	0.58^{b}	0.68^{b}	0.59^{b}	0.000

Table 30. Carbon stock in the plantations of different site qualities falling under age class 40-50

Carbon stock ($Mgha^{-1}$) in 40-50 age class plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	36.09^{b}	37.70^{b}	38.64^{b}	49.15^{a}	0.005
20-40	32.37^{a}	21.95^{b}	31.53^{a}	26.39^{b}	0.000
40-60	31.28^{a}	20.97^{b}	35.24^{a}	32.79^{a}	0.000
60-80	30.03^{a}	17.77^{b}	19.04^{b}	20.33^{b}	0.002
80-100	30.83^{a}	13.64^{c}	18.13^{b}	14.93^{c}	0.000
TOTAL	**160.61**	**112.02**	**142.57**	**143.60**	

4.2.3 Total Nitrogen

Table 31 to Table 35 shows the variation in total nitrogen percentage in soil of the 4 different site quality plantations and the respective contiguous open areas. Table 31 shows that the plantation soil had a higher concentration of Nitrogen compared to the open area. For instance, the top soil (0-20 cm) of plantation had a total nitrogen percentage of 0.223% while the open area had 0.133%. In the plantation under SQ II, there was no significant difference between plantation soil and the treeless open till 60 cm depth (Table 32). Incidentally, the N content was significantly higher in the top two soil layers for the treeless open than the plantation soil in the SQ III plantation (Table 33). It was also seen that there was no significant difference between them in the deeper layers of soil. The total nitrogen content in the SQ IV plantation showed no significant difference from that of contiguous treeless open (Table 34). Among the plantations under different site quality, it was interesting to note that there was no significant difference in terms of N content in the 80-100 cm layer (Table 35). Significant variation in N content was observed for all the remaining soil depths across variable site qualities. In general, the soil N content was highest for SQI for all soil depth intervals. However, a consistent decline in N content with decline in site quality was not evident in the present study.

Table 31. Variation in soil total Nitrogen in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality I at Kariem Muriem, Nilambur, Kerala.

Total N (%) at various depths of SQ I plantation			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.133	0.223	0.009
20-40	0.122	0.213	0.004
40-60	0.097	0.192	0.014
60-80	0.093	0.183	0.038
80-100	0.084	0.092	0.563

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Table 32. Variation in soil total Nitrogen in teak plantation and contiguous treeless open of age class 40-50 belonging to Site Quality II plantation at Elencheri, Nilambur, Kerala.

Total N (%) at various depths of SQ II plantation			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.158	0.138	0.312
20-40	0.12	0.112	0.122
40-60	0.096	0.1	0.616
60-80	0.073	0.085	0.044
80-100	0.081	0.096	0.06

Table 33. Variation in soil total Nitrogen in teak plantation and contiguous treeless open of age class 40-50 belonging to Site Quality II plantation at Paramankunnu, Nilambur, Kerala.

Total N (%) at various depths of SQ III plantation			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.234	0.175	0.007
20-40	0.206	0.119	0.026
40-60	0.134	0.106	0.208
60-80	0.113	0.1	0.54
80-100	0.074	0.077	0.754

Table 34. Variation in soil total Nitrogen in teak plantation and contiguous treeless open of age class 40-50 belonging to Site Quality IV plantation at Muleppadam, Nilambur, Kerala.

Total N (%) at various depths of SQ IV plantation			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.239	0.218	0.591
20-40	0.15	0.179	0.136
40-60	0.078	0.105	0.167
60-80	0.076	0.077	0.804
80-100	0.074	0.062	0.09

Table 35. Variation in total Nitrogen in teak plantation of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.

Total N (%) in the soils of different site quality plantations					
Soil depth (cm)	Site quality				P- value
	I	II	III	IV	
0-20	0.223[a]	0.138[b]	0.175[ab]	0.218[a]	0.005
20-40	0.213[a]	0.112[b]	0.119[b]	0.179[a]	0.000
40-60	0.192[a]	0.100[b]	0.106[b]	0.105[b]	0.000
60-80	0.183[a]	0.085[b]	0.100[b]	0.077[b]	0.000
80-100	0.092[a]	0.069[a]	0.077[a]	0.062[a]	0.096

4.2.3 Available Phosphorus

The available phosphorus content variation between 40–50 year old plantations and their respective contiguous open areas are represented in (Tables 36 to 39). In the plantation of SQ I and IV, generally, there is significant difference in P content between soils of sampling pits inside and outside the plantation (Table 36, Table 39) Such an observation was not found in the other two plantations. The plantation of site quality III showed a trend of declining P with depth. Table 39 shows the P content in soils of SQ IV plantation and the contiguous open area. There is significant difference in P concentration between the two soil pits. Incidentally, inside the plantation, the P concentration increased with increase in depth while an opposite trend was observable in the contiguous open area.

On comparing between site qualities, there is significant difference in p content between the plantations at various depths (Table 40). Among the 4 plantations the lowest P content was seen in the SQ II plantation and the highest was observed in in the SQ IV plantation. Interestingly in the SQ I and SQ IV plantations, the highest P concentration was found in the 80-100 cm layer of soil.

Table 36. Variation in Available Phosphorus in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality I at Kariem Muriem, Nilambur, Kerala.

Available P content at various depths of SQ I plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	5.42	9.72	0.024
20-40	5.45	5.43	0.928
40-60	11.81	7.15	0.020
60-80	6.77	5.18	0.011
80-100	6.25	11.4	0.007

Table 37. Variation in Available Phosphorus in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality II at Elencheri, Nilambur, Kerala

Available P content at various depths of SQ II plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	2.00	2.28	0.095
20-40	3.93	2.53	0.007
40-60	2.43	2.10	0.26
60-80	2.70	2.85	0.803
80-100	2.98	2.93	0.662

Table 38. Variation in Available Phosphorus in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality III at Paramankunnu, Nilambur, Kerala.

Available P content at various depths of SQ III plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	9.35	9.37	0.991
20-40	6.53	6.35	0.708
40-60	6.35	8.65	0.074
60-80	7.08	6.33	0.063
80-100	6.25	5.17	0.055

Table 39. Variation in Available Phosphorus in teak plantation and contiguous treeless open of age class 40-50 belonging to site quality IV at Muleppadam, Nilambur, Kerala.

Available P content at various depths of SQ IV plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	6.87	6.62	0.011
20-40	3.73	7.48	0.000
40-60	5.5	9.27	0.016
60-80	3.87	11.82	0.000
80-100	2.96	17.33	0.000

Table 40 . Variation in Available Phosphorous in teak plantation of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.

Available P (ppm) in the soils of different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	9.72[a]	2.28[b]	9.37[a]	6.62[a]	0.000
20-40	5.43[b]	2.53[c]	6.35[b]	7.48[a]	0.000
40-60	7.15[b]	2.10[c]	8.65[ab]	9.27[a]	0.000
60-80	5.18[b]	2.85[c]	6.33[b]	11.82[a]	0.000
80-100	11.40[a]	1.93[c]	5.17[b]	17.33[a]	0.000

4.2.5 Exchangeable Potassium

Table 41 to Table 44 represents the variations in K content between the plantations of different site qualities falling in age class 40-50 and their respective contiguous open areas. Generally, there was a perceptible decline in the concentration of exchangeable potassium with soil depth, both inside the plantation and in the contiguous treeless open. It can be seen that in SQ I the plantation is having a higher K concentration in soil than the open area (Table 41). Similar results were shown by the plantations of site quality III and IV (Tables 43 and 44). Interestingly, a reverse trend was discernible for the SQ II plantation area, where the open treeless area had a higher K content than the plantation (Table 42). The highest concentration of exchangeable K in each location was seen in the top layer of soil. On comparing across the site qualities, the highest concentration of potassium was recorded in top soil (0-20 cm) of SQ IV plantation (205.65 ppm) while the lowest value was from the 80-100 cm layer of SQ I plantation (Table 45). It was quite interesting to see that, apart from the top layer of soil (0-20 cm), there is no significant difference in terms of K concentration between SQ I and SQ II. Generally, it was the plantation designated as SQ IV, that showed the highest content of exchangeable K in its soil.

Table 41. Variation in Exchangeable Potassium in teak plantation of age class 40-50 and contiguous treeless open belonging to site quality I at Kariem Muriem, Nilambur, Kerala

Exchangeable K content at various depths of SQ I plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	24.35	50.35	0
20-40	23.35	29.35	0.001
40-60	19.5	24.35	0
60-80	23.15	25.5	0.305
80-100	22.5	28.35	0.031

Table 42. Variation in Exchangeable Potassium in teak plantation of age class 40-50 and contiguous treeless open belonging to site quality II at Elencheri, Nilambur, Kerala.

Exchangeable K content at various depths of SQ II plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	80.35	70.00	0.005
20-40	38.35	29.35	0.000
40-60	35.15	26.5	0.000
60-80	39.5	23.65	0.000
80-100	33.35	24.5	0.001

Table 43. Variation in Exchangeable Potassium in teak plantation of age class 40-50 and contiguous treeless open belonging to site quality III at Paramankunnu, Nilambur, Kerala.

Exchangeable K content at various depths of SQ III plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	77.50	165.15	0.000
20-40	38.00	166.00	0.000
40-60	24.65	136.5	0.000
60-80	23.65	93.85	0.000
80-100	23.65	88.65	0.023

Table 44. Variation in Exchangeable Potassium in teak plantation of age class 40-50 and contiguous treeless open belonging to site quality IV at Muleppadam, Nilambur, Kerala.

Exchangeable K content at various depths of SQ IV plantation in ppm			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	124.15	205.65	0.000
20-40	68.0	139.5	0.000
40-60	55.65	162.35	0.000
60-80	22.5	183.35	0.000
80-100	48.5	106.85	0.000

Table 45. Variation in Exchangeable Potassium in teak plantations of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.

Exchangeable K (ppm) in the soils of different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	50.35^{a}	70^{b}	165.15^{c}	205.65^{d}	0.000
20-40	29.35^{c}	29.35^{c}	166^{a}	139.5^{b}	0.000
40-60	24.35^{c}	26.5^{c}	136.5^{b}	162.35^{a}	0.000
60-80	25.5^{c}	23.65^{c}	93.85^{b}	183.35^{a}	0.000
80-100	28.35^{c}	24.5^{c}	88.65^{b}	106.85^{a}	0.000

4.2.6. C: N ratio

Based on the Carbon and Nitrogen content in soil at various depths, the C:N ratio of soil in various depths of the age class 40-50 plantations were calculated. Table 46 represents the variations in C:N ratio of the different SQ plantations. The value ranged from 6.65 in 20-40 cm of the SQ IV plantation to 13.48 in the 80-100 cm layer of SQ I plantation. It was interesting to note that there is no significant difference in C:N ratio between the different site qualities in the 80-100 cm layer.

Table 46. C:N ratio of soils at different depths in the 40-50 age class plantation in Nilambur forests falling to different site qualities.

C:N ratio of the soils in different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	8.03^{b}	12.32^{a}	10.06^{ba}	9.50^{b}	0.011
20-40	7.00^{bc}	8.93^{b}	11.60^{a}	6.65^{c}	0.000
40-60	7.66^{c}	9.00^{bc}	12.26^{a}	11.71^{ab}	0.004
60-80	6.72^{b}	9.06^{ab}	7.80^{b}	11.56^{a}	0.007
80-100	13.48^{a}	8.41^{a}	8.83^{a}	9.52^{a}	0.071

4.2.7. Soil texture /particle size distribution

The percentage content of sand, silt and clay fractions of soil at different depths in the 40-50 age class plantations of different site qualities and their respective contiguous treeless open areas are given in Figures 2 to 5 The least clay fraction percentage was seen in 80-100 cm depth layer of SQ III plantation (2.44%) and the highest clay content was in 0-20cm layer of SQ II plantation (13.22%). For silt fraction, the lowest per cent was observed in 40-60 depth later of SQ IV plantation (6.47%) and the highest content of silt was observed in the 0-20 layer of contiguous treeless open of SQ IV plantation (35.05%). In case of sand, the lowest percentage value was recorded for the 0-20 layer of contiguous treeless open of SQ IV plantation (52.45%) and the highest for the 40-60 cm layer of treeless open of SQ III (88%). The percentage content of sand was more in SQ III and IV plantations compared to the other two.

Figure 2. Particle size distribution in soils of SQ I plantation and the respective contiguous treeless open at Kariem Muriem, Vazhikkadavu, Nilambur

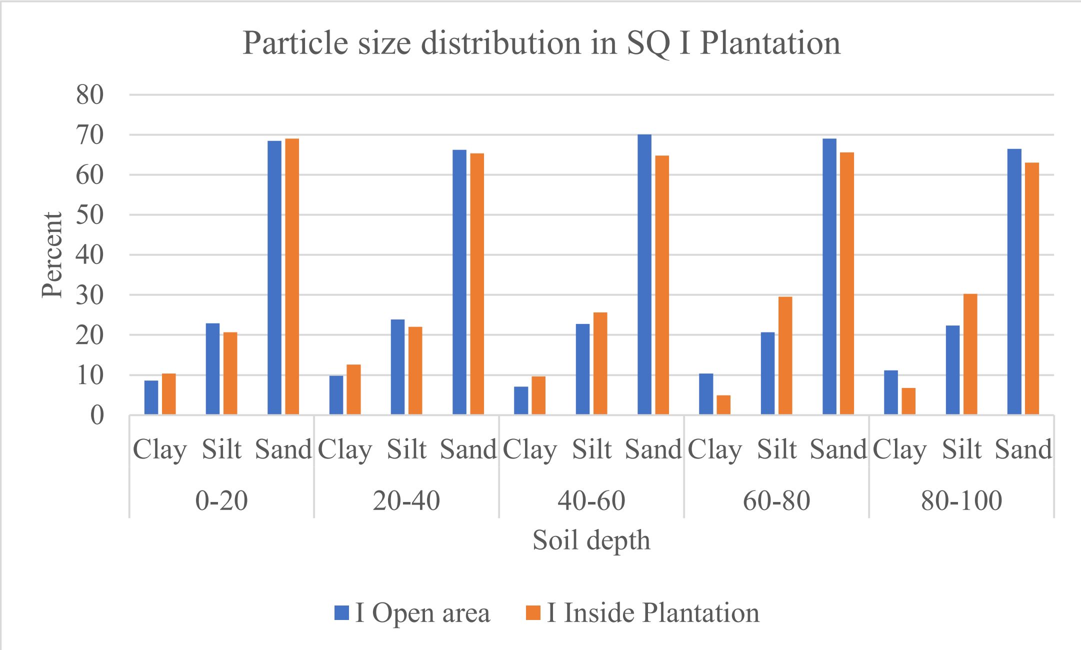


Figure 3.Particle size distribution in soils of SQ II plantation and the respective contiguous treeless open at Elencheri, Edavanna, Nilambur, Kerala.

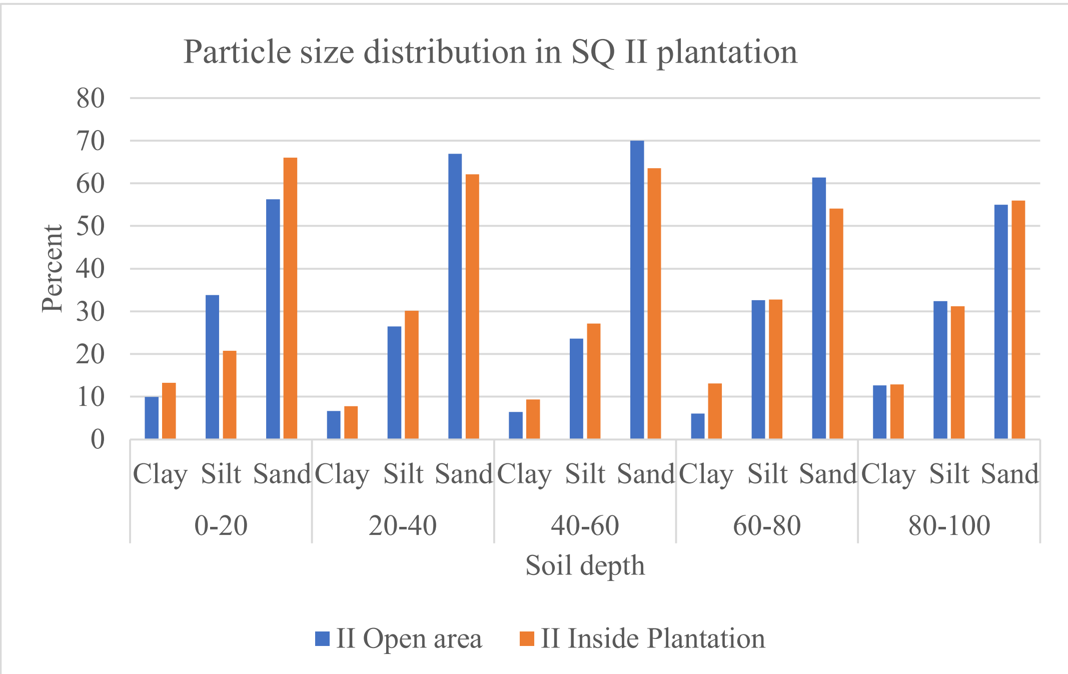


Figure 4. Particle size distribution in soils of SQ III plantation and the respective contiguous treeless open at Paramankunnu, Nilambur, Kerala.

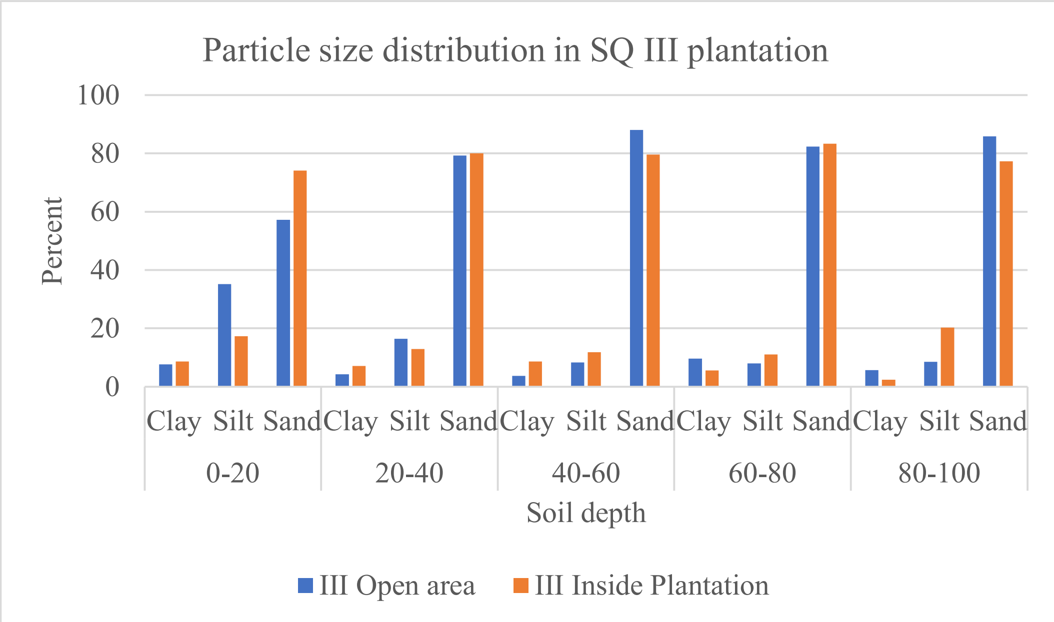


Figure 5. Particle size distribution in soils of SQ IV plantation and the respective contiguous treeless open at Muleppadam, Nilambur, Kerala.

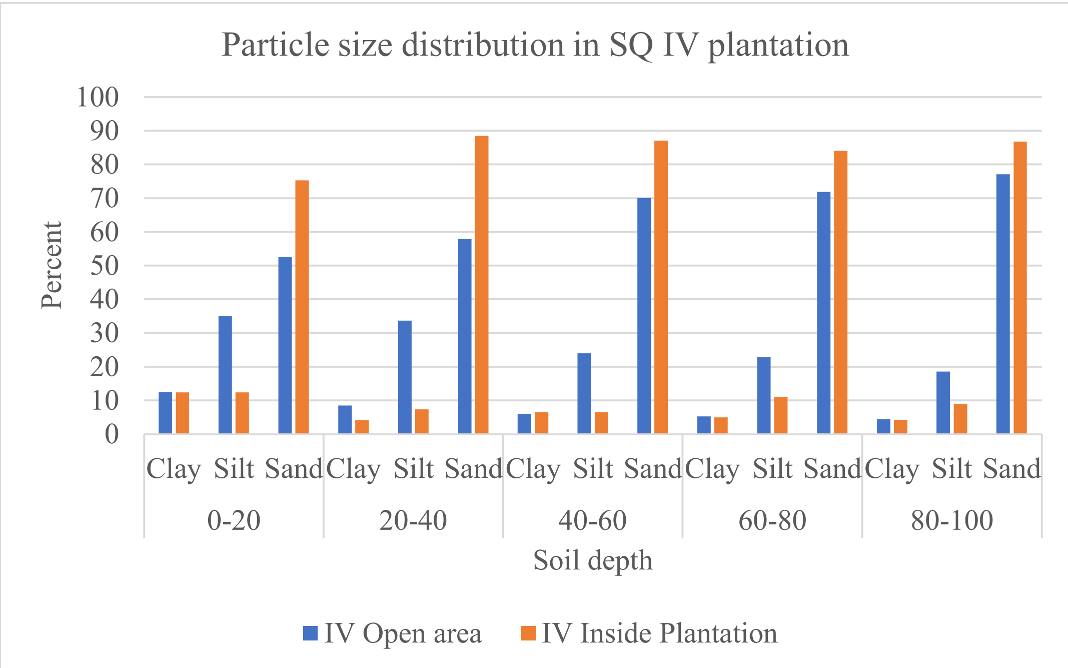


Table 47. Average particle size distribution in soils of 40-50 age class plantations and their respective contiguous treeless open areas belonging to the 4 different site qualities.

Percentage content of different soil size fractions (%)								
Particle	**Site quality**							
	I		**II**		**III**		**IV**	
	Open area	**Inside Plantation**	**Open area**	**Inside Plantation**	**Open area**	**Inside Plantation**	**Open area**	**Inside Plantation**
Clay	9.41	8.84	8.33	11.25	6.184	6.46	7.31	6.42
Silt	22.51	25.63	29.76	28.4	15.28	14.69	26.80	9.24
Sand	68.07	65.53	61.9	60.35	78.53	78.85	65.88	84.33

4.2.7 Bulk Density (BD)

The bulk density of soil at different depths of the different 40-50 age class plantations and their respective contiguous open areas are given in tables 48,49,50 and 51. In the SQ I plantation, the BD of the plantation and treeless open showed no significant difference in the first 3 depth layers, 0-20,20-40 and 40-60 (Table 48). Table 49 shows that in SQ II plantation also a similar condition was observed with the BD values being significantly different only in the depth layer 60-80 and 80-100. It is also interesting to note that though the BD of plantation soil was slightly higher than open area in the depth up to 60 cm, the BD of open area becomes significantly higher in the deeper layers. In SQ III plantation, the bulk density of plantation soil varied from 0.98 to 1.19 gcm^{-3} (Table 50). The BD of plantation soil was significantly lower than the open area till a depth of 80 cm. In the depth layer 80-100, there was no significant difference between the plantation and open area soils. Table 51 shows the variation in BD between the SQ IV plantation and corresponding treeless open. In the top soil layer, the BD of plantation soil (1.06) was higher than the treeless open (0.87). in the rest of the depth classes, the open area had a higher Bulk Density than the plantation. On comparing across the site qualities, the plantation soils showed difference from one another in terms of bulk density. It was observed that there was no significant difference in site qualities in the 20-40 cm layer (Table 52).

Table 48. Variations in bulk density of soil at different depths of SQ I plantation and the adjacent contiguous treeless open at Kariem Muriem, Nilambur, Kerala.

BD (gcm^{-3}) of SQ I soil at various depths of SQ I plantation and contiguous open			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.9	0.92	0.521
20-40	0.97	0.96	0.879
40-60	0.96	0.94	0.757
60-80	1.09	0.97	0.012
80-100	1.18	1.07	0.023

Table 49. Variations in bulk density of soil at different depths of SQ II plantation and the adjacent contiguous treeless open at Elencheri, Nilambur, Kerala.

BD (gcm^{-3}) of SQ II soil at various depths of SQ II plantation and contiguous open			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.97	0.99	0.152
20-40	0.97	0.98	0.425
40-60	1.01	1.04	0.067
60-80	1.13	1.03	0.006
80-100	1.32	1.05	0.003

Table 50. Variations in bulk density of soil at different depths of SQ III plantation and the adjacent contiguous treeless open at Paramankunnu, Nilambur, Kerala.

BD (gcm^{-3}) of SQ III soil at various depths of SQ III plantation and contiguous open			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	1.09	0.98	0.002
20-40	1.16	1.02	0.032
40-60	1.13	1.21	0.041
60-80	1.12	1.09	0.097
80-100	1.18	1.19	0.478

Table 51. Variations in bulk density of soil at different depths of SQ IV plantation and the adjacent contiguous treeless open at Muleppadam, Nilambur, Kerala.

BD (gcm^{-3}) of SQ IV soil at various depths of SQ IV plantation and contiguous open			
Depth (cm)	**Open area**	**Plantation**	**p-value**
0-20	0.87	1.06	0.001
20-40	1.04	0.99	0.051
40-60	1.19	1.09	0.031
60-80	1.10	1.02	0.016
80-100	1.29	1.13	0.003

Table 52. Variations in bulk density of soils at different depths of different plantations of age class 40-50 belonging to different site qualities in Nilambur, Kerala.

Bulk Density of the soils in different site quality plantations					
Soil depth (cm)	**Site quality**				**P- value**
	I	**II**	**III**	**IV**	
0-20	0.90^{c}	0.99^{b}	0.98^{b}	1.06^{b}	0.003
20-40	0.97^{a}	0.98^{a}	1.02^{a}	0.99^{a}	0.087
40-60	0.95^{c}	1.04^{b}	1.21^{a}	1.19^{a}	0.041
60-80	1.09^{a}	1.03^{b}	1.09^{a}	1.02^{b}	0.016
80-100	1.11^{b}	1.05^{c}	1.19^{a}	1.13^{b}	0.008

4.3. Miscellaneous vegetation

During the study, a total of 44 species of trees, 24 species of climbers and lianas, 19 species of shrubs and 38 species of herbs were observed in the teak plantations that were enumerated. Of these, the trees and lianas cause much competition and damage to teak in the plantations. The trees included species like *Terminalia paniculata* Roth. and *Xylia xylocarpa* Roxb. Taub. The most common lianas observed were *Calycopteris floribunda* Lam and *Spatholobus parviforus* (DC.) Kuntze. The species that were recorded are listed in the Table 53 to Table 56.

Table 53. Miscellaneous tree species observed in the teak plantations of variable site quality and age class regimes during the study at Nilambur, Kerala.

SI No	Tree Species Name	Family
1	*Albizia lebbeck* (L.) Benth.	Fabaceae
2	*Alstonia scholaris* (L.) R. Br.	Apocynaceae
3	*Aporosa lindleyana* (Wight) Baill.	Phyllanthaceae
4	*Artocarpus hirsutus* Lamk.	Moraceae
5	*Bambusa bambos* (L) Voss	Poaceae
6	*Bombax ceiba* L.	Malvaceae
7	*Bridelia retusa* (L.) A.Juss	Euphorbiaceae
8	*Callicarpa tomentosa* (L.) Murr.	Lamiaceae
9	*Carallia brachiata* (Lour.) Merr	Rhizophoraceae
10	*Caryota urens* L.	Arecaceae
11	*Cassia fistula* L.	Fabaceae
12	*Cleistanthus collinus* (Roxb.) Benth. ex Hook.f.	Phyllanthaceae
13	*Dalbergia latifolia* Roxb	Fabaceae
14	*Dillenia pentagyna* Roxb	Dilleniaceae
15	*Ficus racemosa* L.	Moraceae
16	*Flacourtia montana* J. Graham	Salicaceae
17	*Gliricidia sepium* (Jacq.) Steud.	Fabaceae
18	*Grewia tliifolia* Vah.	Tiliaceae
19	*Holarrhena pubescen*s Wall. ex G. Don	Apocynaceae
20	*Holigarna arnottiana* Hook.f.	Anacardiaceae
21	*Hydnocarpus pentandrus* (Buch.-Ham.) Oken	Achariaceae
22	*Hymenodictyon orixense* (Roxb.) Mabb.	Rubiaceae
23	*Ixora brachiata* Roxb.	Rubiaceae
24	*Lannea coromandelica* (Houtt.) Mer.	Anacardiaceae
25	*Macaranga peltata* (Roxb.) Muell.-Arg.	Euphorbiaceae
26	*Mallotus philippensis* (Lamk.) Muell.-Arg.	Euphorbiaceae
27	*Mangifera indica* L.	Anacardiaceae

28	*Melicope lunu-ankenda* (Gaertn.) T.G. Hartley	Rutaceae
29	*Mitragyna parviflora* (Roxb.) Korth.	Rubiaceae
30	*Olea dioica* Roxb.	Oleaceae
31	*Pterocarpus marsupium* Roxb	Fabaceae
32	*Pterospermum reticulatum* Wight & Arn	Malvaceae
33	*Pterygota alata* (Roxb.) R. Br	Sterculiaceae
34	*Sapium insigne* (Royle) Trimen	Euphorbiaceae
35	*Schleichera oleosa* (Lour.) Oken	Sapindaceae
36	*Strychnos nux-vomica* L.	Loganaveae
37	*Syzygium cumini* (L.) Skeels	Myrtaceae
38	*Tabernaemontana alternifolia* L.	Apocynaceae
39	*Terminalia elliptica* Willd.	Combretaceae
40	*Terminalia paniculata* Roth.	Combretaceae
41	*Wrightia tinctoria* (Roxb.) R.Br., Mem. Wern. Soc.	Apocynaceae
42	*Xanthophyllum arnottianum* Wight	Polygalaceae
43	*Xylia xylocarpa* Roxb. Taub.	Fabaceae
44	*Zanthoxylum rhetsa* (Roxb.) DC.	Rutaceae

Table 54. Lianas and climber species observed in the teak plantations of variable site quality and age class regimes during the study at Nilambur, Kerala.

SI No	Species Name	Family
1	*Cyclea peltata* Diels.	Menispermaceaea
2	*Abrus precatorius* L.	Fabaceae
3	*Anamirta cocculus* (L.) Wight & Arn	Menispermaceaea
4	*Calamus rotang* L.	Arecaceae
5	*Calycopteris floribunda* Lam	Combretaceae
6	*Cayrata trifolia* (L.) Domin	Vitaceae
7	*Combretum latifolium* Bl.	Combretaceae
8	*Cryptolepis buchanani*i Roem. et Schult.	Apocynaceae
9	*Dalbergia horrida* (Dennst.) Mabb.	Fabaceae
10	*Derris scandens* (Roxb.) Benth.	Fabaceae
11	*Diploclisia glaucascens* (Blume) Diels	Menispermaceaea
12	*Entada rheedei* Spreng.	Fabaceae
13	*Gymnema sylvestre* (Retz.) R.Br. ex Schult	Apocynaceae
14	*Ichnocarpus frutescens* (L.) W.T.Aiton	Apocynaceae
15	*Jasminum malabaricum* Wight	Oleaceae
16	*Passifora foetda* L.	Passifloraceae
17	*Rourea minor* (Gaertn.) Alston	Connaraceae
18	*Smilax zeylanic*a L	Smilacaceae
19	*Spatholobus parviforus* (DC.) Kuntze	Fabaceae

20	*Toddalia asiatica* (L.) Lam.	Rutaceae
21	*Tragia involucrata* L.	Euphorbiaceae
22	*Wattakaka volubilis* (L.f.) Stapf	Apocynaceae
23	*Ziziphus oenoplia* (L.) Mill.	Rhamnaceae
24	*Ziziphus rugosa* Lam.	Rhamnaceae

Table 55. Shrub species observed in the teak plantations of variable site quality and age class regimes during the study at Nilambur, Kerala.

SI No	**Species**	**Family**
1	*Antidesma acidum* Retz.	Phyllanthaceae
2	Canthium coromandelicum (Burm.f.) Alston	Rubiaceae
3	*Catunaregam spinosa* (Thunb.) Tirveng.	Rubiaceae
4	*Crotalaria pallida* Aiton	Fabaceae
5	*Flueggea leucopyrus* Willd	Euphorbiaceae
6	*Glycosmis pentaphylla* (Retz.) DC	Rutaceae
7	*Ixora coccinea* L	Rubiaceae
8	*Lantana camara* L	Verbenaceae
9	*Leea indica* (Burm. f.) Merr	Leeaceae
10	*Melastoma malabathricum* L.	Melastomataceae
11	*Memecylon umbellatum* Burm.f	Melastomataceae
12	*Paveta indica* L.	Rubiaceae
13	*Senna occidentalis* (L.) Link	Fabaceae
14	*Sida acuta* Burm. f.	Malvaceae
15	*Sida cordifolia* L.	Malvaceae
16	*Sida rhombifolia* L.	Malvaceae
17	*Triumfeta rhomboidea* Jacq	Malvaceae
18	*Urena lobata* L	Malvaceae
19	*Waltheria indica* L.	Malvaceae

Table 56. Herb species observed in the teak plantations of variable site quality and age class regimes during the study at Nilambur, Kerala.

SI No	Species	Family
1	*Achyranthes aspera* L.	Amaranthaceae
2	*Aerva lanata* (L.) Juss	Amaranthaceae
3	*Ageratum conyzoides* (L.) L.	Asteraceae
4	*Anisochilus carnosus* (L. f.) Wall	Lamiaceae
5	*Anisomeles indica* (L.) Kuntze	Lamiaceae
6	*Biophytum reinwardtii* (Zucc.) Klotzsch	Oxalidaceae
7	*Cleome rutidosperma* DC	Cleomaceae
8	*Cleome viscosa* L.	Cleomaceae
9	*Commelina benghalensis* L	Commelinaceae
10	*Commelina difusa* Burm. f.	Commelinaceae
11	Corchorus aestuans L.	Tiliaceae
12	*Curculigo orchioides* Gaertn.	Hypoxidaceae
13	*Cyanots axillaris* (L.) D. Don ex Sweet	Commelinaceae
14	*Desmodium gangetcum* (L.) DC.	Fabaceae
15	*Elephantopus scaber* L.	Asteraceae
16	*Emilia sonchifolia* (L.) DC. ex DC	Asteraceae
17	*Euphorbia hirta* L.	Euphorbiaceae
18	*Globba marantina* L.	Zingiberaceae
19	*Heliotropium indicum* L.	Boraginaceae
20	*Kyllinga nemoralis* (J. R & G. Forst.) Dandy ex Hutch. & Dalz.	Cyperaceae
21	*Leucas aspera* (Willd.) Link	Lamiaceae
22	*Lindernia ciliata ciliata*	Linderniaceae
23	*Ludwigia hyssopifolia* (G. Don) Exell	Onagraceae
24	*Malaxis versicolor* (Lindl.) Abeyw.	Orchidaceae
25	*Mesosphaerum suaveolens* (L.) Kuntze	Lamiaceae
26	*Micrococca mercurialis* (L.) Benth	Euphorbiaceae
27	*Mimosa pudica* L.	Fabaceae
28	*Mitracarpus hirtus* (L.) DC.	Rubiaceae
29	*Nervilia infundibulifolia* Blatt. &McCann	Orchidaceae
30	*Oxalis corniculata* L.	Oxalidaceae
31	*Phyllanthus reticulatus* Poir.	Euphorbiaceae
32	*Pilea microphylla* (L.) Liebm.	Urticaceae
33	*Rauvolfa serpentna* (L.) Benth. ex Kurz	Apocynaceae
34	*Senna tora* (L.) Roxb.	Fabaceae
35	*Spermacoce ocymoides* Burm.f	Rubiaceae
36	*Stachyphrynium spicatum* (Roxb.) Schum	Marantaceae
37	*Staurogyne glutinosa* (Wall.) Kuntze	Acanthaceae
38	*Vernonia cinerea* (L.) Less.	Asteraceae

Discussion

V.DISCUSSION

The present study was aimed assessing the growth and productivity of teak as function of site quality and age at Nilambur, Kerala. This involved detailed evaluation of various growth attributes of tree. The previous chapter narrated a detailed account of the results on the growth attributes of teak trees belonging to four site qualities under five age classes. Also, the soil samples from the age class 40-50 were analysed for physico-chemical attributes. The salient results are discussed hereunder.

5.1 Growth parameters

In the present study the growth attributes like total tree height, bole height, canopy width, diameter at breast height, bole volume, total tree volume and form factor was analysed for 20 plantations belonging to four different site qualities and five age classes and the results were discussed in the previous chapter. Considerable variations in growth attributes have been observed among the teak trees belonging to various site qualities and age classes. Detailed account of the possible explanation for the observed trends are given below.

5.1.1. Total tree height.

It is well established that height growth is influenced by the site properties or the site in which in which teak grows (Pérez and Kanninen, 2005a; Minoche *et al.*, 2017). Tree height often reflect the actual productive potential of the site for a particular species and hence it is often regarded as the most effective determinant of the productive potential of the site. All the four site qualities mentioned in the present study have been identified based onsite quality evaluation done by the forest department personnel during the early establishment phase of the existing teak plantation under study. The present study is an attempt to revisit these site quality regimes and critically analyse the conformity of the present growth with these identified site qualities.

In the present study, as a general observation, the SQ I plantations showed the best height performance in all age classes except one (40-50). Though there was a decline in tree height in the lower site qualities, this decline did not follow any regular trend. The plantations studied were selected based on site quality estimations done by the forest department mostly prior to the establishment of the current growing stock present and the temporal changes that the site must have undergone in the previous rotations remain unaccounted.

It is interesting to observe that considerable deviation in height growth has been observed in the designated site qualities under study as compared to their expected height values as per All India Site Quality table (Table 57). For example, the expected top heights range for 40-year-old teak stand is 28.04m to 33.8m but in the present study, the SQ I plantation of age class 40-50 has an average height of only 18.30m making it fall into SQ III. Similarly, the SQ IV plantation with an average height of 23.63 m will actually belong in SQ II.

Table 57. Mean top height expected at different ages, based on All India site quality table for teak.

Mean top height (m)				
Site Quality	**Age**			
	15	**20**	**30**	**40**
SQ I	23.0-18.9	26.4-21.6	30.6-25.2	33.8-28.04
SQ II	18.8-14.6	21.5-16.8	25.1-19.7	28.04-22.2
SQ III	14.5-10.4	16.7-11.9	19.6-14.3	22.2-16.15
SQ IV	10.3-5.8	11.8-7.0	14.2-9.0	16.15-10.16

The deviation from the expected trends indicate that the designated site qualities need to be revised and re-designated accordingly for making meaningful conclusions about the productivity status of teak in Nilambur forests.

Also, the scientific rigour with which these estimations were done is also unknown. These factors have acted as limitations for the present study in arriving at a clear trend of growth difference between teak plantations of different site qualities. Interestingly the height class 40-50 showed decline in tree height as compared to other lower site qualities. This could be primarily attributed to the changes in local conditions the plantation have undergone ever since its establishment.

Age wise height growth increment is evident across all site qualities. The increment in height is more predominant at lower ages, while the mature plantations showed levelling off in terms of tree height. For instance, plantations of age 30 to 50 (age classes 30-40 and 40-50) had the average total tree height falling around 20 to 25 m across different site qualities (Figure 8, 9Figure *9*). Similar levelling off in height in mature teak has been reported in seed production areas of Karnataka by Gunaga *et al.,* (2014). Interestingly, age class 40 to 50 showed average tree height falling below the other three age classes for SQ I plantation. This could be attributed to the potential decline in site quality over the ages on account of poor management. Presence of considerable proportion of miscellaneous vegetation and non-adherence to timely thinning practices may also have contributed to this poor height growth. In the age class 50+, the SQ I plantation is having an age of 111 years and the SQ II plantation is 68 years of age thus resulting in a higher average total tree height.

Figure 6. Individual tree height distribution in age class 10-20 plantations of Nilambur forests, Kerala

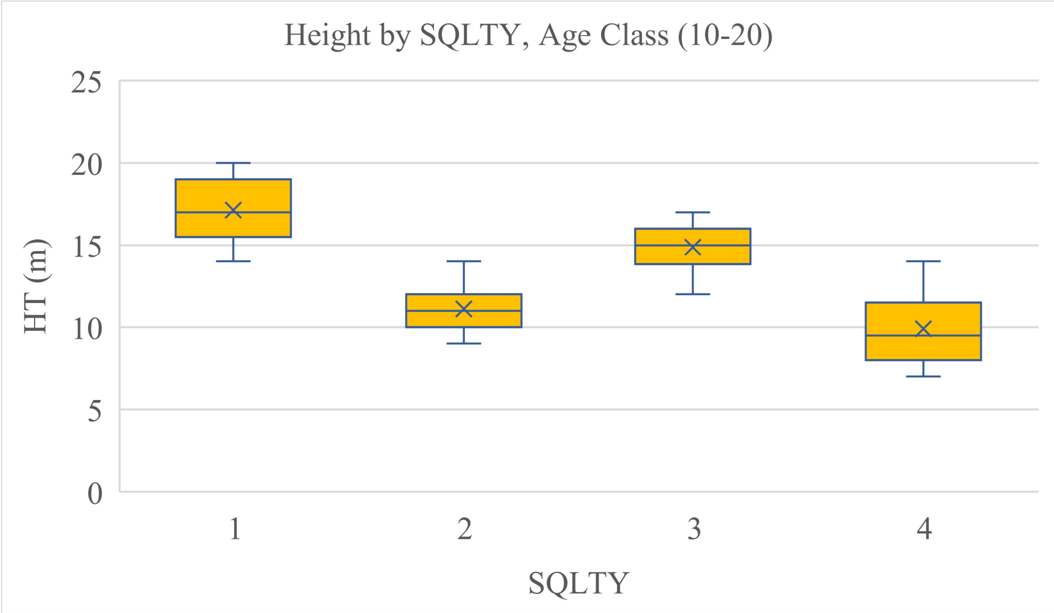


Figure 7. Individual tree height distribution in plantations of age class 20-30 in Nilambur forests, Kerala.

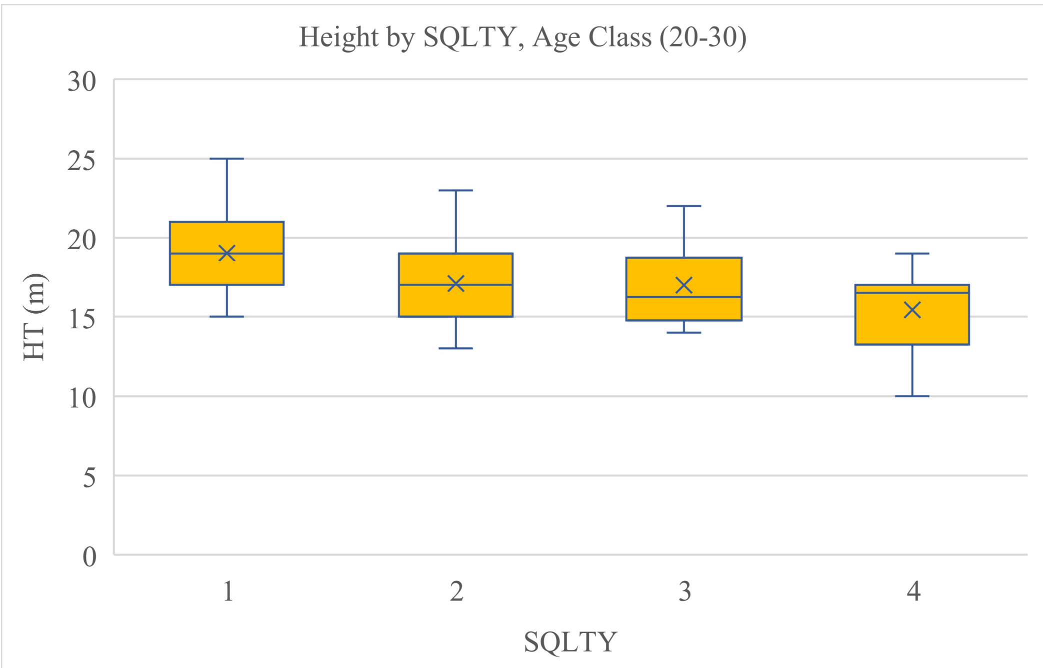
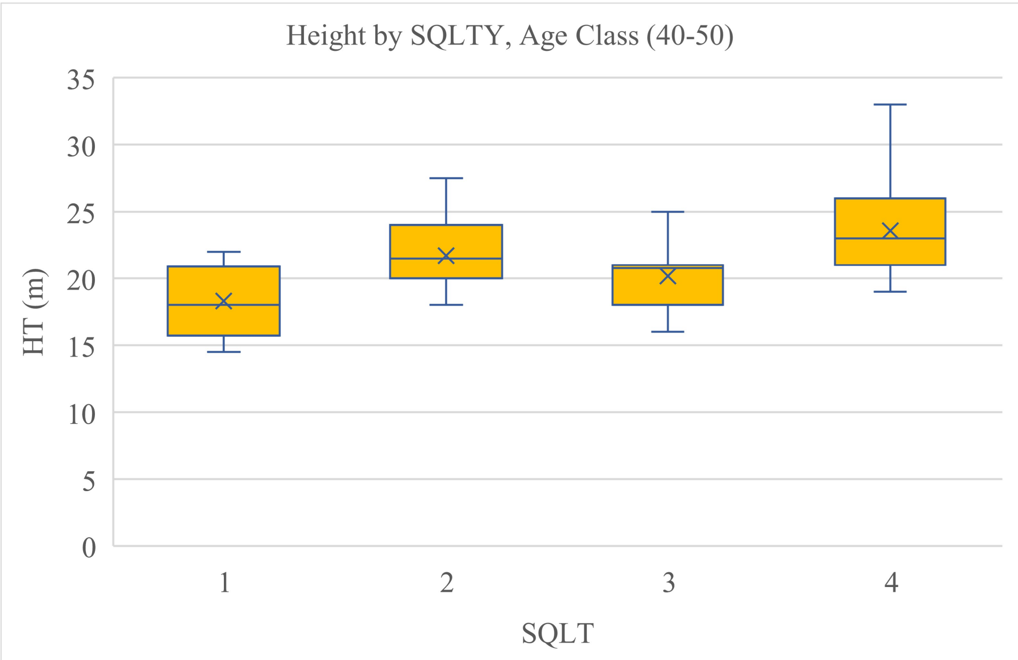


Figure 8. Individual tree height distribution in plantations of age class 30-40 in Nilambur forests, Kerala.

Figure 9. Individual tree height distribution in plantations of age class 40-50 in Nilambur forests, Kerala

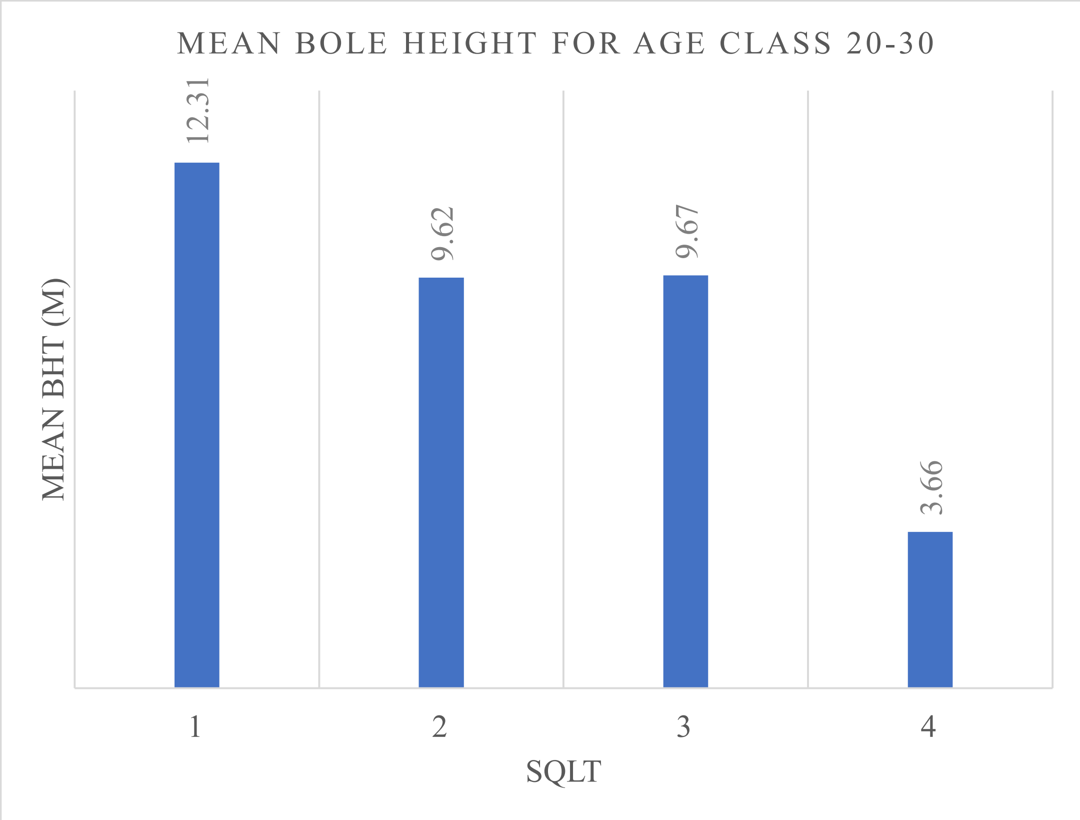


The height of trees in the studied plantations points at an urgent need to revisit and reassess the site quality of plantations of Nilambur. For instance, the SQ I plantation of age class 40-50 recorded a lower height than what is expected of an SQ I plantation at the age of 40 years (28.04-33.8 m) based on the all India site quality table for teak. The observed values place the SQ I plantation in SQ III. Similarly, the SQ IV plantation showed a higher-than-expected value (10.16-16.15) for height, suggesting its reassignment into a higher site quality.

5.1.2. Bole height

The clear bole length of a tree determines its economic or commercial value. Management interventions like pruning are aimed at ensuring the attainment of maximum possible clear bole height. Nilsson (2014) reports that intensive management with timely thinning and pruning resulted in better sawn wood dimensions in Panama. In the present study, in general, the SQ I plantations showed higher bole height. Though there was a decline in bole height in the lower site qualities, this did not follow a regular trend. Among the plantations of age class 10-20, the SQ I and SQ III plantations exhibited a significantly better bole height than the other two plantations. This can be a result of the intensive management that these plantations receive in comparison to the others. As expected, there was a general increase in bole height with age which is obvious. Attainment of better bole height has strong functionality with stand management. For instance, time-bound thinning regulates the crown expansion and crown lifting which has strong bearing on the bole height. Crowded stands with lesser crown release may lead to poor crown height (Kunhamu, 2006). Height growth show insensitivity to site quality changes at advanced ages as compared to younger ages (Figure 10) Elephant damage to plantations was observed in a number of plantations during the study. The SQ IV plantation of age class 20-30 has a significantly low clear bole height of 4.18m (Figure10). Elephant caused damage makes the trees forked and crooked, thereby reducing the length of clear bole. Elephant feeds on the bark of teak trees (Das Chatterjee, 2016). Field observations suggest that stripping of bark may have damage the bole, making it twisted or crooked.

Figure 10. Mean bole height of plantations falling under age class 20-30, belonging to different site qualities in Nilambur forests, Kerala.



Similar observations of elephant damage to plantations has been reported from Parambikulam, where seedling survival had been extensively affected by presence of elephants (Vijayakumaran Nair and Jayson, 1988). During the study, entire plantations that failed to establish due to elephant damage were observed in Karulai range of Nilambur South Forest Division. For instance, there was plantations at Mundakkadavu and Nedungayam adjacent to the plantations

5.1.3. Diameter at Breast Height (DBH)

In the study, the observed results showed that the SQ I plantations had a higher DBH than the lower site qualities. Also, the trends in general suggested a decline in DBH with lowering of site qualities. This clearly indicate the dominating effect of site quality on tree growth. Site quality being the productive potential of the site to convert biophysical resources into biomass, the perceived observation is justifiable. Many studies in the tropics are in conformity with this observation (Jayaraman and Rugmini, 1993; Jayaraman, 1998; Canadas-L *et al.*, 2018; Hu *et al., 2021)* However, deviations from this general trend has been observed especially for SQ III for 10-20 age class and SQ II and SQ IIIs for 40-50 age class. Such anomalies may be attributed to variable management interventions to which these plantations were exposed. Yet another observation was that the effect of site quality showed insensitivity at advanced age. Similar results were reported for *Quercus mongolica* in northern China by Hu *et al.* (2021) where the site quality had no significant impact on the final DBH of a stand. It is well understood that appropriate management is essential to derive best growth output from teak plantations (Ladrach, 2009). Many studies reiterate the fact that radial growth of trees in stands is controlled by stand density (Sagar and Singh, 2006; Kunhamu *et al.*, 2009; Pachas *et al.*, 2019 b) and other management practices in addition to the site quality . For instance, in age class 20-30, we can see that the average DBH of the SQ III plantation was slightly higher than the SQ IV plantation where there is a higher density of trees.

Spacing is an important factor that influences the DBH with a closer spacing resulting in smaller sized trees (Sibomana *et al.*, 1997; Zahabu *et al.*, 2015). However, this trend was not discernible in the present study as the teak trees were managed at variable stand densities. For instance, under the age class 10-20, the plantations of SQ I and SQ III were the better performers. These plantations were receiving better management interventions compared to the other two. They had been subjected to periodic interventions like weed and woody climber removal and thinning, resulting in a superior growth performance. However, such timely management were lacking for SQ II with most of the teak tree appeared crowded having a close tree spacing of 2m x 2m. The effect of site quality will be manifested to the maximum potential provided the stand is subjected to timely density management for deriving the optimal productivity.

Irrespective of the site quality and age class considerations, the attempts to relate the teak diameter growth with mean tree height reflected a linear relationship among the teak trees in Nilambur ($R^2 = 0.703$). The plausible explanation for the more number of individuals within the 30m height and 40 cm diameter could be attributed to the fact that the trees in the stand show normal distribution (Figure 12) in crowded unmanaged condition.

Figure 11. Height- DBH relationship in all the trees enumerated in the 20 plantations spread across Nilambur.

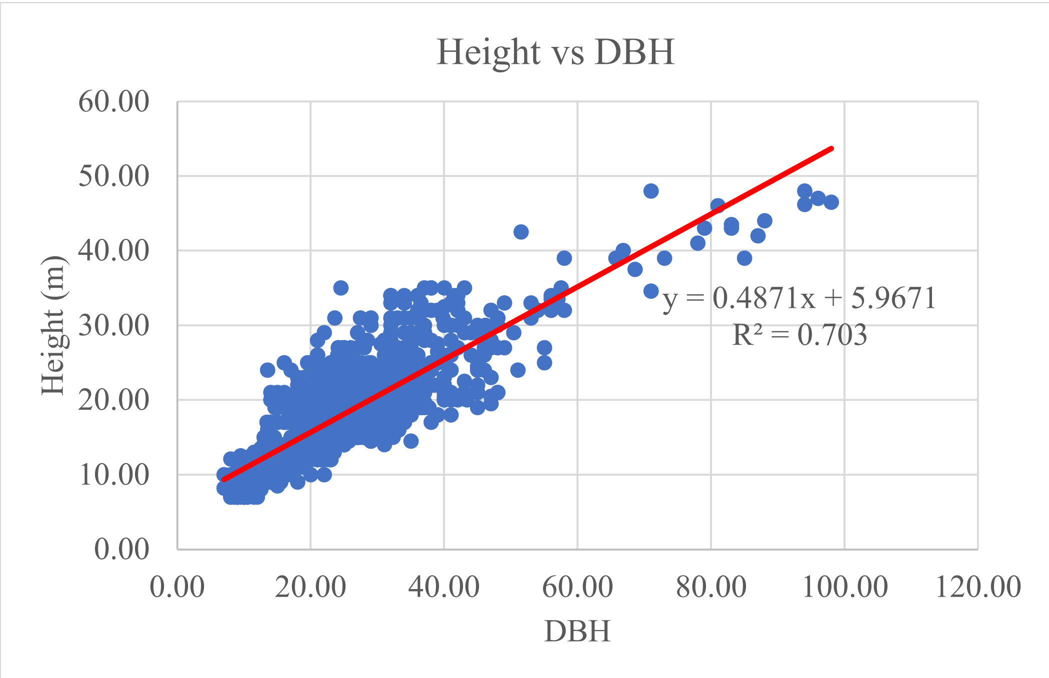
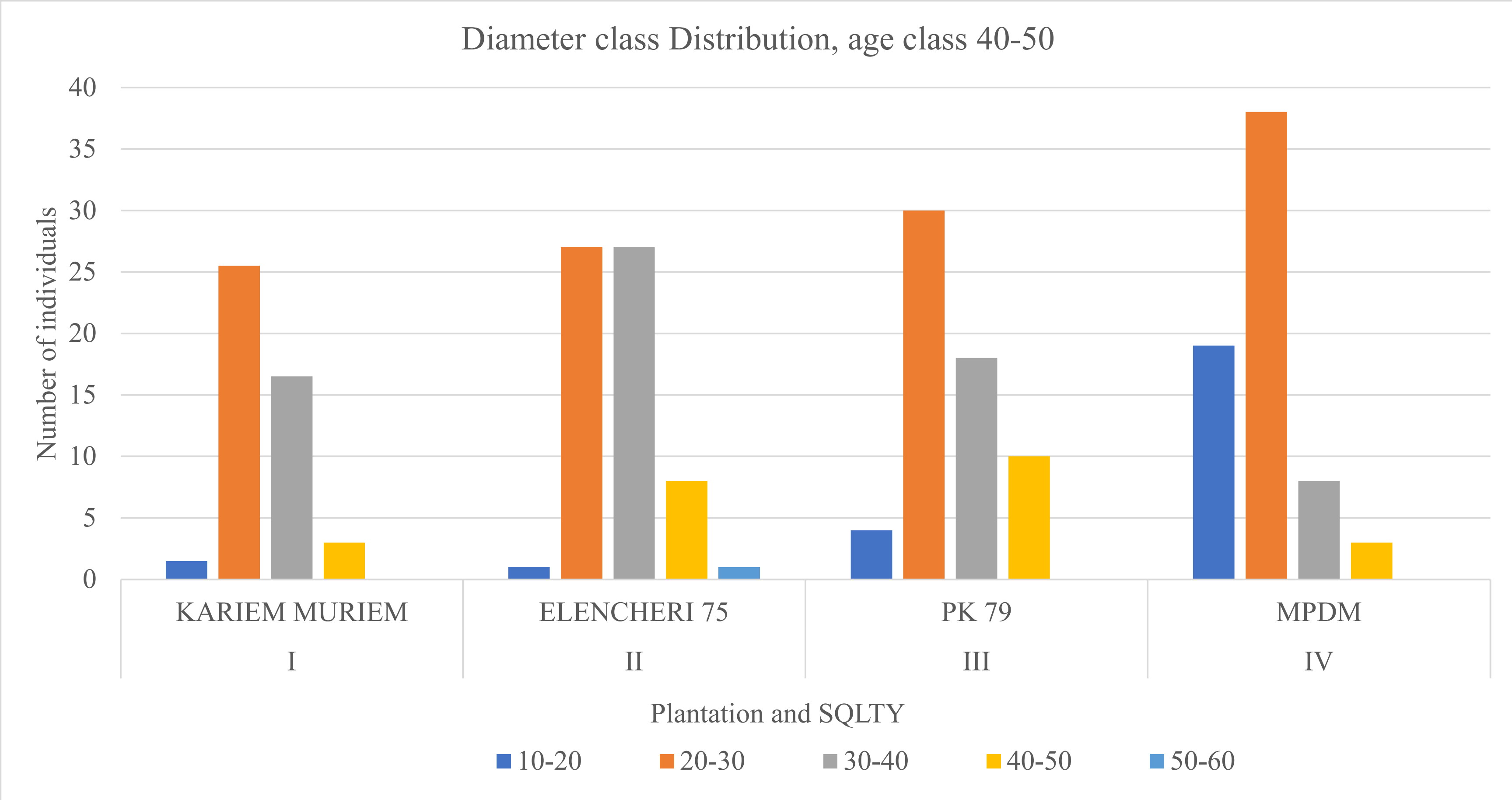


Figure 12. Diameter class distribution in 40-50 age class plantations in Nilambur forests, Kerala.



5.1.4. Diameter at crown point (DCP)

Tree diameter at crown point is a strong indicator of the form of the trees and hence influence the commercial timber value. However, this depends on several factors including the site quality and management conditions. In the present study, the SQ I plantations had the largest diameter at crown point in each of the age classes compared other lower site qualities. However, the lower site qualities showed pronounced variation in lower age classes (10-20 and 20-30) while the differences were marginal at advanced ages. The diameter at crown point is often a function of the bole height of the trees i.e., trees with larger bole height may show reduced DCP compared to short statured trees. Despite this fact, the SQ IV trees with relatively short stature compared to SQI, showed lower DCP. Perhaps, the general poor growth consequent to poor biophysical conditions in the SQ IV may have contributed to their lower DCP. Further, the DCP is strongly influenced by stand management practices, especially density regulation (Karlsson, 2000; Kirby *et al.*, 2016; Saarinen *et al.*, 2020). Non uniformity in DCP observed across site qualities and age classes could be partly attributed to the variability observed in density regulation among the teak stands. The influence of large population of other miscellaneous trees in various teak stands may have compounded the effect of site quality on DCP.

There was a decline in DCP in the lower site qualities but this decline did not follow any steady pattern between the plantations, due to the differences in tree size and the height at which DCP is measured. For instance, in age class 30-40, the SQ I plantation has a difference of 12.79 cm between DBH and DCP owing to a longer clear bole while in the SQ II plantation with a shorter bole, this difference is only 8.54 cm.

5.1.4. Basal Area

Basal rea is widely used as a measure of the growing stock in a plantation. Tree basal area is a strong indicator of the productivity of plantations and hence may have been influenced by variable site qualities. The present study revealed convincingly higher mean tree basal area for SQI for all age classes. A corresponding decline in mean tree basal area has been observed with decline in site quality for all age classes. However, as observed earlier, the changes in mean tree BA with site quality were only marginal at advanced ages (30-40 and 40-50) except in the case of SQI. The trees better respond to the site resources during the younger age and with maturity, their potential to utilize the resources decline substantially. Studies elsewhere also suggest the poor response of trees growth on site resources at advanced age (Weiner and Thomas, 2001; Johnson and Abrams, 2009; Gunaga *et al.,* 2014).

Yet another factor that strongly influence tree BA is the stand density. Trees at higher density (closer spacing) show lower mean tree BA which increase with the increase in spacing (Kunhamu *et al.,* 2009; Sagar and Singh, 2006; Piotto *et al.*, 2010) Similar observation was discernible in the present study as well where less dense plantations showed a higher average mean tree basal area than the higher density plantations. For instance, in the age class 10 to 20, the SQ I and SQ III plantations having a spacing of 6 metres by 6 metre showed higher basal area compared to the other two plantations which were closely spaced. Such a positive relationship between spacing and basal area is well established and reported (Kunhamu *et al.,* 2009; Khanduri *et al.,* 2008; Chukwu and Osho, 2018). Furthermore, miscellaneous tree species present in the teak plantations under study, may have considerably affected the growth performance of teak (Jayaraman and Zeide, 2007). Interestingly, in the age class 40-50, site quality IV plantation shows the highest value for average tree height but in contradiction to expectation, had the lowest mean tree basal area. Probably, the higher number of miscellaneous tree species present in the teak plantation may have competed with teak for resources and thereby resulted in lower sized trees.

The dominating role of site quality on the stand basal area (SBA) was visible in the present study with SQI giving predominantly higher values compared to other lower site qualities. Consistent with this, the poor site qualities (SQ IV) showed lowest stand level basal area in the study. However, the deviation from the general trend was obvious in the study with some lower site qualities giving better SBA compared to higher site qualities. This could be primarily attributed to the gross variability in stand density among such teak stands. Apart from the quality of the site, the tree density (number of trees per ha) plays a cardinal role in regulating the stand basal area (Kunhamu *et al.*, 2010; Kunhamu *et al.,* 2011) The SQ IV plantation showed no significant difference with the SQ II and III plantations in terms of average individual basal area but total basal area per hectare was nearly one fourth of the value observed in the plantations of site quality II and III primarily due to a lower number of trees in the plantation. Similarly, the least value of total basal area per hectare was observed for the SQ IV plantation of age class 30-40 (3.57m^2ha^{-1}) which also attributed to the lower density of teak present (94 ha^{-1}).

The ideal expectation of a plantation forest is one where the trees are of similar sizes. But in the present study it was observed that the individual trees varied widely in size within each stand. The individual tree basal area distributions in each stand till age class 40-50 are shown in Figure 13 to Figure 16.

Figure 13. Individual basal area distribution in plantations of age class 10-20 in Nilambur forest, Kerala

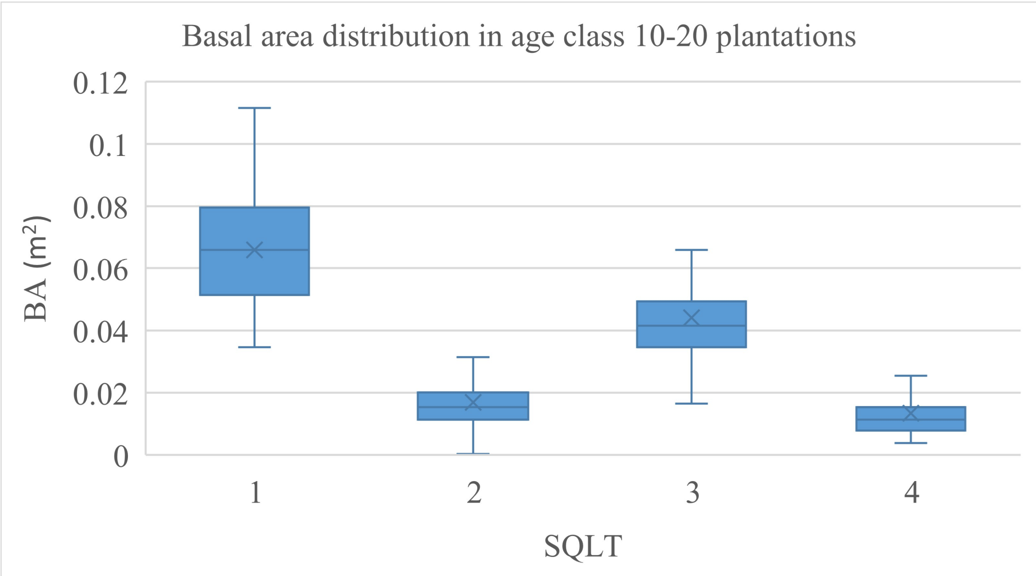
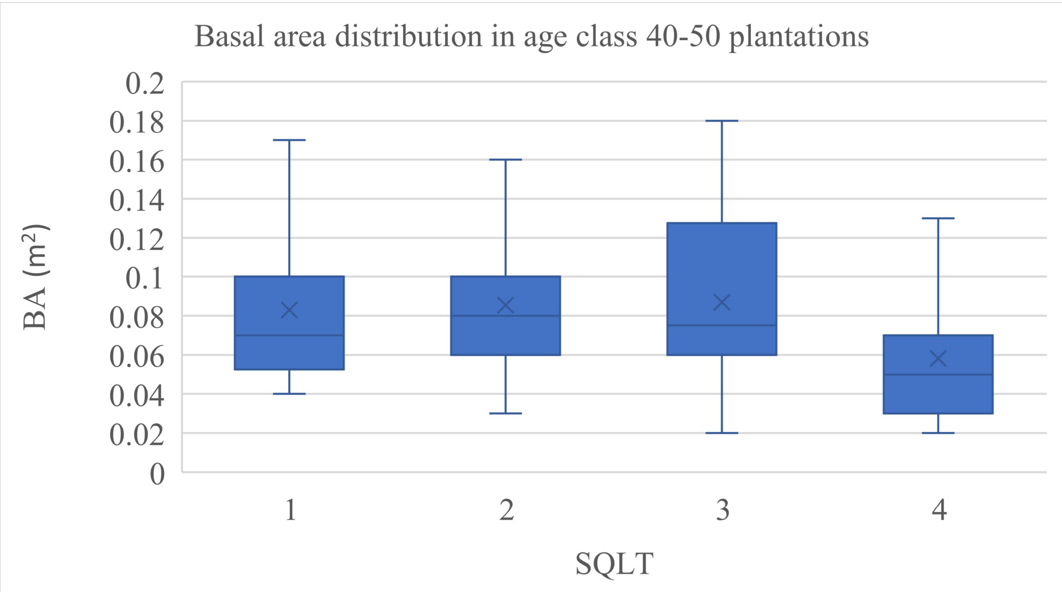


Figure 14. Individual basal area distribution in plantations of age class 20-30 in Nilambur forest, Kerala.

Figure 15. Individual basal area distribution in 30–40 year age class plantations of Nilambur forests, Kerala. (m^2)

Figure 16. Individual basal area distribution in 40-50 age class plantations of Nilambur forests, Kerala.



5.1.5. Mean Annual Increment in Basal area ($MAI_{basal\ area}$)

The mean annual increment of the plantations was calculated in terms of basal area as the DBH is the only variable in determining basal area and its measurement was done by contact with the tree bole with a caliper. Hence calculating MAI in terms of basal area minimizes any optical errors that might occur while measuring height and MAI in terms of volume. Vigulu *et al.*, (2019) reported that the individual MAI in basal area for teak can vary from 0.004 to 0.014 m^2yr^{-1} in 5-year-old teak.

In the present study, the MAI was generally higher for the SQ I plantations and it declined in the lower age classes but this did not follow any general trend. Along age, we can see that the MAI declines towards the mature plantations. The growth of teak trees is more profound in the younger stages and this declines with age (Koirala *et al.,* 2017). The density of teak trees present in the plantation determines the MAI per hectare value. In closely spaced plantations, evens like the SQ IV plantation of age class 10-20, though there is a fairly good value of basal area MAI, this is merely a sum from a large number of small sized trees

5.1.6. Bole volume and total tree volume

Volume is the most important stand growth variable which has considerable commercial significance. Invariably, better site quality plantations are expected to give better volume (Forrester *et al.*, 2013). Obviously, this trend is visible in the present study as well with first site quality showing highest mean tree bole volume in all age classes compared to other site qualities. Also, the lowest site quality (SQIV) represented lower mean tree bole volume except for the 50+ age class. However, strong trends in bole volume production were not observable among SQ II and SQIII. Bole volume being a product of tree basal area and height, it reflects the distribution of basal area and height among the stands. Tree height usually better reflect the site quality than the basal area which has more control on the stand management conditions (Pérez and Kanninen, 2005b; Katsutoshi *et al.*, 2016). In the present study, the mean height though followed the site quality, basal area trends had strong influence on the management conditions. Many of the teak stands under study were poorly or ill managed with considerable variability in stand density. Furthermore, the teak growth was influenced by the miscellaneous vegetation existent in the stands at different locations which had negatively impacted the teak growth and productivity in respective stands.

The local history and the temporal changes that this plantation has underwent in the previous rotations and also the methodology adopted for the site quality estimation are unknown leading to ambiguity in the teak productivity trends under various stands. There are evidences in literature that suggest local conditions and inadequate management interventions can result in decline in site quality (Evans, 2012). Most of the plantations under study were subjected to continuous suppression by elephant attacks. Elephant damaged plantations can have a lower bole volume than what is expected. The decline in average bole volume due to animal presence can especially be seen in the SQ IV plantation of age class 20-30.

Teak growth for each site quality followed consistent increase with increase in stand age. However, this increase was more pronounced in SQ III and SQ IV. The unexpected decline in volume in the SQI for 40-50 age class could be attributed to the growth suppression contributed by local factors such as elephant damage and poor adherence to stand management strategies. This observation is further affirmed by the sharp increase in bole volume in the teak stands at 50+ age which incidentally was under better management conditions. The bole volume production trends in the present study converges to the conclusion that the growth advantages contributed by the site quality are often masked by the stand management conditions to which the stand is exposed as in case of the SQ I plantation of age class 40-50, which is subjected to suppression by elephants

Total bole volume per hectare is essentially a function of the number of trees present in the plantation. Larger densities can result in larger volume of smaller sized boles or trees (Zahabu *et al.*, 2015). In the present study also, it was discernible that the number of trees present has influenced the total bole volume per hectare in the plantations. For instance, in the age class 10-20, the SQ II and IV plantations showed no significant difference between them in terms of average individual bole volume. However, the total bole volume per hectare for SQ IV plantation was nearly the double that of SQ II owing to its higher tree density. Furthermore, as observed before, most of the teak stands were under suppression due to the presence of miscellaneous tree species. For example, the SQ I and IV plantations of age class 30-40 appear to be like moist deciduous forests owing to high densities of miscellaneous trees

The average mean tree total tree volume of the SQ I plantations were generally the highest as compared to other site qualities among the different age class plantations. However, there was enormous increase in mean tree total volume in highest age class (13.52 m3 $tree^{-1}$) as compared to other age classes for SQI. The values declined in the subsequent site qualities of each age class but there was no clear trend or pattern depicting the change. Despite the good statistical significance, the changes in mean tree volume for most of the age classes were modest. This is more pronounced in the SQ III and SQIV at advanced age. The large variation in mean tree volume production in the 50+ age class could be attributed to large differences in stand age under different site qualities. However, the highest productivity in this age group associated with SQI clearly indicate the combined decisive role of site quality and better management on the productivity of teak.

As stated previously, the study was based on the site quality information that was already available with the forest department and the plantations are distributed in 2 forest divisions making them biophysically heterogeneous. The rigor with which the SQ estimations were previously carried out is unknown and this has been a limitation in obtaining clear patterns of change between the site qualities. Across the age classes, there is a general trend of increasing tree volume with age among the four site qualities.

The productivity trends in terms of mean tree volume and stand volume exhibited considerable variation in the present study. For instance, the greater prominence in mean tree volume exhibited by stands under SQI was not reflected at stand level volume production except for the 50+ age group which incidentally was way too higher than all the site quality and age class regimes. For example, teak stands at SQII showed comparable stand volume with SQI especially for age classes 20-30, 30-40 and 40-50. Total tree volume per hectare is a function of stand density and therefor showed different pattern than the average individual tree volume (ref 1,2,3). For example, the mean tree volume for SQ II stand at 20-30 age class was fairly lower (0.59 m^3 $tree^{-1}$) as compared to corresponding value at SQ1 (0.89 m^3 $tree^{-1}$). However, the stand volume production was higher for SQII as compared to teat at SQI. Similarly, the SQ IV plantation for age class 30-40 showed no significant difference from SQ III in terms of mean tree volume. However, the total tree volume per hectare for SQ III plantation was nearly four times the value of SQ IV planation. Many studies have demonstrated the prominent role of site quality on volume production at tree level. However, existing biophysical conditions and management regimes plays cardinal role on the productivity in tree plantations. The investigations on the teak growth in Nilambur forests in general suggest that the advantages of site quality on teak productivity have been often confounded by the poor management followed. Furthermore, the severe damages caused by wild elephants also contributed to the poor volume production of teak in many stands under study.

5.1.7. MAI in volume production

MAI is often considered the most important estimate of productivity of any plantation. The individual tree MAI of the studied plantations of Nilambur varied from 0.036 m^3yr^{-1} to 0.0633 m^3yr^{-1}. The global overview of teak plantations states the productivity of teak in India at 12.3 m^3 ha^{-1} yr^{-1} in the best sites, 7.9 in average sites and 2.7 m^3 ha^{-1} yr^{-1} in poor sites (Ball *et al.,*1999). For the case of Kerala, the average MAI of teak at a mean rotation of 58 years was observed to be 2.49 m^3 ha^{-1} yr^{-1} (Chundamannil, 1997). The management interventions that a plantation receives will impact the MAI of the stand. Chundamannil, (1997) estimates the average MAI of teak plantations of Nilambur at 2.954 $m^3ha^{-1}yr^{-1}$ at an age of 56 years. In the present study, the average MAI of the 50+ year old plantations were estimated to be at 3.305 $m^3ha^{-1}yr^{-1}$. The estimates of MAI for the different plantations of different age classes and site quality regimes varied from 0.56 to 8.70 $m^3ha^{-1}yr^{-1}$. The influence of Site quality in MAI was notable in the SQ I plantations as they showed a general trend of superiority in each age class. There was a decline in MAI in the subsequent site qualities although this decline did no show a regular pattern as each plantation were influenced by various local factors determining the MAI accrual.

The expected MAI for mature teak is SQ I=8.49 to 9.95, SQ II= 5.58 to 7.04, SQ III= 3.12 to 4.38 and SQ IV= 2.16 (Palanisamy *et al.,* 2009). Here in the present study, we can see that the plantations of age class 40-50 have suboptimal productivity mostly due to the poor management they are being subjected to. Maintaining an optimal density is essential to achieve the maximum productive potential of a site. Jayaraman and Zeide, (2007) in their paper on optimizing stand density of teak in Kerala states that by maintaining optimal density regimes with 475 teak trees, at an age of 50 years, the MAI attained will be 2.7, 5.2,7.3 and 12.9 $m^3ha^{-1}yr^{-1}$ for SQ IV, III, II and I, respectively. The effect of density on MAI is clearly observable in the present study. The SQ IV plantation of age class 30-40 has the least value of MAI (0.56). This can be attributed to the low density of teak present in the plantation.

5.1.8. Stem form

Tree form is again an important growth factor that has strong bearing on the commercial value of trees. a poorly formed stand fetch poor returns, despite higher volume production. This is more important for valuable timber species like teak. The present study could not arrive at any characteristic trend in stem form and site quality among the teak stands. For example, teak stands at SQI (40-50 age class), SQ II (30-40) and SQ IV (20-30) represented higher form factor with value 0.75, 0.77 and 0.78, respectively while stands at SQI in the lower age classes represented lower stem form (0.69). Further, the value of form factor depends on the age and bole height of trees (Felipe *et al.,* 2016). The form factor of teak generally lies between 0.55 to 0.77 (Akossou *et al.*, 2013) similar values were estimated for the 20 plantations in the study. It was interesting to note that there was no significant difference in bole form factor between the plantations of age class 40-50 possibly suggesting a leveling of growth in the mature trees irrespective of site quality.

Tree form is primarily a function of the tree growth condition and degree of release of crown at various growth stages (Karlsson, 2000; Kunhamu, 2006). This in turn has considerable functional relation with the stand density (Pérez and Kanninen, 2005a; Kunhamu *et al.,* 2011). Often trees at higher stand density exhibit better form while trees at wider spacing allocate more resources for crown expansion leading to lower stem form (Bonnor, 1968; Shenkin *et al.*, 2020). Proper regulation of stand density hence, may lead to improvement in stem form. Since the biomass productivity is higher in better site qualities, it gives good scope for developing higher volume outturn with improved stem form. However, this trend was not discernible in the present study primarily due to the poor density management of various stand under different site qualities. Furthermore, the situation was further compounded by the presence of large number of miscellaneous tree species along with teak.

5.1.9. Crown diameter

The average crown diameter depends on age of the plantation and competition that the trees experience (Aigbe and Nchor, 2019). Larger and widely spaced trees are expected to have a wider crown (Ogana, 2019). In the present study, generally, the SQ I plantations showed larger canopies than the lower site qualities. The crown diameter declined in the subsequent site qualities but this did not follow any predictable pattern. In the age class 40-50, the SQ II plantation had a larger canopy width, probably because the trees in the respective plantation were subject to better management interventions. Across the age classes, there was no clear trend of increasing canopy width as in many plantations, the competition with miscellaneous trees have limited the crown development of teak. For instance, the

SQ III plantation of age class 40-50 have a lower crown width than the previous age class plantation due to larger number of miscellaneous trees present within the plantation.

5.1.10. Density of teak in plantations

The per hectare number of trees present in a plantation is generally influenced by the level of management that the plantation is subjected to. Jayaraman and Zeide (2007) based on their study in teak plantations of Kerala reported that only 4.8% of the plantations studied by them were having optimal density.

In the present study, though in a number of plantations, the number of teak trees appears to be optimal, there was the presence of a larger number of miscellaneous trees in the plantations, making them overstocked in reality. For instance, the SQ IV plantation of age class 40-50 had 236 teak trees per hectare. It also had 197 trees of miscellaneous trees present per hectare of the plantation, making the stocking 433 trees per hectare. The miscellaneous tree count of the SQ I plantation of age class 30-40 had an extremely high miscellaneous species count at 694 trees per hectare. In this plantation, the teak trees were confined to riverside area of the plantation where the miscellaneous trees were negligible.

In plantations that were severely infested with other than teak flora, the miscellaneous vegetation comprised of trees like *Terminalia paniculata* Roth. and *Xylia xylocarpa* Roxb. Taub. The major lianas that were damaging teak in the plantations were *Spathalobus parviflorus* (DC.) Kuntze and *Calycopteris floribunda* Lam. Lianas can impart severe damage to growth and productivity potential of a plantation. For instance, in the 50+ age class plantation of site quality IV, trees that have dried due to being strangled by *Spathalobus parviflorus* (DC.) Kuntze were observed.

5.2. Soil parameters

The pertinent results seen in the analysis of soil chemical and physical properties in the 40-50 age class plantations of the 4 different site qualities are discussed below.

5.2.1. Soil pH

Soil pH plays a cardinal role in plant nutrition. Neutral or near neutral pH is assumed to be favour the plant nutrient uptake. Obviously, the optimal soil pH for teak is reported to be around 6.2 to 7.2 (Jerez and Coutinho, 2017). In Nilambur, the good teak sites are reported to have a pH of 5.3 to 5.7 which is slightly acidic (Alexander *et al.*, 1981; Balagopalan, 1995). In the present study, similar observations were made with pH varying from 5.17 to 5.98 among the studied plantations. The effect of trees on soil pH is influenced by a number of factors like initial soil pH, the tree species present, presence of ions in the soil, the C:N ratio of plant litter, the composition of root exudates, rhizosphere interactions between plants and soil etc (Hong *et al.*, 2018). In general broadleaved woody ecosystems tend to moderate the extremes in pH to a near neutral pH (Hong *et al.,* 2018; Dijkstra, 2001; Zheng *et al.,* 2017). However, studies have demonstrated that temperate species with acidic litter contribute much to enhance the soil acidity there by lowering the soil pH (Yang *et al.*, 2015; Burgess-Conforti *et al.*, 2019)

In the present study, except for the SQI and SQIV, the remaining site qualities showed significantly higher soil pH in the contiguous treeless open plots as compared to the teak stands. Though the changes were significant, their magnitude was fairly modest. There are reports which suggest lowering of soil pH in teak plantations. In a study, Reddy *et al.* (2017) observed such lowering of soil pH in teak plantations in Nagpur, India as compared to bamboos. The acidic phytochemistry of the litter and the fine roots may contribute to such lowering of soil pH. A characteristic influence of site quality on the soil pH was not discernible in the present study. For instance, despite the lowering in soil pH in SQI and SQIV, the other two site qualities showed a reverse trend with higher pH in the teak plantations. This suggest that apart from the site quality pH variations are driven by intrinsic soil factors such as parent material, soil exposure, litter phytochemistry and other soil biophysical factors (Zhang *et al.*, 2019)

Varying trends in soil pH has been observed with soil depth. For instance, modest increase in pH was observed with increasing soil depth for SQI, II and IV. However, the changes were not significant. This was evident both for teak plantation soil and contiguous open soil. Interestingly, the SQIII soil exhibited a modest decline in soil pH with soil depth. There are experimental evidences which suggest slight decrease in soil pH with soil depth (Reeves and Liebig, 2016). This could be attributed to the abundant rainfall in the study sites which might lead to leaching of calcium and magnesium ions in the lower soil layers thereby leading to a decrease in pH of soil (Lepcha and Devi, 2020). Pronounced changes in soil pH with stand age also was not observable in the various studied teak plantations. The lack of variation in soil pH in the deeper depths could be ascribed to the fact that the effect of litter and fine root mineralization may be minimal at deeper soil and probably parent material may have better role in regulating the soil pH. However, the pH-changes in the top soil can partly be explained by biological mineralization increasing with stand age (Tamm and Hallbacken, 1986).

5.2.2. Soil carbon

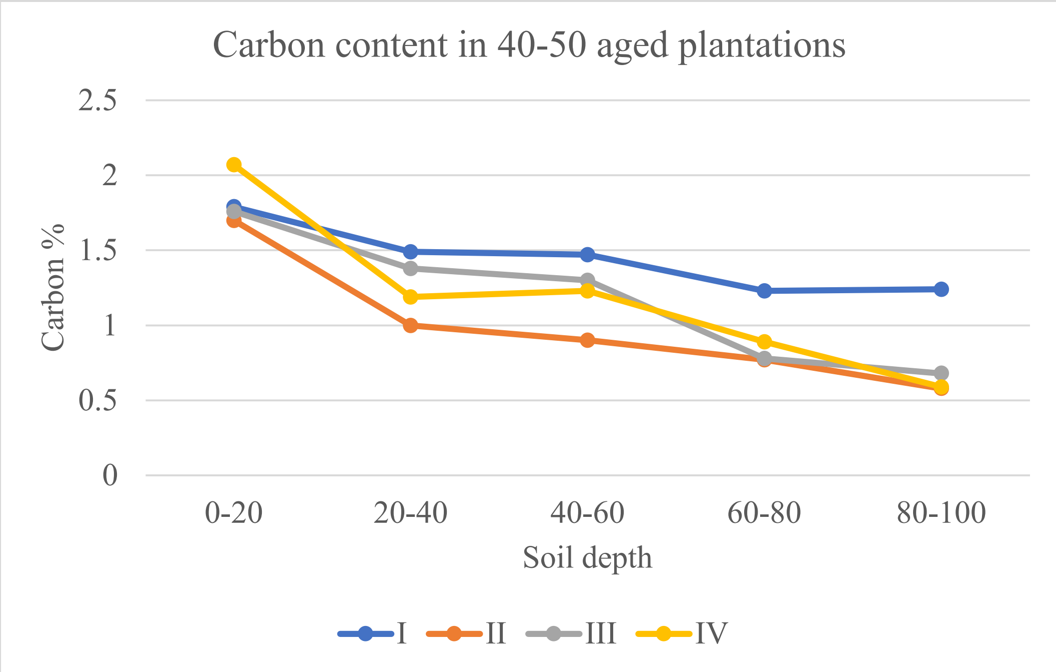
Soil carbon in teak plantations of Kerala at various depths have been estimated to be ranging from 0.18 to 3.31 % (Alexander *et al.*, 1981; Jayaraman and Rugmini, 1993; Balagopalan, 2016). In the present study, the values of soil carbon varied from 0.58 to 2.07% between the plantations and soil depth layers. Studies also revealed that soil organic carbon in teak plantations decreases with depth (Rugmini, *et al.,* 2007; Balagopalan, 1995). This trend is evident in the present study as well though the rate of decline was variable with site qualities (Figure 17). However, the present study could not establish predictable trends in changes in soil carbon content with site qualities. For instance, SQIV registered highest the top soil carbon content while the changes were at par for the remaining site qualities.

The highest total soil carbon stock in the one-meter-deep soil profile was for site quality I (160.61 Mg ha^{-1}) followed by SQIV (143.60 Mg ha^{-1}) and the lowest was for SQII (112.02 Mg ha^{-1}). Boonyanuphap and Kongmeesup, (2016) reports the soil organic carbon of teak plantations of Thailand at 163.29 Mg ha^{-1}. George (2019) reports the soil organic carbon in 5-year-old teak plantations of Kerala at 90 to 121 Mg ha^{-1}. Attempts to compare the SOC in the plantation and its respective contiguous open area suggested that the SQ I plantation showed higher C content in all depths when compared to the contiguous treeless open (Figure 18). This suggests a higher C storage in tree ecosystems compared to open areas. Such increase in SOC in woody ecosystems has been reported from many studies (Kraenzel et al., 2003; Gamfeldt *et al.,* 2013; Kongsager *et al.,* 2013). The litter turnover and belowground fine root dynamics contribute substantially to enrich the soil organic carbon in woody ecosystems (Jha, 2014; Vigulu et al., 2019; Zhang *et al.,* 2020). This clearly demonstrate the better soil organic carbon content associated with better site qualities. However, considerable decline in soil carbon was observed with increase in soil depth for all the remaining site qualities. For example, the top soil in SQIV teak stand reported high C content to the tune of 2.07% which declined drastically across soil depths reaching upto 0.59% in the deepest soil (80-100 cm). The poor sites are usually deficient in organic carbon which may be more pronounced at deeper soil. The soil depth in poor site qualities is usually shallow and the facilitatory role of vegetation in improving the SOC at these sites are often minimal.

Despite the decline in SOC with increasing soil depth, it was interesting to observe that the rate of reduction was more for the treeless open soil as compared to the tree bearing plots. For example, the SQI plantation soil maintained fairly high soil Carbon even at a depth of 80-100cm (1.24%) while the contiguous open soil had only 0.95% for this soil depth. Soils in woody ecosystems are replenished with carbon and minerals made available through the turnover of tree roots even at deeper layer while the mechanism may be totally absent in treeless soils (Kunhamu *et al.,* 2018).

A plausible explanation for the unpredictable variability in SOC among other site qualities is that the teak stands corresponding to these site qualities are distributed at far away locations in the Nilambur north and south divisions and hence the soil biophysical condition and topography may be widely heterogeneous. However, it is pertinent that teak growth in the best quality sites lead to better carbon content maintained even at deeper soils.

Figure 17. Carbon content with depth in the 40-50 age class plantations of different site qualities in Nilambur, Kerala.



It could be noted that despite the general improvement in SOC in teak stands, some of the plantations showed lower SOC in the teak stands as compared to their respective contiguous open. This was more pronounced for SQII, III and IV. In the SQ III and IV plantations, the plantations were in hilly terrain and consequently the adjacent open areas were available in the lower side of the plantation hills. In these plantations, the open areas were having a higher C content than the plantation site. Soil erosion was evident in the hilly terrain, especially for the SQ IV plantation at Muleppadam, which might have washed the C containing litter and top soil from the plantation, causing a lower C content within the plantation soil. In these cases, the plantation soils have been probably subjected to multiple instances of disturbance during felling and other management operations.

Similar results were reported on comparing tropical orchards and grasslands in Brahmaputra -Yamuna plains were the undisturbed soils had higher C content than disturbed soils under tree cover (Yeasmin *et al.*, 2020). Similarly, Balagopalan, (1995) reported higher C content in grasslands compared to teak plantations in Kerala.

Figure 18. Carbon content in various depths of SQ I plantation and contiguous treeless open at Kariem Muriem, Vazhikkadavu, Nilambur, Kerala.

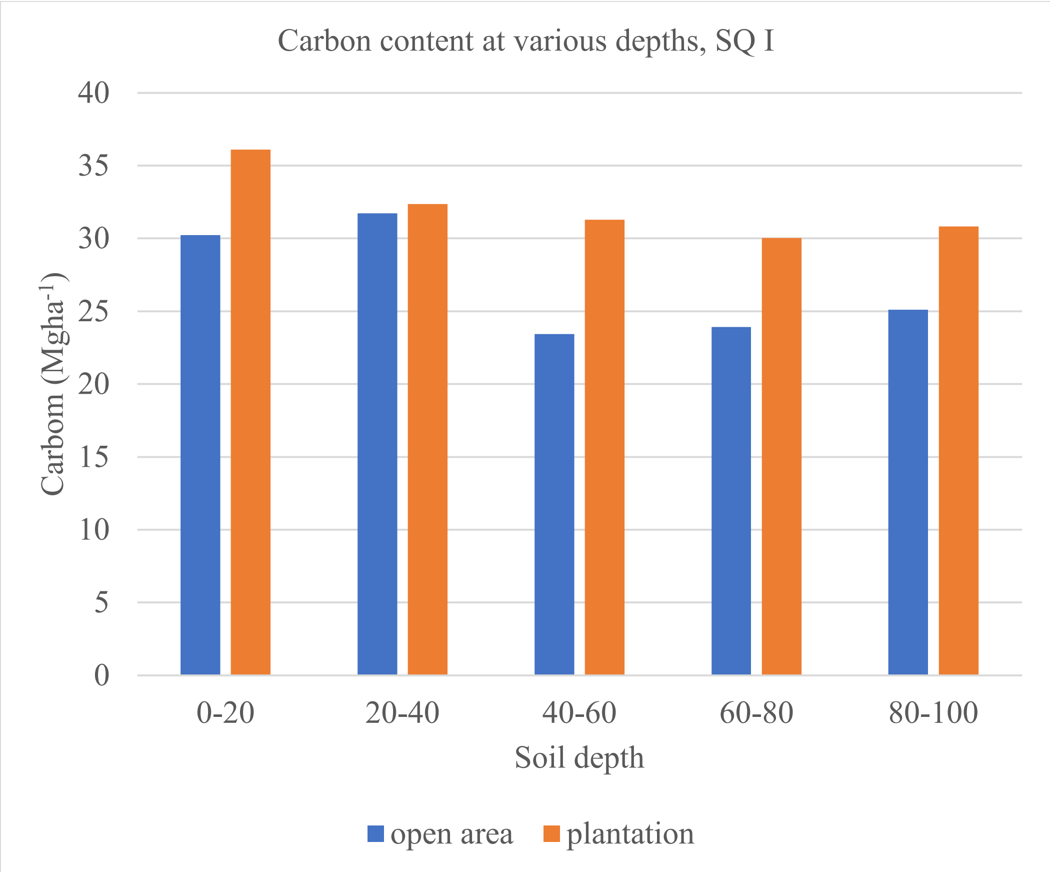


Figure 19. Carbon content in various depths of SQ II plantation and contiguous treeless open at Elencheri, Nilambur, Kerala

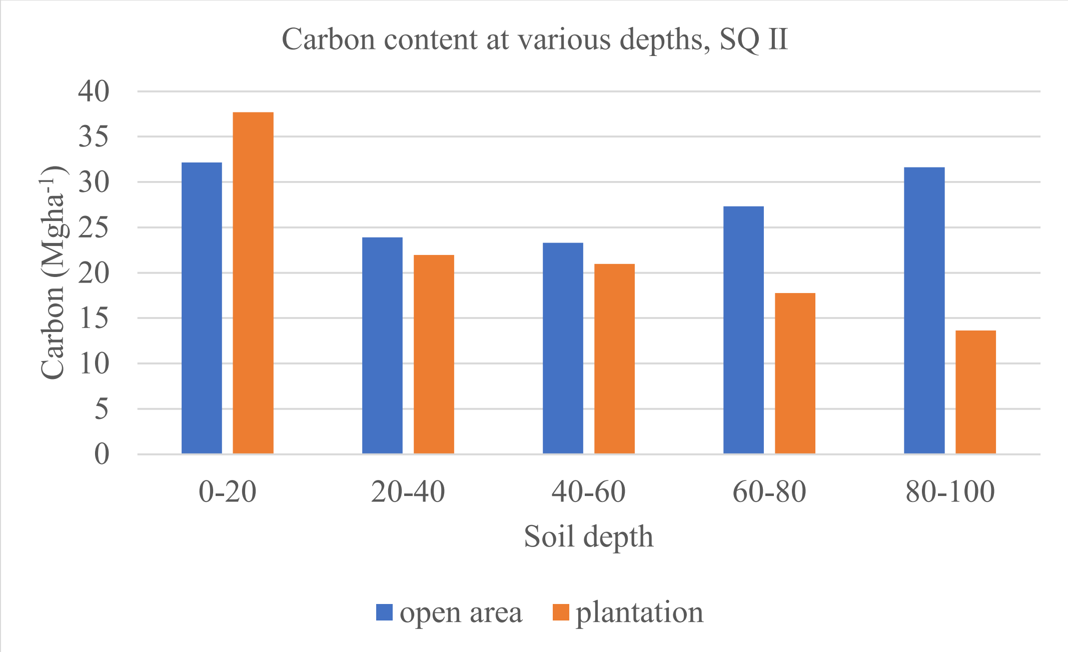


Figure 20. Carbon content in various depths of SQ III plantation and contiguous treeless open at Paramankunnu, Nilambur, Kerala.

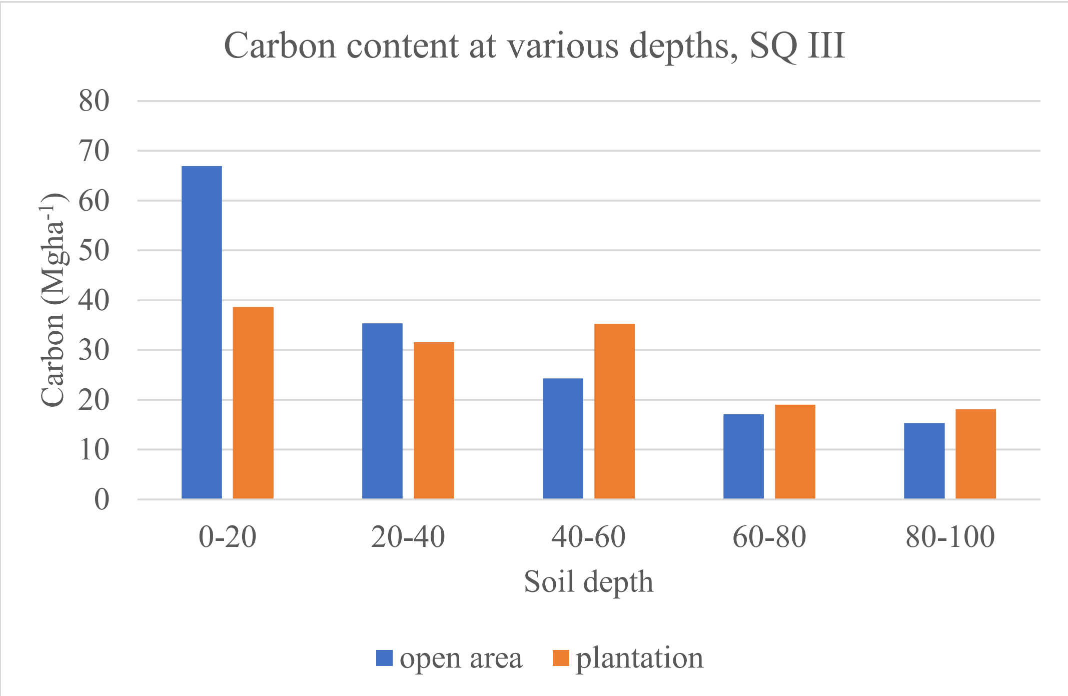
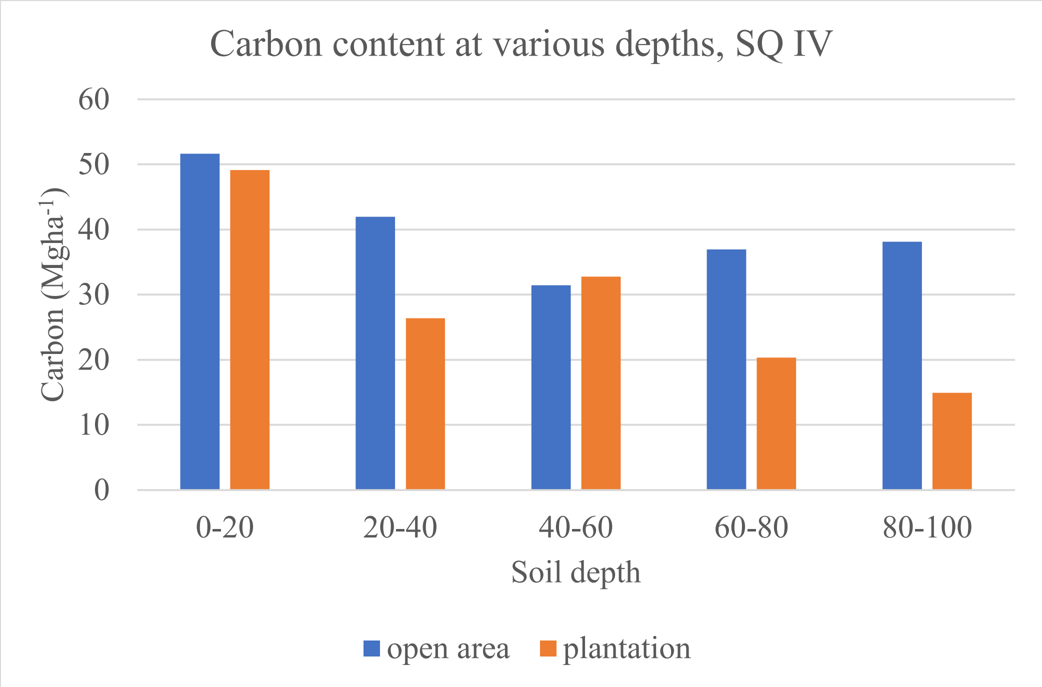


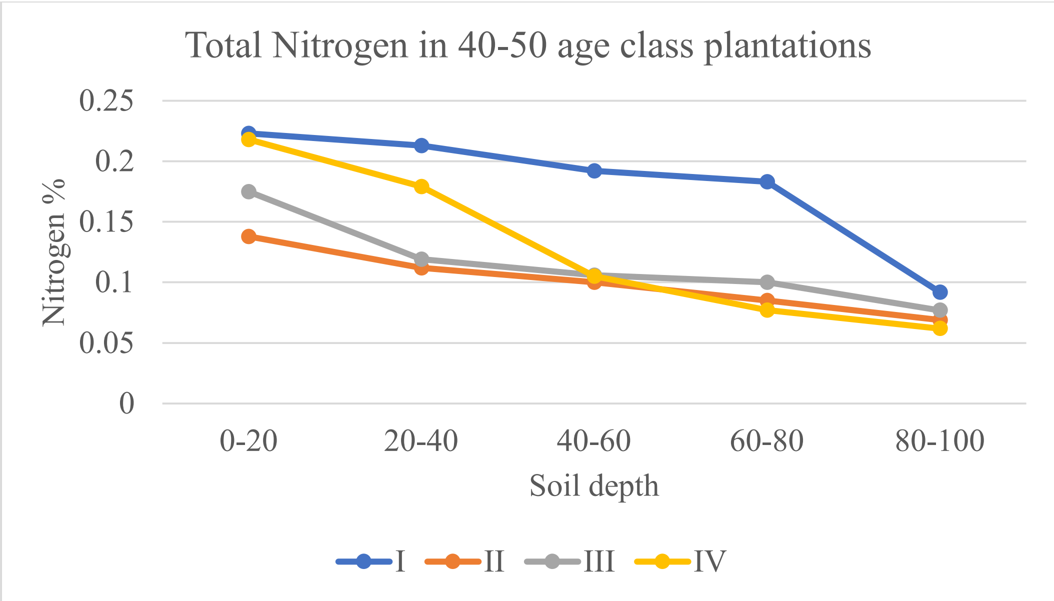
Figure 21. Carbon content in various depths of SQ IV plantation and contiguous treeless open at Muleppadam, Nilambur, Kerala.



5.2.3 Total Nitrogen:

The total Nitrogen content in the plantation soil showed interesting results. In many cases, there was no significant difference between the plantation soil and the contiguous treeless open. Generally, the optimal N content in teak plantations fall between 0.03 to 0.17 % (Balagopalan, 1995; Rugmini, *et al.,* 2007; Jerez and Coutinho, 2017). In the present study, the N content varied between 0.062 to 0.223% between the plantations and different depths. It was observed that the soil nitrogen content decreased with depth of the soil layer (Figure 22). Similar trend of decline was reported by Manjunatha *et al*., (2020) for young teak plantations in Kerala.

Figure 22. Total nitrogen in soil at various depth layers in 40-50 age class plantations of different site qualities in Nilambur, Kerala.



The teak at SQI showed higher N content in the plantation soil as compared to their contiguous open soil quiet significantly till 80 cm depth (Figure 23). Many studies report better nutrient conserving mechanism in woody ecosystems (Knoepp *et al.*, 2000; Nikodemus *et al.*, 2020) compared to open soils. Often the tree roots function as 'safety net' and prevent the leaching of nutrients from the site (Pierret *et al.*, 2016). However, significant difference between the total nitrogen content of plantation soil and contiguous treeless open were not visible for other site qualities. The location and topography of the treeless open sites may influence the nitrogen content. Also, nitrogen is a highly leachable nutrient and can get leached and displaced in tree ecosystems (Rosenqvist *et al.*, 2007; Davis, 2014). The N content of the soils of teak plantations in Nilambur might be subjected to leaching as the area is subjected to heavy precipitation and is in sloppy terrains.

23. Nitrogen content at different depths in soils of SQ I plantation and the respective contiguous open at Kariem Muriem, Vazhikkadavu, Nilambur, Kerala.

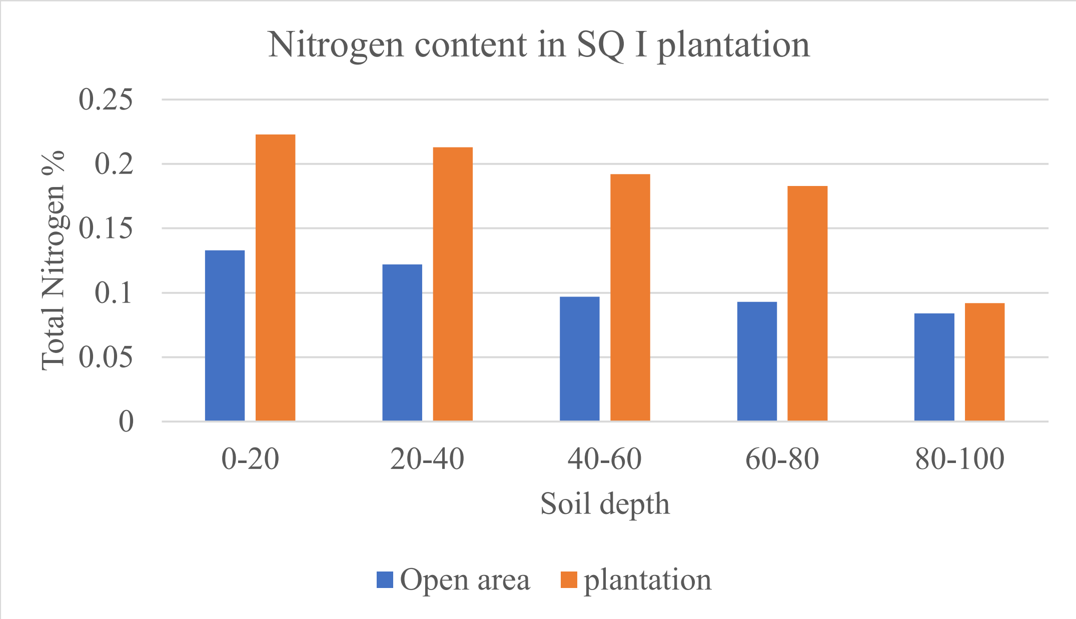
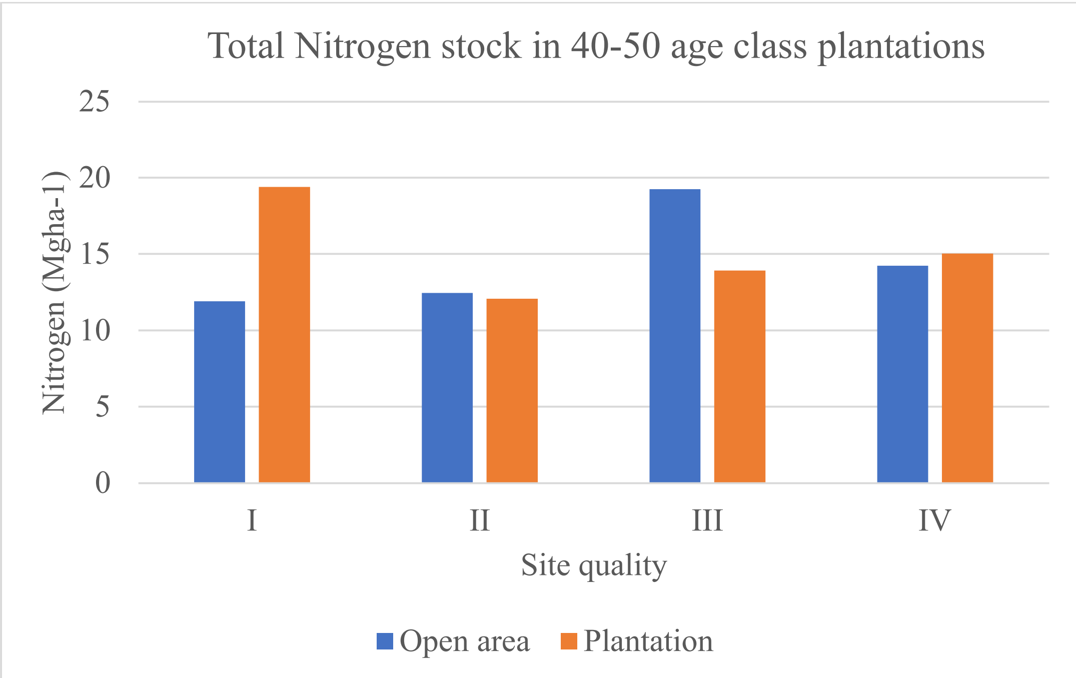


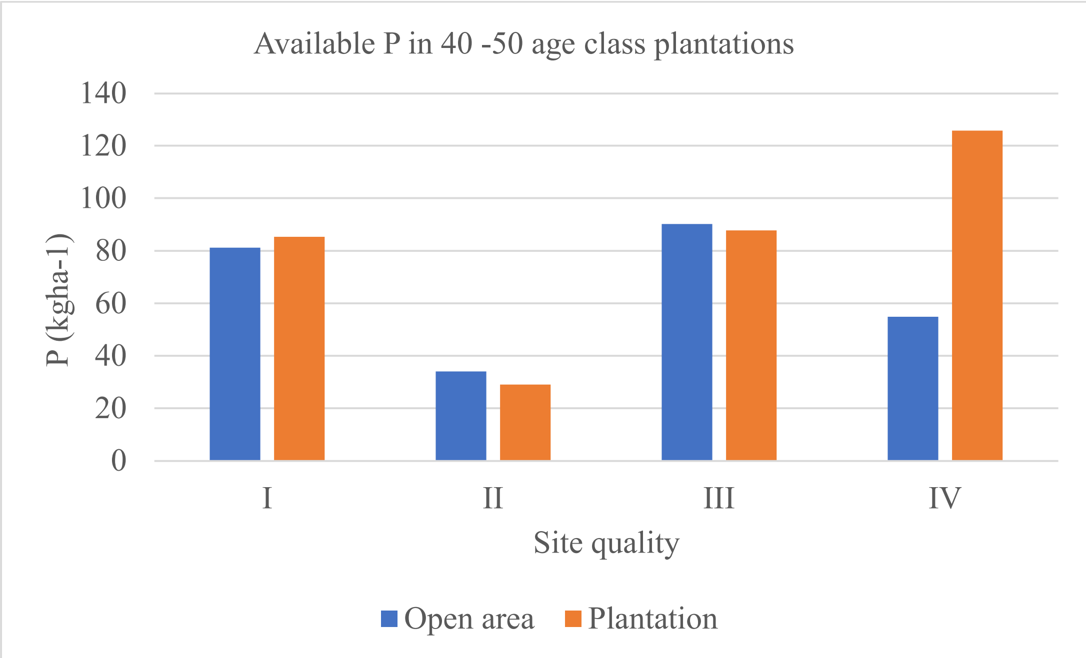
Figure 24. Variation in total Nitrogen stock in teak plantation of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.



5.2.4 Available Phosphorus

Reports suggest available P in teak plantations vary between 0.03 to 15.3 ppm (Balagopalan, 1995; Rugmini *et al.,* 2007). In the present study, the values observed ranged from 1.93 to 17.33 ppm suggesting that available is in adequate supply. Tree stands can increase the available P in soil following afforestation depending on previous site condition and local climate (Deng *et al.*, 2017). In the SQ I and IV plantations, there was a higher P content in plantation soil than the respective contiguous open. The general understanding with respect to available P is that it should decrease with soil depth (Bol *et al.*, 2016; Tian *et al.*, 2021). However, contrary to this, the present study did not show any such trend among the sites suggesting for variation in P content with soil depth. Incidentally, the SQ IV plantation soil showed an increase in available P with increasing soil depth. This might be a result of the local conditions like slope of the terrain and leaching and deposition of nutrients in a high precipitation area such as Nilambur. Also, it was interesting to note that the presence of trees did not bring any significant difference to the soils of SQ II and III from the contiguous open soils. Li *et al.* (2019) reports that though tree cover or afforestation can impact the P content significantly in the top layers, in the deeper layers it remains more influenced by lithology than vegetation.

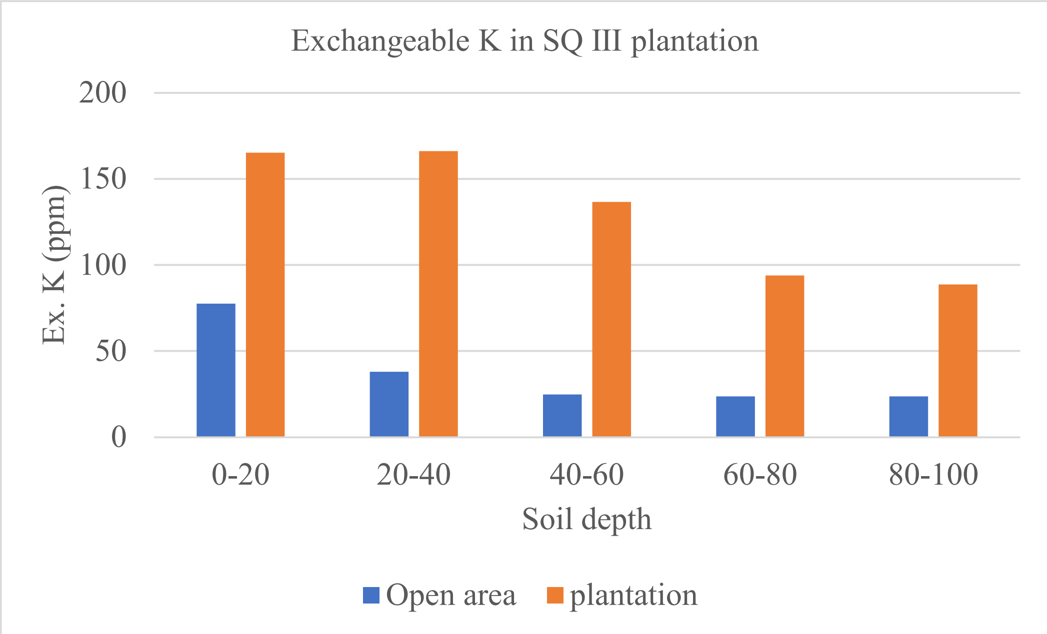
Figure 25. Available Phosphorus in in teak plantation of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.



5.2.5 Exchangeable Potassium

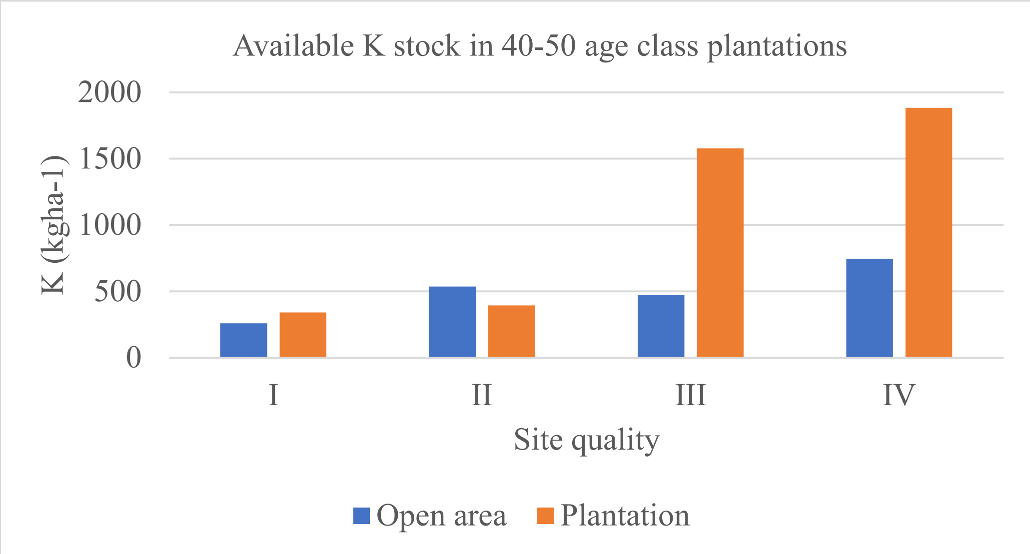
Exchangeable K content in teak plantations varies optimally from 54 to 140.4 ppm (Jerez and Coutinho, 2017). In the present study, the exchangeable K content in various soil depth in the 40-50 age class plantations of Nilambur varied from 23.65 to 205.65 ppm. Tian *et al.*(2021) reported that the exchangeable K content decreases with soil depth. In the present study also, a similar declining trend was observed for Exchangeable K with the concentration of P showing a general trend of decline with depth. (Figure 26).

Figure 26. Exchangeable K in the soils of SQ III plantation and the corresponding contiguous treeless open at Paramankunnu, Edacode, Nilambur, Kerala.



Except for the SQ II plantation, the plantation soils had a higher concentration of exchangeable K when compared to the respective contiguous treeless open. The presence of trees can improve the available K content of soil. Nikodemus *et al.*, (2020) reports an increase in Ex. K content in soil following afforestation. Higher K content was observed at the upper soil layers. Similar observations were made by (Rugmini *et al.,* 2007). This could be attributed to higher possibility of mineralization in the surface soils in teak plantations. Yet another factor influencing K availability in the soil is its high mobility. But the woody component by virtue of the wide root network may contribute to control the leaching of K from the system. This K conservation strategy in the teak plantation is evident in the present study (Figure 27).

Figure 27. Variation in Exchangeable Potassium stock in teak plantations of age class 40-50 belonging to 4 different site qualities in Nilambur, Kerala.



5.2.6. Soil texture or particle size distribution

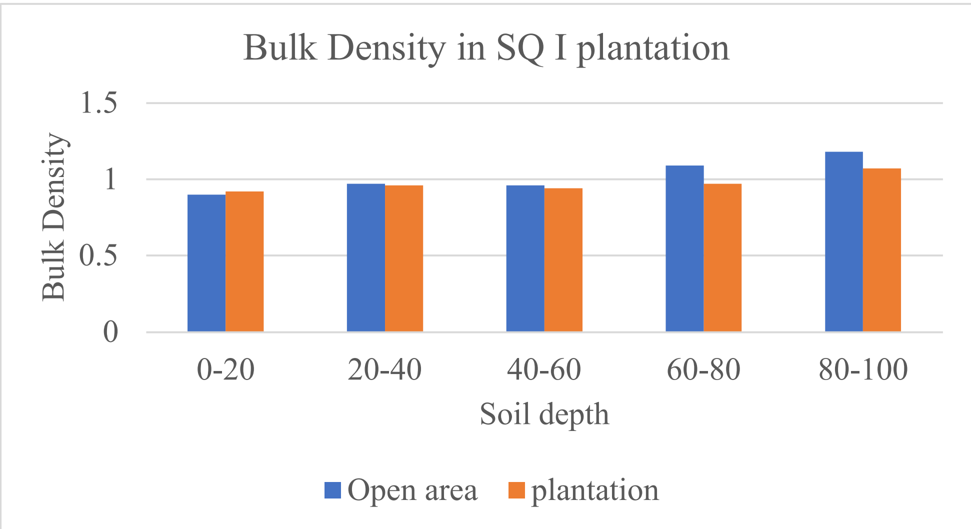
Teak grows well in well drained soils with loamy or sandy texture. The content of sand, silt and clay in teak plantations usually would vary between 76-82, 10-12 and 8-13 % respectively at different depths (Balagopalan, 1995). In SQ I and II plantations, the content of sand in plantation soil decreased with the depth of soil. Similar results were reported by Rugmin *et al.,* (2004) for teak plantations, where the sand percentage declined from an average of 83.15 to 78.02 in the first 60 cm of soil depth.

Land use changes and induced soil disturbances can alter soil texture (Ye *et al.*, 2015; Pedruzzi *et al.*, 2022). There were slight changes in soil particle size distribution between plantation soil and the contiguous open areas. In the SQ IV plantation, the plantation soil had average sand and silt percentage at 84.33 and 9.24 % respectively while for the open contiguous area the corresponding values were 65.88 and 26.80% respectively. Similar results were reported by (Ombina, 2008) from teak plantations in South Sudan where silt was higher in open soil and sand inside the plantation. This further suggest the role of woody vegetation in conserving the soil sand fraction which plays a crucial role in improving soil texture with better drainage and soil aeration. This is particularly important of teak which demand adequate drainage for better growth (Alexander *et al.*, 1980; Wehr, *et al.*, 2017)

5.2.7. Bulk Density

The bulk density of soils under teak varied between 0.90 to 1.21 gcm^{-3} between the plantations and different depths. Similar results were reported by Rugmini *et al.* (2004), who observed the BD under teak in Kerala to vary between 0.81 to 1.17 gcm^{-3}. It was observed that the bulk density in the plantations increased with increasing depth. Similar observations were reported in teak plantations in Ghana where the BD increased from 1.17 to 1.30 (Amponsah and Meyer, 2000). In the SQ I plantation it was interesting to note that the BD showed significant difference in only the deeper layers as the rate of increase with depth of BD was lower inside the plantation than outside (Figure 29). This might be attributed to the influence of tree roots in deeper soil layers which promote soil organic carbon and aeration thereby reducing the bulk density. Tree roots have been shown to decrease the bulk density in deeper soil layers (Zheng *et al.,* 2017).

Figure 28. Bulk density at different depths in soils of SQ I plantation and the respective contiguous open at Kariem Muriem, Vazhikkadavu, Nilambur, Kerala.



5.4 Managerial implications of the study

The growth and productivity of different plantations of various site qualities and age classes were estimated during the study, the findings of which have far reaching implications in future strategies for managing teak plantations in Kerala or elsewhere in India.

- Most of the plantations studied showed sub optimal productivity, primarily due to poor adherence to timely stand management protocols.
- Much more than the site quality variations, the lack of scientific management was the primary driver of teak productivity decline in Nilambur. Any incremental attempt to adhere to the scientific management such as optimal density regulation, can bring substantial improvement in the teak productivity.
- The decline in teak productivity in most of the teak plantations under the study is attributed to the high proportion of miscellaneous tree species. Policy decision need to be taken whether to revert such mixed stands into natural forests or retain as fully fledged teak plantation following teak management strategies that include the removal of miscellaneous vegetation.
- There was considerable deviation in teak productivity in the various site qualities as compared to their expected levels as per All India site quality table. Many plantations belonging to lower site qualities such as SQIV in fact showed much higher tree height as compared to the designated better site qualities. Also, many plantations presently under SQI and SQII showed lower mean tree total height as compared to the standard site quality table. This suggests that there is genuine need for the revising the existing site qualities for deriving meaningful conclusion about productivity of teak in Nilambur.
- The analysed soil in various teak plantations at Nilambur showed nutrient contents within the acceptable ranges for teak, suggesting that

the decline in productivity might be due to managerial problem rather than being caused by nutrient depletion.

- Teak plantations in elephant movement regions showed poor survival and growth. Future plantation activities in such areas may not become fruitful.
- Optimal density and timely management can derive maximum site benefits from teak plantations of Nilambur.

Summary

VI. SUMMARY

The share of government owned teak plantations to the wood demand of Kerala have become a meagre low and the question of declining productivity of teak in plantations under forest department as a result of several reasons, has become an accepted reality that is being discussed in scientific parlance. Site quality has been the accepted yardstick of measuring the potential of a plantation site to yield high economic benefits. With the low and declining productivity of the plantations, the Kerala Forest Department is weighing its options to revert the low performing plantations of lower site qualities back to natural forest. In this background, the present study titled “Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala” was undertaken to investigate the growth variations in selected plantations of different site qualities (SQ I, SQ II, SQ III & SQ IV) across different age classes (Age Class 10-20, 20-30, 30-40, 40-50 and 50+) which were located in the two forest divisions namely Nilambur North and Nilambur South. The study also attempted to evaluate the soil physio chemical characters under the mature trees of age class 40-50 belonging to the four different site qualities along with respective contiguous treeless open. The investigations revealed interesting findings that would add to the knowledge resource for better management of teak plantations in the country. The salient findings of the study are summarised below:

Growth parameters of teak plantations

1. The SQ I plantations had the tallest trees in all age classes except 40-50, yet there was no perceptible trend in variation of height of trees between the site qualities.
2. The higher aged plantations (30 - 40 and 40-50 age classes) showed a characteristic levelling off of height with in a range of 20 to 25m.
3. In terms of bole height, as a general condition, the best site quality (SQ I) showed the higher bole height for all age classes except 40-50. Bole height

showed a general decline from site quality I to IV with modest variations till the age class 30-40 years but this trend became highly variable in the older plantations.

4. Diameter at breast height showed a general declining trend from SQ I to SQ IV in all the age classes with modest variations. Despite this trend, the effect of SQ in the DHB of mature plantations seemed to be wearing off. There were only minimal variations in DBH of age class 30-40 (with exception of SQ I) and 40-50 (with exception of SQ IV) aged plantations.
5. The highest values of diameter at crown point were observed for the site quality I plantations in each age class, in the age classes above 30 years, the lower site qualities showed no significant variations from one another.
6. Mean individual tree basal area was generally higher in the SQ I plantations, which declined in the lower site quality plantations. There were only modest changes in BA among intermediate site qualities (SQ2, SQ3, SQ4) for the age class 30-40 and 40-50.
7. Basal area per hectare values did not follow a trend like that of average individual tree basal area, as it is depended on the number of trees per hectare.
8. The SQ I plantations showed high values for average individual tree bole volume except for the age class 40-50. There was a general decline from SQ I to IV within an age group with modest variations.
9. As it is affected by the density of teak trees present, the total bole volume per hectare values did not show any general trend either across site qualities or across age classes.
10. The average individual tree volume was also highest in the superior site quality (SQ I). There was a general trend of decline in the subsequent site qualities with slight variations.

11. The total volume per hectare varied from 52.9 m^3ha^{-1} to 985.86 m^3ha^{-1}. There was no general trend between the site qualities or age classes as the value is influenced by the density of trees present.

12. Th average bole form factor of teak plantations varied from 0.69 to 0.78. Shorter bole height resulted in a higher bole form factor and a taller bole in smaller form factor. There was a levelling of form factor in the mature age class of 40-50 with no significant difference between the plantations.
13. The canopy width or crown diameter of the plantations varied between 3.53 m to 12.84 m. It showed no perceptible trends either across site quality or age classes.
14. The SQ I plantations showed the largest values of Mean Annual Increment in basal area. The value was higher for the plantations of actively growing ages and declined in the mature stands.
15. The density of teak in the plantations showed large variations from one another. In the well managed plantations (SQ I and III plantations of age class 10-20) there were no miscellaneous trees.

Soil parameters of 40-50 age class plantations.

1. There were weak relation existing in pH value with increasing soil depth. An appreciable trend in pH was observed only for the SQI teak plantations where the pH of soil was found to be increasing with soil depth.
2. Though all the plantations showed declining C content with depth, the SQ I plantation did not show a sudden decline in carbon percentage. Also, it showed higher C content in all depths when compared to the contiguous treeless open. But this trend did not follow in other site qualities.
3. On comparing with the adjacent contiguous open, in the SQ I plantation, the N content was higher in plantation than the treeless open, quiet significantly till 80 cm depth. In the other plantations, in most soil layers, there was no significant difference between the total nitrogen content of plantation soil and contiguous treeless open
4. In the SQ I and IV plantations, there was a higher P content in plantation soil than the respective contiguous open while it was the other way around in SQ II and III plantation sites.

5. The exchangeable K content in various depth of soils in the 40-50 age class plantations of Nilambur varied from 23.65 to 205.65 ppm. Except for the SQ II plantation, the plantation soils had a higher concentration of exchangeable K when compared to the respective contiguous treeless open.
6. There were slight changes in soil particle size distribution between plantation soil and the contiguous open areas except for SQ IV plantation. In the SQ IV plantation, the plantation soil had average sand and silt percentage at 84.33 and 9.24 % while for the open contiguous area, this was 65.88 and 26.80%.
7. The bulk density of soils under teak varied between 0.90 to 1.21 gcm^{-3} between the plantations and different depths. The bulk density in the plantations increased with increasing depth.

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Abstract

ABSTRACT

Teak has been one among the principal timber species widely used across the world due to its matchless combination of qualities. Kerala has around 76,710 ha of pure teak and 14,440 ha of teak with softwood plantation making up 49.08 and 9.24 per cent respectively of the total plantation area in the state. Despite having the largest share of plantations under teak, the productivity of teak plantations of Kerala are under serious decline and has been a matter of concern in the scientific parlance. Evidences suggest that even in Nilambur, the celebrated land of teak, there has been large scale decline in productivity of teak plantations. However, quantitative aspects of the productivity of teak and the drivers of changes especially in the best teak growing region in Kerala such as Nilambur, is lacking.

In this backdrop, a field study entitled "Growth and productivity as function of site quality and age in teak plantations of Nilambur, Kerala" was conducted in selected plantations from Nilambur North and Nilambur South Forest Divisions. The plantations were selected based on the information available from Kerala Forest Department on their age and site quality. Four site qualities (SQ I, SQ II, SQ III and SQ IV) and five age classes (10-20, 20-30, 30-40, 40-50 and 50+) were considered for the study forming a total of 20 plantations (4 site qualities x 5 age classes = 20 plantations). Five sample plots, each of size 24m x 24m were laid out randomly in each of the selected plantations and parameters like total tree height, bole height, diameter at breast height, diameter at crown point and crown width were measured in the field. Also, soil sampling was done in four plantations of different site qualities falling in the mature age class of 40-50. For this, 1 m deep soil pits were dug, one each inside the plantation and in the respective contiguous treeless open. Sampling was done in five depth intervals (0-20, 20-40, 40-60, 60-80 and 80-100 cm). Thus, a total of 120 samples of soil were collected for analysis. The collected soil was analysed for physical properties like bulk density and particle size distribution/ texture and chemical properties like pH, total Nitrogen, organic Carbon content, available Phosphorus and exchangeable Potassium following standard procedures.

The results showed that among the plantations studied in Nilambur, the SQ I plantations showed dominance in all growth parameters of teak while a predictable pattern of change was lacking across the subsequent site qualities. There was large heterogeneity among the plantations in terms of management that had a confounding effect on the potential exploitation of the site resources for optimal growth of teak. Many of the plantations had high density of invaded miscellaneous trees which have increased the effective density and seriously affected the growth of teak. The density of miscellaneous trees varied from 0 to 694 trees per hectare among the studied plantations. The competition with miscellaneous species has created large scale variability within each stand in growth attributes. Normal distribution of diameter classes was observable in the plantations studied due to high effective density. Stand density being a critical factor that decide productivity and product quality in teak plantations, the observed variability in productivity could be attributed to poor adherence to proper density regulation. Also, the productivity of the plantations has been considerably influenced by poor adherence to timely plantation management practices. The Mean Annual Increment varied from 0.56 to 8.70 $m^3ha^{-1}yr^{-1}$ among all the plantations studied. On comparing with the All-India yield table for teak, the plantations showed growth and productivity estimates that were quite different from their assigned site quality. In the age class 40-50, the SQ I plantation showed a height that was corresponding to SQ III according to the yield table, while the SQ IV plantation height corresponded to the SQ II.

All the observed soil parameters with in the experimental plots were well within the range required for the optimal growth of teak. However, except for SQ1, we could not observe any predictable change in soil properties across the remaining site qualities. The Bulk density of soil increased with depth, both inside and outside the plantations. The rate of increase of bulk density was higher in the treeless open areas compared to the plantations. Th soil texture remained as sandy loam or loamy sand for all the analysed soil samples. The soil pH varied from 5.17 to 5.98 between the soil samples that were analysed. The organic Carbon content in various layers of plantation soil varied from 0.58 to 2.07 %. Total Nitrogen varied from 0.077 to

0.223 %. Available Phosphorus varied from 2.10 to 17.33 $kgha^{-1}$. Exchangeable potassium varied from 51.82 to 488.30 $kgha^{-1}$. Attempts to relate the soil properties with the site productivity could not derive meaningful correlations suggesting that the productivity decline might be an effect of poor management rather than depletion of nutrient status. The study suggests that there is an urgent need to revisit and reassess the site quality of the plantations in Nilambur and to give utmost concern for adhering to scientific stand management in timebound manner for deriving optimal productivity from teak plantations of Nilambur.