# FIELD EVALUATION OF STUMP AND ROOT TRAINER GROWN TEAK (*Tectona grandis* L.f.) PLANTATIONS

By

**ELDHOSE GEORGE**
**(2016-17-002)**

## THESIS

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# DECLARATION

I hereby declare that this thesis entitled "**Field evaluation of stump and root trainer grown teak (*Tectona grandis* L.f.) plantations**" is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society.

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# CERTIFICATE

Certified that this thesis entitled "**Field evaluation of stump and root trainer grown teak (*Tectona grandis* L.f.) plantations**" is a record of research work done independently by **Mr. Eldhose George (2016-17-002)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associate ship.

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*Dedicated to my loving family,*

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# *Introduction*

# I. INTRODUCTION

The demand for wood and wood products has been escalating world over at unprecedented rates owing to multiple benefits. The projected demand for the timber ranges from 58 million $m^3$ during 2005 to 153 million $m^3$ during 2020 (Shukla and Viswanath, 2014). However, the projected increase in the supply shows a narrow change from 29 million $m^3$ (2000) to 60 million $m^3$ (2020). Natural forests were the predominant supplier of wood ever since the colonial period. Nevertheless, the renewed focus on conservation of natural forests on account of their ecological benefits gave way to the establishment of plantations for meeting the wood requirements. Globally, forest plantations cover approximately 264 million hectares which has shown an increase from 3.5% (1990) to 7% (2015) of the total forest area (FAO, 2015). FSI (2017) reported that the forest cover of India has increased from 7,01,495 $km^2$ in 2015 to 7,08,273 $km^2$ in 2017. This increase was mainly contributed by forest plantations and trees outside the recorded forest areas.

Teak (*Tectona grandis* L. f.) forms one of the predominant timber tree species of India owing to matchless combination of qualities. This species occurs naturally, although discontinuously, in deciduous forests between latitudes 9°- 26°N, and 73°-104°E longitude, which includes central and southern India, Myanmar, northern Thailand and Laos (Kjaer, 1996). Today, teak ranks third among tropical hardwood species in terms of plantation area established world-wide. It covers 2.25 million ha with 94 per cent in tropical Asia, major area being in India and Indonesia while about 4.5 per cent of teak plantations are in tropical Africa and the rest are in tropical American Countries (Katwal, 2003; Krishnapillay, 2000). Teak enjoys a wide range of distribution throughout India, though it prefers deep well drained alluvial soil with an annual rainfall of 1200 - 2000 mm and with a dry season.

On account of the congenial agro-climatic conditions and the concomitant luxuriant growth, the state of Kerala is often christened as the home of teak in the country. Ever since the historic attempt to raise teak by H.V. Conolly, the then Collector of Malabar during 1841 at Nilambur, teak was extensively cultivated throughout Kerala (FRI, 1961; Chandrasekharan, 1973). Kerala Forest Department has about 57,885 ha under teak, of with approximately 64 per cent in the first rotation and the remaining 36 per cent in the second and third rotation stages (Balagopalan *et al.*, 1998; Prabhu, 2003). Interestingly, these plantations contribute only less than 2 per cent of the total domestic supply market of Kerala (Krishnankutty and Chundamannil, 2012) while major portion of the supply is from the trees outside forest (TOF) sector dominated by agricultural lands and homegardens.

Despite the glorious tradition of teak cultivation in Kerala, recent times have seen a steady decline in productivity of teak plantations over rotations (Chundamannil, 1997). The expansion of teak plantation has been facing widespread criticism from environmental perspectives such as reduced biodiversity, soil erosion by fire treatment and litter raking, nutrient losses during timber harvest, spread of pests such as defoliators, beehole borer, skeletonizer etc (Pandey and Brown, 2000; Hallett *et al.*, 2011). Even in Nilambur, the celebrated 'Mecca of teak' in Kerala, there has been appreciable reduction in productivity over rotations (average MAI of 2.95 $m^3$ $ha^{-1}$ $yr^{-1}$ in second rotation teak as against the expected MAI of 8.21 $m^3$ $ha^{-1}$ $yr^{-1}$; Chundamannil, 1997). Almost all young teak plantations in the state are poorly stocked and unhealthy (Sivaram, 2004). Harvest related resource drain over rotations, poor site quality, inferior quality of planting material, unscientific plantation management practices are assumed to be some of the potential reasons for this productivity decline. Among these, the quality of planting material is one of the major factors that influence teak growth and productivity.

Over a century of plantation history use of root-shoot cutting (stump) has been the prominent planting technique for teak cultivation in Kerala. In the context of massive decline in growth rate, the efficiency of this technique has been subjected to



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criticism. In the absence of prominent tap roots, the root-shoot cuttings produce enumerable shallow fibrous roots confining their rhizosphere to peripheral soils. This may lead to the preferential absorption of water and minerals from surface soil eventually leading to resource drain from the soil in the long run. Furthermore, such surface feeding behavior of teak root system limit the efficiency of nutrient cycling from deep soil as against the deep nutrient turnover expected in woody ecosystems on account of their deep root system.

Kerala Forest Department (KFD), the largest producer of teak seedlings in Kerala has been resorting to other types of planting materials for mass production of teak. Among these, root trainer grown seedlings has received wider acceptance in view of their better root growth and mass production of uniform planting materials. At present, both the techniques are being practiced by the Forest Department. The vast difference in the rooting behavior and resource utilization patterns under these two techniques may inflict large variability in their field performance as well. However, despite stray attempts, no scientific investigation has been made to evaluate the growth performance of teak plantations established through stump technique and root trainer technique. Moreover, limited information is available on the changes in root distribution patterns and resource acquisition potential of teak trees grown by stump and root trainer techniques. In this context, the present study was carried out with the following objectives:

1. To evaluate and compare the field growth performance and root distribution patterns of teak plantations established by stump and root trainer techniques.
2. To compare the effect of variable spacing on the performance of root trainer grown teak plantations.

# *Review of Literature*

# II. REVIEW OF LITERATURE

Historically teak enjoys a glorious tradition in Kerala by virtue of its matchless combination of wood qualities and remarkable growth rate. Despite its recognition right from the medieval period its organized exploitation assumed pace during the British regime. Massive extraction and associated dwindling of the teak recourses prompted British regime to cultivate teak following scientific pursuit. Even since the attempts by Bourdillion to raise teak using root-shoot cutting, the same method is followed for the past 100 years unchanged. However, off late there observed massive productivity decline in teak plantations. The causes remain mostly elusive. The effectiveness of using stump as planting material as against the seedling grown teak, on the overall productivity in the long run, need thorough investigation particularly in view of the perceived productivity decline in teak plantations of Kerala. Attempt is made in this chapter to review the pertinent aspects of teak productivity and the role of planting material on teak growth.

## 2.1. PRODUCTIVITY OF TEAK PLANTATIONS IN KERALA

The term productivity indicates the total production that obtains from an area in a given time. Many factors may affect the productivity of an area such as species, edaphic, topological and climatic conduction. Relative humidity and annual rainfall were identified as the most important climatic factors influencing the growth of teak (Pandey, 1996). There is high degree of regional variation in the productivity of teak plantations in Kerala due to variability in soil, topography and weather conditions in the State (Jayaraman and Rugmini, 1993). However, productivity figures from existing plantations covering a wide range of environmental conditions and management regimes are limited.

Enters and Nair (2000) reported that India has low MAI (Mean Annual Increment) of teak when compared with the MAI of some well-known teak growing



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areas elsewhere. For instance, the maximum MAI of teak for the higher site classes from India was about 12.3 $m^3 ha^{-1} yr^{-1}$ which was much smaller than that of Indonesia (21.0 $m^3 ha^{-1} yr^{-1}$.), Myanmar (17.3 $m^3 ha^{-1} yr^{-1}$.), and Nigeria (23.8 $m^3 ha^{-1} yr^{-1}$). Similar was the trend for the average and poor site classes of teak in the country. The situation in Kerala, was also the same with the MAI of teak at a mean rotation of 58 years was 2.49 $m^3 ha^{-1} yr^{-1}$, (Chundamannil, 1997). In Nilambur, the celebrated land of teak, the average MAI during a rotation of 53 years was 2.85 $m^3 ha^{-1} yr^{-1}$, (Enters, 2000). The MAI obtained from Nilambur for higher site qualities is equivalent to the yield expected in site quality class III / IV (Chundamannil, 1997).

Balagopalan and Chacko (2001) studied the growth of teak in successive rotations in relation to soil conditions and revealed that gravel and organic carbon contents varied significantly between rotations and the discriminant analysis revealed that there was significant decline in soil fertility with change in rotation. This reduction in the productivity over rotations questioned the sustainability of teak plantations in Kerala. Gradual reduction in the productivity of teak plantations in Kerala has been reported earlier (Jayasankar *et al.*, 1999). Chundamannil (1997) reported that reduced productivity of teak plantations from various operations like thinning and final harvest in successive period. Harvest related resource drain over rotations, poor site quality, inferior quality of planting materials, unscientific plantation management strategies are assumed to be some of the potential reasons for this productivity decline. Of many reasons, poor quality planting material has been cited as one among the major factors for the decline in teak productivity (Prabhu, 2005). Century long tradition with stump planting has been questioned in the light of the perceived heavy productivity decline over rotations. This was evidenced by the poor performance of stump grown teak plantations in the recent times, and the poor soil anchorage leading to wind throw. However, scientific attempts are lacking to validate the role of stumps in the productivity decline observed in teak. As an alternative strategy the KFD has been promoting root trainer grown teak seedlings since 1998 (Prabhu, 2005).

2.2. PLANTING TECHNIQUES OF TEAK

Conventionally the planting technique for teak involves raising seedlings. In seedling origin teak, plantation activities are mainly concentrated in stump planting, polybag seedlings and root trainer grown seedlings. Among these stump planting is mostly practiced for the plantation activities. Teak is also reproduced through seeds, but germination is often dismal due to the hard seed coat which limits the production of a large number of seedlings in a defined time. The propagation of teak by using cuttings has been reported by Nautiyal *et al.* (1992), but has several limitations and only provides a few propagules from selected individuals. This type of propagule produced from the rooted cutting shows higher amount of adventitious root (Monteuuis, 1995, Monteuuis *et al*, 1995) which might resist the resource use potential of the plant. The vegetative methods of teak propagation could not make much head way. Tissue culture of the species began in the seventies (Devi *et al.*, 1994; Gupta *et al.*, 1980). Muralidharan and Pandalai (2000) reported that the performance of stump origin teak plants had high growth performance and survival count than micro propagated propagules. However, micro propagation of teak from mature trees has remained problematic. Poor explant response and rapid explant browning are major problems faced in micro propagation of teak. Auykim *et al.* (2017) reported that coppicing from the stump remained in the clear felled area of teak plantations were retained for the next crop in Thailand. This practice utilizes natural regeneration from the cut stump of a harvested tree and can contribute to rapid restoration of forest cover after clear cutting (Sukwong *et al.*, 1976). The primary advantage of coppicing for short rotations are that it is easy, offers a low cost of establishment and accelerates early growth (Chowdhury *et al.*, 2008; Bailey and Harjanto, 2005).

A stump is a seedling with all leaves and root hairs removed, leaving only a portion of main stem and roots. In Kerala after the first plantation raised in 1842 by direct sowing/planting natural seedlings, stump planting was introduced by T.F.



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Bourdillon during 1891 which remained as the major teak propagation activity for more than a century (Pushpom, 2004; Prabhu, 2003). However, recently the Kerala Forest Department introduced root trainer technology as an alternative strategy to improve the productivity of teak in Kerala. Stump planting offers several benefits such as being able to be transported considerable distances while maintaining stump viability and being easy and quick to plant; consequently, this technique is used in several countries (Midgley *et al.*, 2007; Thaiutsa, 1999). Stump planted teak usually show good growth and establishment during the early growth phase. Auykim *et al.* (2017) reported that the mean $CAI_{dbh}$ (cm) and mean ring width (mm) showed higher performance in the stump grown plants when it compared with coppice grown plants after nine years of planting. However, at later stages of growth lack of deep tap root systems might limit the resource acquisition potential from deeper soil (Khedkar and Subramanian, 1997). This condition promotes the growth of lateral roots which proliferates only to a certain depth. Gogate *et al.* (1997) reported that the loss of almost one year's shoot growth in stump planting method could be avoided by using the Entire Transplant Technique (ETP). Such entire transplanting of seedling is practiced in Madhya Pradesh and Orissa, where 3-4 months old seedling in container which is known as 'dona plant' was used (Gartner, 1956). This method was said to be more reliable than stump. In 1980, teak seedlings planted in polythene bags (tubed seedling) was first used by FRI Burma, very successfully for planting teak in the species trials at Burma (Gyi *et al.*, 1983).

Root trainer grown teak has more prominent tap root system that will increase the resource accusation potential of plant (Balagopalan, *et al.*, 2005). Probably, the seed origin teak as in the case of root trainers, have prominent tap root to explore greater soil depths. The root trainer plants have a shorter nursery period than stump plants (Khedkar, 1999). The Forest Development Corporation of Maharashtra made trails with the assistance of World Bank for the development of root trainer teak plants (Khedkar and Subramanian, 1997). They reported that the root trainer grown teak plants have multiple tap roots and are sturdier, healthier and they are putting up better collar girth in comparison to stump origin plants.

Mohanan and Sharma (2005) illustrated the principles behind the root trainer technique: (1) this technique provide ambient conduction for the rapid development of primary roots and subsequent root system (2) this will induce early natural pruning of primary tap rood and also lead to the production of multiple secondary tap roots (3) maintain acute angle of secondary and tertiary root tips, and its subsequent pruning, so as to keep downward movement to attain massive network of root system. These facilitate the better performance in the field level by the extensive root system and more resource use potential (Khedkar, 1999). Mohanan (2000) further reported that the root trainer grown plants have more disease resistance and disease management is easier. Studies revealed that the root trainer seedlings have quick establishment of mycorrhiza in roots (Mohanan, 2002).

## 2.3. RELATION BETWEEN GROWTH AND PLANTING MATERIAL

Stump is the most common technique used by the forest department as well as the private ventures as planting material (Midgley *et al.*, 2007). Stump preparation involves, selection of one year old healthy seedlings with collar diameter of 2-3cm, and the shoot and tap root will be cut retaining only 3 cm and 20 cm portion of the shoot and tap root, respectively, from the collar. All the lateral roots also will be carefully removed without damaging the bark of the tap root (Jayasankar *et al.*, 1999). Studies suggest that the stump size has a prominent role in the survival and height growth of stump plant, the teak stump size over 0.5 inch diameter showed higher survival and more height growth (Anonymous, 1944). The removal of tap root will induce the production of lateral roots.

Recent studies showed that there is a sharp decline in the productivity of teak plantations in the Kerala (Chundamannil, 1997). This situation demanded a search for the possible reasons for this decline. In this context some studies pointed that there should be a shift in the use of planting material from the conventional stump planting to entire planting technique (Gogate, 1997). Khedkar and Subramanian (1997) reported a primary trail on the efficacy of root trainer seedling for teak and were found to be successful. The growth parameters include, survival count, total tree height, bole height, diameter at breast height, crown diameter, leaf area index and are discussed below.

The survival count varies according to factors like, climate, planting material, soil etc. (Gyi *et al.*, 1983). Among the climatic factors the rain fall and temperature are the major factors that decide the success of plantation. Hansen *et al.* (2007) reported that the stump planted plants are sensitive to dry spells in the first two months after planting. A study conducted for the comparison of dona planted seedlings of teak with stump planted ones reported that survival count was 81 % for stump planted compared with 91 %for dona plants and dona planting is more suitable during drought period (Singhal, 1949). Muralidharan and Pandalai (2000) reported that the survival per cent of stump origin plantations were about 83 per cent. Experimental results showed that the root-trainer seedlings had the highest height and girth at ground level and survival than the stumps (Rao *et al.*, 2001). Survival of root trainer grown teak was 24.6 per cent higher than stump plated teak (Murugesh *et al.*, 1997).

Reports suggest that growth of the seedling increased significantly with increase in stump diameter, shoot length and root length. This may be due to higher stored food materials in the stump (Mutnal *et al.*, 2010). Similar observations were reported in teak by Kadambi (1972). Mutnal *et al.* (2010) found that the stump diameter of 1.5 cm with shoot length 6 cm and root length of 8-12 cm is more suitable for production of quality planting material for teak plantation. Stump grown teak shows relatively higher shoot growth in the initial years of establishment. Gyi *et al.* (1983) reported that average height obtained by seed sowing (0.80 ft.) was significantly greater than that obtained by stump planting (0.59 ft.). Khedkar (1999) reported that the diameter increment in the root trainer grown teak plantation has significantly differed from stump grown teak plants. Spacing of teak stand also influence the growth attributes. Studies in Nigeria on seven year old teak plantation suggested only marginal effect of spacing on average tree height and top height of stand (Abegbeihn, 1982). The negative correlation between spacing and height was reported for 18 year old teak (Ola-Adams, 1990). Impact of planting material on bole height was reported for teak established by seed origin and clonal origin plants, suggested that considerable difference in seed origin than clonal origin plants (Mitarini and Harahap, 1994).

DBH was another growth attribute that showed great influence by planting material and spacing. Scientific studies suggested that influence of planting material (stump and root trainer) showed markedly better performance of root trainer grown plantation (Rao *et al.*, 2001; Khedkar, 1999; Khedkar and Subramanian, 1997). Impact of spacing on DBH established a positive correlation, indicate that increased spacing leads to the improvement in the crown spread and also improves DBH of trees (Goss, 2012; Hummel, 2000). Improvement in DBH also manifested in the growth attributes like basal area and volume.

The lateral spread of crown and LAI indicated the health of plantations. Studies to investigate the relation between crown spread and root spread showed direct proportionality (Prasad and Mishra, 1984; Jiang *et al.,* 2007). Tree form characters such as persistence of stem axis and straightness of stem could have influence by the initial spacing. Sibomana *et al.* (1997) studied the impact of spacing on growth of teak, suggested that wider spaced trees had tendency to forking the main stem. Reports suggested that planting spacing and layout influence tree growth and form (Deans and Milne, 1999)

## 2.4. SOIL PROPERTIES

Soil is one of the major factor determine the productivity of the plantation. Both physical and chemical properties of soil have a definite role in the success of teak plantations. The effect of properties such as physical nature of soil, bulk density and chemical properties like soil organic carbon content, pH, mineral nutrient content etc. on the growth of teak plantation trees are discussed below.

### 2.4.1. Physical properties of soil

Physical properties of soil have a great influence on the growth and success of a plantation. The changes in soil properties with variable site qualities for teak has direct implications on the growth of trees (Varghese *et al.*, 2000; Watterston, 1971; Seth and Yadav, 1957). Also site quality and the soil properties like soil texture and pH have direct correlation between them (Alexander *et al.*, 1987). In a similar study to compare the soil properties of natural forest, teak plantations, grassland, and cashew plantation in the Malayattoor Forest Division, Kerala it was revealed that most of soil properties are significantly different in accordance with the vegetation type.

Planation soil are found to be deteriorated, when compared with natural forest (Balagopalan, 1995). Monoculture stands of teak shows pure teak problem associated with physical soil deterioration like soil erosion (Evans, 1976; Bell, 1973). However, there is limited evidence for this concept except when the teak is planted either on steep slopes where there is limited undergrowth (Centeno, 1997). The change in the soil physical properties due to plantation activity in 18 year old *Populus deltoids* plantations showed an increase in bulk density in soils when compared to natural forest (Joshi *et al.*, 1997). Chaudhari *et al.* (2013) conclude that bulk density is a dynamic property of soil that is by and large influenced by soil structural conditions. Bulk density also influenced by the changes in organic matter content, porosity and compaction of the soil. Amponash and Meyer (2000) studied soils of natural forests converted to teak plantations in the Offinso and Juaso Forest Districts in the Ashanti region, Ghana observed that, bulk density increases with the soil depth. Zerfu (2002) reported that land use change from farmland to Eucalyptus plantation or vice-versa did not cause serious change on soil bulk density. Balagopalan and Jose (1997) studied the effect of monoculture plantations of teak, eucalypts and rubber on the soil properties. The study revealed that bulk density increased under monoculture plantation. A similar kind of result was observed in areas where forest cleared and teak plantations established in Andaman and Nicobar Islands in India (Dagar *et al*., 1995).

A study conducted to analyze physico-chemical properties of soil under different land use systems like bamboo, teak plantations, rubber plantation, orange orchard, lowland rice field and natural forest, in Dimoria tribal belt in Assam revealed that the average bulk density of soil ranged from 1.07 to 1.41 for different land use systems with teak plantations had higher bulk density and the bamboo showed the lowest. Jose and Koshy (1972) conducted a study on the morphological, physical and chemical characteristics of soil under 1, 15, 30, 60, and 120 years of teak plantations. They observed that, higher value for bulk density and particle density and lower values for pore space and water holding capacity than those natural forests. Physical properties also showed similar trend for 120 year plantation and natural forest, but there was a considerable increase in the compaction for the second rotation teak plantations. Rathod and Devar (2003) studied the morphological and physical properties of soils of teak plantations of different ages and an increase in compaction was noticed in the older teak plantations.

### 2.4.2. Soil chemical properties in plantations

Varghese *et al*. (2000) studied the variation in growth of teak in different populations in India, and observed that tree growth and cell characteristics were largely influenced by physical and chemical properties of soil. Edaphic characters mainly the parent material or the nature of bed rocks from which soils are formed influenced the quality and distribution of natural teak. Seth and Yadav (1957) reported that teak can grow on a variety of soils, the quality of growth depends on the depth, structure, porosity, moisture holding capacity and drainage of soil. Watterston (1971) studied growth of teak under different edaphic conditions in Lancetilla valley, Honduras. Study concludes that, the most important factors affecting the growth of teak were spacing and soil depth.

The conversion of natural forest to monoculture plantation leads to reduction in the soil nutrient status and alter the composition of the soil. Scientific studies pointed that soil nutrients like N, P, and K was found to be less in the plantation soil as compared to the soil in the natural forest. They concluded that nutrient cycling was negatively affected by the monoculture of commercial plantations (Geetha and Balagobalan, 2005; Amponsah and Meyer, 2000; Okoro *et al.*, 1999; Mongia and Bandayopadhyay, 1994). When considered the impact of plantation on barren land, this shows a positive influence on the soil properties as compared to the treeless soil. The improvement of soil has been reported by many scientific works in the presence of woody vegetation (Kunhamu *et al.*, 2011; Jobbagy and Jackson, 2000). The reduction of nutrient concentration with increasing soil depth was recorded in many soil studies in teak plantations as well as common soil studies (Haridas, 2017; Thakur *et al.*, 2015; Du *et al.*, 2015). Teak stands generally shows lower nutrient status as compared to natural forest (Geetha and Balagobalan, 2005; Amponsah and Meyer, 2000; Mongia and Bandayopadhyay, 1994; Okoro *et al.*, 1999). However age of plantations play crucial role in the improvement in the soil properties and when plantations become aged the soil properties may be become well as compared to initial period of growth (Geetha and Balagobalan, 2005; Chamshama *et al.*, 2000; Jose and Koshy, 1972).

Aweto (1995) studied the organic carbon diminishing and carbon dioxide release from plantation soil in Nigeria, observed that the tree plantations released more carbon dioxide from the soil into the atmosphere than the natural forest suggesting that organic matter content in tree based plantations including teak may show diminishing nature. Impact of vegetation on soil organic carbon showed higher influence for carbon distribution and content. For example, Balagopalan (1995) studied the distribution of organic carbon in plantations and natural forest and concluded that the soil organic carbon decreases with depth, also almost all properties of soil had significant difference in accordance with the vegetation type. Not only the vegetation type but species also influence the soil organic carbon status, for instance studies to compare the ecological impacts of plantations of *Hevea brasiliensis,* and *Tectona grandis* and natural forest on soil properties, nutrient enrichment, understorey vegetation and biomass recycling, revealed that all stand types retained high organic matter input which helps to enrich the soils (Krishnakumar *et al*., 1991). Teak has the highest organic matter content in the surface layer which substantially depleted with increasing soil depth while the reduction was less for natural forests. It can be concluded that monoculture plantations shows a depleting trend in soil organic carbon compared to natural forests (Geetha and Balagobalan, 2005; Amponsah and Meyer 2000; Mongia and Bandayopadhyay, 1994).

Chamshama *et al*. (2000) reported a comparison of chemical properties of soils under first rotation teak and natural forests at Tanzania. The study observed that the soil pH and exchangeable cations from the teak plantations were not significantly different from those of the natural forests. Similar result also reported by Okoro *et al.* (2000) the effective cation exchange capacity, pH and magnesium contents of the soils were not affected by plantation activities. For instance, in yet another study significant decrease in soil pH, organic matter, extractable phosphorus and exchangeable potassium contents was observed in areas cleared for commercial plantation in the Andaman and Nicobar Islands (Dagar *et al*., 1995). The lower pH value for teak also reported by Mongia and Bandayopadhyay (1994) than natural forest. The growth of teak showed better in pH value ranges slightly acidic to neutral (Alvarado, 2006; Zanin, 2005).

Teak stands shows reduced nitrogen content in the soil as compared to the natural forest. Similar observation was reported in a study on the soils of natural forests converted to teak plantations at 21 years age in Ghana where significant decrease in soil



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total nitrogen in the 0-20cm and 20-40 cm depths were observed (Amponsah and Meyer, 2000). Studies further suggested significant correlation between soil organic carbon and nitrogen (Lal, 2005).

Similar to total nitrogen, soil available phosphorus in plantations shows reducing trend with compared to natural forest (Okoro *et al.*, 2000). In contrast, Yang *et al.* (2010) reported an improvement in the soil total P status when natural forest is converted to larch plantation. Soil pH also influence the available P content in the soil. The trace amount of available P could be attributed to the acidic nature of the plantation soil leading to fixation of available form to fixed form (Nykvist and Sim, 2009; Majid and Paudyal, 1999). The decreasing trend of total P across the soil depth has been reported by other investigators (Haridas, 2017; Ali *et al.*, 2009).

In general, exchangeable potassium content in the soil show reducing trend across the soil profile (Haridas, 2017; Geetha, 2008). Mongia and Bandayopadhyay (1994) reported lower soil K content in the plantations as compared to the natural forest. Studies shows that soil Ca has a significant role in the teak plantation growth (Rathod and Devar, 2003; Singh *et al.,* 1990b). Improved concentration of Ca in the soil promotes the growth of teak stand especially in terms of height (Singh *et al.*, 1990a; Kadambi, 1972). This is corroborated by the substantial reduction of soil Ca after the teak tree harvest reported by Hase and Foelster (1983). The conversion of natural tropical forest to monoculture species resulted in significant loss of soil calcium (Okoro *et al.*, 1999). Salifu and Meyer (1998) reported that in B horizons, higher calcium in soils under teak plantations attributed to the active role of teak in pedogenesis. Studies in a 28-year-old even-aged contiguous monocultures consisting of teak, idigbo (*Terminalia ivorensis*), opepe (*Nauclea diderrichii*) and gmelina (*Gmelina arborea*) located in the lowland rain forest belt of southwestern Nigeria, reported significant losses in soil calcium in the plantations (Okoro *et al.*, 2000).

## 2.5. EFFECT OF TEAK PLANTING TECHNIQUE ON SOIL PROPERTIES

Impact of planting material (stump and root trainer) on soil properties are least investigated. But by using existing studies, the impact of stump and root trainer based trees on the soil properties can be correlated. Studies suggested that biological activities like fine root dynamics and soil flora and fauna influence soil properties (Rathod and Devar, 2003; Hosur and Dasog, 1995). Root trainer origin trees have more root spread (Khedkar and Subramanian, 1997) which may greatly influence the soil properties. Stand density also having great impact on soil properties by means of high litter production. Enhanced above- and belowground litter production and nutrient dynamics associated with higher density plantations has been reported in *Acacia* plantation with varying spacing (Kunhamu *et al*., 2011; Rocha, *et* al., 2017). Many studies reported closer spacing and age had a positive correlation with the total nitrogen content in the soil in tree based plantations (Thakur *et al*., 2015 in *Grevillea robesta*; Khobragade *et al*., 2000 in Teak). Khobragade *et al*. (2000) reported closely spaced stand at advanced age of teak plantation showed increase in available potassium in soil.

## 2.6. ROOT DISTRIBUTION

Root distribution of a plant is one of the determining factors of the resource utilization potential of the plant. In woody ecosystems the root production and its spatial distribution assume greater relevance especially under moderate or low management conditions (Lopez-Bucio *et* al., 2003; Schenk and Jackson, 2002). The root distribution is primarily a species depended factor though stand management practices such as planting density can influence root activity considerably (Douglas *et al*., 2010; Atkinson, 1976; Kaufmann *et al*., 1972). The type of the planting material used for planting may also influence the root spread for a given species. In the case of teak plants raised from conventional stump and recently evolved root trainer seedlings may have different rooting pattern.



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### 2.6.1. Methodology for root distribution studies

Root system of plants has a vital role in the growth and development. In agroforestry, the root distribution of trees assumes greater relevance as it determine the adaptability of species to each system, by reducing negative interactions like competition. Despite the overwhelming importance of the root distribution studies, little headway has been made in this field primarily on account of the methodological limitation in root exploration studies (Hendricks *et al.*, 2006; Norby and Jackson, 2000). The adoption of methodology is mainly determined by the effectiveness of the method and the economic considerations (Bohm, 2012; Smit *et al.,* 2000). There are both direct and indirect methods of studying root distribution (Bohm, 2012). The direct methods include root excavation, trenching, monolith, profile wall trenching and indirect methods like radioactive tracer method, gravimetric method, and neutron probe method.

Nadezhdina and Cermak, (2003) used ground-penetrating radar technique for studies on structure and function of root systems of large trees. It provides 3D images of coarse roots (starting with a diameter of about 20 mm) from the soil surface down to a depth of several meters. One of the drawback of this technique is fine roots cannot be visualized by this method, but the total rooted volume of soil can be determined. Radio trace based indirect method of root activity studies is popular in Indian context (Wahid, 2001). Soil injection of radio label $^{32}P$ and quantification of its activity in the young leaves, which provides information about the root distribution. Several such studies have been reported on the root distribution characteristics of tropical trees such as *Acacia mangium* (Kunhamu, *et al.*, 2010), *Artocarpus hirsutus* Lamk (Jamaludheen *et al.*, 1996). Root excavation or destructive sampling has been widely adopted method to quantify the root biomass and also for analyze the root distribution pattern, but it is very difficult to carry out for large number of trees. This method is used as a standard for coarse root biomass estimation (Rocha, 2017; Samritika, 2013). But this method is laborious and time consuming processes, and fails to demarcate the zone of fine root activity (Niiyama *et al.*, 2010).

In order to overcome the problems related to the root excavation method, a new method was proposed by Huguet (1973) where the root system of each tree was partially excavated using a logarithmic spiral trench. This method is applicable for isolated trees, for avoiding the possible cross feeding between the adjacent root system. The spiral nature of the trench allows a large proportion of the root system to be studied with minimal damage to the tree. Later Tomlinson *et al.* (1998) modified the spiral trench procedure so as to suit with broadleaved species though his classical investigations on the root distribution of *Parkia biglobosa* in Burkina Faso, West Africa, using a logarithmic spiral trench technique. Studies in the humid tropics suggest the reliability of this technique (Samritika, 2013; Srinivasan *et al.,* 2004).

### 2.6.2. Rooting behavior of teak

Despite the commercial importance of teak as prominent plantation species in the tropics, very litter information is available on the root distribution and its role in resource acquisition. Ngampongsai (1973) studied the development and distribution of teak-root in plantations at different age. It was found that the rate of increase of the root system declined with increasing age, the roots were confined to the upper 30 cm of the soil surface and with increasing age the tap root lost its ability to penetrate and lateral and vertical roots then developed profusely. Yet another study on root system of important tree species in dry deciduous teak forests observed a well-developed taproot for teak with prominent presence of secondary and tertiary roots (Prasad and Mishra, 1984). Scientific studies suggest that teak shows a surface feeding nature with the rhizosphere of teak confined to the top soil layer. This may be due to the use of conventional planting technique such as stump planting, which reduces the chance of spread of tap root by pruning (Khedkar, 1999; Khedkar and Subramanian, 1997). Trials on raising teak planting stock in root trainers suggested that seedlings raised in root trainers had improved lateral root development than the normal stump stock and produced multiple tap roots (Khedkar and Subramanian, 1997). The root trainer plants were found sturdier, healthier and had a larger collar girth than stump origin plants. These studies reiterate that root system of teak may be influenced by the planting materials such as root trainer or stump.

Root distribution of teak under different stand density regime has been less investigated. Available studies suggested that closer spacing leads to confining root to narrow rhizosphere (Douglas *et al.*, 2010; Atkinson, 1976; Kaufmann *et al.*, 1972). Kunhamu *et al.* (2010) also reported a similar observation in *Acacia mangium* plantation with variable planting densities by using $^{32}P$ soil injection method.

# *Materials and methods*

# III. MATERIALS AND METHODS

The present study aimed at comparing the growth performance and root distribution patterns of stump and root trainer grown teak plantations were carried out during the period 2017-18 at Mallayatoor Forest Division, Kerala. Representative teak stands belonging to different planting materials, ages and planting density were randomly selected and compared for growth and root distribution pattern.

## 3.1. LOCATION

The study was conducted in teak plantations raised from stump and root trainers and maintained at different spacing at Malayattoor Forest Division, Kalady range at Karakkad station (10° 12' 10.8864" N and 76° 28' 36.3144" E). The study area included seven-year and five-year old teak plantations at variable planting densities established by stump and root trainer grown seedlings. The area receives average annual rainfall of about 3000 mm and the average annual maximum temperature is 31.3° C and mean annual minimum temperature 24.2° C (NOAA). The details of teak plantations selected for the study are given below.

Table 1. Details of plantations selected for the study at Karakkad station, Kalady range, Malayattoor Forest Division, Kerala.

| Sl No. | Name of plantation | Year of planting | Planting technique | Spacing (m) | Area (ha) |
|---|---|---|---|---|---|
| 1. | Karakkad Bit-1 | 2010 | Stump | 2x2 | 43.45 |
| 2. | Karakkad Bit-1 | 2010 | Root trainer | 2x2 | |
| 3. | Karakkad Bit-3 | 2012 | Stump | 3x3 | 9 |
| 4. | Karakkad Bit-3 | 2012 | Root trainer | 3x3 | |
| 5. | Karakkad Bit-2 | 2012 | Root trainer | 2x2 | 5.5 |

## 3.2. METHODS

Representative plots belonging to all the above five plantations were selected for growth comparison using random selection method. Teak plantations of same age and spacing raised using stump and root trainers were subjected to growth and root distribution comparisons separately. For instance, the teak plantations raised by stump and root trainers established during the same period (2010) at 2m×2m spacing were compared for growth performance. Similarly, the plantation at 3m×3m spacing established separately using stump and root trainers during 2012 were compared for growth performance. Another plantation at 2m×2m spacing raised from root trainer established in 2012 was compared with 3m×3m spaced root trainer plants primarily for assessing the effect of spacing on root trainer grown trees.

The method involved random selection of plots from the respective plantations, demarcation of each plot and numbering of each tree prior to observations. The detailed description of the plot is given below. The selected plots under each of the plantations were subjected to growth observations at six monthly intervals. Also, the trees belonging to various selected plantations were subjected to root distribution studies. Soil samples were collected from each of the plantations to investigate the changes in soil physio-chemical attributes.

### 3.2.1 Selection and demarcation of plots

Prior to the selection of the plots, the entire study area was surveyed using GPS and the area maps were prepared using software QGIS 2.18.3. Random points were marked on the map corresponding to each of the above plantations and their lat-long recorded and the points identified in the field using GPS. Nine such random points were marked corresponding to each plantation. Considering the random point as one corner, plots of size 20 × 20 m were laid for each of nine random points. For maintaining the plot identity all nine plots in each plantation were serially numbered and tagged (Plate 1).

Plate 1. Plot demarkation and numbering in teak trees at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.



A. Plot demarkation of teak trees; B. Numbering of teak trees.

### 3.2.2. *Growth observations of trees*

Growth characters such as survival count, total tree height, bole height, girth at the breast height and crown diameter of the trees were measured. Border trees were excluded for growth observations, to minimize border effect. (Plate 2)

#### *3.2.2.1. Survival count*

Survival count was made by counting the live tree number and expected number of trees in a plot. These plots were unthinned, which made the assessment of casualties in each sample plots easier. The survival counts were converted into survival percentage.

#### *3.2.2.2. Total tree height, bole height and girth*

Total tree height and bole height were measured by using vertex laser hypsometer (Hagloff, Sweden). Tree girth was measured at breast height using measuring tape upto mm precision. The girth at breast height was converted to DBH and used for the computation of following growth parameters.

#### *3.2.2.3. Basal area and volume*

The basal area of the sampling trees was computed following the equation $\pi d^2/4$ where, d is the dbh. The mean tree volume was computed as $\pi d^2/4 \times H \times F$ where H is the total tree height and F as the form factor (F= 0.70 was considered). Stand basal area and stand volume were computed from their respective mean tree basal area and mean tree volume by multiplying with corresponding stand density (trees per ha).

Plate 2. Growth observatios on teak trees at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.


A. Measuring the height of teak trees using vertex lazer hypsometer; B. Measuring girth at the breast height; C and D. Measurement of leaf area index using LAI-2000 plant canopy analyzer.

#### *3.2.2.4. Crown diameter*

Individual tree crown diameter measurement was done by projecting the crown to ground. Two measurements were taken for each tree, the first in the longest width and the second one perpendicular to the first one. The average of these two values was taken as the crown diameter.

#### *3.2.2.5. Leaf Area Index (LAI)*

LAI measurements were carried out using LAI-2000 plant canopy analyzer (Li Cor, Nebraska, USA). The observations were taken at three random locations within each plots and the plot average were computed.

#### *3.2.2.6. Estimation of tree form characters*

Tree form characters considered in this study included persistence of stem axis and straightness of stem. Each tree was assessed using visual scoring system as given by Indira (1999). The score was assigned in such a way that high score indicate positive or good character than the lower score.

***Persistence of stem axis***

The persistence of stem axis was evaluated by subdividing the total height of tree into four quarters. In addition the occurrence of forking in each quarter was also considered. The scoring system was as follows:

Score 1 – Tree is multiple stemmed at the ground level

Score 2 – Main stem branched out in the lowest quarter

Score 3 – Main stem branched out in the second quarter

Score 4 – Main stem forked in the third quarter

Score 5 – Main stem forked in the fourth quarter

Score 6 – Complete persistence of axis

***Straightness of stem***

The visual scoring method was adopted for this work. Stem straightness of each tree was scored using five point scales as:

Score 1 – Trees with crooked and more than three serious bends

Score 2 – Trees crooked and with 1 or 2 serious bends

Score 3 – Tree slightly crooked with many bends

Score 4 – Trees slightly crooked and with few bends

Score 5 – Straight trees

### 3.2.3. Plant and soil analysis

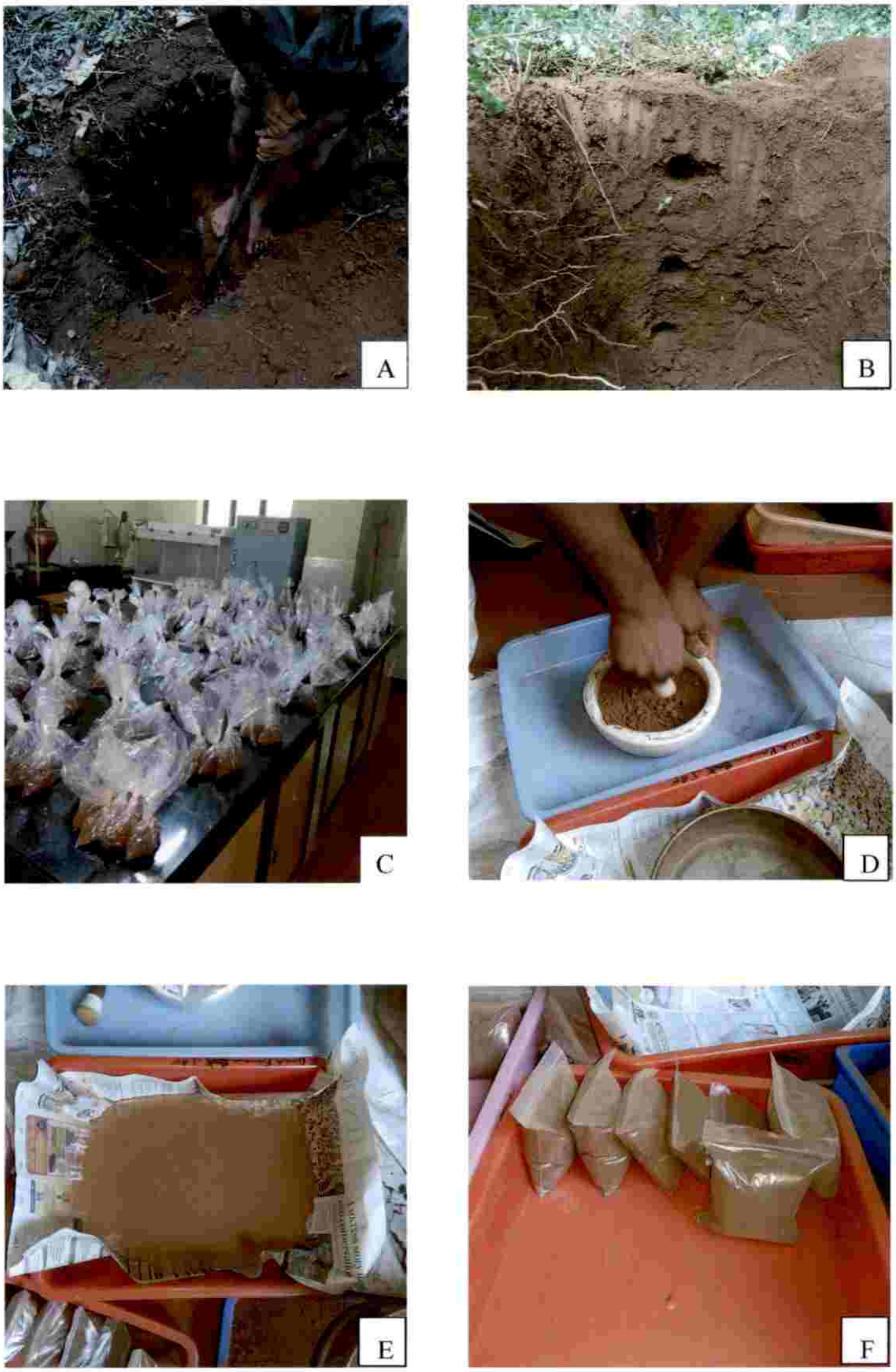
#### *3.2.3.1. Plant Nitrogen content*

Young leaves of teak belonging each of the treatment plots were sampled for nitrogen. Tender leaves were collected from 4 random trees at mid height of the trees. The samples were oven dried, powdered and were digested using digestion mixture ($K_2SO_4$: $CuSO_4$ at a ratio 10:1) and the total nitrogen content was calculated using Microkjeldahl digestion and distillation method (Jackson, 1958).

#### *3.2.3.2. Soil sample collection*

Two sampling procedure were used to study the soil physio-chemical properties. Among the nine plots in each plantation site, three random plots were subjected to detailed study by taking soil profile at 1m depth (Plate 3). The profile were further divided 20cm depth intervals such as 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm. Triplicate soil samples were collected from each of the depth intervals and were subjected to detailed soil analysis such as bulk density, pH, organic carbon, total N, available P, exchangeable Ca and K. The remaining six plots were subjected to soil sampling up to 60cm soil depth. Each of the 60 cm pits were subdivided into 0-20 cm, 20-40 cm, and 40-60 cm and triplicate samples were taken for soil analysis.

Plate 3. Collection and preparation of soil samples from teak plantations at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.




A, B, C. Collection of soil samples from teak plantation; D, E. Grinding and preparation of soil samples; F. Packing of soil samples.

### *3.2.3.3. Soil bulk density*

Soil bulk density measurement was done using specially designed steel cylinder (AOAC, 1995). Bulk density was estimated by taking a core of undisturbed soil from each soil depth in the soil profile by using steel cylinder. The core was taken by gently inserting the cylinder to the soil so as not to disturb the normal bulk density of the soil. The soil samples were oven dried and weight was determined. The bulk density was computed for all the depth intervals in the soil profile of one meter depth. The volume of soil was calculated by measuring the internal volume of cylinder ($\pi r^2 h$). The bulk density was calculated as,

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

### *3.2.3.4. Soil chemical properties*

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

***Soil pH***

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

***Soil organic carbon***

Soil organic carbon was determined by wet digestion method (Walkley and Black, 1934). The soil sample was dried and finely powered using mortar and pestle and then passed through 0.2 mm sieve. One gram sieved soil samples of each depth were transferred into 500 ml conical flasks to which 10 ml of 1N $K_2Cr_2O_7$ was added and mixed thoroughly. Concentrated $H_2SO_4$ (20 ml) was added to the conical flask and it was kept for 30 minutes for oxidation. Then 200 ml of distilled water was added for arresting reaction and this is followed by adding 4-5 drops of ferroin indicator. The resultant solution was titrated against 0.5 N $FeSO_4$ solution until dark green color changed to chocolate brown color. A blank was also run simultaneously and readings were recorded. The soil organic carbon was estimated by using equation:

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

***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 mixed with digestion mixture ($K_2SO_4$: $CuSO_4$ at a ratio 10:1) and 10 ml of Conc. $H_2SO_4$ and was kept overnight for pre-digestion and it was transferred to digestion chamber. After digestion the aliquot was made up to 100 ml and filtration were done with Whatman No 42 filter paper. From the aliquot 10 ml was transferred to auto N distillation Kjeldahl unit and inflamed with 40% NaOH and liberated ammonia collected in 4% Boric acid. This solution was subjected to titration against 0.01 N $H_2SO_4$. A blank was also run simultaneously. The total nitrogen content in the samples were calculated using following formula,

$$\text{Percentage of N in soil sample} = V \times 0.01 \times 0.014 \times 100/10 \times 100/w$$

Where, V = Sample titer value – blank titer value; w is the weight of soil taken

***Soil available Phosphorus***

Available phosphorus in the soil samples were extracted using Bray No.1 reagent and estimated colorimetrically by reduced Molybdate-Ascorbic acid blue colour method (Watanabe *et al.*, 1965) using spectrophotometer (Thermo Scientific, USA).

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

$$\text{Available P (kg/ha soil)} = \text{Available P (ppm)} \times 2.24$$

Where R is the reading obtained from the spectrophotometer in ppm.

***Soil total Phosphorus***

Total Phosphorus in the soil was extracted by di-acid digestion (9:4 mixture of $HNO_3$: $HClO_4$) and the extract was reduced with Molybdate-Ascorbic acid blue colour method (Watanabe *et al.*, 1965) and reading were taken using spectrophotometer.

$$\text{Total P in soil (ppm)} = X \times 100/w \times 25/v$$

Where 'X' is the reading obtained from spectrophotometer in ppm, 'w' is the weight of soil taken and 'v' is the volume of acid extract pipetted.

***Soil exchangeable Potassium***

Available potassium in the soil samples were extracted using neutral normal ammonium acetate and its content in the extract was estimated by flame photometry (Jackson, 1958).

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

$$\text{Available K in soil (kg/ha of soil)} = \text{Available K in soil (ppm)} \times 2.24$$

Where R is the flame photometer reading

***Soil exchangeable Calcium***

Determination of exchangeable Ca involved a complexometric titration using EDTA. This method is usually employed for easer estimation of exchangeable Ca and

Mg in soil. Five gram of soil was extracted with 25 ml of natural normal ammonium acetate. The Ca ions in the extract at high pH (this was achieved by adding 10% NaOH solution to attain pH of 12 or more) were titrated against standard 0.01 N ethylene diamine tetra acetic acid by using Mureoxide as indicator. The color changed from pink to violet.

$$\text{Exchangeable Ca (m. eq per 100g)} = \frac{\text{Titter value} \times \text{N of EDTA} \times \text{volume made} \times 100}{\text{Weight of soil} \times \text{Aliquot taken}}$$

**3.2.4. Root distribution study**

Two trees were randomly selected from each plantation for root distribution study by following logarithmic spiral trenching method (Tomlinson *et al.,* 1998). (Plate 4)

We employed the modified Tomlinson equation. The equation is:

$$x = 1.5\ (d)$$

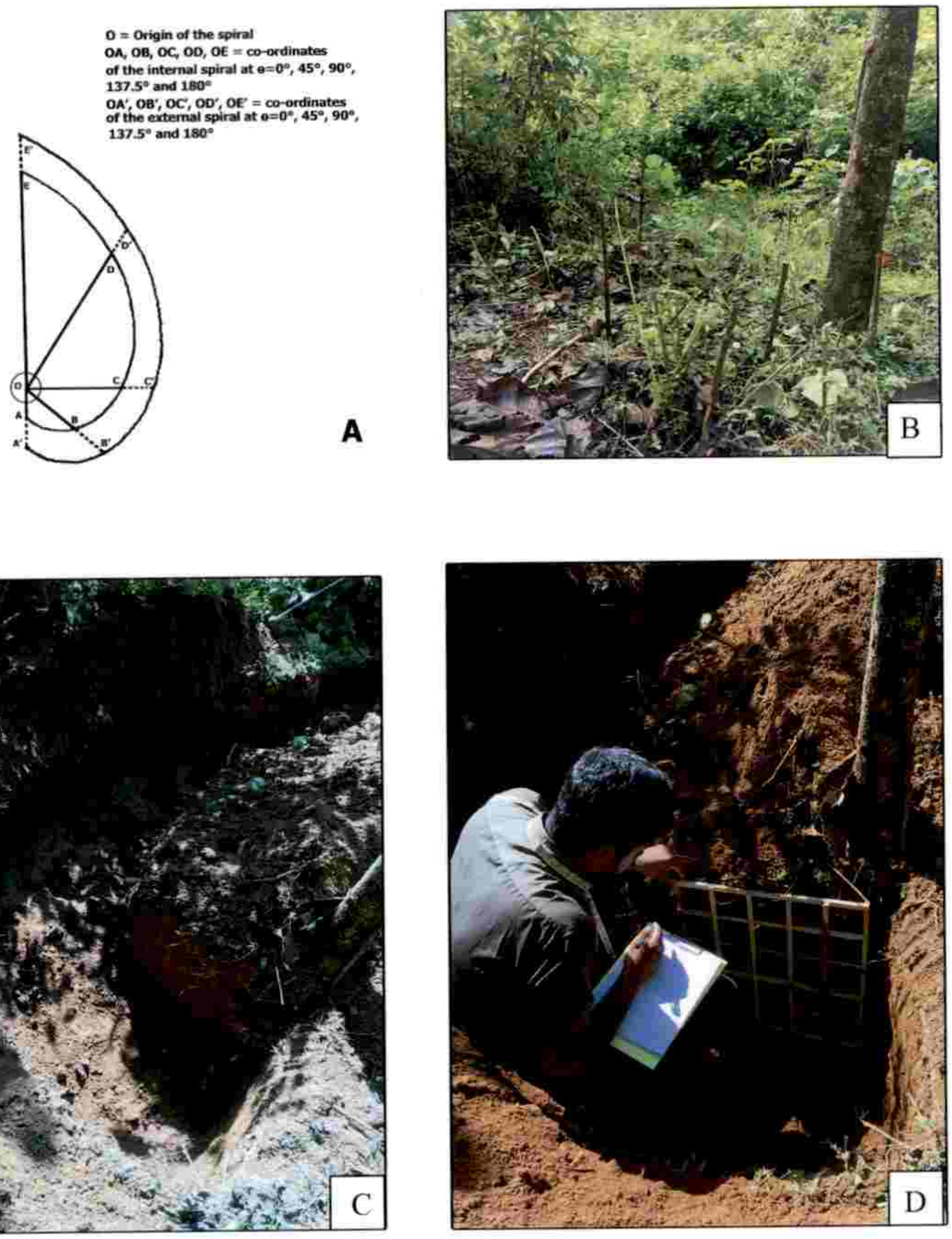
$$y = [\ln (r/d)]/\pi$$

$$z = x\ e^{y\theta}$$

where d is the tree diameter in m; r is the average of the crown radius at four cardinal points in m; a is the distance of the starting point of the spiral from the tree in m; b is the natural logarithmic of the ratio of crown radius to the diameter of the tree divided by π; z = the distance of any point on the spiral from the tree base in m and θ = 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180°.

The trajectory of the trench has to be laid down on the field using plastic ropes by calculating the distance a on the north side from the tree which will be the origin and further extension is done in the spiral clockwise direction with θ taking values 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180°.The trench has to be dug to a depth of 60 cm and a width of 60 cm and care has to be taken so that the

Plate 4. Logarithmic spiral trenching for root distribution assessment in teak stands at karakkad, Kalady range, Malayattoor Forest Division, Kerala.




A. Schematic diagram showing co-ordinates of the logarithmic spiral trench;
B. Marking co-ordinates in field; C. Excavated logarithmic trench in field and
D. 50cm x 50cm grid used for root intensity assesement.

sides remain intact. Severed roots (living) on the internal and external trench walls should be counted by placing a 50 x 50 cm quadrat (subdivided into 10 cm depth intervals). Roots are classified into less than 2 mm, 2 to 5 mm, and > 5 mm diameter classes at the time of counting by placing the quadrats (50 x 50 cm) at fixed distances from the trunk. Root counts are converted into rooting intensity (number of roots $m^{-2}$) (Bohm, 1979).

### 3.2.5. Statistical analysis

The data collected from the field was analyzed using SPSS version 22.0 and Microsoft excel (Office 2010). The growth variation between the treatments for all the observed growth parameters was analyzed using Student's t test at $p < 0.01$. A univariate ANOVA was done for the soil data of respective treatments.

# *Results*

# IV. RESULTS

The present study was undertaken to compare the field level performance of stump and root trainer grown teak stands and also effect of tree spacing of root trainer grown plants on the tree growth and root distribution. Attempt was also made to study the possible effect of the type of planting stock on the physical and chemical properties of soil. The salient results are summarized below:

## 4.1. GROWTH ATTRIBUTES

Growth attributes like total tree height, bole height, girth at breast height, crown diameter, survival percentage and leaf area index were measured for trees corresponding to various stump grown and root trainer grown plantation types established during different periods.

### 4.1.1. Total tree height

Table 2 shows that there were significant difference in height growth among the stump and root trainer grown teak plantations corresponding to various ages. Mean tree height was highest in the teak plantation established in 2012 by root trainer (6.28 m) than stump grown plantation (5.3 m). The plantations established during 2010 also showed higher mean tree height for the root trainer grown teak trees (6.68 m) as compared with the stands planted with stump (5.87 m). This trend was observed for all subsequent measurements for plantations at five and seven-years of age. Attempt to compare the effect of spacing on height growth for the two teak stands viz. 3x3 m and 2x2 m (2012 establishment) suggested only marginal difference in height growth. However, apparently the mean height was found to be marginally higher in 2x2 m spaced plantations (6.67 m) than 3x3 m spaced plantations (6.28 m). Non-significant effect was also observed for the next two measurements taken at six months interval (Table 3).

Table 2. Variation in total tree height of stump and root trainer grown teak plantations at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Height (m) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 5.30 | 5.87 | 5.86 | 6.50 | 6.36 | 7.07 |
| Root Trainer | 6.28 | 6.68 | 6.91 | 7.23 | 7.40 | 7.74 |
| p-value | 0.045* | 0.012* | 0.030* | 0.024* | 0.025* | 0.049* |

* significant at 5% level

Table 3. Variation in total tree height of root trainer grown teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Height (m) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 6.28 | 6.91 | 7.40 |
| 2x2 m | 6.67 | 7.32 | 7.81 |
| p-value | 0.442$^{ns}$ | 0.392$^{ns}$ | 0.359$^{ns}$ |

ns: non- significant

### 4.1.2. Bole height

The bole height of stump and root trainer grown younger teak plantations (2012 establishment) showed significant increase in bole height for the root trainer grown trees (3.38 m) compared to those raised from stump (2.67 m) (Table 4). However, stump and root trainer grown teak plantations established during 2010 was compared and found to have no significant difference between them. Mean tree bole height in root trainer grown teak plantation (2.95 m) showed a modest increase as compared to stump grown plantation (2.70 m). Bole height is one of the parameter that manifested in advanced age; the subsequent measurements indicated a slight increase in bole height for both the aged plantations. Bole height also showed marginal difference across variable spacing (2x2 m and 3x3 m) for the teak plantations raised from root trainers (Table 5).

However, mean bole height was slightly better in the 3x3 m spacing plantation (3.38 m) compared to that grown at 2x2 m spacing (3.08 m). The initial trend was followed throughout the study period for five-year-old root trainer grown stands at varying spacing.

Table 4. Bole height of stump and root trainer raised teak stands at five- and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Bole height (m) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 2.67 | 2.70 | 2.69 | 2.74 | 2.75 | 2.78 |
| Root Trainer | 3.38 | 2.95 | 3.42 | 3.00 | 3.45 | 3.06 |
| p-value | $0.012^{*}$ | $0.241^{ns}$ | $0.011^{*}$ | $0.124^{ns}$ | $0.014^{*}$ | $0.201^{ns}$ |

ns: non- significant; * significant at 5% level

Table 5. Bole height of root trainer raised teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Bole height (m) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 3.38 | 3.42 | 3.45 |
| 2x2 m | 3.08 | 3.14 | 3.18 |
| p-value | $0.387^{ns}$ | $0.425^{ns}$ | $0.473^{ns}$ |

ns: non- significant

**4.1.3. Diameter at breast height (DBH)**

The changes in DBH as a function of type of planting material were analyzed for various teak plantations (Table 6). The results suggested that the differences in average DBH between stump and root trainer grown teak stands established during 2012 (3x3 m spacing) suggested marked increase in DBH for the root trainer grown stands (7.96 cm). However the comparison among stump and root trainer raised stands for the older age (2010 establishment at 2x2 m spacing) was significant though root trainer based trees showed improvement

(9.04 cm) as compared to stump (8.32 cm) One year of growth observation was found to have same tend that showed in the initial measurement for DBH. Root trainer grown plantations showed higher DBH as compared with respective stump origin plants in the entire study period. The effect of spacing on DBH of trees in the plantations established by root trainer at variable spacing (Table 7) showed significant difference with stand at 3x3 m spacing giving higher values (7.96 cm) compared to teak stands at 2x2 m (5.08 cm).Spacing also showed same trend for entire study period as initial measurement, where closer spaced (2x2 m) plantation registered lesser DBH as compared to wider spaced (3x3 m) plantation.

Table 6. DBH of stump and root trainer grown teak stands at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | DBH (cm) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 6.95 | 8.32 | 7.32 | 8.75 | 7.66 | 8.99 |
| Root Trainer | 7.96 | 9.04 | 8.32 | 9.50 | 8.79 | 9.78 |
| p-value | 0.026* | 0.050* | 0.027* | 0.046* | 0.017* | 0.048* |

* significant at 5% level

Table 7. DBH of root trainer grown teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | DBH (cm) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 7.96 | 8.32 | 8.79 |
| 2x2 m | 5.08 | 5.55 | 6.08 |
| p-value | < 0.001** | < 0.001** | < 0.001** |

** significant at 1% level

**4.1.4. Basal area**

The mean tree basal area for each treatment combinations (stump vs root trainer) were computed and analyzed separately (Table 8). Mean tree basal area for plantations established during 2012 showed root trainer raised stands registering better mean tree basal area (50.60 $cm^2$) while the corresponding values for stump grown teak was fairly low (38.48 $cm^2$). But it was not significantly variable among the stump and root trainer raised plantations established during 2010 at 2x2 m spacing. However, it showed similar trend with mean basal area marginally higher in root trainer grown plantation (64.64 $cm^2$) than stump grown plantation (54.82 $cm^2$). Higher basal area was observed in root trainer grown plantations at both the ages and for the entire study period. The root trainer gown plantations established at different spacing recorded significant difference in basal area (Table 9). For instance, the mean tree basal area was highest in stand at 3x3 m (50.60 $cm^2$) spacing as compared to the stand at 2x2 m spacing (21.66 $cm^2$).

Table 8. Mean tree basal area of stump and root trainer grown teak plantations at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Basal area ($cm^2$) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 38.48 | 54.82 | 42.61 | 60.71 | 46.70 | 64.21 |
| Root Trainer | 50.60 | 64.64 | 55.22 | 71.28 | 61.50 | 75.63 |
| p-value | 0.022* | $0.055^{ns}$ | 0.024* | $0.052^{ns}$ | 0.017* | $0.056^{ns}$ |

ns: non- significant; * significant at 5% level

Table 9. Mean tree basal area of root trainer grown teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Basal area ($cm^2$) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 50.60 | 55.22 | 61.50 |
| 2x2 m | 21.66 | 25.55 | 30.47 |
| p-value | < 0.001** | < 0.001** | < 0.001** |

** significant at 1% level

Stand basal area showed similar trends as that of mean tree basal area with marked advantage for root trainer grown stands at both ages (Table 10). Stand basal area showed significantly higher value for root trainer grown stand at five-years of age, however it marginalized at the age of seven-years with an improvement in the root trainer origin stand. Response of variable tree spacing however, showed an inverse trend as compared to mean tree basal area (Table 11). For instance, the closely spaced stands registered higher stand basal area than teak stands at wider spacing during all the observation periods. However, the differences became more prominent at later stages of observation.

Table 10. Stand basal area of stump and root trainer raised teak plantations at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Basal area ($m^2$ $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 4.27 | 13.71 | 4.73 | 15.18 | 5.19 | 16.05 |
| Root Trainer | 5.62 | 16.16 | 6.14 | 17.82 | 6.83 | 18.91 |
| p-value | $0.022^{*}$ | $0.055^{ns}$ | $0.024^{*}$ | $0.052^{ns}$ | $0.017^{*}$ | $0.056^{ns}$ |

ns: non- significant; * significant at 5% level

Table 11. Stand basal area of root trainer raised teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Plantation spacing | Basal area ($m^2$ $ha^{-1}$) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 5.62 | 6.14 | 6.83 |
| 2x2 m | 7.19 | 8.21 | 9.68 |
| p-value | $0.076^{ns}$ | $0.034^{*}$ | $0.012^{*}$ |

ns: non- significant; * significant at 5% level

#### 4.1.5. Tree Volume

Mean tree volume for various teak stands were recorded and analyzed separately (Table 12). The mean tree volume for the teak plantations at five and seven-years of age (2012 and 2010 establishment) showed significant difference between stump and root trainer. Highest volume was observed for root trainer grown plantation (0.023 $m^3$) whereas compared to the plantation of stump origin (0.015 $m^3$) at five-years of age. For seven-year-old stand the corresponding values were 0.031 $m^3$ and 0.023 $m^3$ for root trainer and stump origin plantations. Changes in mean tree volume with variable tree spacing suggested that the highest mean tree volume was associated with stand at 3x3 m spacing (0.023 $m^3$) and stand at 2x2 m spacing showed the least (0.011 $m^3$) (Table 13). The increase in volume at 3x3 m stand was almost 2.09 fold higher as compared to 2x2 m stand.

Table 12. Tree Volume of stump and root trainer grown teak plantations at five- and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Volume ($m^3$) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 0.015 | 0.023 | 0.018 | 0.028 | 0.021 | 0.032 |
| Root Trainer | 0.023 | 0.031 | 0.028 | 0.037 | 0.033 | 0.041 |
| p-value | 0.016* | 0.034* | 0.015* | 0.036* | 0.011* | 0.042* |

* significant at 5% level

Table 13. Tree Volume of root trainer grown teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Volume ($m^3$) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 0.023 | 0.028 | 0.033 |
| 2x2 m | 0.011 | 0.014 | 0.017 |
| p-value | 0.004* | 0.004* | 0.005* |

* significant at 5% level

The stand tree volume on hectare basis showed same trend as that of the mean tree volume for both stump and root trainer grown stand at both the ages (Table 14). The differences in stand volume were prominent with clear-cut increase for root trainer origin teak stands compared with that from stump origin for both the plantations. For instance, at final observation period the stand volume for root trainer and stump grown stands were 36.31 and 23.65 $m^3$ $ha^{-1}$ for five-year-old teak stands while the corresponding values were 103.63 and 80.74 $m^3$ $ha^{-1}$ for the seven-year-old stands. Impact of spacing on stand volume (Table 15) showed same trend as that of stand basal area with marginal improvement at first observation for closer spaced stand, which subsequently showed significant increase as compared to widely spaced sands at later stages of observation.

Table 14. Stand tree volume of stump and root trainer grown teak plantations at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Volume ($m^3$ $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | September 2017 | | March 2018 | | September 2018 | |
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 16.38 | 57.35 | 20.00 | 70.21 | 23.65 | 80.74 |
| Root Trainer | 25.58 | 76.87 | 30.60 | 91.61 | 36.31 | 103.63 |
| p-value | 0.016* | 0.034* | 0.015* | 0.036* | 0.011* | 0.042* |

* significant at 5% level

Table 15. Stand tree volume of root trainer grown teak plantations of five-years of age at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Volume ($m^3$ $ha^{-1}$) | | |
|---|---|---|---|
| | September 2017 | March 2018 | September 2018 |
| 3x3 m | 25.58 | 30.60 | 36.31 |
| 2x2 m | 37.37 | 46.01 | 53.79 |
| p-value | $0.054^{ns}$ | 0.030* | 0.022* |

* significant at 5% level

### 4.1.6. Crown diameter

Table 16 shows the changes in crown diameter with variable planting stock and spacing for teak established at different periods. The relatively younger stand (2012 planting) showed feeble difference in crown diameter among stump and root trainer growth stands which were 2.23 m and 2.70 m respectively. Similarly, the crown diameter of elder teak plantations (2010 planting) were also at par for stump and root trainer grown stands.

Nevertheless, there was significant variation in mean crown diameter across variable spacing for root trainer grown stand with highest in plantation established at 3x3 m (2.7 m) spacing compared those raised at 2x2 m spacing (1.62 m).

### 4.1.7. Leaf Area Index (LAI)

LAI was found to have significant difference between the plantations raised by stump and root trainer seedlings corresponding to both the periods of stand establishment (Table 16). In general the root trainer raised teak stands registered better LAI compared to that grown from stump for both 2012 and 2010 plantations (1.2 and 1.73 respectively) than plantations established by means of stumps (0.88 and 1.08). However, the LAI had limited influence on tree spacing for stand established using root trainers, the differences being marginal with LAI of 1.2 and 1.11 for 3x3 m and 2x2 m spaced plantations respectively.

### 4.1.8. Survival percentage

Survival percentage did not show marked variation between the plantations established by stump and root trainers (Table 16) and also on the tree spacing (Table 17). The mean survival percentage was highest in root trainer grown planation to the extent of 89.43% and 75.85% for five- and seven-year-old plantations respectively as compared to stump grown plantations where the corresponding values were 88.42% 68.32%. In spacing trial, widely spaced (3x3 m) plantation were found to have higher survival percentage (89.43%) than lesser spaced (2x2 m) plantations (86.02%), though the differences were non-significant.

Table 16. Crown diameter, LAI and survival percentage of stump and root trainer grown teak plantations at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Crown Diameter (m) | | LAI | | Survival percentage (%) | |
|---|---|---|---|---|---|---|
| | Year of planting/ spacing | | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 2.23 | 2.53 | 0.88 | 1.08 | 88.42 | 68.32 |
| Root Trainer | 2.7 | 2.72 | 1.2 | 1.73 | 89.43 | 75.85 |
| p-value | $0.070^{ns}$ | $0.290^{ns}$ | $0.038^{*}$ | $< 0.001^{**}$ | $0.776^{ns}$ | $0.056^{ns}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

Table 17. Crown diameter, LAI and survival percentage of root trainer grown teak plantations of five-years of age at variable spacing in Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Crown Diameter (m) | LAI | Survival percentage (%) |
|---|---|---|---|
| 3x3 m | 2.7 | 1.2 | 89.43 |
| 2x2 m | 1.62 | 1.11 | 86.02 |
| p-value | $0.001^{*}$ | $0.718^{ns}$ | $0.272^{ns}$ |

ns: non- significant; * significant at 5% level

### 4.1.9. Persistence of stem axis

Attempts to relate the type of planting material used for raising the teak plantation with the persistence of stem axis showed no significant difference between the plantations (Table 18) as well as spacing (Table 19). Apparently, the stump grown plantations showed marginally higher number of trees with good persistence to the tune of (69.80% and 88.08% for 2012 and 2010 established plantations respectively) while corresponding value for root trainer grown trees were 62.40% and 85.48% respectively. Root trainer grown teak stands at variable spacing also showed poor relation with improvement in stem axis. In general, the 2x2 m spaced plantation (67.10%) was found to have higher persistence of stem axis than 3x3m spaced plantation (62.40%).

### 4.1.10. Straightness of stem

Table 18 and 19 also gives the changes in tree stem straightness in relation to variable planting material of origin and spacing. In general, it can be observed that neither the planting material (stump or root trainer) nor the tree spacing could inflict any change in stem straightness for plantation of 2012 and 2010 establishment. Apparently, the root trainer based stand at 2x2 m spacing showed marginal improvement in stem straightness (90.81%) as compared to 3x3 m stand (87.81%).

Table 18. Persistence of stem axis and straightness of stem of stump and root trainer grown teak plantations at five and seven-years of age at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Persistence of stem axis (%) | | Straightness of stem (%) | |
|---|---|---|---|---|
| | Year of planting/ spacing | | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 69.80 | 88.08 | 89.45 | 91.28 |
| Root Trainer | 62.40 | 85.48 | 87.81 | 87.03 |
| p-value | $0.295^{ns}$ | $0.823^{ns}$ | $0.891^{ns}$ | $0.710^{ns}$ |

ns: non- significant

Table 19. Persistence of stem axis and straightness of root trainer grown teak plantations of five-years of age at variable spacing in Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Persistence of stem axis (%) | Straightness of stem (%) |
|---|---|---|
| 3x3 m | 62.40 | 87.81 |
| 2x2 m | 67.10 | 90.81 |
| p-value | $0.741^{ns}$ | $0.793^{ns}$ |

ns: non- significant

## 4.2. PLANT AND SOIL ANALYSIS

Results obtained from the analysis of plant leaf nitrogen and soil physico-chemical properties such as bulk density, soil pH, organic carbon, total N, available P, total P, exchangeable K and exchangeable Ca content for stump and root trainer grown teak plantations are given below.

### 4.2.1. Plant nitrogen

Plant nitrogen was found to have no significant difference between the stump and root trainer grown plantations while it had marked variation for plantations established at variable spacing. Leaf nitrogen content was found to be highest in the root trainer grown plantations (2.16%; 2012 establishment and 2.35%; 2010 establishment) than that of stump grown plantations (2.14%; 2012 establishment and 2.32%; 2010 establishment). Root trainer grown plantation at 3x3m spacing showed highest leaf N concentration (2.16%) than those at 2x2m spacing (1.94%).

Table 20. Leaf N of stump and root trainer grown teak plantations at five and seven-years of age in Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Leaf total N (%) | |
|---|---|---|
| | Year of planting/ spacing | |
| | 2012 (3x3 m) | 2010 (2x2 m) |
| Stump | 2.14 | 2.32 |
| Root Trainer | 2.16 | 2.35 |
| p-value | $0.709^{ns}$ | $0.793^{ns}$ |

ns: non- significant

Table 21. Leaf N of root trainer grown teak plantations at variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Leaf total N (%) |
|---|---|
| | Year of planting/ Planting material |
| | 2012 (Root trainer) |
| 3x3 m | 2.16 |
| 2x2 m | 1.94 |
| p-value | $0.003^{*}$ |

* significant at 5% level

### 4.2.2. Soil properties

Soil physio-chemical properties such as bulk density, organic carbon, soil pH, total nitrogen, available phosphorus, total phosphorus, exchangeable potassium and exchangeable calcium were analyzed and the results are given below.

#### *4.2.2.1. Soil bulk density*

In general, soil bulk density showed only marginal variation among stump and root trainer grown teak plantations of both five and seven-years age (Table 22 and 23) except the mid soil depth (40-60 cm) of seven-year-old plantation (Table 23). The 7-year and 5-year old root trainer and stump based plantations showed significantly lower bulk density with compared to tree less control plot soil. Over all, tress less open soil had higher value as compared to the wooded soil. Soil bulk density remained modestly variable between root trainer grown teak stands at variable spacing of 2x2 m and 3x3 m (Table 24). However significant differences were observed at top soil depth of 0-20cm for 3x3m and 2x2m spaced plantations. Corresponding to the soil depths of 0-20cm, 20-40cm, 40-60 cm, 60-80 cm, and 80-100 cm the bulk density values varied from 1.05 to 1.98 $gcm^{-2}$, 1.05 to 1.52 g $cm^{-2}$, 1.00 to 1.33 g $cm^{-2}$, 1.01 to 1.35 g $cm^{-2}$, and 0.96 to 1.35 g $cm^{-2}$ respectively among all the five plantations. The mean bulk density across one meter soil depth also showed feeble difference between the plantations established by stump and root trainers.

Table 22. Soil bulk density of five- year- old teak plantation established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Bulk density (g $cm^{-2}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| Stump | $1.13^{b}$ | $1.19^{b}$ | $1.07^{b}$ | 1.01 | $1.02^{b}$ | $1.08^{b}$ |
| Root trainer | $1.13^{b}$ | $1.2^{b}$ | $1.19^{b}$ | 1.16 | $1.15^{b}$ | $1.16^{b}$ |
| Control | $1.45^{a}$ | $1.52^{a}$ | $1.33^{a}$ | 1.18 | $1.35^{a}$ | $1.37^{a}$ |
| p- value | $<0.001^{**}$ | $<0.001^{**}$ | $0.002^{*}$ | $0.341^{ns}$ | $0.027^{*}$ | $<0.001^{**}$ |

ns: non- significant; * significant at 5% level

Table 23. Soil bulk density of seven-year-old teak plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Bulk density (g $cm^{-2}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| Stump | $1.05^b$ | $1.16^b$ | $1.00^b$ | $1.12^b$ | 0.96 | $1.06^b$ |
| Root trainer | $1.05^b$ | $1.05^b$ | $1.18^a$ | $1.02^b$ | 1.09 | $1.08^b$ |
| Control | $1.98^a$ | $1.35^a$ | $1.23^a$ | $1.35^a$ | 1.02 | $1.39^a$ |
| p- value | <0.001 | $0.04^*$ | $0.002^*$ | $0.015^*$ | $0.631^{ns}$ | $<0.001^{**}$ |

ns: non- significant; * significant at 5% level

Table 24. Soil bulk density of five-year-old plantations established by root trainers in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Bulk density (g $cm^{-2}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| 3x3 m | 1.13 | 1.2 | 1.18 | 1.15 | 1.15 | 1.16 |
| Control 1 | 1.45 | 1.52 | 1.33 | 1.18 | 1.35 | 1.37 |
| 2x2 m | 1.30 | 1.16 | 1.17 | 1.14 | 1.1 | 1.17 |
| Control 2 | 1.15 | 1.17 | 0.98 | 0.93 | 1.05 | 1.06 |
| $p_1$-value | $0.008^*$ | $0.547^{ns}$ | $0.715^{ns}$ | $0.896^{ns}$ | $0.816^{ns}$ | $0.451^{ns}$ |
| $p_2$-value | $< 0.001^{**}$ | $< 0.001^{**}$ | $< 0.001^{**}$ | $0.830^{ns}$ | $0.042^*$ | $< 0.001^{**}$ |
| $p_3$-value | $< 0.001^{**}$ | $0.901^{ns}$ | $< 0.001^{**}$ | $0.019^*$ | $0.775^{ns}$ | $< 0.001^{**}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.2. Soil pH*

Table 20 and 22 gives the changes in soil pH in teak plantations established with stump and root trainers grown at variable spacing. In general, the soil pH was higher in both the plantations as compared to tree less control plot soil. Also marginal increase in soil pH was visible with increasing soil depth among all the experimental teak plantations. The soil corresponding to the 5-year-old teak plantation (Table 25) raised at 3x3 m spacing showed significant difference in pH among stump and root trainer raised plantations. Similar trend was observed for the 7-year-old teak plantation (Table 26). Across the soil depths, the first three depths (0-20, 20-40 and 40-60 cm) were found to have significant difference between the plantations established by stump and root trainers. Attempts made to compare the soil pH for root trainer grown teak plantations at variable spacing (Table 27) showed no significant difference between 3x3 m and 2x2 m spaced plantations. However, the plantations showed significant difference between the respective controls for the shallow soil depths.

Table 25. Soil pH of five-year-old plantation established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil pH | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| Stump | 5.10$^{a}$ | 4.90$^{a}$ | 5.30$^{a}$ | 4.58 | 5.43$^{a}$ | 5.06$^{a}$ |
| Root trainer | 3.93$^{b}$ | 4.14$^{b}$ | 4.18$^{b}$ | 4.55 | 4.35$^{b}$ | 4.23$^{b}$ |
| Control | 5.68$^{c}$ | 5.41$^{c}$ | 5.8$^{a}$ | 5.37 | 5.22$^{b}$ | 5.50$^{c}$ |
| p- value | < 0.001$^{**}$ | < 0.001$^{**}$ | < 0.001$^{**}$ | 0.412$^{ns}$ | 0.050$^{*}$ | < 0.001$^{**}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

Table 26. Soil pH seven-year-old of plantation established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil pH | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| Stump | 5.44$^{a}$ | 5.57$^{a}$ | 5.75$^{a}$ | 5.69$^{a}$ | 5.72$^{a}$ | 5.63$^{a}$ |
| Root trainer | 4.83$^{b}$ | 5.16$^{b}$ | 5.19$^{b}$ | 5.53$^{a}$ | 5.81$^{a}$ | 5.30$^{b}$ |
| Control | 4.48$^{b}$ | 4.77$^{b}$ | 4.86$^{b}$ | 4.56$^{b}$ | 4.32$^{b}$ | 4.60$^{c}$ |
| p- value | < 0.001$^{**}$ | 0.001$^{*}$ | < 0.001$^{**}$ | 0.027$^{*}$ | 0.023$^{*}$ | < 0.001$^{**}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 27. Soil pH of five-year-old plantation soil established by root trainers in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil pH | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Mean |
| 3x3 m | 3.93 | 4.14 | 4.18 | 4.55 | 4.35 | 4.23 |
| Control 1 | 5.68 | 5.41 | 5.8 | 5.37 | 5.22 | 5.50 |
| 2x2 m | 4.33 | 4.49 | 4.6 | 3.98 | 3.79 | 4.24 |
| Control 2 | 5.49 | 4.22 | 4.58 | 5.12 | 4.05 | 4.69 |
| $p_1$- value | $0.190^{ns}$ | $0.243^{ns}$ | $0.206^{ns}$ | $0.475^{ns}$ | $0.189^{ns}$ | $0.967^{ns}$ |
| $p_2$- value | $< 0.001^{**}$ | $< 0.001^{**}$ | $< 0.001^{**}$ | $0.130^{ns}$ | $0.066^{ns}$ | $< 0.001^{**}$ |
| $p_3$- value | $< 0.001^{**}$ | $0.247^{ns}$ | $0.942^{ns}$ | $0.118^{ns}$ | $0.050^{*}$ | $0.183^{ns}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.3. Soil organic carbon*

Table 28, 29 and 30 depicts the variation in the soil organic carbon in various teak plantations under study. In general, soil organic carbon content declined from top layer to bottom in the one meter soil profiles for all plantations. Soil carbon concentration was considerably higher in the plantation soil as compared to the contiguous treeless open soil. Prominent differences were visible among the stump and root trainer based plantations. In general, stump grown teak plantations had higher soil organic content as compared to root trainer based plantations. The five-year-old plantation soils showed only marginal differences in soil C concentration among the stump and root trainers though the values were much higher than the corresponding open control soil (Table 28). For instance, the seven-year-old plantation (Table 29) had significantly higher soil C concentration for the stands raised from stump across all soil depths. The respective values were 2.34, 1.73, 1.31 1.29, and 1.07 % for 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm respectively. The corresponding values for root trainer grown teak plantations were 2.04, 1.46, 0.99, 0.67 and 0.59 %. Attempts to relate soil carbon concentration with planting spacing for teak plantation at five-years age

(Table 30) revealed significant variations ($p_1<0.0001$) for the first three soil depths (0-20 cm, 20-40 cm and 40-60 cm). The carbon content was found to be highest for these soil depths for the plantation established at 3x3 m spacing compared to that at 2x2 m spacing and the same trend was followed throughout the soil profile. The first three soil depths also showed significantly higher values of carbon concentration for plantations at 3x3 m and 2x2 m spacing compared to their respective tree less controls.

The carbon stock in the various teak plantations at one meter soil depth were computed and tabulated in Table s 31, 32 and 33. A consistent reduction in soil carbon stock was observed with increase in soil depth for all the plantations under study. Obviously, the carbon build up in the stump grown plantation soils were higher as compared to root trainer grown plantation. For example, the total soil carbon content across one meter soil depth for the five-year-old teak plantation showed a marginal variation with higher value for stump grown plantation than root trainer grown plantation. The corresponding total carbon stock values were 121.82, 120.76 and 90.02 Mg $ha^{-1}$ respectively for stump, root trainer and control. Similar trend was observed for the 7 year old teak plantation with 164.27 and 123.03 Mg $ha^{-1}$ respectively for stump and root trainer while the corresponding value was 144.57 Mg $ha^{-1}$ for treeless open soil (Table 32). Attempts to compare effect of spacing on soil carbon buildup for teak stands at five-years the total carbon stock was found to be highest in the 3x3 m spaced plantation (120.76 Mg $ha^{-1}$) than that of 2x2 m plantation (81.51 Mg $ha^{-1}$) (Table 33). Also all the plantations irrespective of the spacing showed significantly higher carbon stocks as compared to their respective open control plot especially for the top layers (0-20, 20-40 and 40-60 cm).

The percentage distribution of the total soil carbon content for the 5 year old plantation was 29.92%, 30.81% and 32.73% for stump, root trainer and control respectively at 0-20 cm soil depth. The corresponding values at 40-60 cm soil depths were 17.02 %, 18.96 % and 17.68 % respectively. The percentage contribution at the lowest depth (80-100 cm) was 11.57 %, 10.80 % and 11.37 %



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respectively. The percentage distribution of the total soil carbon content for the seven-year-old plantation was 30.39 %, 34.66 % and 37.44 % for stump, root trainer and control respectively at 0-20 cm soil depth. The corresponding values at mid depth (40-60 cm soil depths) were 15.70 %, 18.98 % and 16.90 % respectively. The percentage contribution at the lowest depth (80-100 cm) was 12.11 %, 10.45 % and 8.64 % respectively for stump, root trainer and treeless open plots. The trend of percentage distribution of the total soil carbon content for the 5 year old plantation established by root trainer seedlings at varying spacing was in the order of 3x3 m spacing (30.81 %), respective control (32.73 %), 2x2 m spacing (33.37 %) and respective control (42.07 %) at 0-20 cm soil depth. The corresponding values at 40-60 cm soil depths were 18.96 %, 17.68 %, 16.75 % and 14.88 % respectively. The percentage contribution at the lowest depth (80-100 cm) was 10.80 %, 11.37 %, 13.76 % and 11.25 % respectively for root trainer grown seedlings.

Table 28. Soil organic carbon of five-year-old teak plantation established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil carbon (%) | | | | |
|---|---|---|---|---|---|
| | Soil depth (cm) | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 |
| Stump | 1.61[a] | 1.33[a] | 0.96[a] | 0.91 | 0.68 |
| Root trainer | 1.63[a] | 1.25[a] | 0.97[a] | 0.75 | 0.57 |
| Control | 1.02[b] | 0.76[b] | 0.60[b] | 0.48 | 0.38 |
| p- value | < 0.001** | < 0.001** | < 0.001** | 0.083[ns] | 0.084[ns] |

ns: non- significant ; * significant at 5% level ; ** significant at 1% level

Table 29. Soil organic carbon of seven-year-old plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil carbon (%) | | | | |
|---|---|---|---|---|---|
| | Soil depth (cm) | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 |
| Stump | 2.34[a] | 1.73[b] | 1.31[a] | 1.29[a] | 1.07[a] |
| Root trainer | 2.04[b] | 1.46[ab] | 0.99[b] | 0.67[b] | 0.59[b] |
| Control | 1.37[c] | 1.22[a] | 0.99[b] | 0.76[b] | 0.61[b] |
| p- value | < 0.001** | 0.012 | 0.036* | 0.002* | 0.003* |

* significant at 5% level ; ** significant at 1% level



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Table 30. Soil organic carbon of five-year-old teak plantations established by root trainers in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil carbon (%) | | | | |
|---|---|---|---|---|---|
| | Soil depth (cm) | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 |
| 3x3 m | 1.62 | 1.25 | 0.97 | 0.75 | 0.57 |
| Control 1 | 1.02 | 0.76 | 0.60 | 0.48 | 0.38 |
| 2x2 m | 1.04 | 0.75 | 0.58 | 0.50 | 0.47 |
| Control 2 | 0.60 | 0.29 | 0.25 | 0.19 | 0.18 |
| $p_1$- value | $< 0.001^{**}$ | $< 0.001^{**}$ | $< 0.001^{**}$ | $0.230^{ns}$ | $0.059^{ns}$ |
| $p_2$- value | $< 0.001^{**}$ | $< 0.001^{**}$ | $< 0.001^{**}$ | $0.050^{*}$ | $0.076^{ns}$ |
| $p_3$- value | $< 0.001^{**}$ | $< 0.001^{**}$ | $< 0.001^{**}$ | $0.095^{ns}$ | $0.115^{ns}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

Table 31. Soil carbon stock of five-year-old plantations established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil carbon (Mg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | $36.45^{a}$ | $31.68^{a}$ | $20.74^{a}$ | 18.84 | 14.10 | 121.82 |
| Root trainer | $37.21^{a}$ | $30.33^{a}$ | $22.90^{a}$ | 17.28 | 13.04 | 120.76 |
| Control | $29.47^{b}$ | $23.03^{b}$ | $15.92^{b}$ | 11.36 | 10.24 | 90.02 |
| p- value | $0.038^{*}$ | $0.004^{*}$ | $0.003^{*}$ | $0.280^{ns}$ | $0.435^{ns}$ | $0.500^{ns}$ |

ns: non- significant ; * significant at 5% level ; ** significant at 1% level

Table 32. Soil carbon stock of seven-year-old plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil carbon (Mg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | $49.92^{b}$ | 41.31 | 25.80 | $27.34^{a}$ | $19.90^{a}$ | 164.27 |
| Root trainer | $42.64^{b}$ | 30.44 | 23.35 | $13.75^{b}$ | $12.86^{b}$ | 123.03 |
| Control | $54.12^{a}$ | 33.09 | 24.44 | $20.42^{c}$ | $12.50^{b}$ | 144.57 |
| p- value | $<0.001^{**}$ | $0.194^{ns}$ | $0.709^{ns}$ | $0.002^{*}$ | $0.002^{*}$ | $0.055^{ns}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 33. Soil carbon stock of five-year-old plantations established by root trainer grown teak in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil carbon (Mg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| 3x3 m | 37.21 | 30.33 | 22.90 | 17.28 | 13.04 | 120.76 |
| Control 1 | 29.47 | 23.03 | 15.92 | 11.36 | 10.24 | 90.02 |
| 2x2 m | 27.20 | 17.62 | 13.65 | 11.80 | 11.22 | 81.51 |
| Control 2 | 13.69 | 6.81 | 4.84 | 3.53 | 3.66 | 32.52 |
| $p_1$- value | 0.026$^{*}$ | < 0.001$^{**}$ | < 0.001$^{**}$ | 0.284$^{ns}$ | 0.729$^{ns}$ | 0.011$^{*}$ |
| $p_2$- value | 0.040$^{*}$ | 0.009$^{*}$ | < 0.001$^{**}$ | 0.078$^{ns}$ | 0.198$^{ns}$ | 0.289$^{ns}$ |
| $P_3$- value | < 0.001$^{**}$ | < 0.001$^{**}$ | < 0.001$^{**}$ | 0.086$^{ns}$ | 0.196$^{ns}$ | < 0.001$^{**}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level;
$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.4. Soil total nitrogen*

The total nitrogen content for different aged teak plantations at variable spacing were presented in the Table s 34, 35 and 36. N content in the soil did not show appreciable variations except for the stands at seven-years of age. The five-year-old teak plantations (Table 34) showed marginal difference between the stump and root trainer grown plantations though the stump grown plantation had an upper edge. However, with advancing age, in the seven-year-old plantations (Table 35) the differences were significant with stump grown plantations showing significantly higher soil N content as compared to root trainer grown plantations for the first three layers of soil (0-20 cm, 20-40 cm and 40-60 cm). For instance, the nitrogen content for stump grown plantations were 0.22 %, 0.17 % and 0.12 % respectively while the corresponding values for the root trainer grown plantation were 0.18 %, 0.11 % and 0.08 % respectively. The corresponding total N content considering all the five soil layers were also significantly higher in the stump grown plantations compared with root trainer. In general the N content was lower in the tree less control plots for both five year and seven-year-old teak plantations with marked difference for seven-year-old stump grown plantations. Attempt to compare the effect of spacing on soil N status in five-year-old teak plantation

(Table 36) showed poor correspondence between the plantations established at 3x3 m and 2x2 m spacing except for the mid soil depths (40-60 cm and 60-80 cm).

Table 34. Soil total nitrogen of five-year-old plantations established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil total nitrogen (%) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 0.17 | 0.14 | 0.10 | 0.1 | 0.08 | 0.59 |
| Root trainer | 0.16 | 0.12 | 0.11 | 0.09 | 0.08 | 0.56 |
| Control | 0.14 | 0.11 | 0.10 | 0.06 | 0.03 | 0.44 |
| p- value | $0.082^{ns}$ | $0.144^{ns}$ | $0.803^{ns}$ | $0.300^{ns}$ | $0.351^{ns}$ | $0.735^{ns}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 35. Soil total nitrogen of seven-year-old plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil total nitrogen (%) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | $0.22^a$ | $0.17^a$ | $0.12^a$ | $0.11^a$ | $0.08^a$ | $0.70^a$ |
| Root trainer | $0.18^b$ | $0.11^b$ | $0.08^b$ | $0.06^b$ | $0.04^b$ | $0.47^b$ |
| Control | $0.15^b$ | $0.10^b$ | $0.07^b$ | $0.06^b$ | $0.01^b$ | $0.39^b$ |
| p- value | $0.005^*$ | $< 0.001^{**}$ | $0.002^*$ | $< 0.001^{**}$ | $0.002^*$ | $0.004^*$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 36. Soil total nitrogen of five-year-old plantations established by root trainer grown teak in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil total nitrogen (%) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| 3x3 m | 0.16 | 0.12 | 0.11 | 0.09 | 0.08 | 0.56 |
| Control 1 | 0.14 | 0.11 | 0.10 | 0.06 | 0.03 | 0.44 |
| 2x2 m | 0.13 | 0.09 | 0.06 | 0.05 | 0.04 | 0.37 |
| Control 2 | 0.10 | 0.07 | 0.04 | 0.03 | 0.01 | 0.25 |
| $p_1$- value | $0.094^{ns}$ | $0.149^{ns}$ | $0.024^*$ | $0.024^*$ | $0.387^{ns}$ | $0.069^{ns}$ |
| $p_2$- value | $0.163^{ns}$ | $0.821^{ns}$ | $0.597^{ns}$ | $0.039^*$ | $0.147^{ns}$ | $0.977^{ns}$ |
| $p_3$- value | $0.025^*$ | $0.107^{ns}$ | $0.107^{ns}$ | $0.016^*$ | $0.260^{ns}$ | $0.175^{ns}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing

$p_2$- p value for comparison between 3x3 m spacing and its control

$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.5. Soil phosphorus*

Efforts were made to analyze the available P in the soil for all the teak plantation treatments. However, their content in the soil was considerably lower for making effective comparisons. Hence, the total P content was estimated and the results are furnished in Tables 37, 38 and 39. The P content showed only marginal difference between the soil taken from the five-year-old stump and root trainer grown plantations (Table 37) except for mid soil depth (40-60 cm). Contrary to the N content, the P content in the soil was higher in the root trainer based teak plantations as compared to stump grown plantations though the differences were at par. Interestingly, the total P content (for 100 cm soil depth) for the treeless open control showed marginally higher values as compared to stump while it was faintly lower than root trainer plantations. The seven-year-old plantations (Table 38) showed similar trend in soil P content. Invariably the root trainer showed better soil P for all soil depths though the differences were significant neither with stump nor with the treeless control. Tree spacing comparisons between 3x3 m and 2x2 m for five-year-old stand (Table 39) suggested that P content in the soil was higher for 3x3 m spacing for all the soil depths, though the differences were statistically non-significant except for the mid soil layer (40-60 cm). Also both the spacing treatment showed higher soil P content compared with their respective treeless control plot.

Table 37. Soil total phosphorus of five-year-old plantations established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil total phosphorus (kg ha$^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 2850.40 | 2906.40 | 2292.27$^{b}$ | 3128.53 | 3904.13 | 15081.73 |
| Root trainer | 4512.67 | 3934.93 | 4094.53$^{a}$ | 3828.53 | 4562.13 | 20932.8 |
| Control | 3880.80 | 4020.80 | 3836$^{b}$ | 3788.4 | 4088 | 19614 |
| p- value | 0.150$^{ns}$ | 0.166$^{ns}$ | 0.042$^{*}$ | 0.794$^{ns}$ | 0.921$^{ns}$ | 0.380$^{ns}$ |

ns: non- significant; * significant at 5% level

Table 38. Soil total phosphorus for seven- year- old teak plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil total phosphorus (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 3704.4 | 4081.47 | 2818.67 | 3735.2 | 4127.2 | 18466.93 |
| Root trainer | 4882.27 | 4904.67 | 4942.93 | 4629.33 | 5067.07 | 24426.27 |
| Control | 5174.4 | 5266.8 | 4734.8 | 3950.8 | 4874.8 | 24001.6 |
| p- value | $0.304^{ns}$ | $0.412^{ns}$ | $0.090^{ns}$ | $0.269^{ns}$ | $0.475^{ns}$ | $0.204^{ns}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 39. Soil total phosphorus of five-year-old plantations established by root trainers in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil total phosphorus (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| 3x3 m | 4512.67 | 3934.93 | 4094.53 | 3828.53 | 4562.13 | 20932.8 |
| Control 1 | 3880.8 | 4020.8 | 3836 | 3788.4 | 4088 | 19614 |
| 2x2 m | 2270.8 | 2315.6 | 1834.93 | 2346.4 | 2563.87 | 11331.6 |
| Control 2 | 1618.4 | 1618.4 | 1876 | 2569.28 | 1608.32 | 9290.4 |
| $p_1$- value | $0.066^{ns}$ | $0.069^{ns}$ | $< 0.001^{**}$ | $0.205^{ns}$ | $0.253^{ns}$ | $0.055^{ns}$ |
| $p_2$- value | $0.514^{ns}$ | $0.892^{ns}$ | $0.204^{ns}$ | $0.969^{ns}$ | $0.764^{ns}$ | $0.726^{ns}$ |
| $p_3$- value | $0.021^{*}$ | $0.064^{ns}$ | $0.728^{ns}$ | $0.005^{*}$ | $0.023^{*}$ | $0.046^{*}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.7. Soil exchangeable potassium*

The soil exchangeable K changes in five-year-old teak plantations raised from variable planting stocks showed divergent trends (Table 40). The stump grown plantations showed higher exchangeable K content as compared to root trainer grown teak stands in spite of their lower statistical significance except the mid soil layer (40-60 cm) where the root trainer based plantation soil showed higher K content. Interestingly the total exchangeable K content was the highest in the treeless control plots as compared to root trainer and stump grown teak stands, though the differences were non-significant. For instance, the maximum total soil exchangeable soil K was for treeless open soil (451.92 kg $ha^{-1}$) followed by stump (413.77 kg $ha^{-1}$) and the lowest was for root trainer (406.97 kg $ha^{-1}$) grown teak stands.

At seven-years of growth, the trends were found varying with the soil exchangeable potassium showing higher values for the root trainer grown teak plantations as compared to stump gown plantations of same age (Table 41). However, the differences were not appreciable statistically. Invariably both the plantations registered higher K content as compared to treeless open though the differences were at par except for 20-40 cm soil depth. The total exchangeable K content (100 cm soil depth) was in the order; highest for root trainer (701.56 kg $ha^{-1}$) followed by stump (632.42 kg $ha^{-1}$) and the lowest for open treeless control soil (527.86 kg $ha^{-1}$).

Comparison of the teak trees at 2x2 m and 3x3 m spacing for total exchangeable K (at 100 cm soil depth) at five-years of tree growth showed higher content associated with 2x2 m stands (602.71 kg $ha^{-1}$; p=0.025) as compared to 3x3 m spaced plots (406.97 kg $ha^{-1}$) (Table 37). Treeless control recorded significantly lower value for all the soil depths for stands at 2x2 m spacing. However inverse trend was observed for 3x3 m spaced stands with higher K values attached to treeless open soil despite their lower statistical significance.

Table 40. Soil exchangeable potassium of five-year-old plantations established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil exchangeable potassium (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 123.18 | 89.87 | $61.62^a$ | 70.37 | 68.73 | 413.77 |
| Root trainer | 101.97 | 84.56 | $77.57^b$ | 78.36 | 64.51 | 406.97 |
| Control | 96.21 | 111.89 | $75.49^b$ | 81.31 | 87.02 | 451.92 |
| p- value | $0.180^{ns}$ | $0.099^{ns}$ | $0.044^*$ | $0.706^{ns}$ | $0.089^{ns}$ | $0.129^{ns}$ |

* significant at 5% level; ** significant at 1% level

Table 41. Soil exchangeable potassium of seven-year-old plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil exchangeable potassium (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 177.37 | $121.50^{ab}$ | 113.36 | 114.69 | 105.50 | 632.42 |
| Root trainer | 181.65 | $158.75^{a}$ | 137.28 | 114.16 | 109.72 | 701.56 |
| Control | 144.82 | $101.14^{b}$ | 100.02 | 96.54 | 85.34 | 527.86 |
| p- value | $0.057^{ns}$ | $0.014^{*}$ | $0.075^{ns}$ | $0.507^{ns}$ | $0.431^{ns}$ | $0.652^{ns}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 42. Soil exchangeable potassium of five-year-old plantations established by root trainers in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil exchangeable potassium (kg $ha^{-1}$) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| 3x3 m | 101.97 | 84.56 | 77.57 | 78.36 | 64.51 | 406.97 |
| Control 1 | 96.21 | 111.89 | 75.49 | 81.31 | 87.02 | 451.92 |
| 2x2 m | 137.59 | 137.37 | 116.78 | 106.44 | 104.53 | 602.71 |
| Control 2 | 54.32 | 35.39 | 31.70 | 39.42 | 50.51 | 211.34 |
| $p_1$- value | $0.142^{ns}$ | $0.053^{ns}$ | $0.076^{ns}$ | $0.178^{ns}$ | $0.033^{*}$ | $0.025^{*}$ |
| $p_2$- value | $0.370^{ns}$ | $0.001^{*}$ | $0.764^{ns}$ | $0.860^{ns}$ | $0.004^{*}$ | $0.078^{ns}$ |
| $p_3$- value | $0.002^{*}$ | $0.001^{*}$ | $< 0.001^{**}$ | $0.001^{*}$ | $0.010^{*}$ | $< 0.001^{**}$ |

* significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

#### *4.2.2.8. Exchangeable calcium*

The exchangeable calcium content in the five-year-old teak plantations (Table 43) in general showed marginal variation among the various planting stocks. The total soil calcium content (sum of all the five layers) was higher for the stump grown plantation (5.11 m.eq per 100g) than the root trainer raised plantations (4.50 m.eq per 100g). Interestingly the treeless control showed highest total Ca content (5.85 m.eq per 100g). The teak plantations at seven-years age (Table 44) however showed a variable trend with higher total Ca stock attached to root trainer grown plantations (6.44 m.eq per 100g) as compared to stump (5.50 m.eq per 100g). Invariably the treeless control registered lower values of Ca content as compared to both the plantation soils despite their lower levels of significances. There observed only feeble response to soil Ca content across the 2x2 and 3x3 m plantations at 5-years of age (Table 45) despite a marginal higher value for 3x3 m spacing. Again, the respective treeless control plots showed significant increase in total Ca content compared to teak stands at 2x2 m and 3x3 m spacing.

Table 43. Soil exchangeable calcium of five-year-old plantations established by stump and root trainers at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil exchangeable calcium (m.eq per 100g) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 0.87 | 0.73 | $0.86^{a}$ | 1.28 | 1.37 | $5.11^{ab}$ |
| Root trainer | 1 | 0.76 | $0.84^{a}$ | 0.85 | 1.05 | $4.5^{b}$ |
| Control | 1.1 | 0.75 | $1.2^{b}$ | 1.4 | 1.4 | $5.85^{a}$ |
| p- value | $0.246^{ns}$ | $0.943^{ns}$ | $0.004^{*}$ | $0.482^{ns}$ | $0.433^{ns}$ | $0.001^{*}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 44. Soil exchangeable calcium of seven-year-old plantations established by stump and root trainers at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Soil exchangeable calcium (m.eq per 100g) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| Stump | 1.45 | 0.87 | $1.13^{b}$ | 1 | 1.05 | 5.5 |
| Root trainer | 1.63 | 0.98 | $1.41^{a}$ | 1.32 | 1.1 | 6.44 |
| Control | 1.25 | 1 | $0.7^{b}$ | 0.95 | 1.1 | 5.00 |
| p- value | $0.607^{ns}$ | $0.645^{ns}$ | $0.012^{*}$ | $0.656^{ns}$ | $0.972^{ns}$ | $0.550^{ns}$ |

ns: non- significant; * significant at 5% level ; ** significant at 1% level

Table 45. Soil exchangeable calcium of five-year-old plantations established by root trainer grown teak in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Soil exchangeable calcium (m.eq per 100g) | | | | | |
|---|---|---|---|---|---|---|
| | Soil depth (cm) | | | | | |
| | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 | Total |
| 3x3 m | 1 | 0.76 | 0.84 | 0.85 | 1.05 | 4.5 |
| Control 1 | 1.1 | 0.75 | 1.2 | 1.4 | 1.4 | 5.85 |
| 2x2 m | 1.03 | 0.73 | 0.89 | 0.77 | 0.7 | 4.12 |
| Control 2 | 1.25 | 1.2 | 0.9 | 0.9 | 1.05 | 5.3 |
| $p_1$- value | $0.871^{ns}$ | $0.850^{ns}$ | $0.655^{ns}$ | $0.776^{ns}$ | $0.053^{ns}$ | $0.880^{ns}$ |
| $p_2$- value | $0.484^{ns}$ | $0.932^{ns}$ | $< 0.001^{**}$ | $0.001^{*}$ | $0.028^{*}$ | $< 0.001^{**}$ |
| $p_3$- value | $0.031^{*}$ | $0.002^{*}$ | $0.958^{ns}$ | $0.645^{ns}$ | $0.010^{*}$ | $< 0.001^{**}$ |

ns: non- significant; * significant at 5% level; ** significant at 1% level

$p_1$- p-value for comparison between 3x3 m and 2x2 m spacing
$p_2$- p value for comparison between 3x3 m spacing and its control
$p_3$- p value for comparison between 2x2 m spacing and its control

## 4.3. ROOT DISTRIBUTION PATTERN

The root distribution pattern in various teak plantations were analyzed by spiral trenching technique. The root count was observed and converted into root intensity (number $m^{-2}$). Separate counts for each categories of root diameter size (<2 mm, 2 mm-5mm and > 5mm) were analyzed and the salient findings are given below.

### 4.3.1. Root intensity

The total root intensity was highly influenced by the type of planting materials used for raising plantations. In general, the root trainer grown stands showed higher root intensity for all the lateral distances at five year stand age compared to those raised using stump (Table 46). Also a consistent decline in root intensity was observed with increase in lateral distance from the tree. The highest root intensity was observed near to the tree base for both the plantations (2750 and 3205 number per $m^2$ for stump and root trainer respectively at 0.35m lateral distance). The corresponding values at farthest lateral distance (2.35m) were 900 and 1355 number per $m^2$ for stump and root trainer respectively. Teak at seven year of stand age also showed similar trends with higher root intensity attached to root trainer grown stands (Table 47). The corresponding root counts were higher at seven year stands for both stump and root trainer though the increase was appreciable in the root trainer based teak stands. In general the seven-year-old stand showed higher lateral root spread up to 3.5m from the tree base for root trainer grown trees while the lateral spread was limited to 2.5m from the tree base for stump grown stands. The respective root intensity closer to the tree base (0.6 m) was 2746 for stump and 3415 number per $m^2$ for root trainer. However, roots were absent at farthest lateral distance (3.5m from tree base) for stump while the root trainer trees showed fair root intensity (345 number per $m^2$) at the same lateral distance.

Comparison of root intensity as function of tree spacing showed an initial high value for 2x2 m spaced stands up to 0.75 m lateral distance which however showed a different trend thereafter with higher root intensity in the widely spaced (3x3 m) stands compared to 2x2 m spaced stands with increasing lateral distance (Table 48). For instance, at farthest lateral distance (2.35 m) the root count was highest for 3x3 m spacing (1355 number per $m^2$) while corresponding root count at 2x2 m spacing was only 460 number per $m^2$.

Table 46. Total root intensity of five-year-old teak plantations (upto 50 cm soil depth) established by stump and root trainer at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting technique | Total root intensity (number per $m^2$) | | | |
|---|---|---|---|---|
| | Distance from the base of the tree (m) | | | |
| | 0.35 | 0.75 | 1.55 | 2.35 |
| Stump | 2750 | 1510 | 1065 | 900 |
| Root trainer | 3205 | 1970 | 1965 | 1355 |

Table 47. Total root intensity of seven-year-old teak plantations (upto 50 cm soil depth) established by stump and root trainer at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

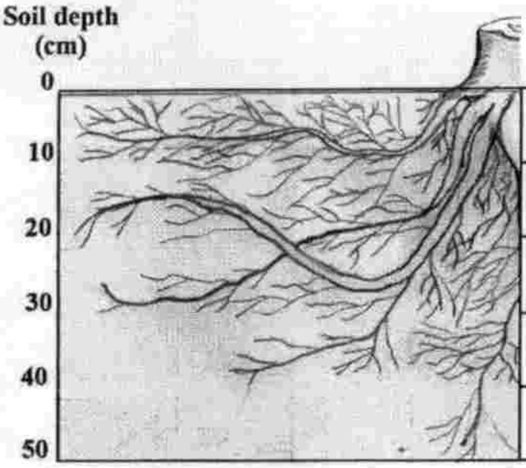
| Planting technique | Total root intensity (number per $m^2$) | | | | |
|---|---|---|---|---|---|
| | Distance from the base of the tree (m) | | | | |
| | 0.6 | 1.05 | 1.60 | 2.5 | 3.5 |
| Stump | 2746 | 1750 | 2020 | 855 | - |
| Root trainer | 3415 | 2520 | 1880 | 1230 | 345 |

Table 48. Total root intensity of five-year-old teak plantations (upto 50 cm soil depth) established by root trainer in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Planting spacing | Total root intensity (number per $m^2$) | | | |
|---|---|---|---|---|
| | Distance from the base of the tree (m) | | | |
| | 0.35 | 0.75 | 1.55 | 2.35 |
| 3x3 m | 3205 | 1970 | 1965 | 1355 |
| 2x2 m | 4035 | 2155 | 1065 | 460 |

Table s 49-51 represent the root distribution for various root size classes across lateral distances and soil depths for various teak plantations. In general, the differential size class wise root intensity showed consistent decline with increasing lateral distance and soil depth for both root trainer and stump grown teak plantations of five-years of age (Table 49). As observed before, all the root size classes in general showed higher root intensity attached with root trainer stands. However, the lowest root diameter class (<2 mm) showed marginally higher root count especially at proximal lateral distances up to 0.75 m from the tree base and shallow soil depths (up to 0-20 cm). For instance, the root intensities at 0-10 cm soil depth and 0.35m lateral distance were 855 and 700 number per $m^2$ for stump and root trainer respectively. However with increasing lateral distance and soil depth there was a shift in root distribution pattern with higher intensity for root trainer grown trees. For example, at farthest lateral distance (2.35 m) the respective root counts were 390 and 400 number per $m^2$ for stump and root trainer respectively at 0-10 cm soil depth. With increase in soil depth at this lateral distance there was substantial decline in root count in the stump grown stands with no count at 30-40 and 40-50 cm soil depths. However, the root trainer grown stands exhibited fair number of root counts (130 and 110) at these respective soil depths.

The percentage contribution to the total root intensity for root class <2 mm in the shallow soil depths (1-20 cm) were 61% and 52% for stump and root trainer respectively for the nearest lateral distance from the tree (0.35 m) and the same for the farthest distance were 93% and 59% for stump and root trainer grown plants. These indicated that in stump grown trees the major portion of the root concentrated in the top layers, whereas in root trainer about half of the root distributed to the deeper layers. There was an overall decline in root intensity with increase in root size class. The higher root size classes also showed a better spread attached with root trainer grown stands. For instance the root counts for 2-5 mm root size at proximal lateral distance (0.35m) was higher for all the soil depths compared to stump grown trees. The respective counts at 50 cm soil depth were 255 and 515 number per $m^2$ for stump and root trainer respectively. Similar observation was observed at 1.55 m lateral distance from the tree with stump and root trainers showing root count of 55 and 155 number per $m^2$ respectively. The higher root size class (>1.0 cm) showed markedly lower counts for stump grown trees with increasing lateral distance and soil depth. For instance, the higher sized root representatives were very less or almost absent in the lateral distance above 0.75 m for stump grown trees. However, good number of larger roots was found in the root trainer based trees even at farther distance and deeper soil depth.

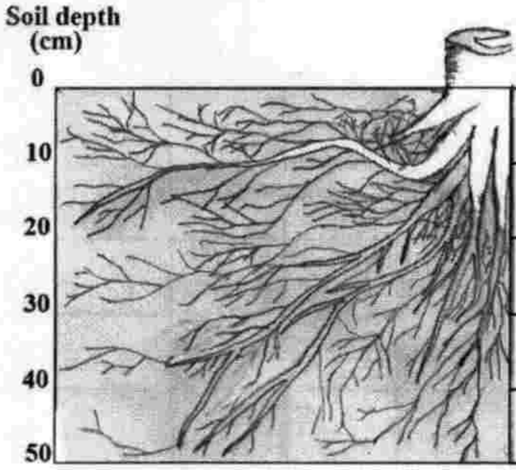



Mean root intensity (%)

| Soil depth (cm) | 0.35 | 0.75 | 1.55 | 2.35 |
|---|---|---|---|---|
| 10 | 15.53 | 9.33 | 7.24 | 7.40 |
| 20 | 11.26 | 7.72 | 6.11 | 5.71 |
| 30 | 7.16 | 5.47 | 3.22 | 1.37 |
| 40 | 7.56 | 1.77 | 0.56 | 0.00 |
| 50 | 2.57 | 0.00 | 0.00 | 0.00 |

**Lateral distance (m) from tree base**

Fig 1. Schematic representation of root distribution pattern of stump grown teak tree at 3x3 m spacing at five-years of age in Karakkad, Kalady range, Malayattoor Forest division, Kerala.




Mean root intensity (%)

| Soil depth (cm) | 0.35 | 0.75 | 1.55 | 2.35 |
|---|---|---|---|---|
| 10 | 10.22 | 6.28 | 6.05 | 5.05 |
| 20 | 8.51 | 5.52 | 4.93 | 4.23 |
| 30 | 8.16 | 3.88 | 5.11 | 3.52 |
| 40 | 7.63 | 4.87 | 4.17 | 1.76 |
| 50 | 3.23 | 2.58 | 2.82 | 1.47 |

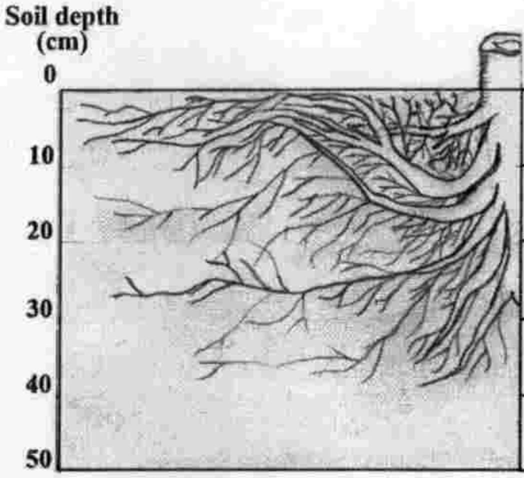
**Lateral distance (m) from tree base**

Fig 2. Schematic representation of root distribution pattern of root trainer grown teak tree at 3x3 m spacing at five-years of age in Karakkad, Kalady range, Malayattoor Forest division, Kerala.

The trends in root distribution were almost similar in teak plantations at seven-year-age also (Table 50). The consistent reduction in root count with increasing lateral distance and soil depth were obvious for 7 year stands also.

Also the general decline in root count with increase in lateral distance and soil depth were obvious for stump grown trees compared to root trainer grown trees except at 1.6m lateral distance. The total root counts (<2 mm root size class) at 50 cm soil depth for various lateral distances viz. 0.6 m, 1.05 m, 1.60 m, 2.5m and 3.5 m were 2845, 2080, 1588, 1025, 345 number per $m^2$ for root trainer grown teak trees while the corresponding values were 2310, 1515, 1910, 750 number per $m^2$ and nil for stump grown trees. The percentage root intensity of total root count for lesser roots (<2 mm) showed higher in the stump grown trees as compared to the root trainer grown trees for the shallow soil depth (0-20 cm). For example, percent root intensity at the proximal lateral distance from the tree base (0.6 m) were 62% and 53% of total root count and 85% and 81% for the lateral distance of 2.5 m. Roots representing mid-size class (2-5 mm) also showed similar trends as that of <2 mm size class. Maintenance of fair number of roots (2-5 mm size) in the farther distance is observable for root trainer grown tree while their corresponding representation was very much poor for stump grown trees. The roots at higher size class (>1.0 cm) also showed similar trends despite their lower number compared to root at lower size classes.

Attempts were also made to study the changes in root distribution patterns with changes in tree spacing for 5 year old teak stands (Table 51). In general the widely spaced stands (3x3 m) showed better root spread as compared to stands at closer spacing (2x2 m). However there were appreciable changes in root intensity with increasing lateral distance. For instance, the lower size class showed higher rooting intensity at proximal distances (up to 1.50 m) and at shallow depths (up to 0-20 cm) for 2x2 m spacing while a gradual improvement in root count was observed for root trainer with increase in lateral distance and soil depth. At 0.35m lateral distance the root count corresponding to 0-10 cm soil depths were 700 and 1215 number per $m^2$ for 3x3 m and 2x2 m spacing respectively which represented




**Mean root intensity (%)**

| Soil depth (cm) | 0.35 | 0.75 | 1.55 | 2.35 |
|---|---|---|---|---|
| 0-10 | 21.72 | 14.04 | 8.13 | 4.16 |
| 10-20 | 13.85 | 9.69 | 3.45 | 1.04 |
| 20-30 | 9.10 | 3.71 | 1.76 | 0.78 |
| 30-40 | 4.23 | 0.59 | 0.52 | 0.00 |
| 40-50 | 3.25 | 0.00 | 0.00 | 0.00 |

**Lateral distance (m) from tree base**

Fig 3. Schematic representation of root distribution pattern of root trainer grown teak tree at 2x2 m spacing at five-years of age in Karakkad, Kalady range, Malayattoor Forest division, Kerala.

29% and 40% of their total counts at 50 cm soil depth. However, 2x2 m spaced trees showed drastic reduction with advancing lateral distance at 0-10 cm soil depth. For example, the root count for 3x3 m spacing at farthest lateral distance was 400 number per $m^2$ which was 31% of the total root count at that lateral distance while the corresponding root counts for 2x2 m spacing was 245 number per $m^2$ which was 66% of the total root count at farthest lateral distance. With increasing soil depth at farther lateral distances there is clearly higher root counts at 3x3 m spacing compared to 2x2 m spacing. The mid-size class (2-5 mm) also followed more or less similar trend as that of small sized roots. However the shallow depth of 0-10 cm maintained higher root count for 2x2 m spacing for all lateral distances compared to 3x3 m. However this trend changed with increasing soil depth with 3x3 m spacing dominating in root intensity subsequently. The deeper soil layers from 20 cm down showed characteristically lower root count for 2x2 m spaced trees with advancing lateral distance from the tree base. An overall reduction in the number of larger roots (>1.0 cm) compared to small and medium size classes was observed from the study. The larger root size category also showed appreciably lower root count for 2x2 m spaced trees as compared to teak trees at 3x3 m spacing. The larger roots had no representative counts in any of the depth intervals at farther distances such as 1.55 and 2.35 m for 2x2 m spaced teak trees.

Table 49. Root density of stump and root trainer grown five-year-old teak plantation established at 3x3 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Root intensity (number per $m^2$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Stump | Root trainer | Stump | Root trainer | Stump | Root trainer | Stump | Root trainer |
| Soil depth (cm) | Distance from the base of the tree (m) | | | | | | | |
| | 0.35 | | 0.75 | | 1.55 | | 2.35 | |
| | <2 mm | | | | | | | |
| 0-10 | 855 | 700 | 510 | 455 | 415 | 475 | 390 | 400 |
| 10-20 | 610 | 555 | 435 | 410 | 365 | 380 | 345 | 340 |
| 20-30 | 410 | 485 | 315 | 275 | 185 | 365 | 55 | 280 |
| 30-40 | 380 | 470 | 95 | 360 | 30 | 295 | - | 130 |
| 40-50 | 155 | 195 | - | 170 | - | 160 | - | 110 |
| Total | 2410 | 2405 | 1355 | 1670 | 995 | 1675 | 790 | 1260 |
| | 2 mm-5 mm | | | | | | | |
| 0-10 | 80 | 110 | 50 | 55 | 30 | 25 | 55 | 5 |
| 10-20 | 75 | 105 | 30 | 30 | 10 | 25 | 10 | 15 |
| 20-30 | 30 | 115 | 15 | 25 | 10 | 35 | 20 | 10 |
| 30-40 | 65 | 130 | 10 | 30 | 5 | 35 | - | 10 |
| 40-50 | 5 | 55 | - | 35 | - | 35 | - | 5 |
| Total | 255 | 515 | 105 | 175 | 55 | 155 | 85 | 45 |
| | >5 mm | | | | | | | |
| 0-10 | 30 | 50 | 20 | 25 | 5 | 15 | 15 | 15 |
| 10-20 | 15 | 65 | 15 | 30 | 5 | 15 | - | 5 |
| 20-30 | 15 | 95 | 10 | 30 | 5 | 35 | 10 | 10 |
| 30-40 | 25 | 50 | 5 | 25 | - | 25 | - | 10 |
| 40-50 | 0 | 25 | - | 15 | - | 45 | - | 10 |
| Total | 85 | 285 | 50 | 125 | 15 | 135 | 25 | 30 |
| | >1 cm | | | | | | | |
| 0-10 | 20 | - | - | 5 | - | - | - | |
| 10-20 | 15 | 25 | - | - | 5 | - | - | 5 |
| 20-30 | 5 | 35 | 5 | 20 | - | - | - | |
| 30-40 | - | 10 | - | 5 | - | 5 | - | |
| 40-50 | - | - | - | - | - | 15 | - | |
| Total | 40 | 70 | 5 | 30 | 5 | 20 | - | 5 |

Table 50. Root density of stump and root trainer grown seven-year-old teak plantation established at 2x2 m spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Root intensity (number per $m^2$) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Stump | Root trainer | Stump | Root trainer | Stump | Root trainer | Stump | Root trainer | Stump | Root trainer |
| Soil depth (cm) | Distance from the base of the tree (m) | | | | | | | | | |
| | 0.6 | | 1.05 | | 1.60 | | 2.5 | | 3.5 | |
| | <2 mm | | | | | | | | | |
| 0-10 | 715 | 895 | 475 | 565 | 575 | 645 | 375 | 575 | - | 225 |
| 10-20 | 740 | 630 | 520 | 670 | 675 | 425 | 265 | 260 | - | 85 |
| 20-30 | 440 | 600 | 365 | 410 | 410 | 255 | 70 | 130 | - | 20 |
| 30-40 | 305 | 470 | 105 | 325 | 205 | 180 | 40 | 55 | - | 15 |
| 40-50 | 110 | 250 | 50 | 110 | 45 | 80 | - | 5 | - | - |
| Total | 2310 | 2845 | 1515 | 2080 | 1910 | 1585 | 750 | 1025 | - | 345 |
| 2 mm-5 mm | | | | | | | | | | |
| 0-10 | 110 | 85 | 40 | 30 | 10 | 85 | - | 95 | - | - |
| 10-20 | 50 | 75 | 35 | 105 | 20 | 70 | 20 | 35 | - | - |
| 20-30 | 50 | 30 | 30 | 70 | 20 | 10 | 30 | 5 | - | - |
| 30-40 | 30 | 25 | 20 | 35 | 15 | 10 | - | - | - | - |
| 40-50 | - | 30 | - | - | - | 15 | - | - | - | - |
| Total | 240 | 245 | 125 | 240 | 65 | 190 | 50 | 135 | - | - |
| >5 mm | | | | | | | | | | |
| 0-10 | 55 | 90 | 35 | 25 | 10 | 40 | 0 | 35 | - | - |
| 10-20 | 35 | 120 | 30 | 75 | 5 | 50 | 20 | 30 | - | - |
| 20-30 | 41 | 45 | 25 | 65 | 15 | 5 | 35 | 5 | - | - |
| 30-40 | 65 | 15 | 20 | 30 | 15 | 10 | - | - | - | - |
| 40-50 | - | 55 | - | 5 | - | - | - | - | - | - |
| Total | 196 | 325 | 110 | 200 | 45 | 105 | 55 | 70 | - | - |
| >1 cm | | | | | | | | | | |
| 0-10 | - | 25 | - | - | - | 5 | - | - | - | - |
| 10-20 | 5 | 40 | 5 | - | - | - | - | 5 | - | - |
| 20-30 | 15 | 5 | 5 | 15 | - | - | - | - | - | - |
| 30-40 | 5 | 5 | - | - | - | 5 | - | - | - | - |
| 40-50 | - | 5 | - | 5 | - | - | - | - | - | - |
| Total | 20 | 80 | 10 | 20 | - | 10 | - | 5 | - | - |

Table 51. Root density of five-year-old teak plantations established by root trainer grown teak in variable spacing at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

| Root intensity (number per m²) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 3x3 m | 2x2 m | 3x3 m | 2x2 m | 3x3 m | 2x2 m | 3x3 m | 2x2 m |
| Soil depth (cm) | Distance from the base of the tree (m) | | | | | | | |
| | 0.35 | | 0.75 | | 1.55 | | 2.35 | |
| | <2 mm | | | | | | | |
| 0-10 | 700 | 1215 | 455 | 840 | 475 | 540 | 400 | 245 |
| 10-20 | 555 | 820 | 410 | 655 | 380 | 230 | 340 | 70 |
| 20-30 | 485 | 560 | 275 | 235 | 365 | 135 | 280 | 55 |
| 30-40 | 470 | 265 | 360 | 40 | 295 | 40 | 130 | - |
| 40-50 | 195 | 205 | 170 | - | 160 | - | 110 | - |
| Total | 2405 | 3065 | 1670 | 1770 | 1675 | 945 | 1260 | 370 |
| 2 mm-5 mm | | | | | | | | |
| 0-10 | 110 | 320 | 55 | 155 | 25 | 65 | 5 | 45 |
| 10-20 | 105 | 160 | 30 | 55 | 25 | 25 | 15 | 10 |
| 20-30 | 115 | 95 | 25 | 40 | 35 | - | 10 | 5 |
| 30-40 | 130 | 35 | 30 | 5 | 35 | - | 10 | - |
| 40-50 | 55 | 35 | 35 | - | 35 | - | 5 | - |
| Total | 515 | 645 | 175 | 255 | 155 | 90 | 45 | 60 |
| >5 mm | | | | | | | | |
| 0-10 | 50 | 135 | 25 | 85 | 15 | 20 | 15 | 30 |
| 10-20 | 65 | 85 | 30 | 35 | 15 | 10 | 5 | - |
| 20-30 | 95 | 45 | 30 | 10 | 35 | - | 10 | - |
| 30-40 | 50 | 25 | 25 | - | 25 | - | 10 | - |
| 40-50 | 25 | 10 | 15 | - | 45 | - | 10 | - |
| Total | 285 | 300 | 125 | 130 | 135 | 30 | 50 | 30 |
| >1 cm | | | | | | | | |
| 0-10 | - | - | 5 | 20 | - | - | - | - |
| 10-20 | 25 | 30 | - | 5 | - | - | 5 | - |
| 20-30 | 35 | 10 | 20 | - | - | - | - | - |
| 30-40 | 10 | 10 | 5 | - | 5 | - | - | - |
| 40-50 | - | - | - | - | 15 | - | - | - |
| Total | 70 | 50 | 30 | 25 | 20 | - | 5 | - |

# *Discussion*

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# V. DISCUSSION

The previous chapter covered the results pertaining to the investigation on "Field evaluation of stump and root trainer grown teak (*Tectona grandis* L.f.) plantations" on growth attributes, soil characteristics and the root distribution pattern in the seven- and five-year-old plantations established by stump and root trainer at varying spacing. Also attempt was made to compare the growth performance of root trainer grown teak at variable spacing viz. 3x3 m and 2x2 m for five-year-old plantations. Scientific interpretations and managerial implications of the results are discussed below.

## 5.1. GROWTH ATTRIBUTES

In the present study the growth attributes such as total tree height, bole height, DBH, basal area, volume, crown diameter, survival percentage, LAI, persistence of stem axis and straightness of stem were investigated for stump and root trainer grown plantations.

### 5.1.1. Total tree height

The total tree height of teak trees were found to be significantly higher for the plantations established by root trainers for both five and seven-year-old stands (Table 2). This shows that type of planting material has prominent influence on the height growth of teak trees. For instance, the mean total tree height for five-year-old plantation was 6.28 m for root trainer grown plantation and 5.30 m for stump grown plantation. The seven-year-old plantation also showed similar trends, the corresponding values being 6.68 m and 5.87 m for root trainer and stump respectively. Many reports suggest such variation in height growth owing to differences in planting materials of teak (Rao *et al.* 2001; Gyi *et al.* 1983). A similar study for consecutive two years suggested root trainer grown planting stock had faster growth in terms of height (Khedkar, 1999). However, he reported an early faster growth for the stump origin plants as compared to root trainer origin at one month after planting (Khedkar and Subramainan, 1997).

Porapakkharm (1963) further reported that stumps with roots had better growth characters than stumps without roots. Differing observations on better seedling height growth for stump grown teak also have been reported (Subramanian and Jha, 1995). The nature of root development in stump and root trainer based teak is quiet variable. Stumps usually produce more of lateral fibrous roots in the absence of a distinct tap root system. Despite the proliferation in root at shallow depths, the sump grown seedlings often fail to explore deeper soil, leading to limitation in resource absorption especially at advanced growth phase. Instead, the root trainer grown seedlings maintain proper taproot system. This could be the reason for the better seedling height growth for root trainer teak seedlings.

Attempts to compare the effect of tree spacing on average height of root trainer grown stand showed non-significant differences between 3x3 m and 2x2 m spacing, with a marginal improvement in 2x2 m spacing (Table 3). This implies that tree growth of two year difference may not be sufficient enough to bring a marked variation in height growth under similar management regimes. Reports on a seven-year-old teak plantation from Nigeria suggested no significant effect of spacing on the average height and top height of the stands (Abegbeihn, 1982). The marginal improvement in height growth in 2x2 m spaced stands could be on account of the vertical competitive advantage in height growth for closely spaced stands (Kunhamu *et al.,* 2010; Kerr, 2003; Long and Smith, 1984). Similar observation has been reported in a study on the effect of spacing on the growth of teak at 18 years of age where increase in the spacing negatively affected the merchantable height and volume of trees (Ola-Adams, 1990). Reports suggested that variation in height due to spacing showed an initial improvement for narrow spaced stand, while as the stand mature, stand density has little effect on height growth (Domec *et al*., 2008; Henskens *et al*., 2001)

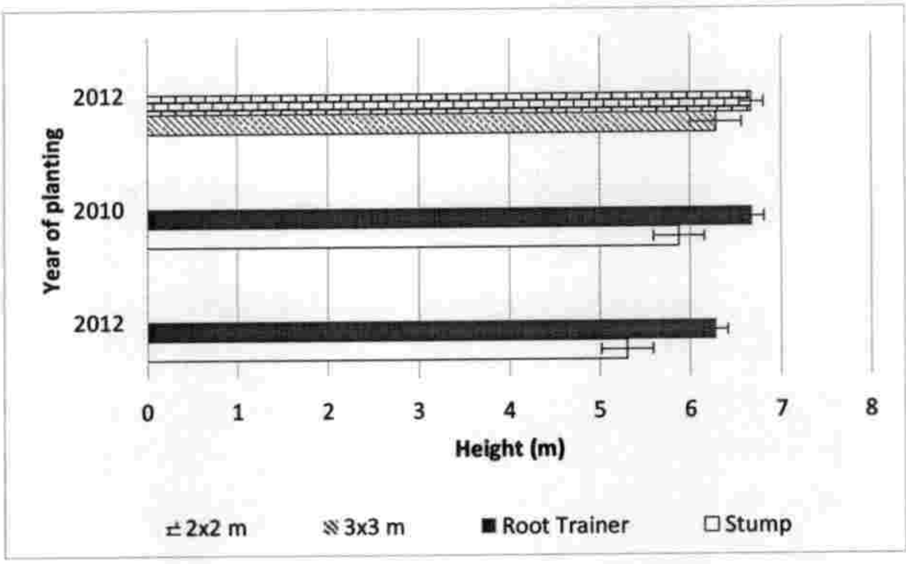


Fig 4. Mean tree height of teak plantations during first observation at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

### 5.1.2. Bole height

The mean bole height had significant variation between stump and root trainer in five-year-old plantations with root trainer plants showing better height growth. However, the trend was not observed for the stands at seven year of age (Table 4). Result suggested that the differences in bole height between the two planting materials get marginalized with advancement in stand age. Limited information is available on the bole height characteristics of stump and root trainer grown teak. However, available reports suggest considerable differences in seedling grown teak as compared to teak stands of clonal origin (Mitarini and Harahap, 1994). Influence of spacing on bole height showed marginal effect between 3x3 m and 2x2 m spaced plantations (Table 5). This also depicts the insensitivity to height growth between plantations at younger age despite the differences in their planting spacing. The implications of bole height growth may be more manifested at advanced age of crown differentiation for teak.

### 5.1.3. Diameter at breast height (DBH)

The average DBH of trees in the stump and root trainer grown plantation at the age of five-years were 6.95 cm and 7.96 cm respectively while the respective values were 8.32 and 9.04 cm respectively at the age of seven-years. The study showed higher diameter growth exhibited by the plantations established by root trainer compared with that from stump. Similar observations have been reported from other studies on teak (Rao *et al.*, 2001; Khedkar, 1999). Yet another study suggested better collar girth associated with root trainer grown plantation than that from stump (Khedkar and Subramanian, 1997). The higher diameter growth associated with root trainer grown teak may be attributed to their better root spread and relative advantage in the absorption of water and minerals. Such improvement in diameter growth has been observed for teak plantations of different ages (Kuerkool, 1965).

The effect of planting spacing on the radial growth of teak showed better performance for 3x3 m than 2x2 m both raised using root trainers (Table 7). Obviously trees at wider spacing show better extension of lateral branches and crown spread with a concomitant increase in radial growth (Goss, 2012; Hummel, 2000; Sibomana *et al.*, 1997; Ola-Adams, 1990; Abegbeihn, 1982). Hence, as tree planting density increases, greater competition is created among the plants resulting in trees with reduced diameter (Kruschewsky *et al.*, 2007; Leite *et al.*, 2006). Provision of wider spacing through planting density regulation or thinning has been a proven management strategy in improving the radial growth in forest plantations especially at younger age. Similar observation has been observed in the present teak stands at subsequent periods of observations (Table 6 and 7).

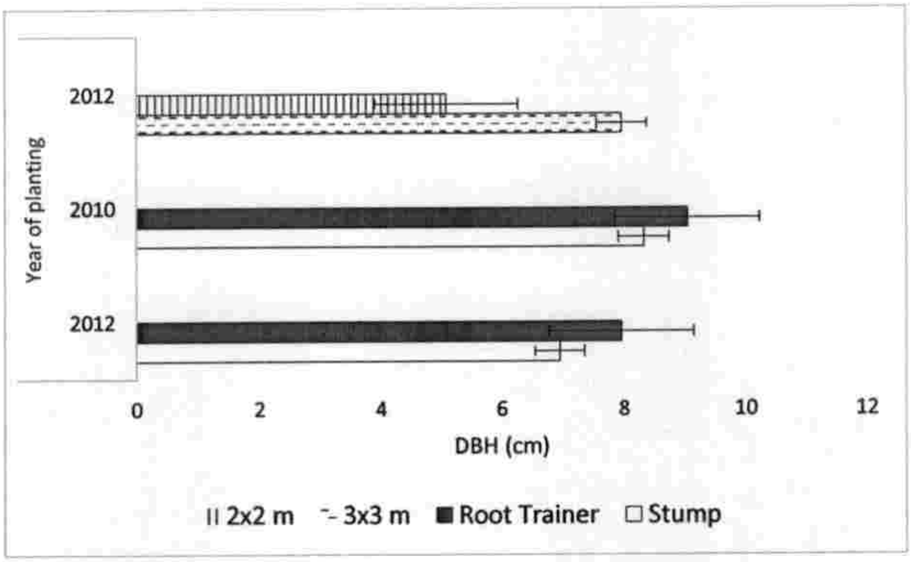


Fig 5. Mean tree DBH of teak plantations during first observation at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

### 5.1.4. Basal area

The mean tree basal area also was better in root trainer teak plantations especially at 5 years of age. However the trend found marginalized in the 7 year old stands (Table 8) though the overall trend was in favor of root trainers. The strong functionality between basal area and DBH could be the reason for the present trend. For instance, the root trainer teak trees had better diameter growth that reflected in their basal area also (Rao *et al.*, 2001; Khedkar, 1999). The impact of planting spacing on the basal area growth also was explicit in the present study with teak trees at wider spacing (3x3 m) having better basal area growth (50.60 $cm^2$) while the corresponding value for the closely spaced teak stands (2x2 m) were considerably lower (21.66 $cm^2$). This wide gap in BA could be primarily attributed to the multiplying effect of DBH differences when BA is assessed. For instance, the smaller differences in DBH for root trainer and stump grown teak was amplified when converted to basal area. The findings in general converge to the conclusion that root trainer trees might show better belowground resource acquisition owing to the competitive advantage contributed by their intact tap root system as compared to the stump grown teak trees.

The better BA performance of widely spaced teak stands compared to stands at closer spacing has been observed in the present study throughout the periods of observation. Aboveground growth often used to be a reflection of the efficiency with which belowground resources are assimilated. Widely spaced stands are usually at lesser competitive stress for resources as compared to closely spaced stands. Tree basal area usually follows a strong linearity with the crown spread which is quite evident in the present study. For example the widely spaced (3x3 m) teak stands had significantly higher BA and crown diameter as compared with trees at closer spacing. Such trends in BA growth have been reported by many workers (Piotto *et al.*, 2003; Schonau and Coetzee, 1989; Abegbeihn, 1982). However, few studies reported inverse trend with BA declining with increase in stand spacing for teak when observed at 18 years of stand age (Ola-Adams, 1990). Sibomana *et al.* (1997) also reported such negative correlation with spacing and basal area. Probably other managerial implications might be the reasons for such deviation from the usual trends.

As expected, the stand level basal area followed the same trend as that of mean tree basal area with conspicuous improvement for root trainer raised teak stands. In even spaced stands the stand basal area often reflects the cumulative effect of the individual tree basal areas. The average stand BA for the root trainer based stand at seven-years of age was 18.91 $m^2$ $ha^{-1}$. The explicit advantage of increase in radial growth for root trainer stands has been observed in the present study as well. The stand basal area is often cited as the strong index of stand productivity and hence the increase in basal area for root trainer origin stand clearly suggest it as the appropriate planting material for future planting programs for teak. The effect of tree spacing showed a reversal trend as compared to the mean tree basal area, with considerable improvement in the closer spaced stand than wider spaced stands. The stand basal area maintains a close functionality with the stand density for all even aged stands (Reukema, 1979). Despite the increase in mean tree basal area in the widely spaced stands, this trend has not been reflected in the case of stand basal area primarily because of the large difference in the number of trees in the two stands. For instance the 2x2 m stands represent 2500 trees $ha^{-1}$ while the 3x3 m stands have only 1111 trees $ha^{-1}$. Better trade off in stand basal area could be expected as the stands matures.

### 5.1.5. Volume

The mean tree volume showed significant difference between the plantations established with stump and root trainer at the age of five and seven-years. Obviously the root trainer grown stand showed higher mean volume than that of stump grown stand at both the ages. The better performance in the height and diameter has reflected in the better volume production for root trainer based stands. Implicit in the observation is that volume production being the most important growth parameter from commercial stand point, planting material selection has a prominent role on the productivity of teak. As observed earlier, the volume production also showed significantly higher value for 3x3 m spaced plantation than 2x2 m spaced plantations, implying the tree advantage in resource absorption at wider spacing (Ola-Adams, 1990). Such reports are in plenty in the production forestry sector (Sukanya, 2014; Magalhaes *et al*., 2007; Medhurst *et al*., 2003; Oliveira *et al*., 2000).

Stand volume also showed the similar result as compared with stand basal area (Table 14 and 15). The root trainer origin plantation showed significantly higher stand volume as compared to stump at five and seven-years of age. As observed in basal area stand volume also showed an inverse trend as compared to mean tree volume. The narrow spaced (2x2 m) stand showed higher stand volume than wider spaced (3x3 m) stand. Initial observation (September 2017) showed only a marginal improvement, while the difference became significant at the later periods of observations. The value obtained for stand volume was comparable with some other studies (Nunifu and Murchison, 1999). The stand volume also closely related with the stand density for all even aged stands (Reukema, 1979; Schonau and Coetzee, 1989). Despite the increase in mean tree volume in the widely spaced stands, this trend has not been reflected in the case of stand volume on account of the large difference in the number of trees in the two stands. For instance the 2x2 m stands represent 2500 trees $ha^{-1}$ while the 3x3 m stands have only 1111 trees $ha^{-1}$. The relative increase in mean tree volume in widely spaced stands may be reflected in the stand volume also at advanced growth of the teak stands (Schonau and Coetzee, 1989).

### 5.1.6. Crown diameter

Crown diameter showed poor response to the type of planting material used. It showed a marginally better response for root trainer grown plantation than that of stump grown at both five and seven-years of age (Table 16). Smith (1964) correlated the lateral root spread and crown width for temperate species and found the crown width showing direct relation with the lateral root spread. In the present study the lateral root spread was better in the root trainer origin trees than stump grown trees (Table 49- 50). Marginally higher crown diameter in the root trainer teak trees could be related to the better lateral root spread. In yet another study, Prasad and Mishra (1984) investigated the relation between root spread and crown spread and found that the lateral root spread was higher than crown spread. Present study also revealed the same result (Table 6, 46 and 47). Nevertheless, both the stands being at relatively younger age, manifestation of such relations in the present stands might take more time.

The initial spacing of root trainer based teak stand showed better crown diameter for widely spaced (3x3 m) plantation than that of closer spaced plantation (2x2 m) (Table 17). Crown spread being a function of the aboveground space availability, such crown expansion is possible in stands maintained at relatively wider spacing in the present study (3x3 m). Probably, the competitive benefit for belowground resources may also contribute to increase in crown spread for widely spaced teak stands (Jiang *et al.*, 2007). For instance, the lateral root spread was better in the trees at wider spacing (Table 45) which in turn had better crown diameter. The direct proportionality between tree diameter and crown spread has already been established (Naji and Sahri, 2012; Macdonald and



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Hubert, 2002). The lack of studies in the hardwood species especially in teak is a major limitation in interpreting our results.

### 5.1.7. Stand leaf area index (LAI)

In the present study LAI showed remarkable variation in accordance with type of planting material. The root trainer grown stand showed higher stand LAI than that of stump origin stands (Figure 3). Growth of stand is directly linked with the photosynthetically functional crown portion. The growth observations so far were found favoring the root trainer teak trees which had positive implications on the stand LAI also. The influence of tree spacing on LAI showed only marginal variation between 3x3 m and 2x2 m stands. Usually closer stands close the canopy at faster rate and hence may show higher stand LAI as compared with wider stands. However, the insensitivity of spacing to LAI observed in the present study suggests that the influence of spacing on LAI may be manifested at advanced age of the teak stands.

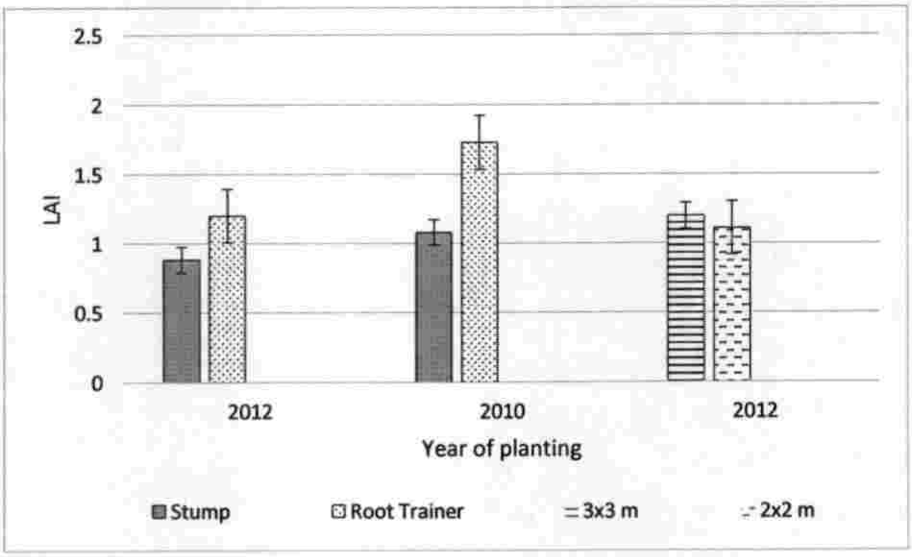


Fig 6. Stand LAI of teak plantations at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

### 5.1.8. Survival percentage

Survival percentage did not show marked variation neither for the type of planting material used nor for the different spacing. However, it showed marginally better performance for the teak stands of root trainer origin. Murugesh *et al.* (1997) reported that survival percent of root trainer grown teak showed 24.6 per cent better performance than stump. Rao *et al.* (2001) reported a similar observation of better survival percent for the root trainer grown teak (92%) than stump grown plants (81%) for two year old seedling. Survival of the plants in addition to the type of planting material may also be influenced by the soundness of the management practices followed especially during the establishment phase of the stand. It is reported that stump seedlings in the present experimental plots had under gone casualty replacement in the first year of planting which however was to the lesser extent in the root trainer seedlings. Probably this might have reflected in the present observations. Effect of spacing on tree survival could be minimum may be due to the uniform growth and efficient casualty replacement from time to time.

### 5.1.9. Persistence of stem axis

Type of planting material showed only poor influence on the persistence of stem axis. The stands of various ages showed only a marginal variation towards the persistence of stem axis. Attempt to study the impact on persistence of stem axis with planting spacing also showed a marginal variation. However, apparently trees at closer spacing showed better persistence of stem. Trees maintained at closer spacing usually have spatial limitation in lateral branching there by giving better stem form (Kearney *et al.*, 2007; Neilsen and Gerrand, 1999). With increase in tree spacing tree enhance radial growth by developing lateral branches leading to crown expansion. However closer teak stands at later stages may change the uniformity in persistence of stem axis with thinning operation or self-thinning under stagnation. Tendency of stem forking and lower persistence of stem for widely spaced teak stand has been reported earlier (Sibomana *et al.*, 1997). Reports suggested that, planting spacing and geometry influence tree growth and form (Deans and Milne, 1999)

### 5.1.10. Straightness of stem

Being a function of the stem form, tree straightness has considerable importance from the commercial plantation forestry. However we could not establish such strong correspondence between stem straightness and type of planting material for teak. Apparently better edge in stem straightness was observed for the stump origin stands though the changes were not significant. Often the management practices are focused on improving the stem straightness through judicial manipulation of the standing density through thinning. Probably the effect of the type of planting material will be more manifested once the teak stands are subjected to thinning practices. First thinning is due in both the plantations under study in the Karakkad location. The present study has observed changing trends in the root distribution patterns of stump and root trainer stands. This may influence the biomass allocation patterns in due course of thinning which could lead to large differences in growth and stem straightness.

## 5.2. PLANT AND SOIL ANALYSIS

Attempts were made to examine the influence of planting material and tree spacing on the soil properties of plantations at various ages. Also plant leaf nitrogen status was compared among these treatments. Scientific explanations of results are discussed below.

### 5.2.1. Plant leaf nitrogen

The type of planting material showed only lower difference in plant leaf N for teak at various ages. Comparison between stump and root trainer grown plantations however suggested a marginal higher value for the root trainer grown plantations. Leaf N content usually is dictated by the soil nutrient status and the relative ability of the tree root system to procure the nutrients. Trends suggest that root trainer based teak may show better efficiency in acquiring nutrients from deeper soil leading to better nutrient content in the leaves. With change in tree spacing nutrient absorption patterns among trees may vary consequent to the extent of competition prevails in the stand. Obviously trees at wider spacing are subjected to lesser competition for the available N leading to their higher absorption (Kennedy, 1993; Atkinson, 1976). This trend may be more explicit when the stand acquires maturity.

### 5.2.2. Soil bulk density

Soil bulk density was found lower for wooded stand than the treeless open area for all treatment combinations (Tables 22 and 23). For instance, the higher BD at surface soil layer was the highest for open soil (1.98) while the lowest was for teak stands (1.05) at seven years stand age. The overwhelming importance of woody ecosystems in improving the soil bulk density need not be over emphasized (Jiao *et* al., 2011; Li and Shao, 2006; Pei *et al.,* 2008). In the present study this was explicit for all sampled soil depths up to one meter. This is mainly contributed by the higher root activity and biological activities in the wooded stand, which leads to higher pore space and loosening of the soil (Rathod and Devar, 2003; Hosur and Dasog, 1995). We could not establish any significant difference in soil bulk density among teak stands grown using variable planting materials. Soil bulk density typically changes very slowly with management interventions. Despite the noticeable influence of teak trees on soil bulk density, the apparent uniformity across the various treatment stands imply such slow changing nature of bulk density. The tree roots obviously play a major role in reducing the soil bulk density with deep rooted trees bringing changes in BD after longer periods of persistent growth. However, in the present study on younger teak trees such changes in BD may not adequately precipitate.

The bulk density of teak plantation soil in the present study showed higher than natural forest (Amponash and Meyer, 2000; Balagopalan and Jose, 1997; Balagopalan, 1995; Dagar *et al.*, 1995; Jose and Koshy, 1972). The plantations showed an improvement in bulk density with advancing age especially at shallow soil depth. Such trends have been reported for teak stands grown at variable ages (Jose and Koshy, 1972). They also reported that the BD improvement in teak stands with age was such that at rotation age the BD may equal to that of natural forests. Tree spacing showed a marked difference between 3x3 m spaced plantation and 2x2 m spaced plantation only at shallow soil depth (0-20 cm) with lesser value for wider spaced plantation. This may be due to the better spatial root spread of wider spaced plantation than close spaced plantation.

### 5.2.3. Soil pH

Teak grows well in slightly acidic soil. The analytical result showed the pH value in the present study ranged in the moderately to strongly acidic nature (5.68 to 3.93). Similar variation in soil pH in teak plantations has been reported elsewhere (Chamshama *et al.*, 2000; Okoro *et al.*, 2000). Soil pH showed significant difference between the stump and root trainer grown plantations for the shallow soil depths (0-20, 20-40 and 40-60 cm) for both the ages (Tables 25 and 26). Soil pH of 20-40 cm and 40-60 cm layers showed greater influence on the tree growth (Balagopalan and Rugmini, 2006). However the soil pH variation did not follow a predictable pattern. This could be partly attributed to the uneven terrain in the entire plantations. The five-year-old plantation showed lower pH values for wooded plots than treeless open soil. However, the seven-year-old plantation showed lesser pH values in the treeless control plot than wooded plot. This apparent difference in pH in the open plots could be due to the intrinsic locations differences between the five year and seven year old stands. However, Balagopalan and Jose (1997) reported lesser values for pure teak stand at varying age than the natural forest. In general, the root trainer grown teak showed lesser soil pH for both the stand ages under study suggesting it as the possible reason for the better growth of root trainer teak (Akinsanmi, 1985; Bhatia, 1955). However such trend need validation at advanced ages of the present teak stands (Singh *et al.*, 2003).

### 5.2.4. Soil organic carbon and stock

Soil carbon is the single most important indicator in the assessment of soil producivity (Sikora *et al.,* 1996). The organic carbon concentrations within the teak plantations were considerably higher than the treeless open soil. For instance, the soil C concentration was 1.02% in surface soil (0-20cm) for the treeless open soil while the corresponding C concentrations were 1.63% and 1.61% for the root trainer and stump grown teak stands at five-years of age (Table 28). Geetha and Balagopalan (2005) reported similar values for teak plantations. Irrespective of the treatment plots, the C concentration showed consistent decline with increasing soil depth. The soil C usually found to be higher in the surface soil on account of the addition of organic matter which decline with increase in soil depth (Haridas, 2017; Du *et al.*, 2015; Manjunatha, 2015; Thakur, 2015; Joshi *et al.* 1997). However in woody ecosystems by virtue of the root activity and fineroot turn over, the soil organic carbon show better presence in the deeper layers as compared to open soil (Kunhamu *et al.*, 2011; Jobbagy and Jackson, 2000). This observation is explicit in the present study with both the plantation types (root trainer and stump) showing higher carbon status in the deeper soil as compared to open treeless control. Despite this, the five-year-old teak plantations showed marginal differences in soil C concentrations between stump and root trainer teak stands. Manifestation of differences in soil C owing to variation in planting material usually happens at longer periods of plantation growth (Singh *et al.*, 2003; Hansen, 1993). In the present study five year period probably may be too early a time to manifest such changes. The better response of soil C to planting material in the seven-year-old stand is a clear indication of this trend. For instance, the soil C content was higher in the stump grown teak plantations compared to root trainer trees for all the soil depths in the seven-year-old stand. This is however, contradictory to the observed root growth and distribution trend which was better for the root trainers. Probably, the expected advantage of better root growth observed for root trainer trees may be manifested at later stages of the stand growth. Furthermore, the intrinsic differences in initial carbon concentration in the stump and root trainer teak stands may also contribute to the present observations.

The present study showed higher soil organic carbon concentration in the widely spaced teak stands (3x3 m) as compared to the stands at closer spacing. However it is noteworthy that the open treeless control corresponding to the 2x2 m spaced stands had considerably lower C concentration compared to the control plots corresponding to the teak stands at 3x3 m spacing. For instance, the percentage increase in soil C in the 2x2 m stands compared to the control plot was 73% while the corresponding increase in 3x3 m spaced stand was only 59%. At deeper layers (80-100 cm) the soil C at 2x2 m spaced stands was about 2.6 times higher than the treeless control while the corresponding improvement was 1.5 times higher in the 3x3 m spaced stands. This clearly suggests better accumulation of soil C at 2x2 m stands as compared to 3x3 m spaced stands. The better correspondence of higher density to soil C content has been reported by many authors (Kunhamu *et al.*, 2011; Kunhamu *et al.*, 2009).

The investigations on soil carbon stocks among the stump and root trainer grown teak stands also showed higher stocks associated with stump based stands especially for seven-year-old stands. This again could be attributed to the better soil conditions existing in the stump based stands. Yet another observation was that the control plots had higher soil C stocks in the shallow soil depths compared to both the teak stands of different planting material origin. Despite the lower carbon concentrations, the higher soil C stocks in the control plots could be attributed to their higher soil bulk density. However, at deeper depths (80-100 cm) the teak stands showed marked improvement in soil C stocks, indicating the potential ability of woody ecosystems to improve the soil C stocks (Rocha, 2017; Gupta and Pandey, 2008; Jobbagy and Jackson, 2000).

The response of C stocks to tree spacing showed similar result as that of soil C concentrations with 2x2 m stands showing better accumulation as compared to control (1.99 times higher) while the 3x3 m spaced stands showed

1.27 times higher value as compared to corresponding treeless control. Closely spaced stands by virtue of their higher litter addition and decomposition may add higher C to the soil carbon pool (Rocha, 2017; Kunhamu *et al.,* 2009).

**5.2.5. Soil total nitrogen**

Total nitrogen content in the soil also showed higher value in the teak plantations compared to treeless control though it was not significant as compared to the changes in soil C concentration. The addition of woody litter in to a system increases the nutrient turn over and nutrient status of soil. In the present study, the soil nitrogen showed only marginal variation in the five-year-old plantations, but with advancing age (seven-year-old plantation) it showed marked variation. Chamshama *et al*. (2000) reported similar trend with increase in the nitrogen content in the semi-mature plantation than younger plantation. Lal (2005) reported a positive correlation between soil organic carbon and total nitrogen. The soil N values obtained in the present study showed similarity with a long term trial on teak where consistent increase in soil N was observed with advancing stand age (Geetha and Balagopalan, 2005)

The total nitrogen content in the soil was highest for the top layers of soil and consistently decreased with soil depth (Tables 34-36). As discussed above, the well weathered soils are always confined to the surface layers due to better microclimatic and edaphic conditions. The soil faunal activity also will be higher in the top layers which result in better nutrient availability (Haridas, 2017; Rocha, 2017; Manjunatha, 2015).

Stump and root trainer grown plantations did not show significant difference in N content at five-years of age while the corresponding change turned appreciable for 7 year old stand with stump grown plantation showing higher N concentration for all the soil depths. Interestingly, this observation is against the expected lines where root spread and general growth of root trainer trees where better compared to stump based trees and hence possibly should have higher soil

C concentrations. This variation in soil N content may be attributed to the intrinsic differences in the soil nutrient status of the above two plantations. The soil carbon and nutrient status could also be a function of litter addition and microbial activity which might have favored the higher C and N content in the stump based plantation. However, these aspects were not investigated as part of the present study.

Our study also could not establish striking relation between tree spacing and total N status. However, many studies reported closer spacing and age had a positive correlation with the total nitrogen content in the soil for tree based plantations (Thakur *et al.*, 2015 in *Grevillea robusta*; Khobragade *et al.*, 2000 in Teak). This non-significance between the treatments and the control may be mainly due to the younger age (five-years) of the stands. The treatment effects could give better trends at later stages of the stand development.

**5.2.6. Soil phosphorus**

The present study revealed that soil available phosphorus content in the selected plantation soil was extremely low. This can be attributed to the acidic nature of the selected plantation soil leading to possible fixation of available phosphorus (Nykvist and Sim, 2009; Majid and Paudyal, 1999). In this context, the total phosphorus content in the soil was examined and compared for the root trainer and stump grown teak plantations. It was clear that neither planting material nor spacing showed any influence on the total phosphorus content in the soil (Tables 37-39). Also soil did not show characteristic trend in the total phosphorus content across the soil depths. Generally soil P content in the soil is subjected to less variation as it remain in the fixed form (Aborisade and Aweto, 1990). In yet another study a similar observation was recorded by Manjunatha (2015) who reported poor difference in available P values of teak plantation and adjacent natural forest. Yang *et al.* (2010) reported conversion of natural secondary forest to larch plantations showed improvement in the total P content in the soil. Nevertheless, other studies reported soil profile showing decreasing trend for total soil phosphorus across the soil profile (Haridas, 2017; Ali *et al.*, 2009). The present study also showed marginal differences in total P concentration with changes in planting spacing. As discussed above, soil total P remain least affected by density manipulations especially when the stand is at younger age (five-years).

### 5.2.7. Soil exchangeable potassium

The present study revealed that exchangeable potassium content in the soil showed declining trend with increasing soil depth. For instance exchangeable K content in the soil was 123.18 kg ha$^{-1}$ for stump grown stands at 0-20 cm soil depth which considerably declined to 68.73 kg ha$^{-1}$ at 80-100 cm soil depth for 5-year-old stands (Table 40). Haridas (2017) and Geetha (2008) reported similar trend in the soil profile. Also the upper soil layer (0-20 cm) had the highest K content for all teak plots under investigation which substantially reduced at 20-40 cm soil depth. Similar observation has been made in teak stands with upper layer showing high potassium content (Joshi *et al.*, 1997). This could be attributed to the higher possibility of mineralization at surface soil. Also K is highly mobile in the soil and could change the content in respective soil depths quiet often.

Similar to total phosphorous in soil, the exchangeable potassium also showed non-significance with respect to planting material, spacing and with treeless open plots. Continued investigations at advanced ages of the above stands probably may give meaningful trends. Studies elsewhere however indicate that closely spaced stands at advanced age of teak plantation showed increase in available potassium (Khobragade *et al.*, 2000).

### 5.2.8. Soil exchangeable calcium

The exchangeable calcium in the soil among various teak plots showed similar trend as that of exchangeable potassium with poor relation with planting material and tree spacing especially for younger aged teak stands (five-years). However, with increase in age there was higher buildup of exchangeable Ca in the teak plantations as compared to treeless control. However, we could not establish



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variation in exchangeable Ca with changes in planting material. As indicated above, the expression of such changes may become more pronounced when the plantation turn maturity. The content of exchangeable Ca may influence the teak tree growth. Kadambi (1972) reported that soil exchangeable Ca showed a positive relation with tree growth. Salifu and Meyer (1998) reported that higher calcium content in the B horizon was attributed to the active role of teak in pedogenesis. Rathod and Devar (2003) and Sigh *et al.* (1990b) reported positive impact of soil Ca on teak growth.

## 5.3. ROOT DISTRIBUTION

The changes in root intensity and distribution pattern for stump and root trainer grown teak stands showed interesting trends. In general, both the stands showed decrease in root intensity with increasing lateral distance from the tree base and increasing soil depth (Van Noordwijk *et al.*, 2015; Niiyama *et al.*, 2010; Afas *et al.*, 2008). However, the changing trends were different. For instance, the stump based teak stand showed better intensity of small roots in the top soil (0-20 cm) which was 61% of the total root intensity (2410 number per $m^2$) at proximal end (0.35m) at 50 cm soil depth for 5 year old stand (Fig. 4). The corresponding root intensity for root trainer based stands was only 55% of the total root intensity at the proximal lateral distance and 50 cm soil depth (2405 number per $m^2$). However, the trends showed gradual reversal at deeper soil depths with an increase in root intensity of root trainer based teak stands. For example the corresponding root intensities for stump and root trainer stands at deeper depth (30-50 cm) were 22% and 28% respectively of the total root count at the same proximal lateral distance (0.35 m). These trends clearly illustrate the differences in the root growth habit of the two stands. The increase in root intensity at deeper soil for root trainer trees clearly indicates its better vertical spread contributed by multiple taproots. However the stump grown trees lack a well-defined tap root system leading to lower vertical root spread (Khedkar and Subramanian, 1997). It is also noteworthy that in the absence of prominent tap root, the stump grown teak produced larger number of small roots at shallow depth at proximal end. Further, this increase could not be maintained neither with increase in lateral distance nor with increase in soil depth.

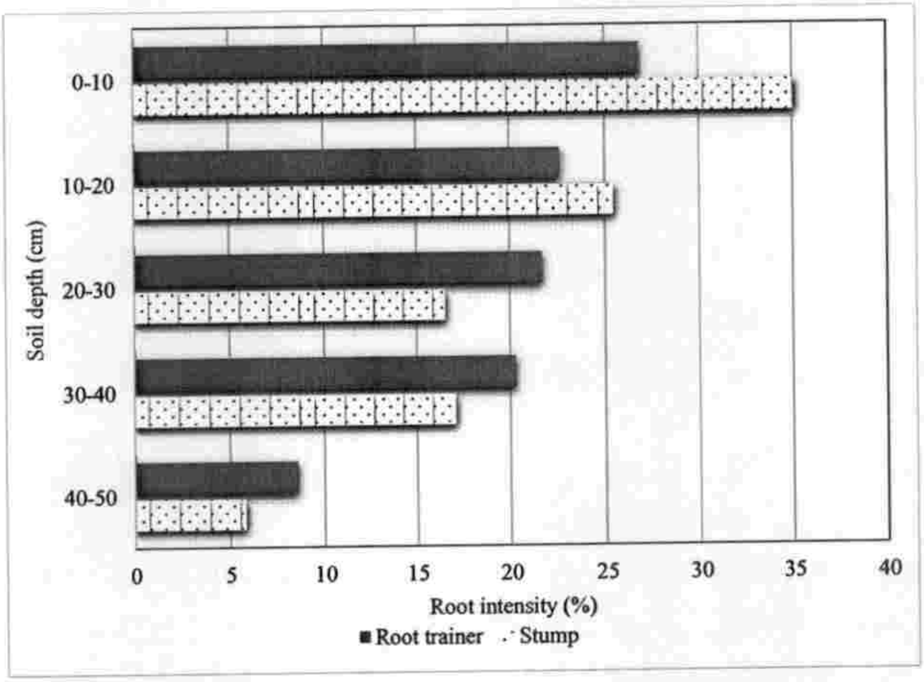


Fig 7. Variation in root intensity of stump and root trainer grown teak trees of five-years of age across soil depths at proximal lateral distance (0.35 m) at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

The stump and root trainer stands at seven year of stand age also showed similar trends in the distribution of small roots (fine roots) (Fig. 5). With increase in stand age the differences in root spread also was visible in the present study. For example the root intensity observed for shallow root depth (0-20 cm) were 62 per cent and 54 per cent of the total root intensity at proximal lateral distance (0.6 m) for 50 cm depth, respectively for stump and root trainer. Root intensity at deeper rooting depth showed a reverse trend. The corresponding values for deeper depth (30-50 cm) were 18 per cent and 25 per cent respectively.


Fig 8. Variation in root intensity of stump and root trainer grown teak trees of seven-years of age across soil depths at proximal lateral distance (0.6 m) at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

A clear reduction in root intensity has been observed with increase in root size irrespective of the planting material of stand origin (Samritika, 2013). For instance, the total number of medium sized roots (2 mm to 5 mm) at closest lateral distance at 50 cm soil depth was 255 number per $m^2$ for stump and 515 per $m^2$ per root trainer stands at five-years of age. A clear cut shift in root intensity with better counts for root trainer both at shallow depth and deeper depth has been observed for this root size class. For example the total root intensity for the shallow root depth (0-30 cm) were 155 number per $m^2$ for stump origin plants and 215 for root trainer based teak trees. This advantage in root spread was more explicit at farther lateral distances with root trainer teak showing better later and vertical root spread compared to stump. The same pattern of root spread has been observed for > 5.0 mm root size class also though the number was lesser as compared to smaller roots. Interestingly, the larger roots (> 1.0 cm) spread was very much restricted in the stump grown teak with virtually no representative roots at longest lateral distance at all soil depths (2.35 m). The relatively higher count of larger roots (> 1 cm) for root trainer grown trees indicated the prominent nature of multiple tap rooting habit of root trainer grown plants (Mohanan and Sharma, 2005; Khedkar, *1999*; Khedkar and Subramanian, 1997). Insawadhi (1963) made a comparative study on growth of single and double tap rooted stumps, the result showed that double tap rooted stumps showed better growth than single tap rooted stump.

Kuerkool (1965) reported better performance of teak in terms of DBH with more root spread. Root trainer grown plantations showed more lateral root spread along with more DBH. Boonkird *et al.* (1960) reported positive relation of rooting depth and total tree height. Present study also showed similar findings, with better rooting depth for root trainer origin trees along with higher height growth. Gopikumar and Mahato (1993) reported similar result in the nursery study of teak, with significant correlation between plant height and root length.

Attempts were made to compere the effect on root spread by varying spacing in the root trainer grown teak trees at five-years of age. Decline in root intensity with increasing lateral distance and soil depth was also observed in the spacing trail. The prominent influence of tree spacing on root spread was observed in the present study. For instance, closely spaced (2x2 m) trees showed better rooting percentage (Fig. 6) at shallow depth (0-20 cm) at proximal lateral distance (0.35 m), than widely spaced trees (3x3 m). The corresponding root intensities (smaller sized roots, < 2 mm) were 52% and 66 % of total root intensity at 50 cm depth for 3x3 m and 2x2 m spaced trees respectively. However the trend showed a gradual reversal at deeper soil depth (30-50 cm) with increasing root intensity for wider spaced trees. For example, the rooting intensity of wider spaced trees registered 28 per cent of total root intensity at proximal lateral distance (0.35 m) and 15 per cent for closer spaced trees. This shift in root intensity was prominent at farthest lateral distance (2.35 m) with no roots at deeper soil depth (30-50 cm) for narrow spaced plants while it was 19 per cent for widely spaced trees. The root intensity of medium sized roots (2-5 mm) for shallow depth at farthest lateral distance (2.35 m) were better for wider spaced trees (740 number per $m^2$) than trees at narrow spacing (315 number per $m^2$). This trend in the root distribution could be primarily attributed by the competitive nature of trees in the closer spaced stand. The trees concentrate more roots at proximal region to base of tree and reduce spread as compared to wider spaced stand (Atkinson, 1976; Douglas *et al*., 2010). Similar result was observed in young *Acacia mangium* plantation while analyzing the effect of stand density and pruning on root activity by using $^{32}$P soil injection method (Kunhamu *et al*., 2010). The result revealed that high stand density of *Acacia mangium* induces greater root uptake capacity close to the stem and from the subsoil and low density plantations showed higher root activity at far lateral distance from tree base.

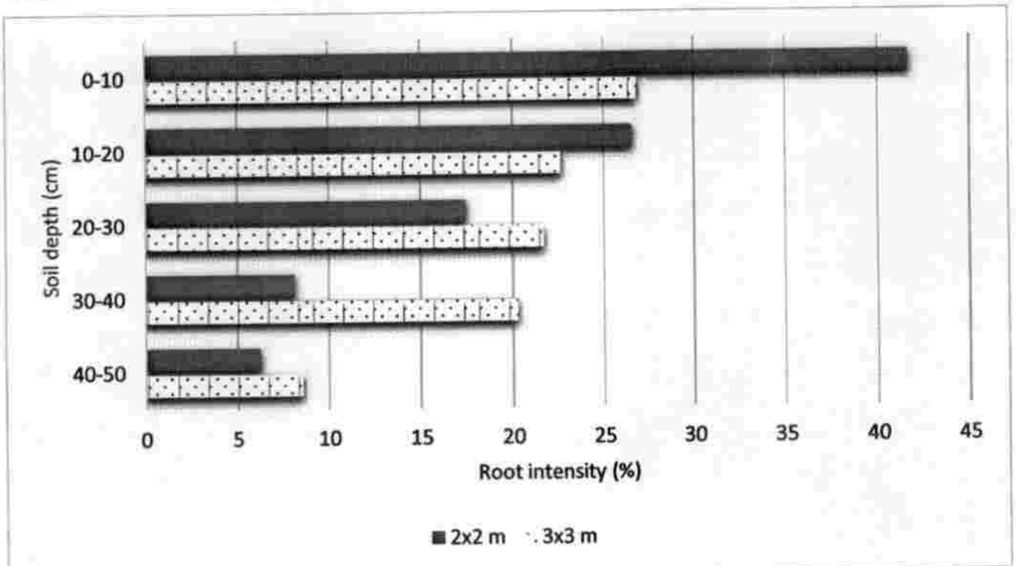


Fig 9. Variation in root intensity of root trainer grown teak trees of five-years age at variable spacing across soil depths at proximal lateral distance (0.35 m) at Karakkad, Kalady range, Malayattoor Forest Division, Kerala.

Comparative reduction of root intensity for higher root size class also reported for spacing trial (Samritika, 2013; Douglas *et al*., 2010). The distribution of higher sized roots also followed the trend of smaller roots. The distribution of higher sized roots also restricted to the proximal lateral distance and shallow depths for closer spaced trees (Boswell, 1975; Afas *et al*., 2008). This reduction in numbers of roots at deeper soil depths and farthest distance for narrow spaced trees again reiterates the differences in belowground competition on account of the spatial limitations.

## 5.4. MANAGERIAL IMPLICATIONS OF THE STUDY

The better performance of root trainer raised teak in terms of aboveground growth and root distribution patterns has been observed in the present study. This observation may have far reaching implications in developing protocols for large scale cultivation of teak. Some of the pertinent managerial implications of the study are mentioned hereunder:

- The study converges to the conclusion that teak stands developed from root trainers had better growth attributes as compared to stump grown teak.
- The root spread also was better with root trainer teak both in terms of lateral and vertical spread.
- The restricted root spread confining the roots to the shallow depths near to the tree base in stump based teak trees suggest that stump technology make the teak trees more of a surface feeder which could possibly lead to nutrient drains from the surface soil at advanced stages of stand growth. The observed productivity decline in stump grown teak plantations could be partly attributed to this massive nutrient drain from the soil.
- Also, the root trainer based trees may give better stability to the trees on account of the deeper and wider distribution of roots.
- This is explicit in the case of stump grown teak which is often liable to wind throw.
- The recent floods in Kerala have seen drying of stump based trees which could be attributed to the damages to the shallow fibrous roots due to flooding.
- Hence considering the potential advantages of root trainer teak, this technology may be followed for the future cultivation of teak in Kerala.
- However, long term studies need to be undertaken to confirm the present observations.

# *Summary*

# VI. SUMMARY

Consistent decline in the productivity of teak plantations in Kerala has been an accepted reality and several reasons have been discussed in the scientific parlance. Apart from harvest related resource depletion from the site and unscientific managerial practices, the productivity may also be influenced by variability in the belowground resource acquisition potential of teak developed from different planting materials. Present investigation entitled "Field evaluation of stump and root trainer grown teak (*Tectona grandis* L.f.) plantations" was undertaken in this background to investigate the influence of planting material (stump and root trainer) on the productivity of teak plantations managed at five and seven years of age at spacing of 3x3 m and 2x2 m respectively at Karakkad, Kalady range, Malayattoor forest division. The study also attempted to evaluate the effect of tree spacing on the growth of root trainer based teak plantations at five years of age managed at 3x3 m and 2x2 m spacing. The various teak plots were assessed for tree growth, root distribution and soil properties at periodic intervals. The investigations lead to interesting findings which could bring far reaching changes in the production strategies of teak across the country. The salient findings of the study are summarized below:

**Root trainer vs stump grown teak**

1. The total tree height showed marked increase for teak stands developed from root trainers (6.68 m at seven years old) as compared to those developed from stump (5.87 m at seven years old) for both stands at five and seven years of age.
2. The bole height also showed significant improvement for root trainer grown teak at five years of age while the trend was not conspicuous for teak stands at seven years of age.

3. Root trainer grown teak stand showed better diameter growth (DBH) than stump origin stand at both five and seven years of age.
4. Mean tree basal area was significantly higher for root trainer grown teak stand at five years of age while the increase was only marginal for seven-year-old stands.
5. Mean tree volume showed marked improvement in the root trainer grown stand as compared to stump origin stands at various ages. The mean volume for seven-year-old root trainer stand was 0.031 $m^3$ while the corresponding value for stump based teak was 0.023 $m^3$
6. Crown diameter showed only minimal improvement for root trainer grown stand at both ages (five and seven) compared to stump grown stands.
7. Stand LAI showed marked variation in accordance with type of planting material with better performance by root trainer based stand as compared to stump originated stand.
8. Type of planting material showed only marginal influence on persistence of stem axis at both the ages. Similarly we could not establish any relation between straightness of stem and type of planting material.
9. Concentration of leaf nitrogen as a result of planting material showed only marginal improvement in root trainer based stand than stump. However, stand with wider spacing showed marked higher concentration of leaf nitrogen than 2x2 m spaced plantation.

**Effect of tree spacing on teak growth**

1. Investigations on the effect of initial spacing on the growth of five-year-old teak raised from root trainers revealed variable effects. Tree total height and bole height showed a marginal increase in closer spaced (2x2 m) trees than stands at wider spacing (3x3 m).
2. The diameter and basal area growth were better in widely spaced teak as compared to closer spacing. The average DBH for stands at 3x3m spacing

(7.96 cm) was better as compared to 2x2 m spaced stands (5.08 cm). The corresponding mean basal area was 21.66 $cm^2$ and 50.60 $cm^2$ respectively for stands at closer and wider spacing.

3. Mean tree volume and stand volume showed variable trends for teak at variable planting spacing with a marked advantage for widely spaced stands. Also there was significant increase in crown diameter for stands at wider spacing.
4. Change is tree spacing viz. 2x2m and 3x3m did not show appreciable influence on stand LAI which may become pronounced at advanced stages of stand development.
5. Apparently trees at closer spacing (2x2m) showed better persistence of stem axis and straightness.

**Changes in soil properties**

1. Generally treeless open soil showed higher bulk density than teak stands irrespective of planting material indicating the prominent role of trees in improving the soil physical properties. However planting material (stump or root trainer) had no influence on soil bulk density for all the soil depths. Influence of spacing on bulk density showed lower value at shallow soil depth (0-20 cm) for widely spaced teak stands.
2. Root trainer based teak stands showed lower soil pH as compared to stump grown stands both at five year and seven year of stand age. However initial spacing showed only marginal variation.
3. Variation in planting material could not inflict any perceptible change in soil organic carbon concentration and carbon stocks for younger stands. However the changes were prominent for teak stands at seven years of stand age with stump grown stands showing higher soil C concentration carbon stocks. The average soil carbon concentration values were 1.15 % and 1.55 % for the root trainer and stump grown teak stands at seven years of stand age. The

corresponding soil carbon stocks were 24.60 Mg $ha^{-1}$ and 32.85 Mg $ha^{-1}$ for teak stands at seven years of stand age. The influence of planting material on soil carbon status may become pronounced only at later age of the teak stands.

4. Consistent decline in soil carbon concentration and stocks were observed with increase in soil depth for all wooded treatments.
5. Despite the lower C concentrations across soil depths, the open soil had higher carbon stocks in the corresponding soil depths which could be attributed to the higher bulk density compared to the soils under teak stands.
6. Tree spacing showed improvement in soil organic carbon in the closely spaced stand as compared to widely spaced stands and treeless open soil.
7. Soil nitrogen concentration showed significantly higher value in the stump originated stand at seven years of age which however was not prominent for the younger aged stands (five years). This higher value for stump origin stand could be attributed to the differences in the basic soil N status. Soil nitrogen concentration was not influenced by tree spacing.
8. Available phosphorus content in the selected plantation soil and treeless open soil was found extremely low.
9. Total phosphorus, exchangeable potassium and exchangeable calcium contents were only marginally influenced by planting material and spacing for teak.

**Root distribution pattern**

1. Investigations on root distribution among various teak stands indicated that root trainer based trees showed higher root spread both laterally and vertically.
2. The stump origin stands confined the smaller roots only at the base of the tree which declined considerably with increase in lateral distance and soil depth. Reduced root spread was observed for closely spaced teak stands primarily on account of the spatial limitation in root spread.

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# FIELD EVALUATION OF STUMP AND ROOT TRAINER GROWN TEAK (*Tectona grandis* L.f.) PLANTATIONS

By

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**ABSTRACT OF THE THESIS**

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## ABSTRACT

Teak (*Tectona grandis* L.f.) stands out to be the most popular commercial timber species in the tropics by virtue of its matchless combination of properties. Over a century, root- shoot cutting (stump) has been the common nursery production technology for teak across the world. However, the recent decade has seen unprecedented decline in the productivity of teak plantations which could be attributed to diverse reasons. In this context, the efficiency of the stump based planting method for teak hence assume close scrutiny by virtue of the limitation in the root spread and consequent belowground resource acquisition.

In this backdrop, a field study entitled "Field evaluation of stump and root trainer grown teak (*Tectona grandis* L.f.) plantations" was conducted on teak plantations established at Karakkad, Kalady range, Malayattoor forest division, Kerala during 2017-18, to evaluate the influence of planting material viz. stump and root trainer on growth aspects, soil physio-chemical properties and root distribution separately in five and seven-year-old teak plantations. The teak plantations selected for study included; five-year-old (2012 establishment) stump and root trainer grown stands at 3x3 m spacing, seven-year-old (2010 establishment) stump and root trainer based stands at 2x2 m initial spacing. Attempt were also made to study the effect of planting spacing on the growth of teak that was raised from root trainers and managed separately at 2x2 and 3x3 m spacing. Nine random plots of size 20x20 m were demarcated for each of the treatments such that there were 45 experimental plots for observation. Altogether there were three treatment combinations for comparison viz. stump vs root trainer at 3x3 m spacing and five-year-old; stump vs root trainer at 2x2 m spacing and seven-year-old; five-year-old root trainer based teak stands at 3x3 m vs at 2x2 m spacing. Each treatment combinations were analyzed separately with independent t- test.

Biometric observations on teak growth showed considerable difference with variable planting material and spacing. Root trainer grown teak stands showed better performance in total tree height (6.68 m at seven-years of age), DBH (9.04 cm at seven-years of age), and mean tree volume (0.031 $m^3$ at seven-years of age) as compared to stump origin stand both at five and seven-years of stand ages. The basal area and bole height showed marginal improvement in root trainer grown stand at five-years of age. Initial spacing showed only marginal influence on total height and bole height with an advantage for stands at 2x2 m spacing as compared to 3x3 m spaced stands. However, DBH, basal area and volume showed discernible improvement in the stands at 3x3 m spacing. Crown diameter showed a nominal increase in the root trainer grown stand than stump grown stand at both ages. However, spacing had great influence on the crown diameter with more spread (2.7 m) by widely spaced stands (3x3 m). Stand LAI also was better for root trainer stand while spacing had poor influence on LAI. Persistence of stem axis and straightness of stem showed limited advantage for stump grown teak origin stand. Also closely spaced teak stands (2x2 m) developed from root trainer stands showed slightly better performance than teak at wider spacing (3x3 m).

Attempts to analyze the influence of planting material and spacing on plant leaf nitrogen and soil physio-chemical properties suggested that plant leaf nitrogen concentration was modestly better for root trainer grown trees than stump grown trees. However effect of spacing indicated that widely spaced trees (3x3m) showing significantly higher nitrogen up take than narrow spaced trees. Soil physical and chemical properties were found to be less influenced by the planting material. However, all teak stands irrespective of planting material showed considerable improvement in soil organic carbon and nitrogen concentration and reduction in soil bulk density as compared with respective treeless open plots. Also there was consistent reduction in carbon content and nitrogen with increase in soil depth up to one meter soil depth. The average soil carbon concentration values were 1.15 % and

1.55 % for the root trainer and stump grown teak stands at seven-years of stand age. The corresponding soil carbon stocks were 24.60 Mg $ha^{-1}$ and 32.85 Mg $ha^{-1}$ for teak stands at seven-years of stand age.

Investigations on root distribution among stump and root trainer grown teak trees revealed obvious advantage in root spread and root intensity for root trainer raised teak stands. Teak trees grown from stump had smaller roots confined to the base of the tree at shallow depths which drastically reduced with increase in lateral distance of soil depth. The presence of prominent multiple tap root systems could be the reason for the high root spread observed with root trainer based teak trees. The trends were the same for small, medium and larger root intensity. Yet another noteworthy observation was that teak trees at closer spacing showed reduction of root spread and restricted the root system at proximal lateral distance while widely spaced trees showed wider root distribution.