BIOMASS PRODUCTION AND ROOT DISTRIBUTION PATTERN OF SELECTED ACACIAS

BY

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(2011-17-106)

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DECLARATION

I, hereby declare that this thesis entitled **"BIOMASS PRODUCTION AND ROOT DISTRIBUTION PATTERN OF SELECTED ACACIAS"** 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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Mereena, M. J.

Dedicated to my Family

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Introduction

INTRODUCTION

The demand on natural resources is increasing because of the rapid increase in the population growth and the consequent increasing demand for fuel woods, food and timber leading to large scale deforestation and environmental degradation. The only way to overcome the pressure on natural resources is to make their adequate availability to the people artificially for meeting their multiple needs. Raising plantations in degraded areas and other bare lands play an important role in promoting sustainable development in the tropics through meeting the above said objectives. The need for plantations and agroforests are more felt today than ever before. Fast growing short rotation trees have greater potential to sequester substantial quantities of atmospheric carbon (Kumar *et al.*, 1998). In this context, fast growing exotic tree species have greater relevance in the current scenario of global warming and climate change.

Acacia is one of the most widely introduced trees in India. *Acacia mangium* and *Acacia auriculiformis,* native of Australia, received a wider acceptance on account of their growth rate and other desirable wood qualities. In South India, they are highly preferred in raising plantations as well as by marginal farmers as a component in small holdings and homegardens. Apart from high fuel wood value, *Acacia mangium* with 4800-4900 kcal/kg, the timber makes attractive furniture, door frames, window parts and sliced veneer (Kunhamu *et al.*, 2005) Also, *Acacia mangium* is reported to have an MAI of 46 m^3ha^{-1} (Tham, 1976). However, the detailed information on the growth, productivity, nutrient accumulation, soil nutrient content and rooting pattern of the lesser known species of acacias like *Acacia crassicarpa and Acacia aulacocarpa* are lacking from this part of the world with a typical warm humid tropical climate.

Information on biomass productivity helps to draw valuable conclusion on carbon sequestration potential of different tree species. Assessment of biomass production not only facilitates the choice of species but also helps to assess the impact of deforestation and re-growth rates on the global carbon cycle (Deans *et al.*, 1996). The increasing trend of total utilization of trees has necessitated the estimation of total biomass production on weight basis rather than conventional volume estimate. The biomass production potential and its component wise partitioning will again differ with respect to the species, age and spacing. Generally, a huge portion of the total biomass accumulated is in the stem wood (>60-70%) and hence a sizeable proportion of absorbed CO_2 can be efficiently locked in the biomass.

Besides the greater production potential, planting of fast growing multipurpose tree species will also help in arresting the deterioration of the environment and improving the quality of life of people. To realise and appreciate the multiple benefits from different acacias, a thorough knowledge on growth and productivity is inevitable.

Fast growing tropical plantations of multipurpose tree species like acacias may incorporate considerable amounts of nutrients in their biomass over a relatively short period of time. This can lead to site fertility declines which can limit sustainable plantation forestry in tropical regions. Soil fertility can be decreased through excessive removal of living biomass, particularly if nutrients in tree crowns are lost through the harvest or site preparation (Jorgensen and Wells, 1986, Perry and Maghembe, 1989). Hence bringing back the tops and lops, with higher nutrient concentration compared to the bole wood, is a viable option so as to minimize the harvest related nutrient export from the site (Kumar *et al.*, 1998).

No much studies have so far been done on these aspects in the humid tropics, especially in the lesser known *Acacia crassicarpa* and *Acacia aulacocarpa* and data on the rate of biomass accumulation, carbon sequestration and nutrient dynamics are lacking. Hence a detailed study was under taken in an 18-year-old acacia plantation in the arboretum of College of Forestry, Vellanikkara, Kerala during 2012-2014 to evaluate the aboveground and belowground biomass accumulation, nutrient (N, P, K) accumulation in the biomass and soil and to develop allometric prediction equations for relating above parameters of four species of acacias such as *Acacia auriculiformis*, *Acacia mangium*, *Acacia crassicarpa* and *Acacia aulacocarpa*. The study also explored the root distribution pattern of these four acacia species.

Review of Literature

REVIEW OF LITERATURE

A thorough search of literature pertaining to the study entitled "Biomass production and root distribution pattern of selected acacias" is arranged under the following major headings.

2.1 A brief note on acacias

2.2 Biomass production by trees

2.3 Carbon sequestration

2.4 Nutrient accumulation

2.5 Biomass prediction equations

2.6 Root distribution pattern

2.1 A BRIEF NOTE ON ACACIAS

The genus acacia includes more than 1000 species of trees and shrubs distributed in Africa, America, Asia and Australia with the majority of species found in Australia. About 40 species occur in India; in addition a few more have been introduced from Australia and Africa. The ability to grow quickly helps young plants to thrive successfully in almost all areas. Acacias are leguminous and have an ability to fix atmospheric nitrogen through symbiotic association with N-fixing organisms, including the root nodule-forming bacteria of the genus *Rhizobium*. They can fix significant amount of nitrogen, which has a positive influence on yields in N-deficient soils (Neil, 1990). Acacias can tolerate salt also. Outstanding acacia of this group include *Acacia auriculiformis, Acacia ligulata, Acacia maconochieana, Acacia salicina* and *Acacia stenophylla*. All except for *Acacia auriculiformis* occur naturally on saline soils in Northern Australia (Thomson, 1987). This capacity to grow in poor and degraded soils make it as a best candidate for land reclamation and restoration also.

2.2 BIOMASS PRODUCTION BY TREES

The biomass production by a plant community is the reflection of its capacity to assimilate solar energy under some set of environmental conditions. Biomass is an essential aspect of studies of carbon cycle (Cairns *et al.*, 2003; Ketterings *et al.*, 2001). They are important as potential carbon pools and sinks (Cannell and Dewar, 1994 and Schimel *et al.*, 2001). Plantations have significant role in carbon sequestration. Rate of reforestation and afforestation worldwide are likely to grow over the next decades as many countries seek to compensate for the loss of natural forests, thus the role of plantations in sequestering C may also increase (Gladstone and Ledig, 1990; Rotmans and Swart, 1991; Houghton, 1996). Tropical forests harness more carbon than most other ecosystems and roughly 44 times more than agricultural lands; therefore, although young plantation forests sequester C at a higher rate than mature forests, primary forests conserve much more C per hectare (Cairns and Meganck, 1994; Bruenig, 1996). There are two methods to calculate forest biomass, namely direct method and indirect method. Direct method (destructive methods) involves felling of trees to determine biomass. Indirect method is based on allometric equations using measurable parameters (Salazar *et al.*, 2010).

A survey was conducted by Bin *et al.* (2012) to study the spatial distribution of biomass in an 8-year-old *Acacia melanoxylon* plantation in Nanning of Guangxi Zhuang Autonomous Region. Results showed that the total biomass of the plantation was 108.47 t hm^{-2}. Out of the total biomass maximum contribution (85.85%) was by the arbor layer followed by shrub layer (7.26%), litter layer (4.47%), and herb layer (2.42%).

Biomass production potential of trees varies considerably with variation of species site relationships, rotation age, stand density interactions and cultural treatments (Landseberg *et al.*, 1995). Different plant communities have different rate of biomass production based on their efficiency (Rai, 1984). High biomass production is an important consideration in all tropical tree planting programmes. And biomass has a significant role in sequestering rising CO_2 levels (Landseberg *et al.*, 1995). The information about stocks of carbon as biomass per unit area is important for assessing the impact of deforestation and re-growth rates on the global carbon cycle (Deans *et al.*, 1996).

2.2.1 Tree species and biomass production

There are many studies from the tropics which reveal that there is a vast variation in the biomass accumulation potential of trees (Cobb *et al.*, 2008, Arias *et al.*, 2011). Gopikumar (2000) compared biomass production of four MPT's and found that *Albizia falcataria* produced highest biomass compared to *Artocarpus hirsutus, Artocarpus heterophyllus* and *Erythrina indica*. The study on biomass production of 11 MPT species compared on sandy loam soils in Andhra Pradesh by Rao *et al.* (2000) found that *Dalbergia sissoo* yielded maximum biomass (214.6 Mg ha^{-1}) followed by *Leucaena leucocephala* (187.8 Mg ha^{-1}) and *Acacia auriculiformis* (162.4 Mg ha^{-1}). Jamaludheen (1994) reported that out of 9 species *Acacia auriculiformis* and *Paraserianthes falcataria* recorded the highest growth rate in terms of height, radial growth and biomass yield (344.2 Mg ha^{-1} and 197.23 Mg ha^{-1} respectively) and the lowest biomass yield was for *Leucaena leucocephala* (26.03 Mg ha^{-1}).

A comparison of aboveground biomass production of four MPTs in silvopasture system in humid tropics of Kerala by Kumar *et al.* (1998) reported that there are considerable variation in biomass production among various MPTs. Highest biomass reported is 183.54 $Mgha^{-1}$ in the case of *Acacia auriculiformis* and the lowest value for *Ailanthus triphysa* (19.38Mg ha^{-1}). The ABG (aboveground biomass) of 20 year old *Bambusa bambos* raised in hedges, bamboo clumps averaged 2417 kg per clump with a an average per hectare accumulation of 241.7 Mg ha^{-1} (Kumar *et al.*, 2005). Kunhamu *et al.* (2005) reported a biomass range from 5.58 Mg ha^{-1}to 97.58 Mg ha^{-1}for seven –year old *Acacia mangium.* Another study conducted by Ming *et al.*, (2010) estimated the aboveground biomass and carbon storage in *Phyllostachys makinoi* were 105.33 and 49.81 Mg ha1 respectively. Gopikumar (2009) compared the biomass production potential of 12 MPTs grown in Kerala; among the all species studied maximum biomass production was found for *Terminalia tomentosa* followed by *Adenanthera pavonina* while the lowest was for *Swietenia macrophylla.*

2.2.2 Rotation age and biomass production

Many studies conducted in the global level revealed that biomass production is directly proportional to the age (Evans, 1982; Zhang *et al.*, 2012). Even the biomass yield increases with age, after reaching a particular age (at maturity) the biomass will be stable. Lodhiyal (1995) estimated total plantation biomass of 5-8 year old poplar (*Populus deltoids*) plantations growing in the Tarai belt of U.P, increased from 84 Mg ha^{-1}at 5 years to 170 Mg ha^{-1} in 8 years. In dry tropical region, it varied from 5.65 Mg ha^{-1}in 5 year-year old plantation to 135 Mg ha^{-1}in 8 year. Negi *et al.* (1995) found the biomass production of 10 and 30 year old *Tectona grandis* was 74 Mg ha^{-1}and 164.1 Mg ha^{-1}respectively. Vidyasagaran (2003) had studied the biomass production of *Casurina equisetifolia* at two age and the result shown that aboveground biomass increased nine times from 2 years to 9 years in the plantations of central Kerala (42.3 Mg ha^{-1} and 366.82 Mg ha^{-1}respectively). The total standing tree biomass of *Dalbergia sissoo* increased with increasing age and diameter from 53.09 Mg ha^{-1}at 3 years to 160.04 Mg ha^{-1}at 7 years (Das and Chaturvedi, 2003).

Rawat and Negi (2004) estimated the biomass production of *Eucalyptus tereticornis* which varied from 11.9 Mg ha^{-1} in 3 years to 146 Mg ha^{-1}in 9 year old plantations in moist regions. Above ground biomass production estimated for 5-21 years of *Gmelina arborea* (Roxb) plantations in Nigeria showed a high biomass yield, ranging from 83.2 t ha^{-1} (5 years) to 394.9 t ha^{-1} (21 years) and the mean annual biomass increment varied from 16.2 to 20.9 t $ha^{-1}yr^{-1}$ (Onyekwelu, 2004). In a 10 year old *Grevillea robusta* stands in the mid hill of western Himalaya, biomass production was found to be 345.274 Mg ha^{-1} (Gopichand and Singh, 2011). The biomass production in an age series of *Casurina equisetifolia* in Puri, Orissa ranged from 19Mg ha^{-1} (5 years) to 130 Mg ha^{-1} (15 years) with 76 % to 83 % being contributed by the aboveground biomass. In an age series of 12, 24, 36 the total biomass production of *Anthocephalus chinensis* was 0.71 Mg ha^{-1}, 12.3 Mg ha^{-1} and 35.8 Mg ha^{-1} respectively (Chandra, 2011).

2.2.3 Biomass Partitioning

Biomass partitioning among various tree components namely, leaf, reproductive parts, bole, twigs, branch wood and roots considerably vary with species, age and spacing. The relative allocation of biomass to various above ground parts is a decisive factor that reflects the productivity of any wooded system. Partitioning of dry matter between different components is having importance in production forestry and agroforestry systems.

2.2.3.1 *Aboveground biomass partitioning*

Biomass partitioning varies considerably in different components of the tree and among species. Jaimini and Tikkara (2001) compared the biomass partitioning of 15 multipurpose trees grown in an agroforestry system in Gujarat and found that among the trees, *Albizia lebbeck* had the maximum bole and branch wood biomass while *Acacia nilotica* var. *Cupressiformis* had the minimum values. The highest twig biomass per tree was observed in *Dalbergia sissoo* while minimum values for *Moringa oleifera*. The biomass studies conducted in a 22 year old pepper based production system with six MPTs the aboveground biomass ranged from 264 Mg ha^{-1} in the case of *Grevillea robusta* to lowest of 122 Mg ha^{-1} in the case of *Macaranga peltata* in a pepper based biomass production system (Aneesh, 2014). Devi *et al.* (2013) studied the biomass production potential of different plantation ecosystems of eight different tree species; *Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa*. Among all *Ulmus villosa* showed the maximum aboveground biomass (185.57±48.99 t ha^{-1}).

Biomass allocation also increases with increasing age but the percentage contribution of each component varies considerably. Study conducted by Tandon *et al.* (1988) in *Eucalyptus grandis* at different age reported that percentage contribution of bole biomass varied from 28% to 86% over a period of 3-9 years. In an age series of teak plantation from Madhya Pradesh showed that during initial phase of establishment, leaves contributed nearly 1/4th (24.95%) of the total biomass but with increase in age, it declined to less than 1/16th (6.01%) in the 24th year of age while a reverse trend was noticed in case of branch and stem biomass (Shukla, 2009). In *Tectona grandis*, the bole fraction accounted for 64.6% of the total aboveground biomass (AGB) at the age of 10 years, which declined to 60.2% at the end of 30th year. However, branch wood proportion substantially increased from 8.3 to 35.15% over the same period (Negi *et al.*, 1995).

Biomass Partitioning in an age series of *Gmelina arborea* (Roxb) plantations in Nigeria, stem accounted for an average of 83.6% (range: 81.8-85.7%) of total above ground biomass, while branch and foliage biomasses accounted for an average of 13.2 (range: 11.5-14.7%) and 3.3% (range: 2.4-4.2%), respectively (Onyekwelu, 2004). Changes in aboveground biomass of *Pinus halepensis* over a time period was assessed by using aerial photographs and allometric equations (Massada *et al.*, 2006). Allometric equations ere developed by using height and crown-diameter as variables and these measurements were generated from 28 harvested Aleppo pine (*Pinus halepensis*) trees. The mean tree biomass increased from 6.37 kg to 97.01 kg (1978 and 2003).

Generally bole component consist of major portion of the total tree biomass and the component wise contribution to the total aboveground biomass was highest for the bole fraction. A study conducted by Jangra *et al.* (2010) in 25 year old *Grevillea robusta,* at, Karnal revealed that biomass accumulation in different tree components was highest for bole (216.943 Mg ha^{-1}) followed by branches (41.380 $Mgha^{-1}$) and the least by foliage (7.590 Mg ha^{-1}). The percentage contribution of different tree components to the total aboveground biomass was: bole = 66.91%; branches = 12.76% foliage = 2.34%. Similarly biomass partitioning analyzed in seven-year-old *Acacia mangium* in Kerala by Kunhamu *et al.* (2011) reported component yield on per ha basis to the tune of 152.12 Mg ha^{-1} for stem wood, 37.72 Mg $ha^{-1}$for branch wood, 11.92 Mg ha^{-1} for foliage and 8.48 Mg ha^{-1} for twigs. For all the size classes, stem wood accounted for bulk of the above ground biomass (65-75%) followed by branch wood (12.5-25.2 %), foliage (5.0-6.5%) and twigs (4.1-6.5%). In a 20 year old *Grevillea robusta* plantation the stem portion is reported to have maximum biomass allocation to the above ground biomass followed by branch and the lowest were recorded for the twig portion in a for all the diameter classes (Paul, 2013). In all the six MPTs studied the stem wood was having maximum contribution to the bulk of the aboveground biomass and in all species and the percentage contribution follows the order stemwood> branchwood> twig> leaves (Aneesh, 2014).

The biomass partitioning is also influenced by spacing or planting density. Bernardo *et al.* (1998) found that with increased spacing levels the relative amount of growth allocated to the bole of the tree was decreased and increase in allocation to the root system. In widely spaced 8 year *Ailanthus triphysa* stands, branch wood and foliage biomass per tree were, 38 and 84% more in 3x3 m spacing than that of 3x1 m; yet, the highest total stand biomass of 135 Mg ha^{-1} and MAI of 13.6 Mg ha^{-1} per year were obtained in the 3 x1 m spacing. They also found that stem wood contribution was 70% and least by foliage (7%) (Shujauddin and Kumar, 2003).

A study by Shooshtari *et al.* (2011) on effects of spacing and admixture of three leguminous species on above ground biomass on sandy hills of Khuzestan, Iran with main treatments consisted of three levels of spacing (3 m × 3 m, 4 m × 4 m and 5 m × 5 m) and the secondary treatments consisted of three species (*Prosopis julijlora, Acacia victoriae* and *Acacia farensiana*) in form of pure and mixed (50%) in six levels. The result shows that the maximum total woody biomass achieved by *P. julijlora* in pure plantation in all three planting spaces. The maximum forage biomass was for *Acacia victoriae* (1719.67 kg/ha in 3 m × 3 m planting space) and least by *Acacia farnesiana* (191.33 kg/ha in 5×5 m spacing).

Biomass in the mixed plantation of *Azadirachta indica* and *Acacia auriculiformis* was 16.525 $t.hm^{-2}$. Biomass *Azadirachta indica* was 7.837 $t.hm^{-2}$; and for *Acacia auriculiformis* it was 27.802 $t.hm^{-2}$. The component wise contribution of biomass of the mixed plantation was in the order stem > branch > root > leaf > bark (Gao *et al.*, 2012). Swamy *et al.* (2012) studied the difference in performance of six agroforestry tree species with respect to their growth, biomass and carbon stock at northern transitional zone of Karnataka. Among six tree species superior growth performance was shown by *Acacia auriculiformis*, *Dalbergia sissoo* and *Azadirachta indica*. Maximum aboveground biomass was by *Acacia auriculiformis* (57.65 t/ha) followed by *Tectona grandis* (55.57 t/ha) and *Azadirachta indica* (46.10 t/ha). Plant diversity and carbon stock in a natural forest and plantation at Saraswati Reserve Forest, Haryana, India was studied by Bhalla *et al.* (2013). The study revealed that aboveground biomass ranged from 2.29 to 224.01 Mg/ha.

2.2.3.2 *Belowground biomass*

Knowledge of the quantitative assessment and structural development of root systems is essential to improve and optimize productivity of agroforestry systems (Das and Chaturvedi, 2008). The belowground biomass can make a substantial contribution to soil organic matter, carbon and nutrient cycling. According to Sanchez (1995) belowground biomass accumulation by tree roots can be very high (3 to 6 Mg $ha^{-1}yr^{-1}$).

The belowground biomass production varies among species. Study conducted by Kumar *et al.* (1998) on 8.8 year old MPTs in a woodlot experiment of the humid tropics of Kerala for estimating the root biomass reported higher root biomass in the case of *Acacia auriculiformis* (17.73 Mg ha^{-1}) and the lowest for *Leucaena leucocephala* (3.23 Mg ha^{-1}) and in silvopasture experiment *Acacia auriculiformis* produced highest root biomass of 16.3 Mg ha^{-1} and *Casuarina equisetifolia* recorded lowest value at 5 years. The study conducted by Das and Chaturvedi (2008) in five agroforestry species at Pusa Bihar found that the belowground biomass production varies among species and the total root biomass accounted for 18.2-37.9% of total tree biomass. The biomass study conducted by Aneesh (2014) in a 22 year old pepper based production system with six MPTs shows significant difference in root biomass production. *Grevillea robusta* showed higher root biomass production (63.29 Mg ha^{-1}) followed by *Acacia auriculiformis* (62.26 Mg ha^{-1}) and lowest for *Ailanthus triphysa* (24.26 Mg ha^{-1}).

And within a species the rate of biomass production depends on density or spacing, site quality and management operations. The study conducted by Samritika (2014) in 21 year old *Grevillea robusta* plantation found that mean tree root biomass production based on diameter class ranged from 12.94 to 59.81 kg $tree^{-1}$ and the mean stand level root biomass accumulation was found to be 18.45 Mg ha^{-1}.

With increasing age the rate of belowground biomass production increases and the percentage contribution of roots to the total biomass decrease gradually. Dhyani *et al.* (1990) studied the root biomass of five multipurpose tree species in an age series at Doon valley revealed that root biomass increases with age in all the species and it was directly related to above ground biomass and dbh of the plants and the percentage contribution of roots to the total biomass decreases gradually with increasing age. Study conducted by Razakamanarivo *et al.* (2012) on 9 *Eucalyptus robusta* stands (47-87 years of plantation age, 3-5 years of coppice-shoot age) and the stand biomass ranged from 102 to 130 Mg ha^{-1} with more than 77% contained in the belowground biomass components. The highest biomass of belowground was contributed by the stump (51%) followed by coarse root (42%).

Among the species, there was a wide range of variation in biomass accumulated in the main roots, lateral roots and fine roots. Coarse roots generally contribute more to total biomass than fine roots in terrestrial systems (Eamus *et al.*, 2002). Belowground coarse root biomass in four year old *Gmelina arborea* planted at four different spacing in agrisilviculture system in the subhumid region of Central India varied from 0.886 Mg ha^{-1} to 1.419 Mg ha^{-1} (Swamy *et al.*, 2003) and it decreases with increasing spacing. The coarse root (tap root + laterals) accounted for 65.0 to 78.2% of total below ground biomass. The root: shoot ratio increased with an increase in spacing. Belowground root biomass including fine roots accounted for 17.97% of total tree biomass in 25 year old plantation of *Grevillea robusta*, at, Karnal (Jangra *et al.*, 2010). The coarse roots constitute about 47 Mg ha^{-1} and the fine root biomass varied from 2.279 to 8.732 Mg ha^{-1} in different seasons. The fine root biomass was greatest in July (rainy season) coinciding with the production of high foliage biomass production.

Devi *et al.* (2013) studied the biomass production potential of different plantation ecosystems of eight different tree species; *Quercus leucotrichophora*, *Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa.* Among all *Ulmus villosa* showed the maximum belowground biomass (42.47±10.38 t ha^{-1}) production. Swamy *et al.* (2012) studied the difference in performance of six agroforestry tree species with respect to their growth, biomass and carbon stock at northern transitional zone of Karnataka. Among six tree species superior growth performance was shown by *Acacia auriculiformis, Dalbergia sissoo* and *Azadirachta indica.* Maximum belowground biomass was by *Tectona grandis* (20.25 t/ha) and followed by *Acacia auriculiformis* (14.75 t/ha) and *Azadirachta indica* (12.12 t/ha). Plant diversity and carbon stock in a natural forest and plantation at Saraswati Reserve Forest, Haryana, India was studied by Bhalla *et al.* (2013). The study revealed that belowground biomass accounted for 15.60 to 23.95% of the total tree biomass.

2.2.3.3 *Root: Shoot ratio*

The belowground living biomass in trees is assessed using root-to-shoot ratio (Nair, 2011). The lower root: shoot biomass ratio indicated that the species has a tendency of accumulating more above ground biomass for building up canopy and is still in the growing phase (Das and Chaturvedi, 2008).The ratios depends mainly on species (e.g., higher in palms than in dicot trees) and ecological regions (e.g., higher in cold than in warm climates).Mangroves accumulate large amounts of biomass in their roots, and the above-ground biomass to below-ground biomass ratio of mangrove forests is significantly low compared to that of upland forests (Komiyama *et al.*, 2008). The comparison of the data of Hase and Foelster, (1983) and Kraenzel *et al.* (2003) shows a progressive decrease in root to shoot ratio with increasing plantation age.

The ratio is different for each species. Bimlendra and Toky (2006) studied six MPT species viz. *Eucalyptus tereticornis, Acacia nilotica, Dalbergia sissoo, Ailanthus excelsa, Azadirachta indica* and *Prosopis cineraria.* Among the six the highest root and shoot ratio was reported for *Prosopis cineraria.* A comparison of root to shoot biomass ratio of nine excavated trees by Toky and Bisht, (1992) observed wide differences in the values, ranging from 0.10 in *Acacia catechu, Azadirachta* and *Melia* to 0.41 in *Albizia.* The root:shoot biomass ratio of young *Azadirachta indica* and *Acacia auriculiformis* for different restoration patterns in dry-hot valley as studied by Gao *et al.* (2012). The study revealed the root/shoot ratio of *Azadirachta indica* in the mixed plantation (0.280) was significantly smaller ($P<0.05$) than in the pure plantation (0.400) and for *Acacia auriculiformis* mixed (0.163) it was larger ($P>0.05$) than the pure plantation (0.132).

Additions of nutrients had no effect on root:shoot allocation. For example Bush (2008) studied above and belowground growth of seedlings of an early and late successional species in infertile and fertile soil. Shoot, root, and total dry mass of seedlings of *A. farnesiana* was significantly greater than in *Celtis laevigata.* Addition of nutrients increased dry masses of both species and root:shoot ratios were greater in *C. laevigata* than for *Acacia farnesiana.* Another study conducted by Raman *et al.* (2006) in *Acacia mangium* to assess the influence of FYM and fertilizers on biomass production and quality of seedlings, the highest value for root:shoot ratio was recorded in the treatment receiving lower rate of inorganic fertilizers in addition to FYM.

In a growth response study of *Acacia planifrons,* the lower root to shoot ratios and increased seedling quality index were obtained in the combined application of arbuscular mycorrhizal fungi and nitrogen fixing bacteria under nursery conditions (Karthikeyan and Muthukumar, 2006).

The root:shoot biomass ratio of five agroforestry species studied by Das and Chaturvedi (2008) at Pusa Bihar varied from 0.22 to 0.66. Similarly the root to shoot ratio of 20 year old teak plantation in panama (R:S) ranged from 0.11 to 0.23 in the nine excavated trees, with mean of 0.16 (Kraenzel *et al.*, 2003). Konopka *et al.*

(2010) studied the effect of soil waterlogging on below-ground biomass in Norway spruce. The study revealed that increase in stone content in soil decreases the root/shoot ratio, while soil waterlogging leads to an increase in this ratio.

The root:shoot ratio is also helpful to assess the carbon stored in a tree. For example Alam *et al.* (2013) studied the tree biomass across the Sudanese woodland savannah reported that the below-ground biomass C densities, estimated using root shoot ratios is averaged 33 g C m^{-2}.

2.3 CARBON SEQUESTRATION

The United Nations Framework Convention on Climate Change (UNFCCC, 2007) defines carbon sequestration as the process of removing carbon from the atmosphere and depositing it in a reservoir. Carbon dioxide is considered to be the most important greenhouse gas that plays a vital role in global warming and climate change (USEPA, 2005). The concentration of CO_2 and other greenhouse gases (GHGs) in the atmosphere has considerably increased over the last century and is set to rise further. C is accumulating in the atmosphere at a rate of 3.5 Pg (Pg = 10^{15} g or billion tons) per annum, the largest proportion of which resulting from the burning of fossil fuels and the conversion of tropical forests to agricultural production (Paustian *et al.*, 2000).

The major carbon sinks in terrestrial systems include the aboveground plant biomass, durable products derived from biomass, soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments. And forest carbon sequestration is a vital and cost effective option for reducing global greenhouse gas emissions (Newell and Stavins, 2000; Sanchez, 2000; Roshetko *et al.*, 2002; Richards and Stokes, 2004; Sharrow and Ismail, 2004; Kirby and Potvin, 2007). The total carbon stock in Indian forests amount to 10.01Gt C, the forest soil accounts for 50 per cent of the total soil carbon (FAO, 2006). The organic carbon content of Kolli forest (Eastern Ghats, India) soil varied from 1.71 to 12.59%. The total carbon stock of soil, surface litter, coarse wood debris and total above ground biomass were estimated as 5.54, 0.034, 0.001 and 4.49 Tg C, respectively (Saravanan *et al.*, 2011).

2.3.1 Plantations as potential Carbon sinks

Forest tree plantations have a potential in sequestering carbon to reduce the buildup of CO_2 in the atmosphere (IPCCC, 2001). Besides its ecological and economic functions plantations can act also as terrestrial Carbon pool. Trees play an important role in the global carbon cycle and they are important as potential carbon pools and sinks and carbon sequestration by trees is a function of their biomass production (Cannell and Dewar, 1994 and Schimel *et al.*, 2001).

Tree based systems accumulate large amount of biomass and sequester substantial amount of carbon in perennial tree components. According to Haile *et al.* (2008) the incorporation of tree in cropland and pasture would result in great net aboveground as well as belowground C-sequestration. Approximately 88 per cent of the total tree biomass in plantation and agroforestry system is stored in tree trunks as aboveground biomass, and the remaining as belowground (Sharrow and Ismail, 2004). The C sequestration potential of agroforestry systems is estimated between 12 and 228 Mg $ha^{-1}$with a median value of 95 Mg ha^{-1} (Albrecht and Kandji, 2003).

Land cover changes mainly due to tropical deforestation contribute about 25% of anthropogenic carbon (C) emissions and are the leading cause of species extinctions (Sala *et al.*, 2000; IPCC, 2001; Thomas *et al.*, 2004). The effects of these global warming and land cover changes on ecosystem functioning and human wellbeing are driving the development of mitigation initiatives at local to international levels (eg., UNEP, 1992; UNFCCC, 1997; MEA, 2005). Stem biomass values were the key factors for calculating the carbon accumulation by each plantation species, because most leaves and a great portion of branches are expected to turnover every year, ie., they represent only short term carbon storage. Average stem biomass increments were converted to total carbon content by assuming that biomass is approximately 50 % carbon (Brown and Lugo, 1982).

A survey was conducted Bin *et al.* (2012) to study the spatial distribution of carbon storage in an 8-year-old *Acacia melanoxylon* plantation in Nanning of Guangxi Zhuang Autonomous Region. Results showed that total carbon storage in the plantation ecosystem amounted to 143.06 $t.hm^{-2}$. And the contribution of various layers to the total carbon storage of the plantation was in the order; forest soil (62.24%), arbor layer (32.39%), shrub layer (3.34%) and litter layer (1.58%).

2.3.1.1 ***Aboveground Carbon sequestration***

Estimates of aboveground C-sequestration potential are based on the assumption that 45% to 50% of branch and 30% of foliage dry weight constitute C (Shepherd and Montagnini, 2001; Schroth, 2003). And aboveground carbon Sequestration is the direct manifestations of above ground biomass production (Nair *et al.*, 2010). A large number of ecological and management factors influence the rate at which the C sequestration process proceeds. However, for all plantations, the time taken to reach 95% of total equilibrium carbon storage was over 80 years, because of the limitation imposed by the slow buildup of soil organic matter (Dewar and Cannell, 1992).Variations in environmental conditions can affect carbon sequestration potential even within a relatively small geographic area (Montagnini and Nair, 2004).

Tree plantations, especially in the tropics, play an important role in carbon sequestration through the accumulation of carbon in the wood and increase in soil carbon storage. In a study of nine native and exotic taxa in the humid tropics of peninsular India, Kumar *et al.* (1998) found that the above ground carbon stock ranged from 9.9 to 172 Mg C ha^{-1} with the highest for exotic species such as *Acacia auriculiformis*, followed by *Paraserianthes falcataria*. Carbon sequestration studies conducted in 25 year old *Grevillea robusta* at Karnal by Jangra *et al.* (2010) observed higher concentration of carbon in the boles and branches followed by leaves and roots. The carbon concentration in different tree components was bole= 49.50%; branches= 48.46%, leaves= 45.57%, roots (coarse) = 42.18%, and fine roots= 43.52%. The carbon flux through total net primary productivity was 11.322 Mg C ha^{-1} yr^{-1}.

Devi *et al.* (2013) studied the carbon sequestration potential of different plantation ecosystems comprising of eight different tree species; *Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa*. Maximum aboveground carbon density was showed by *Albizia procera* (118.37±1.49 t ha^{-1}) and minimum (36.50±9.87 t ha^{-1}) in *Acacia catechu*. Swamy *et al.* (2012) studied the difference in performance of six agroforestry tree species with respect to their growth, biomass and carbon stock at northern transitional zone of Karnataka. Among six tree species maximum above ground carbon sequestration potential was observed in *Acacia auriculiformis* (13.30 t/ha) followed by *Tectona grandis* (12.20 t/ha) and *Azadirachta indica* (11.34 t/ha).

A study was conducted by Pal *et al.* (2013) to determine the long-term impact of different land uses on carbon sequestration. Soil samples were collected from existing land-use systems of *Eucalyptus tereticornis, Terminalia chebula, Acacia nilotica, Leucaena leucocephala, Embilica officinalis, Zizyphus spp*. The result shows that *Eucalyptus teriticornis* had a greater potential in sequestering aboveground carbon (472.37 Mg ha^{-1}) compared to *Acacia nilotica* (376.05 Mg ha^{-1}).

Carbon stock estimated in the aboveground biomass of three dominant mangrove species of Sundarbans follows the order *Sonneratia apetala* >*Avicennia* *alba* >*Excoecaria agallocha* and the total carbon stock vary with spatial location due to varying salinity (Mitra *et al.*, 2011).Comparative study on the storage and sequestration of carbon in leguminous trees (*Cassia siamia* and *Dalbergia sissoo*) vs. non-leguminous tree (*Tectona grandis*) in red lateritic soil of Chhattisgarh and found that carbon sequestration by leguminous trees was higher than the non-leguminous trees (Dhruw *et al.*, 2009). The Carbon concentrations of different components of eight-year-old trees were found to be 39.3-42.55, 41.06-43.3 and 40.74-46.5 and 44.4-45.3% in leaves, branches, stems and roots, respectively. The total storage of carbon ranged from 1354.7 to 3079.86 kg ha^{-1}.

Tree pruning is one of the main silvicultural strategies that influence tree growth and productivity, which determine the potential of tree stands to store C in the vegetation and soil. Kunhamu, *et al.* (2011) observed a significant reduction in vegetation carbon pool of 6.5 year-old *Acacia mangium* stands planted at four different spacing in response to pruning. Widely spaced stands showed greater reductions in C sequestration potential consequent to pruning compared to the denser or closely spaced stands.

Carbon sequestration potential of a plantation is also influenced by thinning. Normally unthinned plantations store more carbon than thinned plantations. They also accumulate carbon faster than thinned plantations over the first rotation. And the thinning also decreases the average amount of carbon stored in all carbon pools. Simulated thinned plantations of *Picea sitchensis* stored about 15% less carbon than unthinned plantations. The study also revealed that by increasing the lifetime of thinnings from 5 years to the lifetime assumed for harvested trees (57 years) increased storage in products to 44 Mg C ha^{-1}, but the total storage was still only 198 Mg C ha^{-1}, less than the 215 Mg C ha^{-1} stored by unthinned stands (Dewar and Cannell, 1992).

2.3.1.2 *Belowground biomass carbon sequestration*

Even though the quantity of carbon sequestered in the tree root is substantial, only very less species has been studied yet. Roots play an important role in C balance, because they transfer large amount of C into the soil. Fine-root dynamics are one of the least understood aspects of plant life (Strand *et al.*, 2008).Carbon sequestration studies conducted in 25 year old *Grevillea robusta* at Karnal by Jangra *et al.* (2010) observed the carbon concentration in different root components was roots (coarse) = 42.18%, and fine roots = 43.52%. In case of 20 year old teak plantation at Panama the carbon stored in their root was an average of 13.1% of carbon stored in the tree (Kraenzel *et al.*, 2003).

Kunhamu *et al.* (2011) studied the carbon sequestration potential of six MPTs in a pepper based system revealed that the belowground carbon production varies considerably among different MPTs with *Acacia auriculiformis* (30.13 Mg C ha $^{-1}$) maximum belowground carbon production followed by *Grevillea robusta* (29.64 Mg Cha $^{-1}$) and the lowest was recorded for *Ailanthus triphysa* (11.13 Mg C ha^{-1}). Another study conducted in a 6.5 year old *Acacia mangium* plantation shows that the stand based belowground carbon stocks varies with planting density and the value ranges from 15.39 Mg C ha^{-1} in closer spacing stand to 5.42 Mg C ha^{-1} in wider spacing stand. Similar study was conducted by Samritika (2014) reported stand level C sequestered in below ground biomass of 20 year old *Grevillea robusta* plantation was 8.04 Mg ha^{-1}.

Swamy *et al.* (2012) studied the difference in performance of six agroforestry tree species with respect to their growth, biomass and carbon stock at northern transitional zone of Karnataka. Among six tree species maximum below ground carbon sequestration was observed in *Tectona grandis* (4.35 t/ha) and followed by *Acacia auriculiformis* (3.95 t/ha) and *Azadirachta indica* (2.58 t/ha). Similar study conducted by Devi *et al.* (2013) in carbon sequestration potential of different plantation ecosystems comprising of eight different tree species; *Quercus leucotrichophora, Pinus roxburghii, Acacia catechu, Acacia mollissima, Albizia procera, Alnus nitida, Eucalyptus tereticornis* and *Ulmus villosa*. Soil carbon density was maximum (219.86±10.34 t ha^{-1}) in *Alnus nitida*, and minimum (170.83±20.60 t ha^{-1}) in *Pinus roxburghii*. Maximum Carbon sequestration (7.91±3.4 t ha^{-1}) and CO2 mitigation potential (29.09±12.78 t ha^{-1}) was shown by *Ulmus villosa*.

2.3.1.3 *Soil Carbon sequestration*

Soils play a major role in the global C cycle (Kumar *et al.*, 2009). Soil carbon sequestration is the net removal of atmospheric CO_2 by plants and its storage as soil organic matter. Humification, aggregation, trans-location of biomass into subsoil by deep roots, and leaching of soil inorganic C into groundwater as bicarbonates are processes that lead to SOC sequestration (Lal, 2005). Soil has a higher capacity to store C compared to vegetation and atmosphere (Bellamy *et al.*, 2005). The soil carbon sequestration in an agro ecosystem depends on large number of location and system-specific factors such as climate, soil type, vegetation, and management practices (Saha *et al.*, 2010). Carbon sequestration by soil is through two ways: direct (inorganic chemical reaction) and indirect (photosynthesis) (Soil Science Society of America, 2001). Most suitable soil for carbon storage is in fine-textured soils, where C is better protected through soil aggregation (Ingram and Fernandes, 2001). But soils have a finite sink capacity of 0.4-0.6 Pg C per year over 50-100 years (Paustian *et al.*, 2000; Ingram and Fernandes, 2001).

The amount of C sequestered at a site reflects the long-term balance between C uptake and release mechanisms (Kumar *et al.*, 2009).The soil C pool comprises soil organic C (SOC) (1550 Pg)and soil inorganic C (approximately 750 Pg) both to 1 m depth (Batjes, 1996). The soil C pool is 2300 Pg, which is 3 times the size of the atmospheric (770 Pg) and 3.8 times the size of biotic poll (610 Pg) (Lal, 2005). Along with the increase of atmospheric CO_2 the fertility of tropical soils that are generally nutrient-poor is also reduces due to the loss of organic carbon.

The C sequestration potential of trees to the soil differs among different tree species, which differ in biomass production, tissue nutrient concentrations and their effects on soil quality (Post and Kwon. 2000). Study conducted by Gower *et al.* (1997) on *Picea mariana* (black spruce) and jack pine stands in Saskatchewan and Manitoba, Canada found that soil carbon content was greatest in jack pine stands (980 kg C ha^{-1}) than black spruce stand (380 kg C ha^{-1}) and which is 87-88% of total ecosystem C content. The soil carbon stock estimated in the rhizosphere of five black pepper support trees viz *Ailanthus triphysa, Erythrina variegata, Gliricidia sepium* and *Garuga pinnata* in the humid tropics of Kerala by Dinesh *et al.* (2011) registered greater levels of soil organic C in the rhizosphere of *G. sepium* (26.5 g kg^{-1}), and the lowest level was registered under *Ailanthus triphysa* (21.6 g kg^{-1}). Soil carbon stock estimated in three MPTs interplanted coconut plot by Sreenivasan *et al.* (2010) registered highest soil carbon levels under *Leucaena* interplanted coconut followed by *Casuarina* and *Ailanthus* inter-planted plots. Moreover surface soil showed highest organic carbon percentage as compared to soil from deeper layers.

Trees and tree-based land-use systems have greater potential of soil carbon sequestration than agronomic crops. A comparison of soil carbon stock under different land use system in Kerala by Saha *et al.* (2010) reported higher SOC stocks under tree based system like Forest (177 Mg ha^{-1}), Home garden (119Mg ha^{-1}), Rubber plantation (119Mg ha^{-1}), and Coconut (91Mg ha^{-1}) compared to Rice paddy (54Mg ha^{-1}). A study was conducted by Pal *et al.* (2013) to determine the long-term impact of different land uses on carbon sequestration. Soil samples were collected from existing land-use systems of *Eucalyptus tereticornis, Terminalia chebula, Acacia nilotica, Leucaena leucocephala, Embilica officinalis, Zizyphus spp. Eucalyptus teriticornis* exhibited the greatest impact in increasing soil OC in all depths, followed by *Acaccia nilotica* and *Terminalia chebula*, and the lowest was in agriculture (0.778, 0.749, 0.590, and 0.471%, respectively, in surface soil).

In each land use system there exists depth wise difference in soil carbon distribution. Recent research has reported higher soil C stock under deeper soil profiles in tree based agroforestry systems compared to treeless agricultural or pasture systems under similar ecological settings (Haile *et al.*, 2008; Nair *et al.*, 2009). Roots help in accumulation of SOC by their decomposition (Brady and Weil, 2008) and supply C to soil through the process known as rhizodeposition. Roots are the sources of SOC in deeper soil depth, where they are better protected. The deeper root development accumulates C at lower depths and the soil at lower depths is better protected from the disturbances leading to longer residence time (Fontaine, 2007).

Plant diversity and carbon stock in a natural forest and plantation at Saraswati Reserve Forest, Haryana, India was studied by Bhalla *et al.* (2013). Total biomass carbon stock ranged from 102.57 to 141.79 Mg/ha. The carbon stock up to 60 cm soil depth was: organic carbon 32.59 to 38.21 Mg/ha and inorganic carbon 13.08 to 16.96 Mg/ha. Study conducted by Aneesh (2014) in a pepper based production system involving six MPTs revealed that soil organic carbon content decreases with depth and the highest value recorded for *Acacia auriculiformis* (71.39 Mg ha^{-1}) next by *Ailanthus triphysa* (65.56 Mg ha^{-1}) and lowest for *Grevillea robusta* (61.26Mg ha^{-1}).

In an agroforestry system the extent of soil carbon storage is also influenced by tree management practices like thinning, pruning and litter fall removal also. Several studies in tropical and temperate agroforestry systems concluded that organic matter input from tree prunings and litterfall are important because they help to maintain or increase the soil organic carbon pool. For example, Fassbender (1998) reported that in Costa Rica over a 9-year-periodthe inputs of organic material from tree prunings and litterfall in a *Theobroma cacao- E. poeppigiana-* shade tree system increased the levels of soil organic carbon from 115 to 140 Mg C ha^{-1} (to a 45 cm depth). Soil organic carbon study conducted by Samritika (2014) in a 21 year old *Grevillea robusta* plantation found 77.45 Mg C ha^{-1}.

2.4 NUTRIENT ACCUMULATION

The nutrient accumulated in a forest ecosystem depend mainly on the type of forest, species present, density, age, basal area, attitude, climate, soil conditions and the relative moisture content (Wang *et al*., 1996, Mitchell *et al*., 1996 and Das and Chaturvedi, 2003). That is the nutrient requirement of each species is different and they do not compete similarly for nutrients. Nutrient accumulation has been observed to be strongly influenced by biomass accumulation. And the amount of nutrients taken up from soil depends on species. Fast growing plantations can extract large amounts of nutrients from the soil, and site fertility declines may limit sustained plantation forestry after a few rotations.

The study conducted by Das and Chaturvedi (2003) on *Dalbergia sissoo* revealed that the nutrient content of the trees increased with plantation age because of the increase in dry matter accumulation ie, biomass production leads to considerable nutrient accumulation in the aboveground plant parts. In a study conducted by Kumar *et al.* (1998) on the nutrient accumulation (NPK) in an age series of MPTs in Kerala, *Acacia auriculiformis* had the height nutrient accumulation (1539 kg N, 1113 kg P and 623 kg K) at 7 years of age than 5 years (998 kg N, 49 kg P and 478 kg K). Similar study conducted by Mohsin *et al.* (2005) on *Populus deltoids* at 2-3 and 6-7 age found that the nutrient accumulation increased with age.

2.4.1 Nutrient concentration in plant biomass

In a tree the concentration of nutrients in different biomass components vary and is depends mainly on tree species, phonological stage, management and site factors (Schroth, 2003). The accumulation and distribution of nutrients in the plant body is affected by several factors such as age, species, soil conditions, spacing and climate (Ovington, 1968). Biomass accumulation and nutrient concentration in different tree components are used for the estimation of tree nutrient uptake and nutrient removal by harvest and are crucial for understanding of nutrient dynamics in an ecosystem (Holmquist *et al*, 2002). Nutrient concentration in plant biomass is the result of the balance between nutrient uptake, growth and nutrient retranslocation and loss. The relative importance of site and species as factors determining nutrient concentration in plant biomass may differ depending on nutrient element and biomass concentration (Thorn *et al.*, 2004).

The amount of nutrients accumulated in a tissue type also varies with increase in age. Alifragis *et al.* (2001) compared 9 pine species with an age series of 23, 48, 70, > 100 and reported that nutrient accumulation followed an increasing rate with increasing age. Wright and Will (1958) reported that Scots and Corsican pine growing on sand dunes exhibited decreasing pattern of some nutrients with age. Increased trend of nutrient contents with plantation age was largely in the order of nitrogen > potassium > calcium > magnesium > phosphorus (Kadeba, 1991). The distribution of nutrients was studied in *Bambusa bamboos* plantations of different ages growing in Kallipatty, Tamilnadu. The percentage distribution of nutrients in different biomass components varied.

Nutrient accumulation potential is different for different species and also varies with pruning. Nitrogen fixing trees normally have higher N concentrations in their biomass than non N fixing trees but this characteristic also varies widely between species (Palm 1995). Deciduous species generally have higher N concentrations in the leaves than evergreen species (Eamus, 1999). Study conducted by Tanavat *et al.* (2011) on nutrient storage in aboveground biomass and nutrient return in three 3 year old fast growing tree species planted for bio-energy revealed that among 3 species, *Acacia hybrid* have the highest nutrient in aboveground biomass (N=41.94 ton/ha) followed by *E. camaldulensis* and *L. leucocephala.* N return was also highest for *Acacia hybrid* (34.51 ton/ha) followed by *L. leucocephala* and *E. camaldulensis*. Similarly, the young leaf rich biomass of frequently pruned trees have higher nutrient concentrations than the more woody biomass of infrequently pruned trees, although the quantity of biomass produced decreased with pruning frequency (Duguma *et al.*, 1988).

In general, the order of nutrient content is reported as leaves> bark> branches> stem (Lugo and Murphy, 1986). Ranasinghe (1992) studied the distribution of nutrients in *Eucalyptus camaldulensis* plantations ranging in age from two to fourteen years, at two sites in the dry zone of Sri Lanka. There were high nutrient concentration in leaves and bark, the lowest concentration in bole (without bark). Aneesh (2014) studied six multipurpose trees shows a decreasing trend of nutrient concentration in the order leaves> twigs> branches> roots> bole. Kumar *et al.* (1998) reported marked variations in a wood lot experiment involving nine fast growing species and they observed that mineral element concentration decreased in the order: foliage > branches > roots > bole and also noticed markedly higher levels of foliar nitrogen in N- fixing leguminous trees. Shujahudin and Kumar (2003) showed that N, P, K concentration was highest in leaf followed by branchwood, course root and stem wood. Bin *et al.* (2012) studied the distribution of nutrient in middle aged *Acacia crassicarpa* and found that nutrient distribution in tree components were in the order leaves > bark > branches > roots >bole. But in case of *Dalbergia sissoo* stands growing in Himalaya the order of nutrient distribution were in the order leaf > twig > bole > branch >bole wood (Lodhiyal *et al.*, 2002).

2.4.2 Soil enrichment by trees

Tree based land use systems are more efficient in maintaining soil fertility than annual cropping system. Trees have a great potential to enrich the site through processes such as efficient nutrient cycling and nutrient pumping (Huxley, 1985; Nair, 1983). Many studies have been revealed the role of agroforestry in enriching and maintaining long term soil productivity and sustainability. The levels of soil available nutrients (N, P and K) have increased significantly under MPTs (Leucaena and Casuarina) inter planted coconut than sole coconut and coconut + ailanthus in the humid tropics of Kerala (Sreenivasan *et al.*, 2010).

Nitrogen fixing trees have the additional potential of fixing atmospheric nitrogen into the available form. And the major portion of the fixed nitrogen is probably released into the rhizosphere and is utilized by field crops. Many studies reported an increase in available nitrogen content of soils under different multipurpose trees (Puri and Barraclough, 1995; Bheemaigh *et al.*, 1995). Another study by Seiter *et al.* (1995) in a maize alley cropping system in Oregon using N-fixing red alder (*Alnusrubra*) showed that 32-58% of the total N in maize was obtained from N fixed by red alder and that nitrogen transfer increased with decreasing distance between the trees and crops.

2.4.3 Nutrient accumulation and harvest related loss

Repeated harvesting in short rotation cycles could remove considerable amount of nutrients from the site and decrease the productivity of trees by depleting the soil nutrients (Richter *et al.*, 2001; Mackensen *et al.*, 2003; Yamada *et al.*, 2004). Neither all plants have similar nutrient requirement nor do they compete similarly for nutrients there for the amount of nutrient absorbed from the soil is species specific. The other factors that depend on the nutrient losses from site are species characteristics, growth rate, tissue nutrient content, harvesting rotation period, harvesting methods and nutrient reserves in the soil. Fast growing plantations can extract large amounts of nutrients from the soil, and site fertility declines may limit sustained plantation forestry after a few rotations. Nutrient accumulation also has been observed to be strongly influenced by biomass accumulation and biomass production leads to considerable amount of nutrient accumulation in the aboveground plant parts. Nutrient removals from wood generally represented only a small percentage of available soil reserves. Nutrient content of bark was higher compared to stem wood and therefore, export of nutrients, especially of Ca and Mg as a result of wood harvesting could be significantly reduced by on site debarking (Burger, 2002).

There are many examples for the depletion of nutrients from soil by the extraction (harvest) of whole bole. Nutrient losses accompanying biomass harvest has been of great concern in the recent years, especially, in the context of planting high yield species followed by the whole tree harvesting. Loss of nutrients during harvest, especially when rotations are short, may far exceed the rate of replenishment by weathering of minerals in soils and / or by input via precipitation (Goncalves *et al.*, 1997). The nutrient cost of biomass removal is partly dependent on the nutrient characteristics of the parts of the tree removed (Kumar *et al.*, 1998). Kumar *et al.* (2005) estimated the nutrient export (N, P, K) of hedge row raised 20 year old *Bambusa bambos*, which varied highest in live clums followed by leaves, twigs and dead clums. Average N, P, K removal was 9.22, 1.22 and 14.4 kg per clump respectively. Heavy nutrient loss through harvest has been reported by Negi *et al.* (1995) for *Tectona grandis* (removal of 148 Mg ha^{-1} biomass) which resulted in the loss of 247, 41, 170, 632 and 198 kg ha^{-1} of N, P, K, Ca and Mg, respectively. Hopman *et al.* (1993) analysed the impact of harvesting on nutrients in eucalyptus ecosystem in south eastern Australia.

In a seven year old plantations of *E. tereticornis* and *E. grandis* in 4 different sites of Kerala, removal of all aboveground biomass led to potential exports of nutrients (312 % K, 619 % Ca and 764% Mg) compared with the removal of stem-wood only (Sankaran *et al.*, 2005). Shujauddin and Kumar (2003) observed a higher foliar N, P and K concentrations followed by branchwood, coarse roots and bole in an 8.8 year old *Ailanthus triphysa* stand. Significant variations in stem wood (N, P and K) and coarse root (P and K) elemental concentrations in response to tree spacing were also noticed. Nutrient analysed in a 12 year old *Eucalyptus tereticornis* planted at high-density spacings of 60x60cm by Bharadwaj *et al.* (2000) observed 1532.85 kg/ha, 196.40 kg/ha and 885.93 kg/ha of N, P and K, respectively were retained by the plantation and only 309.26 kg/ha N, 15.80 kg/ha of P and 138.80 kg/ha of K were returned in litter fall to the soil at 60 cm x 60 cm spacing. Among different tree components, the bole accumulated maximum nutrients followed by leaves and branch + twig in all the spacing treatments.

Nutrient removal due to harvest depends mainly on both nutrient concentration of tissue fraction and the biomass yield. Fast growing tropical tree plantation in cooperate considerable amounts of nutrients in their biomass over a relatively short period of time. Site fertility declines can limit sustained plantation forestry in tropical regions: soil fertility can be decreased through excessive removal of living biomass, particularly if nutrients in tree crowns are lost through harvest and site preparation (Jorgensen and Wells, 1986). This can be particularly serious when plantations are established on soils that are inherently poor. Therefore examination of the role of tropical plantations as C sinks necessitates integrative approaches to evaluate not only the rates of C sequestration by different tree species, but also their design and management to minimize potential deleterious effects on the ecosystem nutrients and to make the plantations economically, socially and environmentally sound land use system. The nutrient content of the *Dalbergia sissoo* increased with plantation age because of the increase in dry matter accumulation (Das and Chaturvedi, 2003). Nutrient use efficiency provides a good measure to evaluate the differences in nutrient costs of biomass production (Wang *et al.*, 1991and Kumar *et al.*, 1998).

2.5 BIOMASS PREDICTION EQUATIONS

The most accurate method of measurement of biomass and carbon stock of a tree or a stand is through destructive sampling (Brown *et al.*, 2004 and Saglan *et al.*, 2008). But cutting and weighing of sufficient number of trees to represent size of an ecosystem is complex, time consuming, destructive, tedious and labour intensive (Kale *et al.*, 2004 and Delittiet *et al.*, 2006). There for there is a need to develop indirect methods for estimating biomass (Lott *et al.*, 2000c; IPCC, 2003 and Saatchi *et al.*, 2007). Even though a large number of biomass equations exist for different species and forest types, new equations need to be developed for accurate estimation. The development and application of allometric equations is the standard methodology for indirect above ground tree biomass estimation (Brown *et al.*, 1989; Chave *et al.*, 2001, 2003 and Navar, 2009). These regressions are developed by measuring biomass or production of either trees or their components and regressing these data against some easily measured variable or growth parameters like dbh, height etc (Kumar *et al.*, 1998 and, Litton and Kauffman, 2008).

Over the past five decades, considerable number of allometric equations has been developed to quantify the AGB of individual trees and for the forest ecosystems (Jenkins *et al.*, 2003 and Naver, 2009). Estimates of C pools in the vegetation component of forest ecosystems can be obtained by using allometric functions (Navar *et al.*, 2002 and Perez-Quezada *et al.*, 2011). Such functions allow the estimation of plant biomass from variables that are easily and non-destructively measured, such as plant height and trunk diameter at breast height (Perez-Quezada *et al.*, 2011). Allometric equations are developed for many species including fast growing tropical species (Dudley and Fownes 1992). These biomass equations can be applied directly to develop tree level and stand level inventory data (Lehtonen *et al.*, 2004). Regression equations are widely used for predicting the tree or component biomass (Onyekwelu, 2004 and Montagu *et al.*, 2005).

The prediction equations will vary generally with species, age bole shape and wood density (Clark and Clark, 2000 and Chambers *et al.*, 2001). Relationships between tree biomass and stem allometric properties vary depending on the age of the tree, management practices, structure of the system, climate, and biophysical characteristics of the site (Lott *et al.*, 2000 and Claesson *et al.*, 2001). Location specific allometric equations of large number of tree species have been developed across age sequence. Allometric equations of 2 to 8 year old *Eucalyptus tereticornis* growing in the Tarai region of Central Himalaya were studied by Bargali (1992). Multiple regression models were found to be suitable for predicting biomass of many species including *Casurina equisetifolia* as reported by Dash *et al.* (1991) and Ghan *et al.* (1993).

Number of variables representing prediction equations is often important for tree species. Tree diameter at breast height is one often used and it has a direct relationship with aboveground biomass and volume. However, equations based on one variable ie, dbh can make fair prediction with high R^2values. Aneesh (2014) have developed allometric equation for 22 year old pepper based stand containing six MPTs by linking above ground biomass, total above ground biomass, carbon sequestration, total volume and bole volume with DBH and /or total height of the trees which gave reasonable good predictions. Among the models tried, simple linear and quadratic equations showed better fit with high R^2 value. The prediction equation for *Ailanthus triphysa* based on dbh and height recorded the higher R^2 value for biomass.

Simple linear regression of log DBH versus log dry biomass and log carbon storage developed for 20 year old teak plantation in Panama showed that these relations are strong, yielding coefficient of determination (r^2) of 0.978 for both regressions. The linear regression of DBH versus root system biomass and carbon storage showed that 87% of the variation in root biomass and carbon storage in teak plantation can be explained by DBH of the trees (Kraenzel *et al.*, 2003). Ceulemans and Xiao (2004) reported the allometric relationship of the 10 year old Scots pine (*Pinus sylvestris*) trees describing the branch and needle biomass at the branch level as well as a biomass of stems, branches, needles, coarse roots, small roots and total biomass at the tree level.

In some cases more than one variable is used for making biomass prediction equations. For example, Kunhamu *et al.* (2005) attempted regression equations linking aboveground biomass, tree volume with GBH (cm) and tree height (m) in a seven year old *Acacia mangium* stand in, Kerala. They observed that prediction equations based on single variable gave good fit with high R^2values. Similarly, Kumar *et al.*, (2005) developed allometric relationship linking clump biomass and clump number with clump diameter of 20 year old hedge rows of *Bamboosa bambos.* Samritika (2014), found that the prediction equation with high R^2 value. The best fitted prediction model for determining belowground biomass is related to dbh and height as independent variable was model ∞{In Y= a_0+a_1*InD+a_2*InH1} with highest coefficient of determination (0.879).

Gurumurthi and Rawat (1989) estimated both dbh and height as independent variables gave best equations for predicting biomass of *Casuarina equisetifolia*. The diameter and height are used as predictor variable for the biomass prediction equation. For *Eucalyptus pilularis*, Montagu *et al.* (2005) observed that using dbh alone as the predictor variable produced the most stable relationship. The inclusion of height as a second predictor variable decreased the performance of the general model dbh alone can be an independent variable for the purpose of prediction of biomass (Dudley and Fownes, 1992 and Rana *et al.*, 2001)

Roy *et al.* (2006) calculated the biomass prediction equation based on regression analysis with D^2DBH and D^2H were developed in eight year old *Melia azadirach* planted on farm boundaries. The relationship of bole and total aerial biomass was found to be strong with all the predictor variables whereas relationship of foliage was strong with D^2 and D^2H only. Thapa (2005) developed prediction models for above ground wood of some fast growing trees *Acacia auriculiformis*, *Acacia catechu, Dalbergia sissoo, Eucalyptus camaldulensis* and *Eucalyptus terticornis* was conducted on a five and half years old Fuel wood species trial under short rotation. Among the six models tested, the transferred model Ln W= a+b Ln DBH from a power equation W=a DBH_b was selected. The quadratic prediction model of leaf branch yield with two variables (dbh and crown diameter) was reliable predictor of leaf branch yield of thirteen agroforestry species suitable to Himalayan areas was estimated by Gupta *et al.* (1990).

Allometric equations were developed by Bakhtiari and Sohrabi (2012) for estimating carbon content at above and below ground and whole tree biomass for four species, including *Morusalba, Robinia pseudoacacia, Pinus eldarica* and *Cupressus arizonica.* Allometric relationships between independent variables and carbon storage of different components and whole tree were established by nonlinear regression analysis. DBH for Pine and Cypress and diameter at 0.3 m for Mulberry established models with highest coefficient of determination at all cases. For Black Locust, there was not special variable which can establish model with high coefficient of determination in all cases. For estimating the whole above- and below ground carbon storage of different organs highest coefficient of determination was shown by tree height. Generally coniferous have higher coefficient of determination of modeling rather than for broadleaved species. Allometric equation and carbon sequestration of *Acacia mangium* Willd were studied by Ilyas (2013) in coal mining reclamation areas. The contribution of carbon by stem, branch and leaf biomass of *Acacia mangium* were 67%, 19% and 14% respectively. Allometric expressions of diameter breast height and stem volume for *Acacia mangium* stand is $Y=0,000004\ X^{2.7126}$ with correlation coefficient R^2=0.9838.

2.6 ROOT DISTRIBUTION PATTERN

Information on the root distribution of active roots is a pre-requisite for formulating a rational method for fertilizer application (Wahid *et al.,* 1989). The distribution of root systems through space and time is usually influenced by the genetic character of a species, silvicultural management, and localized soil conditions (Huck 1983). Root distribution pattern is important in understanding the extent of soil space explored by component species in polyculture in view of the competition or complimentary root level interactions taking place among them (Willey, 1979). For the proper designing and management of a sustainable agroforestry system we should have knowledge of the size of the resource pool, their accessibility to the system components and the concept of resource sharing between and among the components (Buck, 1986). And for the effective resource sharing both temporal and spatial arrangement should be considered i.e. selection of tree or crop species with differential root system behavior and at different time period. The lateral spread of trees is affected mainly by the planting space and trees with wider spacing are having longer lateral roots or lateral spread.

The root excavation method probably gives a clear picture of the entire root system of a plant as it exists naturally. It gives the length, size, shape, colour, distribution of each individual root, also it gives the inter-relationship between competing root systems of other plants (Coker, 1959 and Kolesnikov, 1971) and also it is capable of characterising the functional roots (physiologically active roots). It is usually practiced for woody trees and shrubs than for annual crops (Bohm, 1979). However, the excavation methods are laborious and time consuming.

The management practices such as pruning, planting density, fertilization, and tillage can have important effects on the vertical distribution of roots in tree-based cropping systems (Lehmann, 2002). Peter and Lehmann (2000) reported reduction in root length density at all depths and lateral positions of hedgerow plantings of *Acacia saligna* after tree pruning as a result of the lowering the supply of assimilates from the leaves and retrains locating sugars to above-ground organs. Similarly Fownes and Anderson (1991) reported reduction of the root length density following pruning in the case of *Sesbania sesban* and *Leucaena leucocephala*.

Jamaludheen, (1994) studied root distribution in eight-year-old trees of nine MPTs in humid tropics of Kerala through direct excavation method and reported highest lateral spread in the case of *Artocarpus heterophyllus* (304.7cm) followed by *Phyllanthus emblica* (206.7cm) and the lowest lateral spread in the case of *Ailanthus triphysa* (76 cm). The length of tap root ranged from 153 cm in the case of *Emblica officinalis* followed by *Artocarpus heterophyllus* (120cm) and *Ailanthus triphysa* (115cm) and the lowest was reported for *Casuarina equisetifolia* (60 cm). Root distribution pattern studied in four year old *Gmelina arborea* planted at four different spacing in agrisilviculture system in the sub humid region of Central India showed that most of the coarse roots were distributed in the top 40 cm of soil, whereas fine roots were concentrated in the top 20 cm (Swamy *et al.*, 2003). The lateral spread of root systems was confined beneath the tree canopy in the case of 2 m x 2 m and 2 m x 3 m stands. However in the case of widely spaced stands that extends beyond canopy. The average depth of coarse roots increased from 35 cm at 2 m x 2 m spacing to 75 cm at 2 m x 5 m spacing.

A study conducted by Schumacher *et al.* (2003) in a 18-month-old *Acacia mearnsii* plantation in Rio Grande doSul, Brazil found that as the soil depth increases, root biomass and root density increases. Approximately 78.8% of the roots were observed in the 30 cm soil depth and 99% of the roots has a diameter < 1.0 mm. Dhyani and Tripathi, (2000) observed large variation in the root configuration of four multipurpose tree species studied with regard to rooting depth, fraction of fine and coarse root biomass at different soil depths and distance from tree in an agrisilviculture system in north east India.

Root distribution studies carried out by Suresh and Khan (2007) in an18-year old silvopastoral systems with trees *Acacia tortilis*, *Leucaena leucocephala*, *Hardwickia binata*, *Albizia amara*, and *Albizia lebbeck* found out that the mode biomass accumulation in roots varied among species and depths. The density of roots decreased significantly with increase in depth from 10-30 cm. Root density was highest in *Albizia amara* and lowest in *Albizia lebbeck*. Rooting characteristics studied in 10 year-old Tea - *Grevillea robusta* based system in Western Ghat, Munnar showed a spatial segregation of coarse and fine roots in *Grevillea robusta*. The coarse roots were abundant near the soil surface than the feeder (fine) roots. The tree component had only a relatively smaller proportion (33%) of their fine roots in surface (0 to 22.5 cm) and sub-surface (22.5 to 45.0 cm) layers of the soil and the feeder roots of *G. robusta* (67%) were mostly found in the soil layers below 45 cm (Niranjana and Viswanath, 2008).

Chaturvedi *et al.* (2008) compared the root distribution (coarse and fine roots) pattern of an agrisilviculture system of *A. lenticularis* and turmeric (*Curcuma domestica*) in a 4-year-old *A. lenticularis* plantation at a spacing of 2 m × 2 m, 2 m ×3 m, 2 m × 4 m and 2 m ×5 m. Most of the coarse roots were distributed in the top 40 cm of soil, whereas fine roots were concentrated in the top 20 cm. Coarse root biomass decreased with an increase in spacing. Root spread was asymmetrical for trees planted at 2 m × 2 m and 2 m × 3 m spacing, while it was symmetrical in trees planted at wide spacing.

Another study by Das and Chaturvedi, (2008) on a large variation in root depth and horizontal root spread in four-year-old individuals of five agroforestry tree species viz. *Acacia auriculiformis*, *Azadirachta indica*, *Bauhinia variegata*, *Bombax ceiba* and *Wendlandia exserta* studied at Pusa, Bihar. The root depth was maximum for *W. exserta* (2.10 m) and minimum in *B. variegata* (1.00 m). Horizontal root spread was maximum for *Acacia auriculiformis* (8.05m) and minimum in *Bombax ceiba* (2.05 m). In all the species the root spread exceeded crown cover and primary roots were more horizontal than the secondary ones. The maximum length and diameter of the main root were highest in *A. indica* (108.3 cm) and B. ceiba (23.2 cm), respectively. Highest length and diameter of lateral roots were recorded in B. variegata (201.6 cm) and *A. indica* (1.8 cm) respectively.

Trenching technique has been used to characterise the root distribution pattern of trees in relation to their diameter and crown spread. Tomlison *et al.* (1998) also employed spiral trenching technique for investigating the root distribution pattern of *Parkia biglobosa*. They found that the tree roots extended upto 10 m from the trunk, there by exploiting an area twice that of the crown. The study by Samritika (2014) on the root distribution of *Grevillea robusta* revealed that about 74.51% of roots within a section comprising a depth of 30 cm and lateral distance of 2.97 m. The rooting intensity was found to be negligible beyond a lateral distance of 2.90 m. A study involving six multipurpose trees in Kerala reported maximum rooting depth for *Artocarpus heterophyllus* and minimum for *Grevillea robusta*. Root spread was also highest for *Artocarpus heterophyllus* followed by *Macaranga peltata* (93.67cm), *Grevillea robusta* (68.33cm) and *Ailanthus triphysa* (67.67cm) and minimum for *Casuarina equisetifolia* (55cm) (Aneesh, 2014).

Methods involving radioactive isotopes have gained significance in ecological root research considering the limitations of excavation approach and it is more precise and informative. ^{32}P is the most commonly used isotope because of its short half-life period (14.3 days). It is also mobile in plants to become rather uniformly distributed in root system in a short time and is relatively less expensive. Root distribution studied in eight and a half year old *Artocarpus hirsutus* through selective placement of ^{32}P at various depths and lateral distances from the tree reported the presence of physiologically active roots upto 2.25m from the trunk even though most of the physiologically active roots were concentrated within a radius of 75 cm radius (Jamaludheen *et al.*, 1997).

Kunhamu *et al.* (2010) studied the pattern of root activity in two-year-old *Acacia mangium* using ^{32}P soil injection technique by observing the spatial variations in the distribution pattern of physiologically active roots under varying planting density and pruning regimes. High stand density of *Acacia mangium* induces greater root uptake capacity close to the stem and from the subsoil compared to low density stands suggesting the restricted spread of absorbing roots in high density stands. Similarly root pattern study conducted in a 20 year old *Grevillea robusta* plantation using ^{32}P soil injection revealed that in *G. robusta* trees the active foraging zone use within top 30 cm depth and 150 cm lateral distance (Samritika, 2014).

Materials and Methods

MATERIALS AND METHODS

The study entitled "Biomass production and root distribution pattern of selected acacias" was carried out with the objective of assessment of aboveground and belowground biomass, root distribution pattern, soil and plant nutrient dynamics, soil and plant C sequestration and development of allometric equations. The materials used and the methods followed in the study are furnished hereunder.

3.1 LOCATION

The study was conducted in an eighteen year old acacia plantation established during 1996 at the arboretum of College of Forestry, Vellanikkara, Thrissur, Kerala (between 10^0 32' North latitude and 76^0 16' East longitude.). The area has an elevation of 23 m above mean sea level.

3.2 CLIMATE AND SOIL

The experimental site has a warm humid climate, having mean annual rainfall of 239.08 cm (average past 21 years i.e. from 1991-2012), most of which is received during South West monsoon (June to August). The mean maximum temperature ranges from 29.10°C (July) to 35.49°C (March) and the mean minimum temperature varies from 22.19 °C (December) to 24.83°C (April). Soil is laterite in origin with a pH of 5.45.

3.3 EXPERIMENTAL MATERIAL

The experimental area was developed as part of a provenance comparison trial of four species of acacias namely *Acacia auriculiformis*, *Acacia mangium*, *Acacia crassicarpa* and *Acacia aulacocarpa* planted at a spacing of 3m×3m. The plantation was established during 1996 with seeds obtained from the Australian Tree Seed Centre, Division of Forestry, CSIRO, Australia.

Plate 1. An over-view of 18-year-old acacia plantation at Vellanikkara, Thrissur.

3.4 EXPERIMENTAL DESIGN

The experiment was laid out in a Randomized Complete Block Design (RCBD). The treatments selected for the research work are four species of acacias (*Acacia auriculiformis*, *Acacia mangium*, *Acacia crassicarpa* and *Acacia aulacocarpa*) with 3m×3m spacing. Twenty trees from each species, thus a total of 80 trees, were selected for the species-wise comparison of the aboveground biomass production and the nutrient status. For the assessment of belowground biomass and root distribution pattern, four trees from each species, thus a total of 16 trees, were excavated following the procedure as described by Bohm, *et al.* (1979).

3.5 BRIEF DESCRIPTION ABOUT SELECTED ACACIAS

The genus Acacia includes more than 1000 species of trees and shrubs distributed in Australia, Africa, Asia and America with majority of the species found in Australia. The genus includes climbers also which are distributed mainly in the warmer and drier regions of the world, chiefly in Australia and Africa. About 40 species occur in India; in addition a few more have been introduced from Australia and Africa.

3.5.1 *Acacia mangium* Willd.

Acacia mangium Willd. is a leguminous tree species indigenous to Australia and was unknown as an exotic until 1966 when it was first introduced into Sabah, Malaysia by D. I. Nicholson, an Ausrtalian forester. *Acacia mangium* has a fragmented natural distribution which stretches from Indonesia to Irian Java, the Western province of Papua New Guinea (PNG), and North East Queensland in Australia. The wood is mainly used for furniture, construction purposes and in paper and pulp manufacture. Because of its density and calorific value (4800-4900 Kcal/kg), the wood is also useful as an excellent fuelwood.

3.5.2 *Acacia auriculiformis* A. Cunn. ex Benth.

A medium sized tree reaching about 30 m in height and 90 cm in diameter. It is an exotic from Papua New Guinea and Australia. The species has become naturalized in many parts of India including Kerala. *A. auriculiformis* grows successfully in all types of soil and climate. Wood is mainly used for furniture and construction purposes.

3.5.3 *Acacia crassicarpa* A. Cunn. ex Benth.

A. crassicarpa occur along the north east coast and Hinterland of Queensland. It is found in north of 20°S and extends to the tip of Cape York Peninsula close to the sea and on offshore Islands. It is widely spread in the Western Provenance of Papua New Guinea and Indonesia. Main occurrences are in the hot humid climatic zones with limited areas in the hot and warm humid zones. The wood is attractive and excellent for fuelwood and furniture.

3.5.4 *Acacia aulacocarpa* A. Cunn. ex Benth.

The specific name of this species *A. aulacocarpa.* Cunn. Ex. Benth refers to the prominent furrowing and thickened transverse bands on the pod. The tree is fast growing, capable of tolerating a wide variety of infertile sites in the humid and sub-humid tropics. It is found in the adjacent areas of Iriyan Java, Indonesia and western province of Papua New Guinea. The wood is attractive for furniture and cabinet making and is good fuel also.

3.6 FIELD EXPERIMENT

3.6.1 Tree allometric observations

The growth observations taken from the 18-year-old acacia stand include total tree height and DBH. For that purpose all the trees in the stand were serially numbered and marking was done with paint. The preliminary observations on girth and height of the standing trees were measured by means of tape and Haga Altimeter. Since the growth observations prior to the felling showed considerable heterogeneity, trees were grouped into different diameter classes (40-70 cm, 71-100 cm and 101-130 cm) for all the four acacia species. Boarder plants were excluded from the measurement in order to avoid the edge effect. For each species, 20 trees were selected for the above ground biomass estimation and four trees for assessing belowground biomass and root distribution pattern of the four acacia species. The number of trees selected from each diameter class was worked out in accordance with frequency of trees in each diameter classes so as to give proportionate representation of all the diameter classes.

3.7 VOLUME ESTIMATION OF FELLED TREES

For estimating the volume of felled trees, the trees were divided into 2m section up to the tip of the tree and midgirth of each 2m section was recorded. The volume of each section was estimated following Huber's formula, $(g^2/4\pi) \times L$ (where, g is the midgirth of each sections and L is the length of the section). Volume of each section was added up to obtain the total volume and volume corresponding to the bole height. Stand volume per ha was derived at by multiplying the mean tree volume with number of trees per ha.

3.8 BIOMASS ESTIMATION

3.8.1 Aboveground biomass estimation

For estimating the aboveground biomass, a total of 80 trees were destructively sampled, such that there were 20 trees each from all the four species of acacias (4x20=80). After recording the total height and diameter at breast height (dbh), the trees were felled at ground level by using power saw.The above ground portions of the felled trees were separated into the biomass components such as stem wood, branchwood, twigs and foliage. Fresh weights of the above components were recorded immediately after felling using appropriate spring scales (nearest to 0.1kg or 10 mg). Triplicate samples (250g each) of stem wood, branchwood, twigs and foliage were collected from all the felled trees and transferred to laboratory in double-sealed polythene bags and fresh weights

Plate 2. Separation of biomass components (leaf, twig, branchwood and bole).

Plate 3. Weighing of logs in the field for biomass estimation.

Plate 4. Fresh bole discs collected from the field.

Plate 5. Sample collection (leaf, twig, branchwood and bole) from the field.

recorded soon. The samples were oven dried at 70°C for constant weights and dry weights recorded for moisture estimation. Estimates of biomass dry weight were obtained from the fresh weights of various tissue types (stem, branchwood, twig and leaf) and from their corresponding moisture contents. Biomass of tree parts was summed up to obtain the total above ground biomass per tree. Then the average biomass per tree (mean tree biomass) was multiplied by the number of trees per hectare and expressed the biomass on hectare basis.

$$\text{Moisture \%} = \frac{\text{Fresh weight (g)} - \text{Dry weight (g)}}{\text{Fresh weight}} \times 100$$

$$\text{Dry matter (kg)} = \frac{\text{Dry weight of the sample (g)}}{\text{Fresh weight of the sample (g)}} \times \text{Fresh weight of the tree (kg)}$$

3.8.2 Belowground biomass estimation

The belowground biomass was estimated following root excavation technique. Average sized, four trees each from all the four species, thus making a total of 16 trees, were excavated using JCB for estimation of belowground biomass (up to 1.4 cm root diameter) and the fresh weights were recorded after thorough cleaning. Triplicate samples (250 g each, covering small, medium and large roots) were collected for moisture and chemical analyses. Dry weight of the roots was derived from the fresh weights of the roots and their corresponding moisture contents.

3.9 BIOMASS C- SEQUESTRATION

Elemental Carbon in different biomass fractions of trees were analyzed by Dry-ash method. Triplicate samples of each tissue types (stem, branchwood, twig, leaf and root) were analyzed for total carbon. Carbon concentration in different components were tabulated and statistically analyzed. Biomass C stock in the different tree component parts were calculated by multiplying their oven dry

Plate 6. A view of the Soil profile (1 meter depth) after sample collection.

Plate 7. Cleaning of excavated tree roots.

biomass with the corresponding carbon concentration. Total for whole tree were obtained by adding the component parts. Stand level biomass C stock were estimated by multiplying the average C stock per tree with the number of trees per hectare.

3.10 ROOT DISTRIBUTION PATTERN

Four trees from each species were excavated following the method of Bohm (1979) by using JCB. For estimating the root distribution pattern the length of tap root and maximum lateral spread were recorded.

3.11 PHYTOCHEMICAL ANALYSIS

In order to estimate the nutrient accumulation in the aboveground and belowground biomass, triplicate samples of different tissue types (bole, branchwood, twig, leaf and coarse root) were analyzed for C, N, P and K. Three samples were drawn from the composite samples for phytochemical analysis. The collected samples were oven dried for a constant weight at 72 ^{0}C and the samples were converted into powder form for the analysis. Nutrient accumulation in the tree component parts were calculated by multiplying their oven dry biomass with the corresponding nutrient concentrations. Total for whole tree were obtained by summing up the component parts. Mean nutrient accumulation per tree then was multiplied by the number of trees and expressed as nutrient accumulation per hectare. The nutrient concentration of each tissue types were multiplied with corresponding biomass to get the nutrient accumulation in different biomass fractions.

3.11.1 Organic carbon

Organic carbon content in the tree components were determined by using dry ash method in a muffle furnace. Ten gram of the sample was weighed in a crucible. The crucibles were then placed inside the muffle furnace and heated at 506^{0}C for 6 hours. Thereafter, crucibles were taken out and the residual weight was calculated to determine the carbon content (Walkley and Black method; Jackson, 1958).

3.11.2 Total nitrogen

Total nitrogen content in plant samples was determined by using Continuous flow analyzer (SKALAR).

Sulphuric acid and Selenium powder mixture - One liter of conc. H_2SO_4 was poured carefully and into a two liter beaker. Selenium powder (3.5g) was then dissolved into the H_2SO_4 by heating the beaker for 4 to 5 hours at 300^0C. The black colour of the solution changed to deep blue colour and then light yellow. The solution was then cooled.

Digestion mixture -10.8 g salicylic acid was weighed and added into 150 ml of H_2SO_4 and Selenium mixture which was already prepared.

For estimation of N, 0.3g of the leaf sample was taken in the digestion tube. Then 2.5 ml of the digestion mixture was poured into the digestion tube. The tube was then swirled well and allowed to stand for 2 hours or overnight. It was then inserted into the digestion block and heated at 100^0C for 2 hours. After cooling, the tubes were removed from the block and 1 ml of 30% H_2O_2 was added. After the reaction ceased, they were again placed in the digestion block and heated at 330^0C for 2 hours. When the digest turned colourless, the digest was made upto 75 ml in a standard flask. The reagents were added and the readings were then read directly from the Continuous flow analyzer.

3.11.3 Phosphorous

Total phosphorous content in plant samples was also determined by using Continuous flow analyzer. The digestion mixture and the procedure followed for digestion were same as described for nitrogen.

3.11.4 Available Potassium

The potassium content was estimated in a known aliquot of diacid extract using flame photometer (Jackson, 1958).

3.12 SOIL ANALYSIS

3.12.1 Soil C- sequestration

For estimating the soil C stock, soil samples were collected from five plots (4 treatments +1 control). Triplicate soil samples were collected from five soil depths viz. 0-20, 21-40, 41-60, 61-80 and 81-100 cm from the top. The samples were stored in plastic zip lock bags, sealed for transport and re-opened within 24 hours. Samples were air-dried and sieved in a 2 mm sieve prior to the analysis. The soil organic carbon was analyzed following wet digestion method (Walkley and Black method; Jackson, 1958). A separate set of undisturbed soil cores were also collected for determining the bulk density by inserting a steel cylinder of known volume upto the above depths mentioned (Jackson, 1958). The soil was oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of the soil. Soil C-sequestration was calculated for each soil depth by multiplying soil mass with soil organic C-concentration (%). Also, representative triplicate soil samples were collected from contiguous treeless plots as a control.

3.12.2 Soil nutrient analysis

Composite soil samples were collected from each tree plot from five soil depths viz. 0-20, 21-40, 41-60, 61-80 and 81-100 cm. They were air-dried and ground to pass through a 2 mm sieve. Triplicate samples were drawn from the composite samples and analyzed for total nitrogen total phosphorus (both by continuous flow analyzer) and the total potassium by flame photometry (Jackson, 1958). Representative triplicate soil samples were also collected from contiguous treeless plots as control.

Plate 8. Muffle furnace for estimating plant carbon.

Plate 9. Flame photometer for estimating exchangeable potassium.

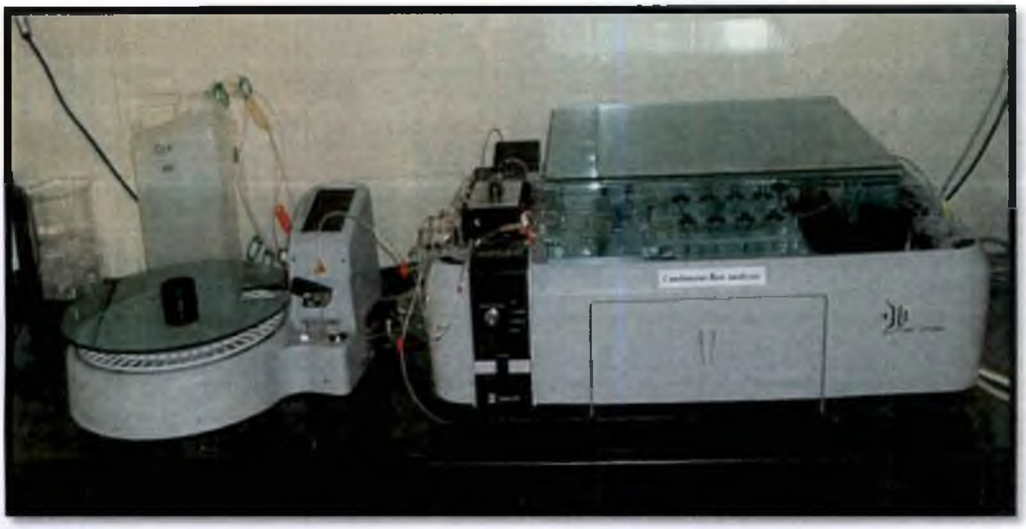


Plate 10. Continuous flow analyzer for plant and soil nutrient estimation.

3.13 ALLOMETRIC EQUATIONS

The data on aboveground biomass, biomass C sequestration and volume obtained from all the sampled trees were used to develop the allometric equations. Simple, linear, quadratic and cubic equations were attempted for predicting the total aboveground biomass, total aboveground biomass C sequestration, total mean tree volume and bole volume using tree height and dbh as predictor variables.

3.14 STATISTICAL ANALYSIS

Biomass, phytochemical and soil data were analysed following the one way ANOVA technique (using SPSS V.20.0). LSD test was used to compare mean biomass yield, nutrient concentration, nutrient content of tree parts and the soil parameters.

Results

RESULTS

Results of the study entitled "Biomass production and root distribution pattern of selected acacias" are presented in this chapter. The field experiment was conducted with four species of acacias namely; *A. mangium*, *A. auriculiformis*, *A. aulacocarpa* and *A. crassicarpa*. It included assessment of aboveground and belowground biomass, soil and plant nutrient dynamics, carbon sequestration and root distribution pattern. The detailed results are furnished hereunder.

4.1 Tree growth

Aboveground morphometric data of four acacia species of 18 years of age are presented in Table 1. All growth parameters except DBH (diameter at breast height) showed significant variation among species. Total tree height and clean bole height shows significant variations among different acacias. Maximum tree height was registered for *A. aulacocarpa* (22.40m) immediately followed by *A. auriculiformis* (21.55m) and *A. mangium* (21.05m). The lowest total tree height was recorded in *A. crassicarpa* and was statistically distinct from all other species.

With respect to bole height also *A. aulacocarpa* recorded the maximum value (13.85 m) followed by *A. mangium* (11.50 m) and *A. crassicarpa* recorded lowest value of 9.85 m. The maximum DBH was registered for *A. mangium* (27.15 cm) and lowest for *A. crassicarpa* (24.75 cm). There was no significant difference in DBH of different acacias at 18 years of age.

Table.1. Mean growth characteristics of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	DBH (cm)	Total Tree Height (m)	Clean Bole Height (m)
A. mangium	27.15 (1.43)	21.05^{a} (1.06)	11.50^{ab} (0.89)
A. auriculiformis	26.51(1.32)	21.55^{a} (1.01)	11.05^{b} (1.02)
A. aulacocarpa	27.07(1.44)	22.40^{a} (0.67)	13.85^{a} (0.69)
A. crassicarpa	24.75(1.62)	18.25^{b} (1.07)	9.85^{b} (0.72)
F test	*(ns)*	*	*
P value	0.624	0.020	0.01

ns – non significant at 0.05 level

** Significant at 0.05 level*

Values in parenthesis are standard error of the mean.

4.1.1 Volume

Highest mean tree volume production was recorded for *A. aulacocarpa* (0.625 m^3) followed by *A. mangium* (0.545m^3) and *A. auriculiformis* (0.526m^3). The lowest mean tree volume production of 0.413 m^3 was shown by *A. crassicarpa* (Table. 2 and Fig.1). There was significant variation among species for bole volume production. Maximum bole volume was registered for *A. aulacocarpa* (0.516m^3) and lowest for *A. crassicarpa* (0.334m^3). *Acacia mangium* and *A. auriculiformis* recorded a mean bole volume of 0.407m^3 and 0.414m^3 respectively which were at par.

Table 2. Mean tree volume and bole volume of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Bole volume (m^3)	Mean tree volume (m^3)
A. mangium	0.407^{ab} (0.060)	0.545 (0.074)
A. auriculiformis	0.414^{ab} (0.067)	0.526 (0.071)
A. aulacocarpa	0.516^{a} (0.056)	0.625 (0.068)
A. crassicarpa	0.334^{b} (0.054)	0.413 (0.063)
F test	*	*(ns)*
P value	0.02	0.203

ns – non-significant at 0.05 level

** significant at 0.05 level*

Values in parenthesis are standard error of the mean.

4.1.2 Stand volume and Mean Annual Increment (MAI)

Table.3 shows the stand volume and mean annual increment (MAI) of four acacia species. They showed similar trend as mean tree volume production with *A. aulacocarpa* recording maximum stand volume of 694.05 m^3 ha^{-1} with mean annual increment of 38.558 m^3 $ha^{-1}yr^{-1}$. This was followed by *A. mangium* with stand volume of 605.302 m^3 $ha^{-1}$and MAI of 33.627 m^3 $ha^{-1}yr^{-1}$ and *A. auriculiformis* stand with 584.392 m^3 ha^{-1} and 32.466 m^3 $ha^{-1}yr^{-1}$ while the minimum stand volume was recorded in *A. crassicarpa* (459.202 m^3 ha^{-1}) with a MAI of 25.51 m^3 $ha^{-1}yr^{-1}$.

Table 3. Stand volume and MAI in volume of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Stand volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})
A. mangium	605.302	33.627
A. auriculiformis	584.392	32.466
A. aulacocarpa	694.050	38.558
A. crassicarpa	459.202	25.511
F test	*(ns)*	*(ns)*
P value	0.203	0.203

ns – non-significant at 0.05 level

4.2 Biomass accumulation

The biomass production for four acacia species at 18 years of stand age are presented in Table.4. Mean tree aboveground biomass (AGBM), belowground biomass (BGBM) and total biomass were calculated for all four species (Fig.3). Among the species, the maximum mean total biomass accumulation (388.9 kg $tree^{-1}$) and mean tree AGBM (302.69 kg $tree^{-1}$) were registered for *A. auriculiformis* followed by *A. aulacocarpa* (365.5kg $tree^{-1}$, 297.1 kg $tree^{-1}$) and *A. mangium* (331kg $tree^{-1}$, 270.7 kg $tree^{-1}$). *Acacia crassicarpa* recorded the lowest total biomass of 322.3kg $tree^{-1}$ and 248.3 kg $tree^{-1}$ of total aboveground biomass production. In the case of mean tree BGBM production highest value was recorded for *A. auriculiformis* (86.2 kg $tree^{-1}$) and lowest for *A. mangium* (62.4 kg $tree^{-1}$).

Table 4 Mean tree biomass accumulation (kg $tree^{-1}$) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	**Total above ground biomass (kg $tree^{-1}$)**	**Total belowground biomass (kg $tree^{-1}$)**	**Total biomass (kg $tree^{-1}$)**
A. mangium	270.78(81.80)	62.41 (18.85)	331.02
A. auriculiformis	302.69(77.83)	86.22(22.17)	388.91
A. aulacocarpa	297.41(81.36)	68.31(18.69)	365.54
A. crassicarpa	248.38 (77.06)	73.95(22.94)	322.32
F test	*(ns)*	*(ns)*	*(ns)*
P value	0.755	0.904	0.856

*ns – non significant at 0.05 level, * significant at 0.05 level*

Values in parenthesis indicate the percentage contribution to the total mean tree biomass

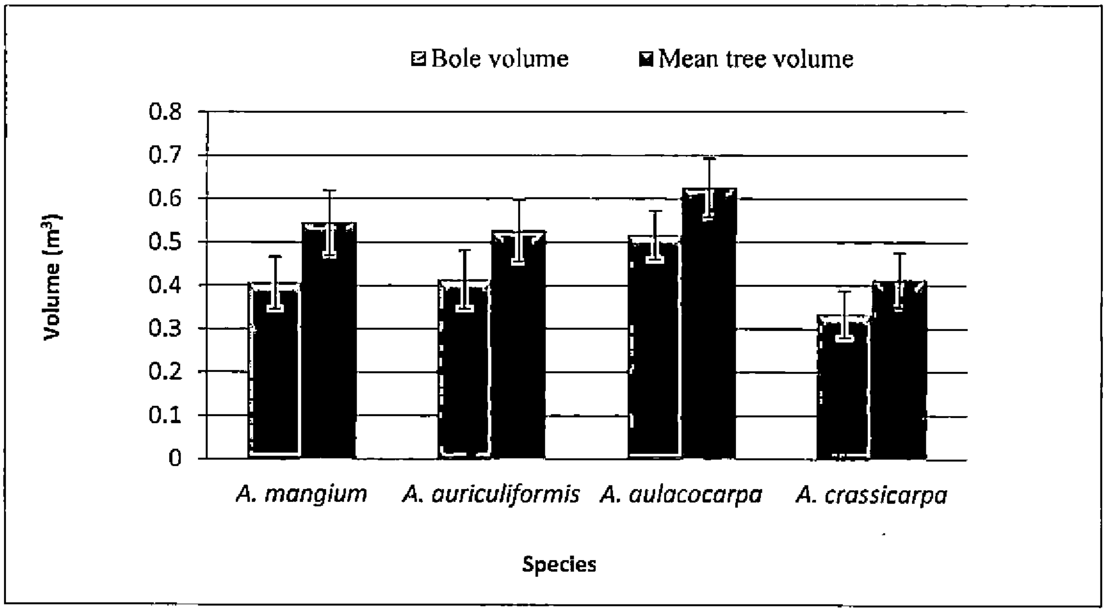


Figure 1. Mean tree volume and bole volume of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

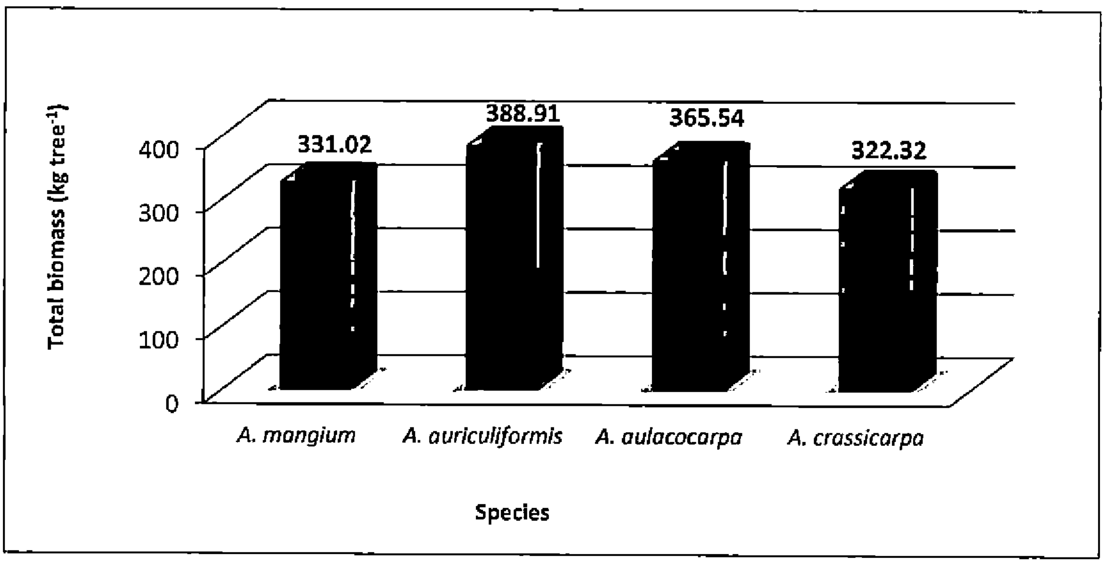


Figure 2. Mean tree total biomass (kg tree^{-1}) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

4.2.1 Biomass partitioning of trees

Table.5 shows the allocation of biomass to different components viz. bole, branchwood, twig, leaf and root and their percentage contribution to total biomass (Fig.4). Invariably bole constituted the highest percentage to the total biomass in all the species and its contribution varies from 64.52 % in *A. crassicarpa* (207.95 kg tree^{-1}) to 71.86% in *A. aulacocarpa* (262.66 kg tree^{-1}).

Table 5. Partitioning of mean tree biomass (kg) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Biomass in different tree components (kg)				
	Bole	Branch	Twig	Leaf	Root
A. mangium	230.63 (69.67)	31.09 (9.39)	4.07^{b} (1.23)	2.83^{b} (0.85)	62.41 (18.85)
A. auriculiformis	263.40 (67.73)	26.20 (6.74)	9.21^{a} (2.37)	3.88^{ab} (1.00)	86.22 (22.17)
A. aulacocarpa	262.66 (71.86)	25.42 (6.95)	5.82^{ab} (1.59)	3.34^{ab} (0.91)	68.31 (18.69)
A. crassicarpa	207.95 (64.52)	29.09 (9.03)	6.65^{ab} (2.06)	4.69^{a} (1.46)	73.95 (22.94)
F test	*(ns)*	*(ns)*	*	*	*(ns)*
P value	0.628	0.872	0.021	0.026	0.822

*ns – non significant at 0.05 level, * significant at 0.05 level*

Values in parenthesis indicate the percentage contribution of tree components to the total mean tree biomass.

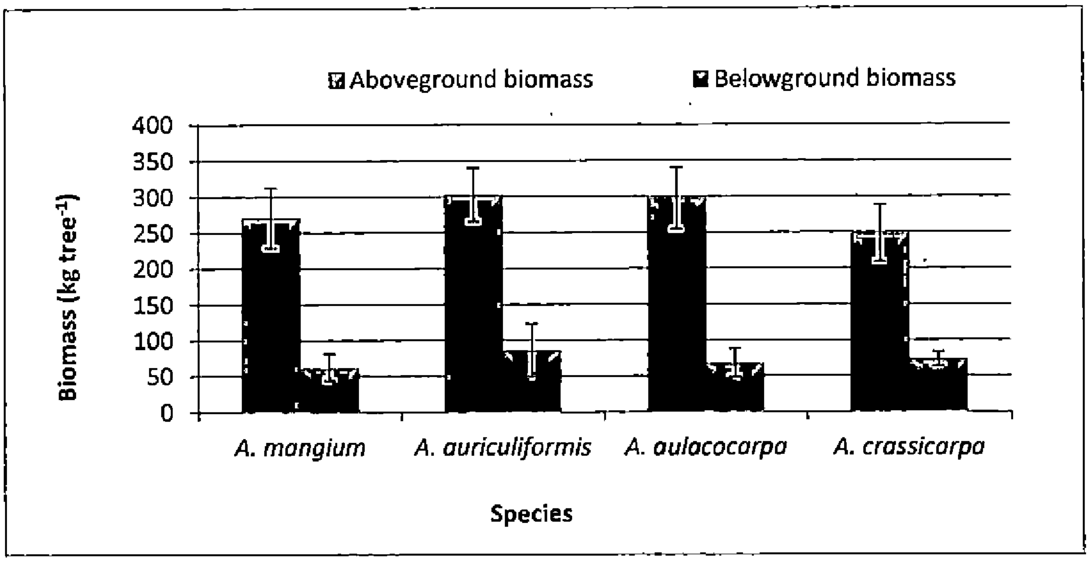


Figure 3. Total aboveground and belowground biomass (kg $tree^{-1}$) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

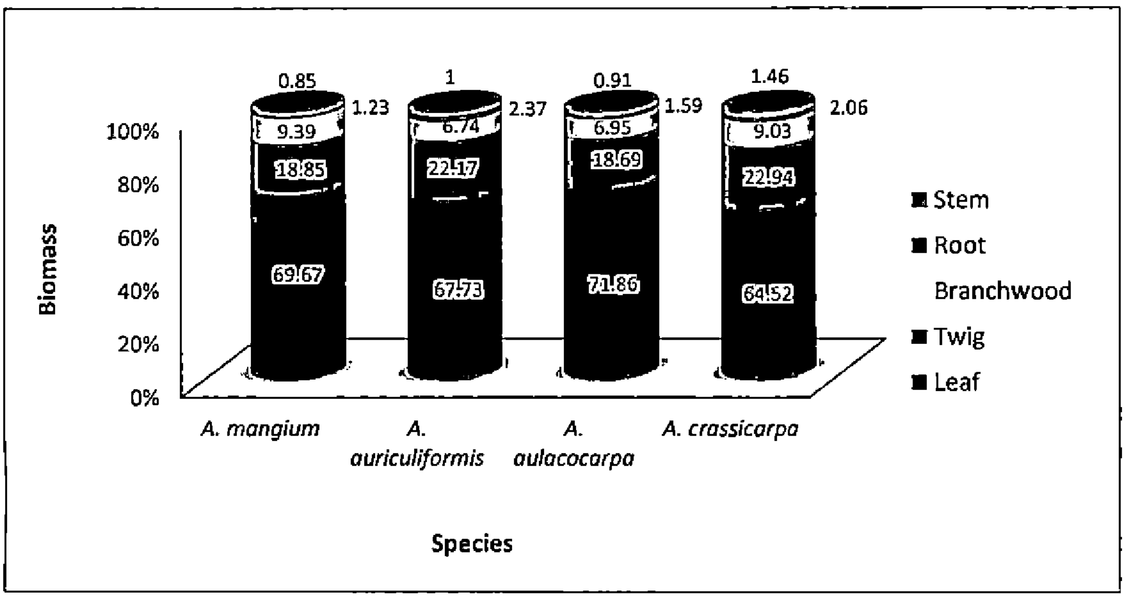


Figure 4. Percentage contribution of different components to the total biomass of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Root biomass accounted for the second largest share to the total biomass in all species. The maximum root biomass percentage was recorded for *A. crassicarpa* (22.94%) while the minimum was recorded for *A. aulacocarpa* (18.69%). Contribution of root to the total biomass in *A. mangium* and *A. auriculiformis* were 18.85% and 22.17% respectively. The maximum mean tree root biomass was recorded in *A. auriculiformis* (86.22 kg $tree^{-1}$) followed by *A. crassicarpa* (73.95kg $tree^{-1}$), *A. aulacocarpa* (68.31 kg $tree^{-1}$) and the lowest in *A. mangium* (62.41 kg $tree^{-1}$). With regard to branchwood maximum percentage was allocated in *A. mangium* (9.39 %) and minimum in *A. auriculiformis* (6.74%). Percentage contribution of twig and leaf was generally low. The maximum twig and leaf percentage was reported for *A. crassicarpa* (2.06% and 1.46% respectively) and the minimum for *A. mangium* (1.23% and 0.85% respectively).

4.2.2 Biomass production on stand basis

Total stand biomass accumulation followed a similar trend as mean tree biomass accumulation with decreasing order of *A. auriculiformis, A. crassicarpa, A. aulacocarpa* and *A. mangium* with values to the tune of 432.08 Mg ha^{-1}, 418.45 Mg ha^{-1}, 406.11 Mg ha^{-1} and 367.76 Mg ha^{-1} respectively(Table. 6 and Fig.5).

Component yield of different fractions on a hectare basis is presented in Table 6. As expected, bole production was maximum for *A. auriculiformis* (292.63 Mg ha^{-1}) followed by *A. aulacocarpa* (291.81 Mg ha^{-1}), *A. mangium* (256.23 Mg ha^{-1}) and the minimum was recorded for *A. crassicarpa* (231*.03Mg* ha^{-1}). Branchwood biomass accumulation however, showed a different trend with maximum for *A. mangium* (34.54 Mg ha^{-1}) followed by *A. crassicarpa* (32.32 *Mg* ha^{-1}), *A. auriculiformis* (29.11 Mg ha^{-1}) and the minimum was recorded in *A. aulacocarpa* (28.24 Mg ha^{-1}).

Stand accumulation value for the twig component was recorded maximum for *A. auriculiformis* (10.24 Mg ha^{-1}) followed by *A. aulacocarpa* (6.47 Mg ha^{-1}) and *A. crassicarpa* (7.39 Mg ha^{-1}) and which were at par. The lowest value was recorded for *A. mangium* (4.52 Mg ha^{-1}). Mean leaf biomass accumulation was recorded highest for *A. crassicarpa* (5.21 Mg ha^{-1}) and minimum for *A. mangium* (3.14 Mg ha^{-1}). The recorded leaf biomass accumulation of *A. auriculiformis* and *A. aulacocarpa* stand were 4.13 Mg ha^{-1} and 3.71 Mg ha^{-1}repectively and which were at par. For root portion biomass accumulation was registered maximum for *A. auriculiformis* (95.79 Mg ha^{-1}) and minimum for *A. mangium* (69.33 Mg ha^{-1}).

Table 6. Biomass accumulation (Mg ha^{-1}) in different components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Stand biomass accumulation (Mg ha^{-1})						MAI (Mg ha^{-1} yr^{-1})
	Bole	Branch wood	Twig	Leaf	Root	Total	
A. mangium	256.23	34.54	4.52^{b}	3.14^{b}	69.33	367.76	20.43
A. auriculiformis	292.63	29.11	10.24^{a}	4.13^{ab}	95.79	432.08	24.00
A. aulacocarpa	291.81	28.24	6.47^{ab}	3.71^{ab}	75.89	406.11	22.56
A. crassicarpa	231.03	32.32	7.39^{ab}	5.21^{a}	82.16	418.45	23.25
F test	*(ns)*	*(ns)*	*	*	*(ns)*	*(ns)*	*(ns)*
P value	0.628	0.872	0.02	0.026	0.877	0.755	0.953

*ns – non significant at 0.05 level, * significant at 0.05 level*

Out of the total tree biomass, aboveground biomass constituted the highest proportion (Table.7). Aboveground biomass production was highest for *A. auriculiformis* (336.29 Mg ha^{-1}) immediately followed by *A. aulacocarpa* (336.29 Mg ha^{-1}) and *A. mangium* (298.43 Mg ha^{-1}). Lowest aboveground biomass was registered for *A. crassicarpa* (275.94 Mg ha^{-1}). Belowground (root) biomass production however followed a varying trend among the tree species. The belowground biomass production was registered highest for *A. auriculiformis* (95.79 Mg ha^{-1}) followed by *A. crassicarpa* (82.16 Mg ha^{-1}) and *A. aulacocarpa*

(75.89 Mg ha^{-1}). *A. mangium* registered lowest root biomass production (69.33 Mg ha^{-1}) despite its comparatively higher aboveground biomass production.

Table 7. Biomass accumulation (Mg ha^{-1}) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	**Above ground biomass (Mg ha^{-1})**	**Belowground biomass (Mg ha^{-1})**	**Total biomass (Mg ha^{-1})**	**Root : shoot ratio**
A. mangium	298.43	69.33	367.76	0.23
A. auriculiformis	336.29	95.79	432.08	0.29
A. aulacocarpa	330.22	75.89	406.11	0.23
A. crassicarpa	275.94	82.16	418.45	0.30
F test	*(ns)*	*(ns)*	*(ns)*	*(ns)*
P value	0.624	0.877	0.755	

ns – non significant at 0.05 level
** significant at 0.05 level*

Root: shoot ratio depicted in Table.7 showed variable trend with highest ratio for *A. crassicarpa*(0.30) followed by *A. auriculiformis* (0.29). Root: shoot ratio was recorded lowest for *A. mangium* and *A. aulacocarpa* with value 0.23. The ratio of 0.30 for *A. crassicarpa* indicates that the roots constituted almost 30% of the aboveground biomass.

4.2.3 Mean annual increment (MAI)

MAI on hectare basis for each species of acacias are given in Table.6. Highest MAI was recorded for *A. auriculiformis* (24 Mg ha^{-1} yr^{-1}) followed by *A. crassicarpa* (23.25 Mg ha^{-1} yr^{-1}) and *A. aulacocarpa* (22.56 Mg ha^{-1} yr^{-1}). Lowest MAI was registered for *A. mangium* (20.43 Mg ha^{-1} yr^{-1})

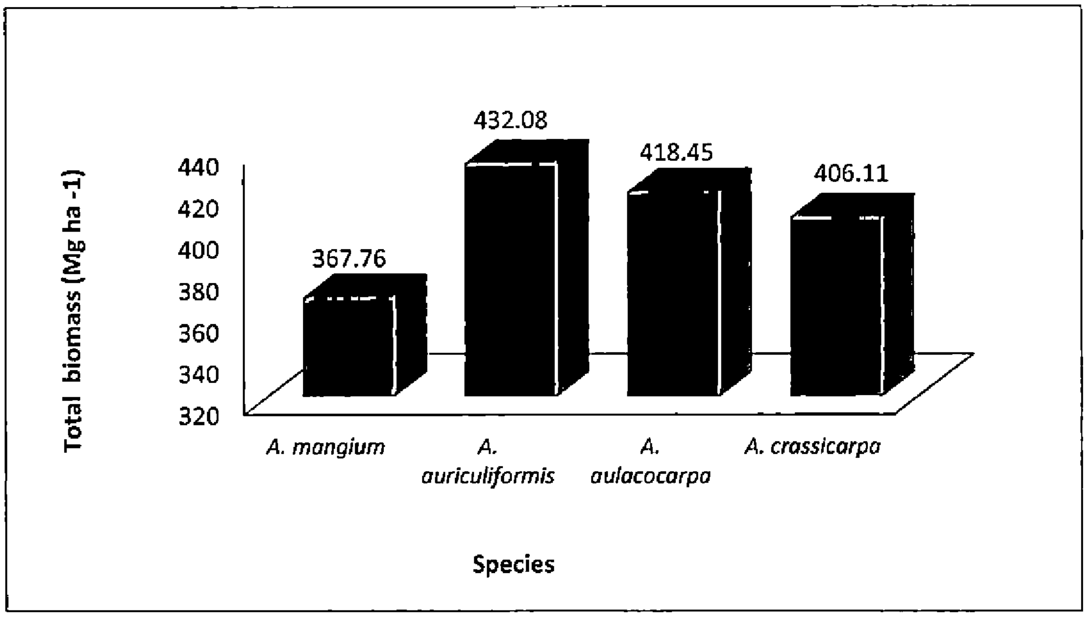


Figure 5. Stand biomass accumulation of 18-year-old acacia species at Vellanikkra, Thrissur, Kerala.

4.3 Biomass Carbon sequestration

4.3.1 Carbon concentration

Organic carbon content in the tree components were determined by using dry ash method in a muffle furnace. Ten gram of the sample was weighed in a silica crucible. The crucibles were then placed inside the muffle furnace and heated at 506^{0}C for 6 hours. The crucibles were then taken out and the residual weight was calculated to determine the percentage carbon content. Carbon concentration in different tissue fractions of acacia species are presented in Table.8. The general trend followed by all species with regards to C concentration was leaf> root> bole= branchwood> twig. Significant differences were observed in the bole concentration of four acacia species and it varied from 44.98% to 47.79%. Among the species, maximum bole carbon concentration was recorded for *A. crassicarpa* (47.79%) followed by *A. auriculiformis* (46.14%) and *A. mangium* (45.91). Lowest bole carbon was recorded in *A. aulacocarpa* (44.98%). However branchwood followed a slightly different pattern with *A. auriculiformis* recording maximum value of 47.81% followed by *A. crassicarpa* (46.57%) and *A. mangium* (45.84%), while minimum concentration was recorded in *A. aulacocarpa* (45.53%). In general, leaves registered higher tissue C concentration which varied from maximum value of 49.20% (*A. aulacocarpa*) to a minimum value of 47.81% (*A. crassicarpa*). For twig, the C concentration was almost same for all the four species values from 44.06% to 44.80%. For root the maximum C concentration was recorded for *A. mangium* (48.39%) and minimum for *A. auriculiformis* (46.20%).

The average value for C concentration of acacia species varied from 46.17% to 46.69%. Highest mean tree C concentration was recorded in the case of *A. mangium* (46.69%) and lowest concentration was observed in *A. aulacocarpa* (46.17%).

Table 8. Carbon concentration (%) in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Carbon concentration (%)					
	Bole	**Branchwood**	**Twig**	**Leaf**	**Root**	**Average**
A. mangium	45.91	45.84	44.67	48.66[b]	48.39	46.69
A. auriculiformis	46.14	47.81	44.06	47.98[a]	46.20	46.44
A. aulacocarpa	44.98	45.53	44.80	49.20[ab]	46.33	46.17
A. crassicarpa	47.79	46.57	44.34	47.81[ab]	47.10	46.72
F test	*(ns)*	*(ns)*	*(ns)*	*	*(ns)*	*(ns)*
P value	0.634	0.858	0.056	0.021	0.056	0.863

ns – non significant at 0.05 level

** significant at 0.05 level*

4.3.2 Mean tree C sequestration

By using the dry weight and percentage C concentration in each tree components, C stock for each tree and mean tree C stocks were calculated. Mean tree biomass C stock for different acacia species are presented in Table.9 and Fig.6. Mean tree biomass C stock was highest for *A. auriculiformis* (176.38 kg Ctree^{-1}) followed by *A. aulacocarpa* (165.54 kg C tree^{-1}) and *A. mangium* (151.35 kg C tree^{-1}). Lowest mean tree biomass carbon was registered in the case of *A. crassicarpa* with carbon value 147.28 kg C tree^{-1}.

Table 9. Mean tree biomass C stock (kg C tree^{-1}) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Total (kg C tree^{-1})
A. mangium	151.35
A. auriculiformis	176.38
A. aulacocarpa	165.54
A. crassicarpa	147.28
F test	*(ns)*
P value	0.763

Ns- non significant at 0.05 level

4.3.3 Partitioning of biomass C stock

Partitioning of biomass C stock in different components of acacia species is furnished in Table 10 and Fig.7. Among the different fractions, bole accounted for largest percentage to the total biomass C in all the species. Percentage contribution of bole varied from 71.28% in *A. aulacocarpa* to lowest value of 63.61% in *A. crassicarpa.* Corresponding bole C storage in *A. aulacocarpa* was about 118.07 kg C tree^{-1}and is followed by *A. mangium* (103.70 kg C tree^{-1}) with

68.52% and *A. auriculiformis* (118.35 kg C tree^{-1}) with 67.10%. The lowest bole C was recorded in *A. crassicarpa* with 93.68 kg C tree^{-1}.

Interestingly, roots account for second largest contributor to the mean tree biomass C stock in all the species. Root contribution to the total biomass C stock varied from 23.78% in *A. crassicarpa* to the lowest value of 19.10% in *A. aulacocarpa.* Component yield of root to total biomass C stock were 40.04, 35.03and 31.63 kg C tree^{-1} respectively for *A. auriculiformis, A. crassicarpa* and *A. aulacocarpa.* Lowest root biomass C sock was recorded in *A. mangium* (30.23 kg C tree^{-1}). Allocation of C to branchwood in different acacia species vary from 14.25 kg C tree^{-1} in case of *A. mangium* to minimum value of 11.60 kg C tree^{-1} in the *A. aulacocarpa.* With regards to twig biomass C stock maximum value was registered for *A. auriculiformis* (4.12 kg C tree^{-1}) and minimum for *A. mangium* (1.82 kg C tree^{-1}). And for leaf biomass C stock values varies from 1.37 kg C tree^{-1} (*A. mangium*) to 2.29 kg C tree^{-1} (*A. crassicarpa*).

Table 10. Biomass C stock (kg C tree^{-1}) in different tree components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	**Biomass C stock (kg C tree^{-1})**				
	Bole	**Branchwood**	**Twig**	**Leaf**	**Root**
A. mangium	103.70 (68.52)	14.25 (9.42)	1.82^{b} (1.20)	1.37^{b} (0.91)	30.23 (19.97)
A. auriculiformis	118.35 (67.10)	11.97 (6.79)	4.12^{a} (2.34)	1.90^{ab} (1.07)	40.04 (22.70)
A. aulacocarpa	118.07 (71.28)	11.60 (7.00)	2.60^{ab} (1.57)	1.62^{ab} (0.98)	31.63 (19.10)
A. crassicarpa	93.68 (63.61)	13.29 (9.02)	2.98^{ab} (2.02)	2.29^{a} (1.55)	35.03 (23.78)
F test	*(ns)*	*(ns)*	*	*	*(ns)*
P value	0.634	0.775	0.021	0.025	0.905

*ns – non-significant at 0.05 level, * significant at 0.05 level*

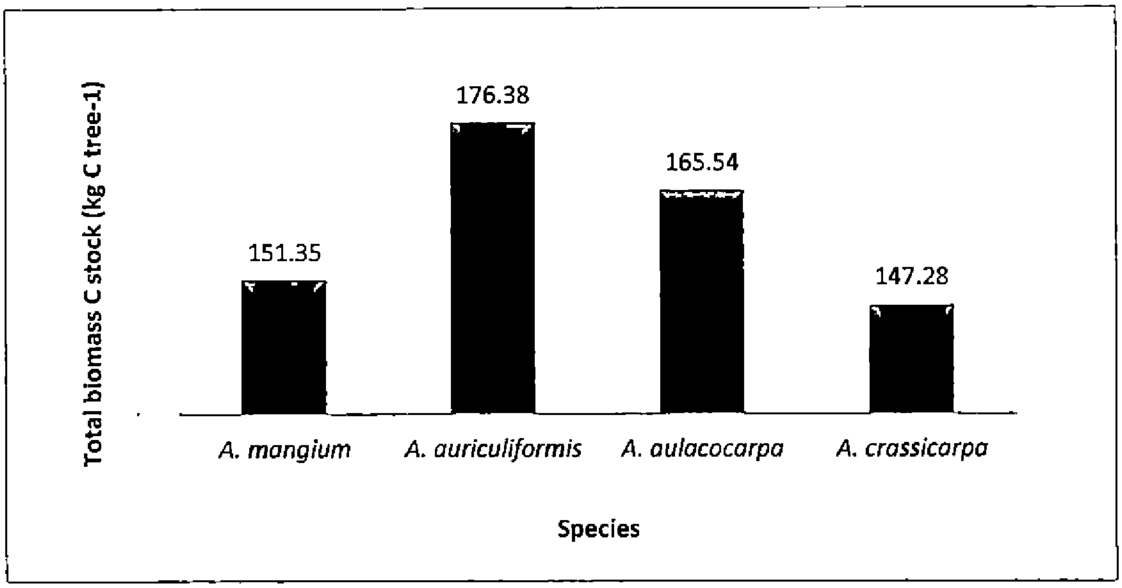


Figure 6. Mean tree total biomass C stock (kg C tree^{-1}) of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

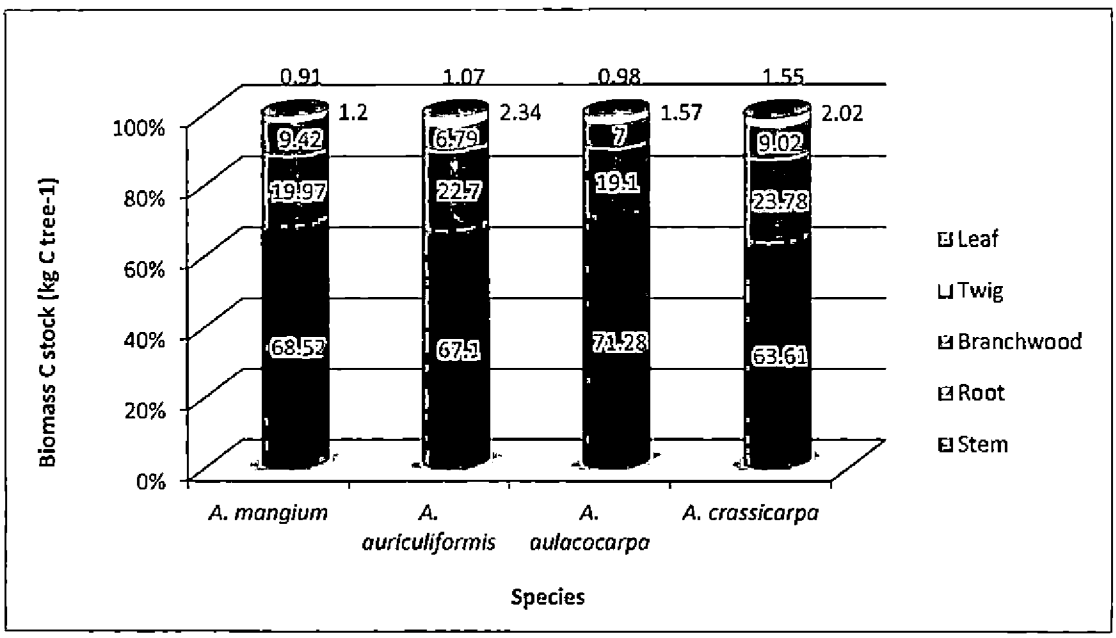


Figure 7. Percentage contribution of different components to the total biomass C stock of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Values in parenthesis indicate the percentage contribution of tree components to the total mean biomass C stock.

4.3.4. Stand level biomass C sequestration

Stand level biomass C stock were calculated by extrapolating the mean tree C stock on hectare basis (for 1111 trees) for all the four species of acacia (Table.11). This followed a trend well in line with mean tree C sequestration. Among different acacia species, *A. auriculiformis* recorded the highest total biomass C stock to the tune of 195.94 Mg C ha^{-1} which is followed by *A. aulacocarpa* (183.93 Mg C ha^{-1}) and *A. mangium* (168.16 Mg C ha^{-1}). Lowest value was recorded for *A. crassicarpa* (163.62 Mg C ha^{-1}).

Bole C stock of acacias showed almost the same trend as stand level total biomass C stock. Maximum bole C stock was recorded for *A. auriculiformis* (131.48 Mg C ha^{-1}) which is closely followed by *A. aulacocarpa* (131.18 Mg C ha^{-1}). Lowest bole carbon stock was registered for *A. crassicarpa* (104.08 Mg C ha^{-1}). However with regards to branchwood acacia species shows a varying trend, *A. mangium* (15.81 Mg C ha^{-1}) recorded the maximum value followed by *A. crassicarpa* (14.77 Mg C ha^{-1}) and *A. auriculiformis* (13.30 Mg C ha^{-1}). Lowest value for branchwood C stock was reported in *A. aulacocarpa* (12.90 Mg C ha^{-1}). Leaf C stock was registered highest for *A. crassicarpa* (2.54 Mg C ha^{-1}) and lowest for *A. mangium* (1.53 Mg C ha^{-1}). With regards to root and twig C stock shown the same trend with highest C stock for *A. auriculiformis* (44.49 and 4.56 Mg C ha^{-1}respectively) and lowest registered for *A. mangium* (33.59 and 2.02 Mg C ha^{-1} respectively).

In case of *A. auriculiformis* all models (linear, quadratic and cubic) recorded almost the same R^2 values for total biomass, carbon sequestration and total volume (Table.13). However for bole volume, the model based on two variable recorded higher R^2 values compared to quadratic and cubic equations based on one variable. While in *A. aulacocarpa* cubic and quadratic models based on dbh (Table.14) recorded higher R^2value for biomass ($B = 0.05D^3 - 2.52D^2 + 53.72D - 343.46$; $R^2=0.86$) and carbon sequestration ($CS = 0.023D^3 - 1.16D^2 + 24.69D-158.17$; $R^2=0.86$). But in case of total volume, all models (linear and quadratic) recoded the same R^2 value (0.83). For bole volume equations height and dbh as independent variable were found to be the beast fit with high R^2 value (0.81).

In case of *A. crassicarpa* cubic models with dbh as independent variable recorded the high R^2 value for biomass ($B = -0.08\ D^3 + 6.40D^2 - 142.36D + 1032.52$; $R^2 = 0.85$), biomass carbon sequestration ($CS = -0.04D^3 + 2.89D^2 - 64.38D + 466.94$; $R^2 = 0.86$), total volume ($V1 = 0.00D^3 + 0.012D^2 - 0.27D + 1.86$; $R^2 = 0.88$) and bole volume ($V2 = 0.00D^3 + 0.01D^2 - 0.215D + 1.53$; $R^2 = 0.85$).

Table 11. Stand level biomass C stock and MAI of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Stand level biomass C sequestration (Mg C ha^{-1})							MAI (Mg C ha^{-1} yr^{-1})
	Bole	Branch wood	Twig	Leaf	Total above ground	Root	Total	
A. mangium	115.21	15.81	2.02^{b}	1.53^{b}	134.57	33.59	168.16	9.34
A. auriculiformis	131.48	13.30	4.56^{a}	2.11^{ab}	151.45	44.49	195.94	10.89
A. aulacocarpa	131.18	12.90	2.90^{ab}	1.81^{ab}	148.79	35.14	183.93	10.22
A. crassicarpa	104.08	14.77	3.31^{ab}	2.54^{a}	124.70	38.92	163.62	9.09
F test	*(ns)*	*(ns)*	*	*	*(ns)*	*(ns)*	*(ns)*	
P value	0.634	0.775	0.021	0.025	0.763	0.905	0.845	

ns – non-significant at 0.05 level
** significant at 0.05 level*

4.4. Allometric equations

Allometric relationships were attempted in the present study linking aboveground tree biomass, total aboveground biomass carbon sequestration, total volume and bole volume with DBH and/or total height of the trees which gave reasonably good predictions (Table 12-15, Fig. 8-11). Among the models tried, simple linear, quadratic and cubic equations showed better fit with reasonably higher R^2 values. Table.12 shows the allometric equation developed for *A. mangium* for total aboveground biomass, aboveground biomass C sequestration, total volume and bole volume. In *A. mangium,* equations with height and dbh as independent variables were found to be the least fit with high R^2 values for biomass ($B = 17.27D + 15.57\,H - 526.19$; $R^2 = 0.71$), carbon sequestration ($CS = 7.784D + 7.017H - 237.002$; $R^2 = 0.71$), total volume ($V1 = 0.035D + 0.027H - 0.972$; $R^2 = 0.83$) and bole volume ($V2 = 0.033D + 0.033H - 0.86$; $R^2 = 0.83$).

In case of *A. auriculiformis* all models (linear, quadratic and cubic) recorded almost the same R^2 values for total biomass, carbon sequestration and total volume (Table.13). However for bole volume, the model based on two variable recorded higher R^2 values compared to quadratic and cubic equations based on one variable. While in *A. aulacocarpa* cubic and quadratic models based on dbh (Table.14) recorded higher R^2value for biomass ($B = 0.05D^3 - 2.52D^2 + 53.72D - 343.46$; R^2=0.86) and carbon sequestration ($CS = 0.023D^3 - 1.16D^2 + 24.69D-158.17$; R^2=0.86). But in case of total volume, all models (linear and quadratic) recoded the same R^2 value (0.83). For bole volume equations height and dbh as independent variable were found to be the beast fit with high R^2 value (0.81).

In case of *A. crassicarpa* cubic models with dbh as independent variable recorded the high R^2 value for biomass ($B = -0.08\ D^3+ 6.40D^2 - 142.36D + 1032.52$; $R^2 = 0.85$), biomass carbon sequestration ($CS = -0.04D^3+ 2.89D^2- 64.38D+ 466.94$; $R^2 = 0.86$), total volume ($V1 = 0.00D^3+ 0.012D^2 - 0.27D + 1.86$; $R^2 = 0.88$) and bole volume ($V2 = 0.00D^3+ 0.01D^2-0.215D+1.53$; $R^2 = 0.85$).

Table 12. Allometric prediction equations developed for 18-year-old *A. mangium* trees at Vellanikkara, Thrissur, Kerala.

Dependent variable	Independent variable	Equation	R^2 value	Standard error
Total aboveground biomass	DBH	$B = 17.27D + 15.57 H - 526.19$	0.71	105.81
	Total height	$B = 0.51D^2 - 4.95D + 7.59$	0.61	123.74
Total AGB Carbon sequestration	DBH	$CS = 7.784D + 7.017H - 237.002$	0.71	48.04
	Total height	$CS = 0.223D^2 - 1.86D - 1.146$	0.60	56.12
		$CS = -8.002D^3 + 0.223D^2 - 1.87D - 1.15$	0.60	56.12
Total volume	DBH	$V1 = 0.035D + 0.027H - 0.972$	0.83	0.15
	Total height	$V1 = 0.002D^2 - 0.050D + 0.551$	0.76	0.17
Bole volume	DBH	$V2 = 0.033D + 0.033H - 0.86$	0.83	0.12
	Bole height	$V2 = 0.002D^2 - 0.0067D + 0.802$	0.66	0.17

Table 13. Allometric prediction equations developed for 18-year-old *A. auriculiformis* trees at Vellanikkara, Thrissur, Kerala.

Dependent variable	Independent variable	Equation	R^2 value	Standard error
Total aboveground biomass	DBH Total height	$B = 12.13D + 15.55H - 352.52$	0.65	104.38
		$B = 22.01\,D - 280.97$	0.60	109.28
		$B = 0.58D^2 + 18.96D - 242.29$	0.60	112.43
Total AGB Carbon sequestration	DBH Total height	$CS = 5.47D + 6.95H - 157.53$	0.65	46.85
		$CS = 0.001D^3 - 13.33D^2 + 8.75D - 106.66$	0.60	50.41
		$CS = 0.02D^2 + 8.73D - 111.08$	0.60	50.43
Total volume	DBH Total height	$V1 = 0.001D^2 - 0.009D - 0.028$	0.82	0.14
		$V1 = 0.041D + 0.12H - 0.818$	0.81	0.15
		$V1 = 0.048D - 0.761$	0.80	0.15
Bole volume	DBH Bole height	$V2 = 0.027D + 0.034H - 0.678$	0.84	0.13
		$V2 = 0.001H^3 - 0.017H^2 + 0.185 - 0.413$	0.73	0.17
		$V2 = 0.001D^2 - 0.029D + 0.205$	0.69	0.18

Table 14. Allometric prediction equations developed for 18-year-old *A. aulacocarpa* trees at Vellanikkara, Thrissur, Kerala.

Dependent variable	Independent variable	Equation	R^2 value	Standard error
Total aboveground biomass	DBH Total height	$B = 0.05D^3 - 2.52D^2 + 53.72D - 343.46$	0.86	79.04
		$B = 1.09D^2 - 29.12D + 243.73$	0.85	78.86
		$B = 30.14D - 12.45H - 240.64$	0.79	91.77
		$B = 25.97D - 405.87$	0.77	93.73
Total AGB Carbon sequestration	DBH Total height	$CS = 0.023D^3 - 1.16D^2 + 24.69D - 158.17$	0.86	35.17
		$CS = 0.49D^2 - 13.07D + 109.38$	0.85	35.13
		$CS = 13.57D - 5.56H - 108.64$	0.80	41.00
Total volume	DBH Total height	$V1 = 0.001D^2 + 0.016D - 0.227$	0.83	0.13
		$V1 = 0.04D + 0.008H - 0.65$	0.83	0.13
		$V1 = 0.043D - 0.543$	0.83	0.13
Bole volume	DBH Bole height	$V2 = 0.033D + 0.11H - 0.541$	0.81	0.11
		$V2 = 0.034D - 0.413$	0.80	0.12
		$V2 = 0.00D^2 + 0.023D - 0.279$	0.80	0.12

Table 15. Allometric prediction equations developed for 18-year-old *A. crassicarpa* trees at Vellanikkara, Thrissur, Kerala.

Dependent variable	Independent variable	Equation	R^2 value	Standard error
Total aboveground biomass	DBH Total height	$B = -0.08\ D^3 + 6.40D^2 - 142.36D + 1032.52$	0.85	73.34
		$B = 21.79D - 290.98$	0.81	78.85
		$B = 21.67D + 0.22H - 291.73$	0.81	81.13
Total AGB Carbon sequestration	DBH Total height	$CS = -0.04D^3 + 2.89D^2 - 64.38D + 466.94$	0.86	32.67
		$CS = 9.86D - 131.71$	0.81	35.25
		$CS = 9.84D + 0.032H - 131.82$	0.81	36.27
		$CS = 0.037D^2 + 7.91D - 108.11$	0.81	35.21
Total volume	DBH Total height	$V1 = 0.00D^3 + 0.012D^2 - 0.27D + 1.86$	0.88	0.11
		$V1 = 0.025D + 0.016H - 0.512$	0.83	0.12
		$V1 = 0.04D - 0.46$	0.81	0.13
Bole volume	DBH Bole height	$V2 = 0.00D^3 + 0.01D^2 - 0.215D + 1.53$	0.85	0.10
		$V2 = 0.022D + 0.21H - 0.431$	0.83	0.11
		$V2 = 0.03D - 0.40$	0.80	0.11

Figure 8. Prediction models for total aboveground biomass of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

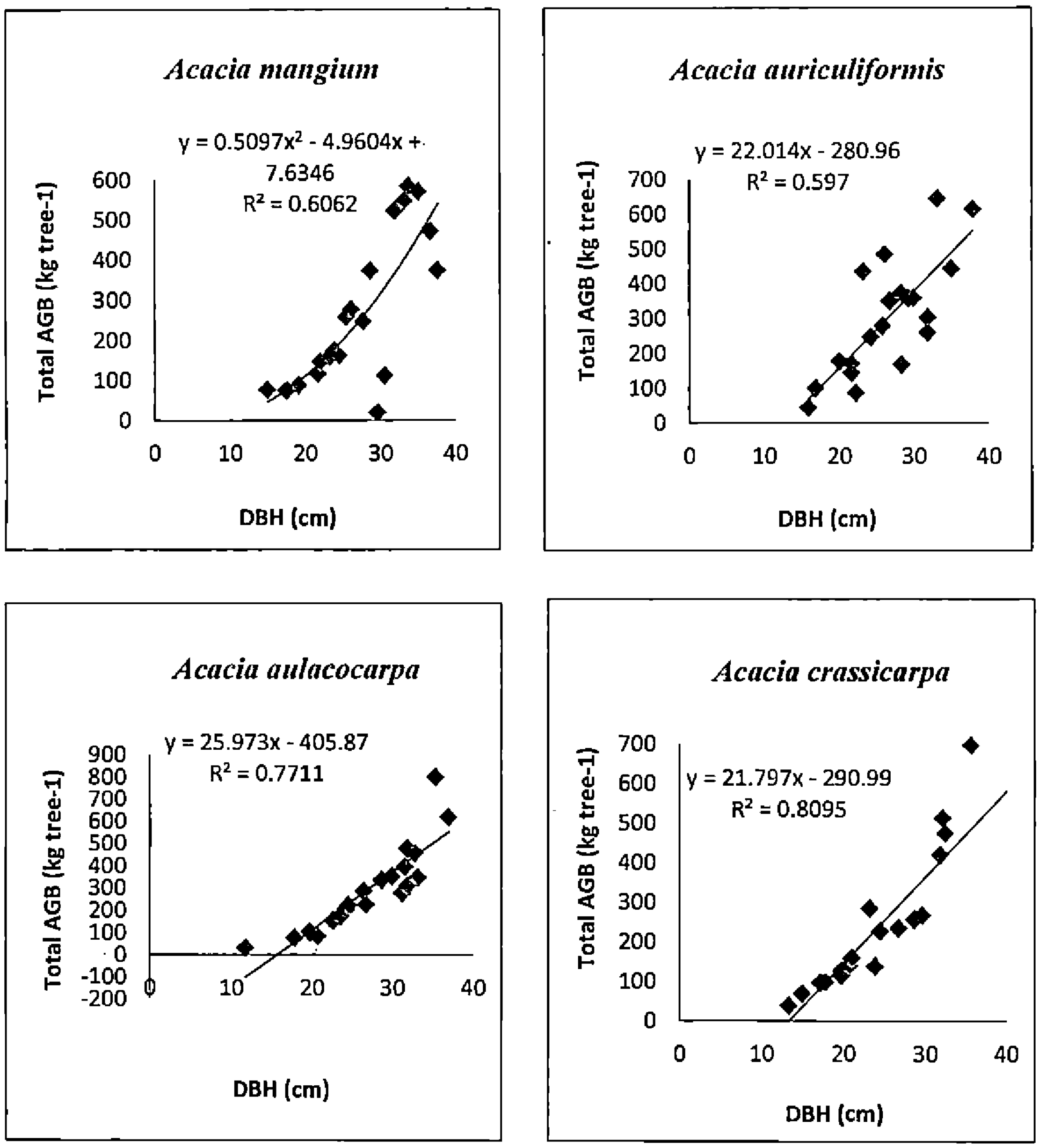


Figure 9. Prediction models for total aboveground carbon sequestration of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

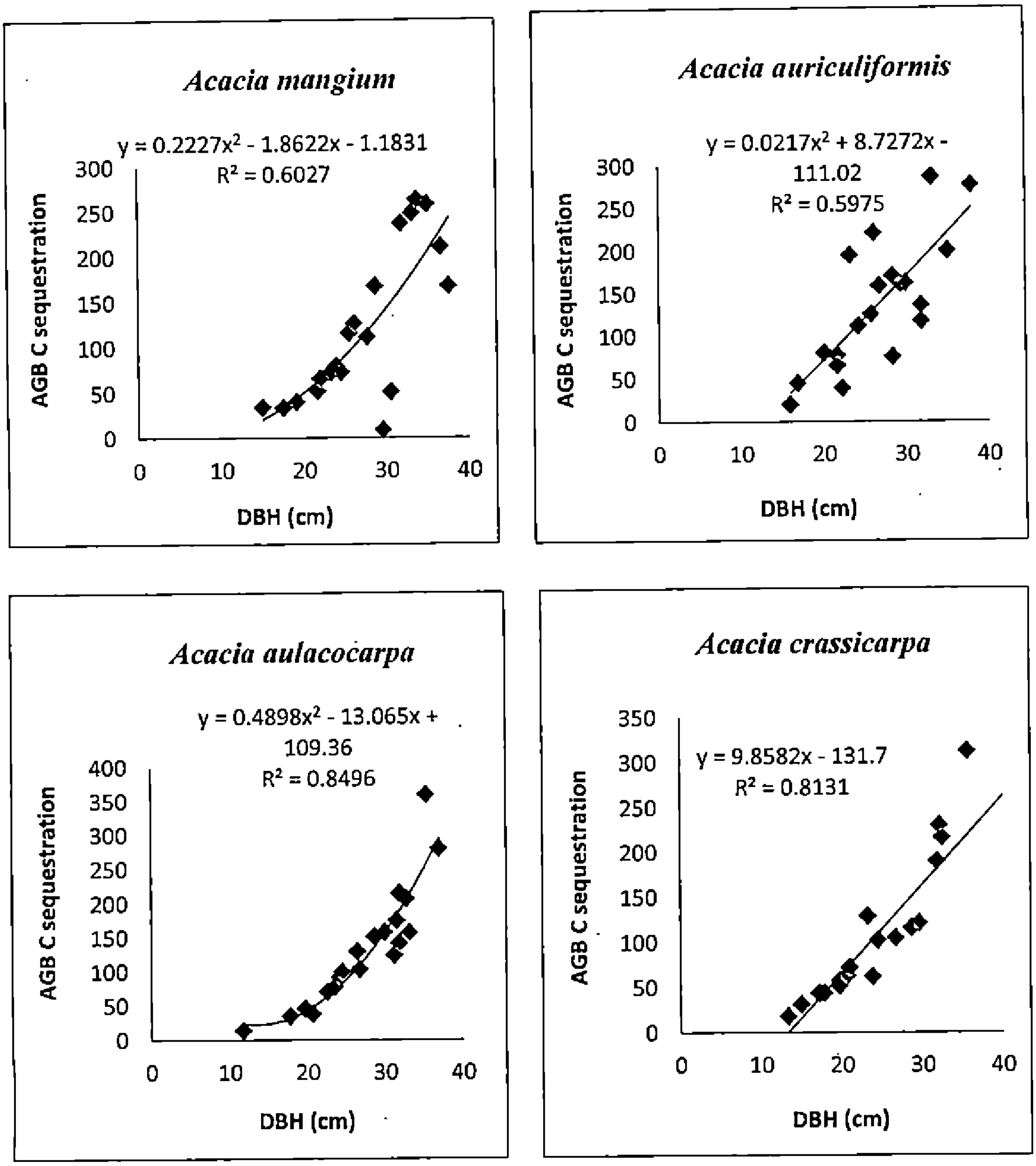


Figure 10. Prediction models for total volume of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

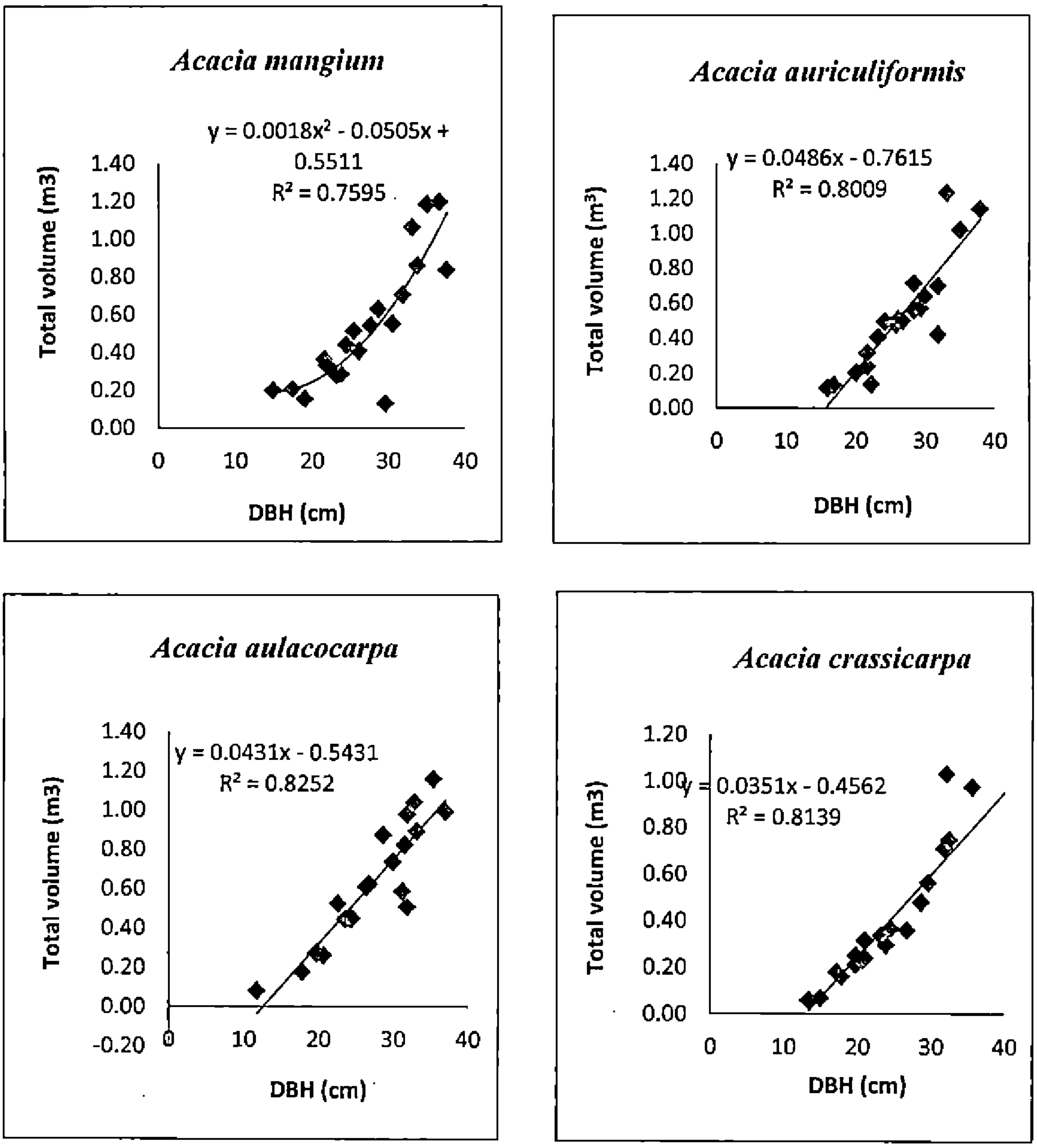
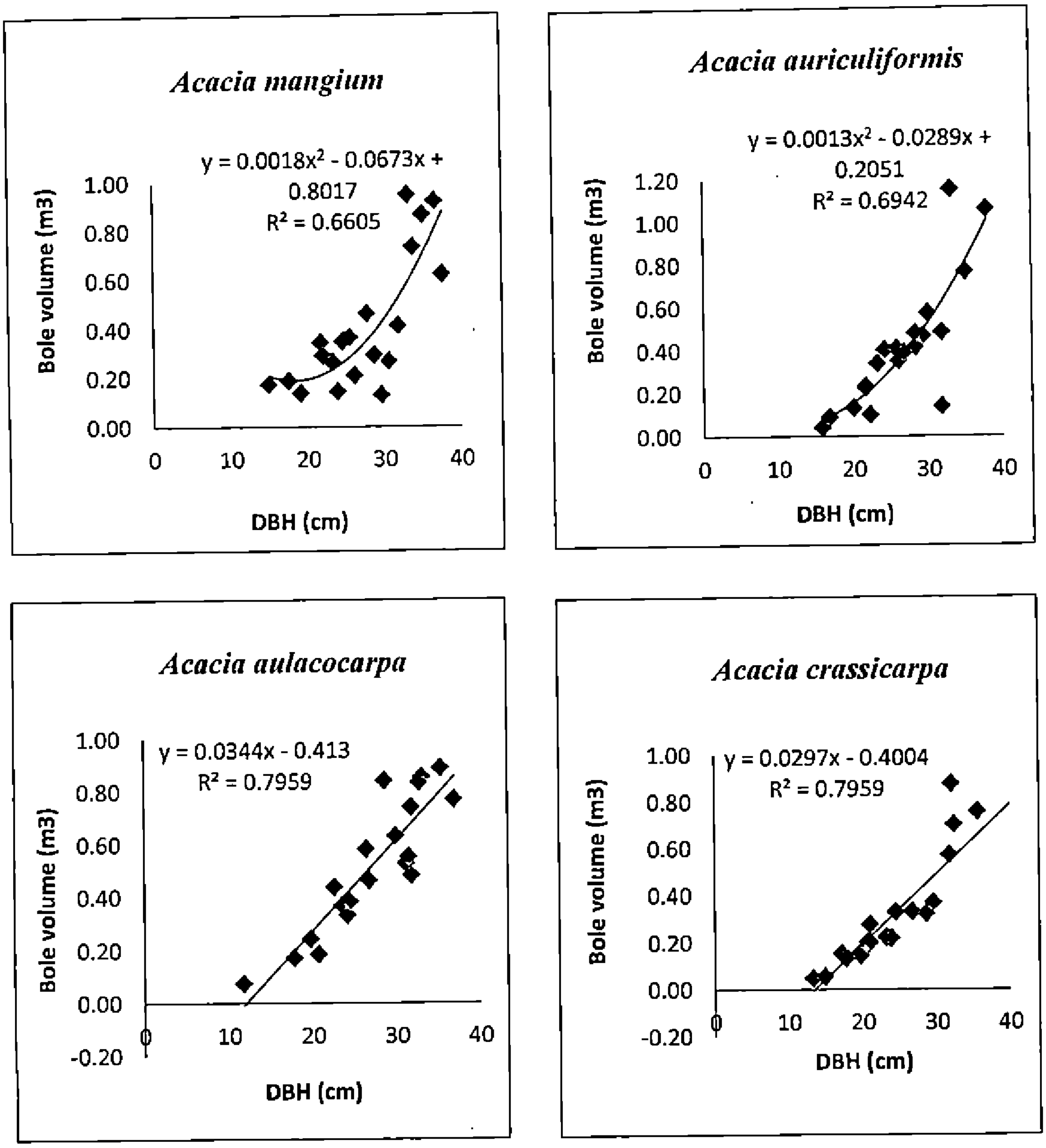


Figure 11. Prediction models for bole volume of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.



4.5. Nutrient concentration

The nutrient concentrations (N, P and K) in various tissue fractions in acacia species are detailed as below (Table 16-18 and Fig. 12-14).

4.5.1. Nitrogen

Nitrogen concentration was found to vary markedly among the acacia species for different tissue types. Nitrogen concentration followed the general order of Leaves> twigs> branchwood> root> bole (Table 16, Fig.12). Among the species *A. auriculiformis* (2.412%) recorded the highest N concentration for leaves while the lowest was reported in *A. crassicarpa* (2.065%).*Acacia mangium* and *A. aulacocarpa* recorded the N concentration of 2.316% and 2.201% respectively and which were at par. However for twig there is no significant variation for the N concentration among species and the maximum N concentration was recorded in *A. auriculiformis* (0.646%) and is closely followed by *A. crassicarpa* (0.645%) and *A. aulacocarpa* (0.637%). The lowest twig N concentration was registered for *A. mangium* (0.618%).

Different trend was shown by branchwood N concentration and the maximum value was recorded for *A. auriculiformis* (0.617%) and minimum by *A. aulacocarpa* (0.549%) closely followed by *A. crassicarpa* (0.555%) and were at par. An intermediate value was shown by *A. mangium* with 0.578%. For the bole, maximum N concentration was recorded for *A. aulacocarpa* (0.433%) which were at par with *A. mangium* (0.428%) and *A. auriculiformis* (0.406%). N concentration was lowest for *A. crassicarpa* (0.374%).

Table 16. Nitrogen concentration in the different biomass component of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Nitrogen (%)				
	Bole	Branch wood	Twig	Leaf	Root
A. mangium	0.428[a] (0.010)	0.578[ab] (0.021)	0.618 (0.033)	2.316[ab] (0.124)	0.562[ab] (0.022)
A. auriculiformis	0.406[a] (0.007)	0.617[a] (0.013)	0.646 (0.013)	2.412[a] (0.074)	0.598[a] (0.013)
A. aulacocarpa	0.433[a] (0.005)	0.549[b] (0.014)	0.637 (0.010)	2.201[ab] (0.040)	0.526[b] (0.006)
A. crassicarpa	0.374[b] (0.018)	0.555[b] (0.013)	0.645 (0.020)	2.065[b] (0.087)	0.518[b] (0.009)
F test	*	*	(*ns*)	*	*
P value	0.001	0.011	0.763	0.048	0.007

ns – non-significant at 0.05 level

** significant at 0.05 level*

Values in the parenthesis are standard error of the mean.

4.5.2.Phosphorus

The concentration of P in different biomass fraction showed marked variability (Table. 17, Fig. 13). The concentration of P in the aboveground portion followed the order leaf > twig > branchwood > bole. For all the components the percentage concentration of P was highest for *A. auriculiformis* and minimum for *A. crassicarpa.* Not much variation was shown by the tissue components of acacia species.

Table 17. Phosphorous concentration in the different biomass component of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Phosphorous (%)				
	Bole	Branchwood	Twig	Leaf	Root
A. mangium	0.065 (0.000)	0.117[b] (0.005)	0.140[ab] (0.008)	0.566 (0.037)	0.130[ab] (0.004)
A. auriculiformis	0.069 (0.000)	0.133[a] (0.008)	0.146[a] (0.004)	0.571 (0.003)	0.134[a] (0.004)
A. aulacocarpa	0.067 (0.000)	0.115[b] (0.003)	0.123[ab] (0.009)	0.561 (0.006)	0.124[ab] (0.003)
A. crassicarpa	0.062 (0.000)	0.111[b] (0.002)	0.121[b] (0.010)	0.530 (0.020)	0.121[b] (0.003)
F test	*(ns)*	*	*	*(ns)*	*
P value	0.634	0.011	0.021	0.557	0.043

ns – non-significant at 0.05 level

** Significant at 0.05 level*

Values in the parenthesis are standard error of the mean.

The concentration of P in leaf was maximum for *A. auriculiformis* (0.571%) and the minimum was in *A. crassicarpa* (0.530%). As regards twig the repoted P concentration in *A. auriculiformis* was 0.146%, and in *A. crassicarpa* 0.121%. Intermediate value was shown by *A. mangium* (0.140%) and *A. aulacocarpa* (0.123%) and they were at par. However for branchwood the reported P concentration for *A. auriculiformis* was 0.133% and for *A. crassicarpa* with 0.121%. In case of bole P concentration no significant variation was observed among the species.

4.5.3. Potassium

Potassium concentration varied moderately among the tree species for different tissue types. In different tissue types the K concentration follows a general order of leaf> twig> branchwood> root> bole (Table.17, Fig.13).With regards to leaf there was no significant difference among species. Leaf K concentration was reported highest for *A. mangium* with 0.282% P concentration and the lowest concentration was reported for *A. crassicarpa* (0.252%).Maximum twig P concentration was recorded for *A. auriculiformis* (0.239%) closely followed by *A. mangium* (0.237%) and lowest value was registered for *A. crassicarpa* (0.213%).

Table 18. Potassium concentration in the different biomass component of 18-year-old acacia species at Thrissur, Kerala.

Species	Potassium (%)				
	Bole	Branchwood	Twig	Leaf	Root
A. mangium	0.190^{b} (0.007)	0.210^{a} (0.005)	0.237 (0.011)	0.282 (0.015)	0.209^{a} (0.003)
A. auriculiformis	0.198^{ab} (0.005)	0.226^{a} (0.009)	0.239 (0.000)	0.276 (0.003)	0.224^{a} (0.008)
A. aulacocarpa	0.215^{a} (0.003)	0.170^{b} (0.006)	0.225 (0.000)	0.267 (0.007)	0.171^{b} (0.005)
A. crassicarpa	0.198^{ab} (0.009)	0.157^{b} (0.004)	0.213 (0.000)	0.252 (0.016)	0.158^{b} (0.007)
F test	*	*	*(ns)*	*(ns)*	*
P value	0.053	0.000	0.398	0.531	0.000

ns – non-significant at 0.05 level
** significant at 0.05 level*
Values in the parenthesis are standard error of the mean.

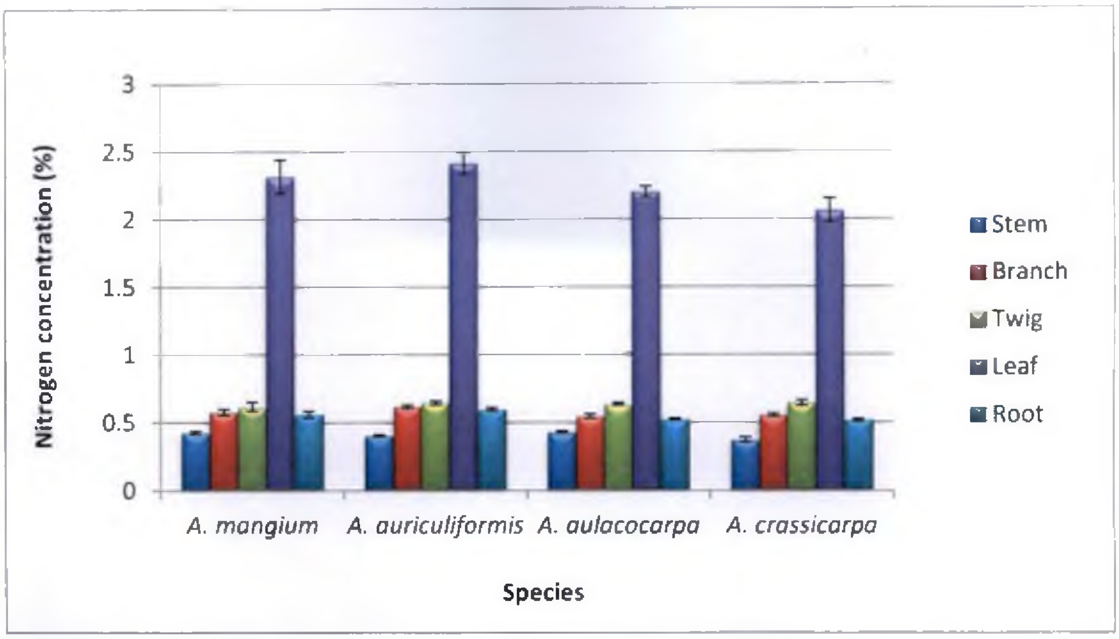


Figure 12. Nitrogen concentration (%) in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

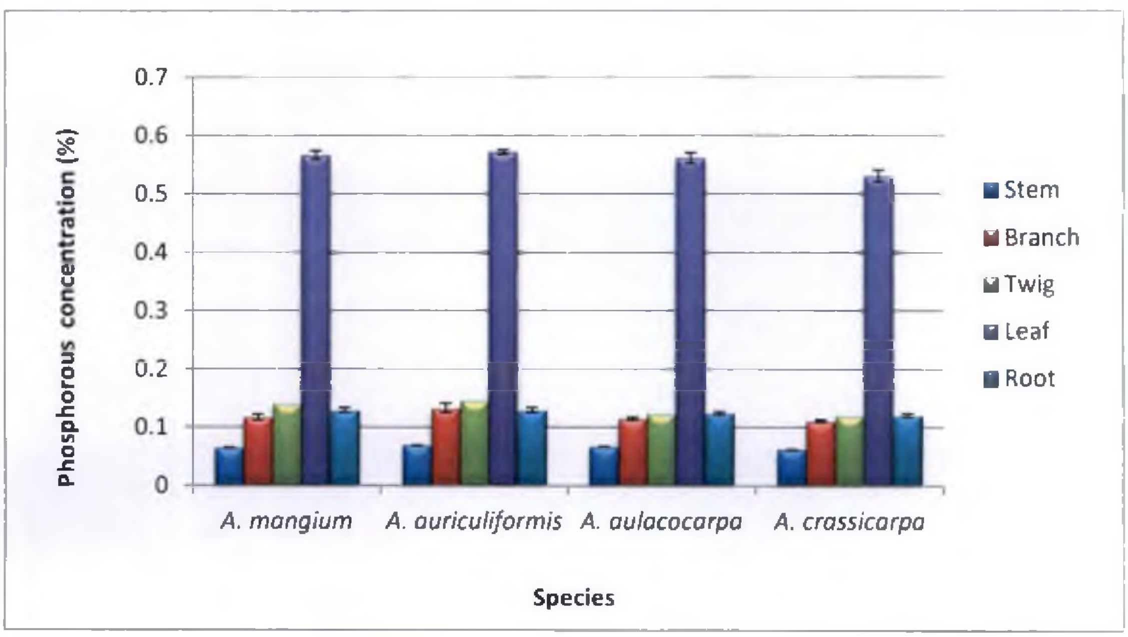


Figure 13. Phosphorous concentration (%) in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

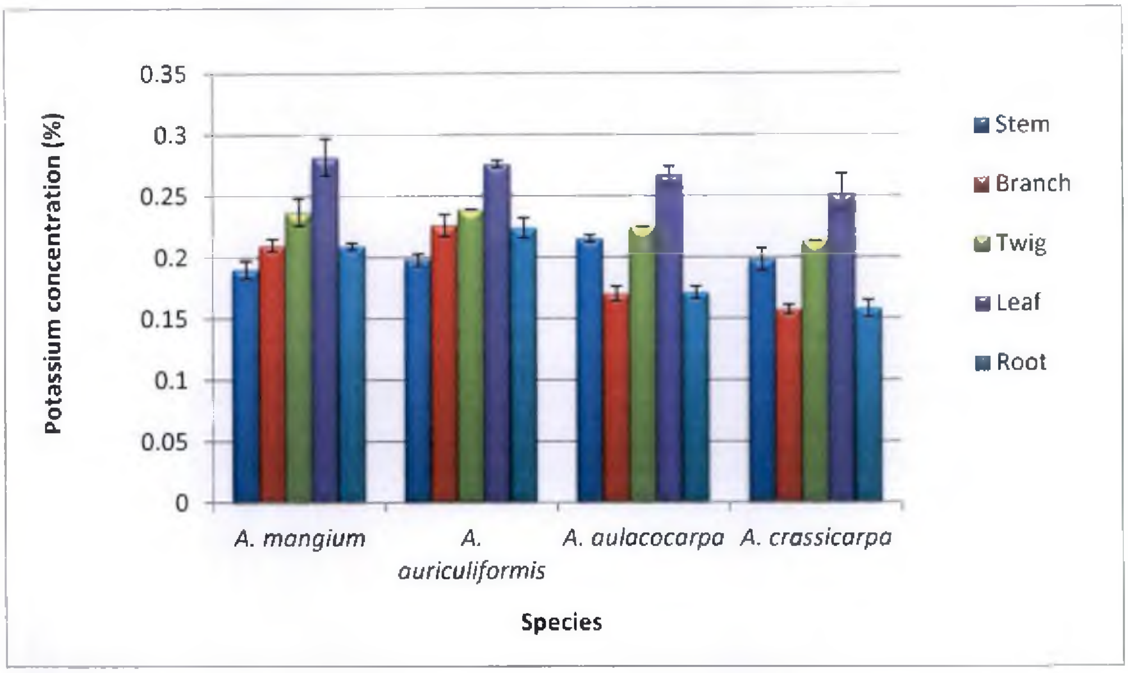


Figure 14. Potassium concentration (%) in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

However for branchwood there were no much differences among species for the K concentration and maximum concentration was registered for *A. auriculiformis* (0.226%) and which were at par with *A. mangium* (0.210). Lowest branchwood K concentration was reported for *A. crassicarpa* (0.157%). Among the acacia species highest bole K concentration was recorded for *A. aulacocarpa* (0.215%) which were followed by *A. auriculiformis* (0.198%) and were at par with *A. crassicarpa* (0.198%). Lowest bole concentration was registered for *A. mangium* (0.190%).

4.6. Nutrient accumulation

By using the dry weight and percentage concentration of nutrients in each components, total nutrient stock in each tree was calculated. Stand level nutrient accumulation was calculated by extrapolating the mean tree nutrient accumulation in hectare basis (for 1111 trees) for all the four species of acacia. Accumulation of N, P and K in various tree components for different acacia species is given in Table.19-21 and their percentage allocation in different biomass components is presented in Fig.15-17. The relative proportion of nutrients tied up in twigs showed significant variation among species.

4.6.1. Nitrogen accumulation

In different tissue types, the amount of N accumulation followed the general order of bole > root> branchwood> leaf> twig. Nitrogen accumulation was highest in bole for all four species of acacias and the accumulation of N in the bole biomass varied from a minimum of 881.61 kg ha^{-1} in *A. crassicarpa* to a maximum of 1279.65 kg ha^{-1}in *A. aulacocarpa* and is followed by *A. auriculiformis* (1213.90 kg ha^{-1}) and *A. mangium* (1137.25 kg ha^{-1}).

With regards to branchwood and leaf there is no significant difference among species. Twig N accumulation was recorded highest for *A. auriculiformis* (65.35 kg ha^{-1}) and minimum for *A. mangium* (29.10 kg ha^{-1}). Intermediate values were reported for *A. crassicarpa* (46.50 kg ha^{-1}) and *A. aulacocarpa* (41.67 kg ha^{-1}) which were at par.

Table 19. Nitogen accumulation in the different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Nitrogen accumulation (kg ha^{-1})				
	Bole	Branch wood	Twig	Leaf	Root
A. mangium	1137.25 (189.37)	207.52 (41.89)	29.10^{b} (4.33)	74.05 (10.29)	395.97 (130.16)
A. auriculiformis	1213.90 (164.05)	181.65 (23.78)	65.35^{a} (1.369)	104.83 (12.38)	582.25 (252.62)
A. aulacocarpa	1279.65 (184.11)	156.97 (35.65)	41.67^{ab} (6.35)	80.05 (12.91)	400.14 (119.66)
A. crassicarpa	881.61 (148.65)	160.01 (32.73)	46.50^{ab} (4.49)	109.03 (13.85)	426.20 (61.45)
F test	*(ns)*	*(ns)*	*	*(ns)*	*(ns)*
P value	0.387	0.704	0.022	0.132	0.813

ns – non-significant at 0.05 level

** significant at 0.05 level*

Values in the parenthesis are standard error to the mean.

4.6.2 Phosphorous accumulation

Bole and root fractions accounted major share of the total P accumulation for all the tree species. Bole P accumulation varied from a maximum of 203.45 kg ha^{-1}in *A. auriculiformis* to a minimum of 147.70 kg ha^{-1}in *A. crassicarpa*. No significant difference among the trees species were observed in P accumulation in bole and branchwood. Leaf portion shows significant differences among trees for P accumulation with values variyng from 17.80 kg ha^{-1} in *A. mangium* to29.12kg ha^{-1}in *A. crassicarpa*. *A. auriculiformis* (24.91 kg ha^{-1}) was par with *A. aulacocarpa* (20.89 kg ha^{-1}) with intermediate values. With regards to twig, maximum P accumulation was reported for *A. auriculiformis* with value 15.78 kg ha^{-1} and minimum for *A. mangium* (6.38 kg ha^{-1}) which was at par with *A. aulacocarpa* (8.52 kg ha^{-1}) and *A. crassicarpa* (9.15 kg ha^{-1}).

Table 20 Phosphorous accumulation in the different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Phosphorous accumulation (kg ha^{-1})				
	Bole	Branch wood	Twig	Leaf	Root
A. mangium	167.46 (26.15)	42.11 (8.21)	6.38^{b} (1.05)	17.80^{b} (2.26)	92.90 (30.60)
A. auriculiformis	203.45 (26.55)	42.06 (7.62)	15.78^{a} (3.52)	24.91^{ab} (3.10)	132.00 (56.66)
A. aulacocarpa	199.79 (29.85)	33.48 (7.44)	8.52^{b} (1.48)	20.89^{ab} (3.67)	96.52 (29.99)
A. crassicarpa	147.70 (24.72)	35.90 (7.82)	9.15^{b} (1.18)	29.12^{a} (3.83)	101.04 (16.32)
F test	*(ns)*	*(ns)*	*	*	*(ns)*
P value	0.403	0.813	0.013	0.044	0.866

*ns – non-significant at 0.05 level, * significant at 0.05 level*
Values in the parenthesis are standard error to the mean.

4.6.3 Potassium accumulation

Potassium accumulation among different taxa showed variation (Table.20). Like N accumulation potassium is also accumulated more in the bole portion and its contribution varied from minimum of 484.01 kg ha^{-1} in *A. crassicarpa* to a maximum of 646.96 kg ha^{-1}in *A. aulacocarpa.* However no significant differences among the tree species were observed in K accumulation in bole, branchwood and root biomass of different acacia species while the leaf showed significant difference with maximum leaf accumulation of K in *A. crassicarpa* (14.22 kg ha^{-1}) and minimum for *A. mangium* (9.01 kg ha^{-1}). Intermediate value was recorded for *A. auriculiformis* (12.07 kg ha^{-1}) and *A. aulacocarpa* (9.73 kg ha^{-1}) which were at par. Twig also showed significant variation among species P accumulation with highest value recorded for *A. auriculiformis* (25.54 kg ha^{-1}) followed by *A. crassicarpa* (15.95 kg ha^{-1}) which were at par. The minimum twig P accumulation value was registered for *A. mangium* (10.64 kg ha^{-1}).

Table 21. Potassium accumulation in the different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala

Species	Potassium accumulation (kg ha^{-1})				
	Bole	Branch wood	Twig	Leaf	Root
A. mangium	517.82 (89.37)	74.48 (14.24)	10.64^{b} (1.65)	9.01^{b} (1.25)	147.38 (46.84)
A. auriculiformis	606.43 (87.82)	69.03 (11.13)	25.54^{a} (5.62)	12.07^{ab} (1.52)	225.38 (104.74)
A. aulacocarpa	646.96 (101.67)	49.00 (11.37)	14.54^{b} (2.34)	9.73^{ab} (1.54)	129.97 (37.97)
A. crassicarpa	484.01 (88.92)	51.25 (11.18)	15.95^{a} (1.72)	14.22^{a} (2.17)	131.59 (20.11)
F test	*(ns)*	*(ns)*	*	*	*(ns)*
P value	0.569	0.349	0.015	0.032	0.661

ns – non-significant at 0.05 level

** significant at 0.05 level*

Values in the parenthesis are standard error of the mean.

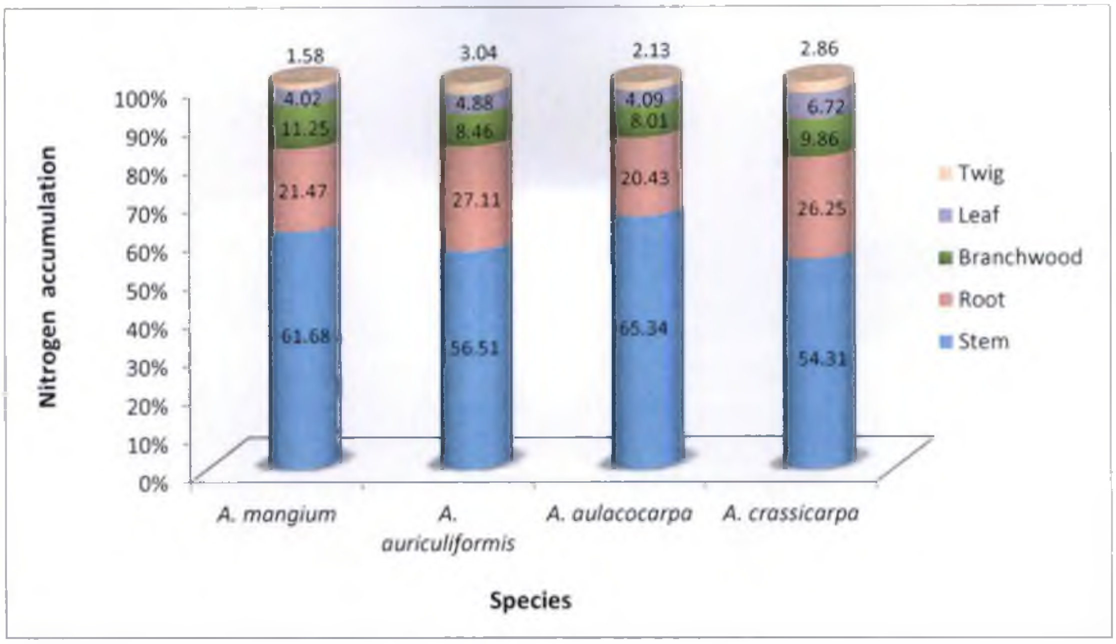


Figure 15. Percentage nitrogen accumulation in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

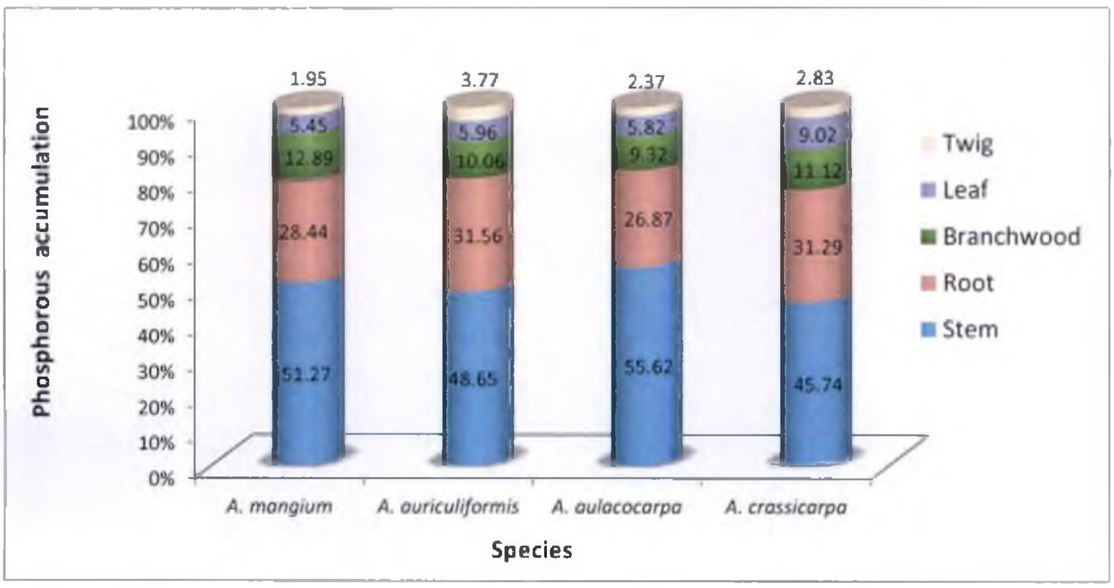


Figure 16. Percentage phosphorous accumulation in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

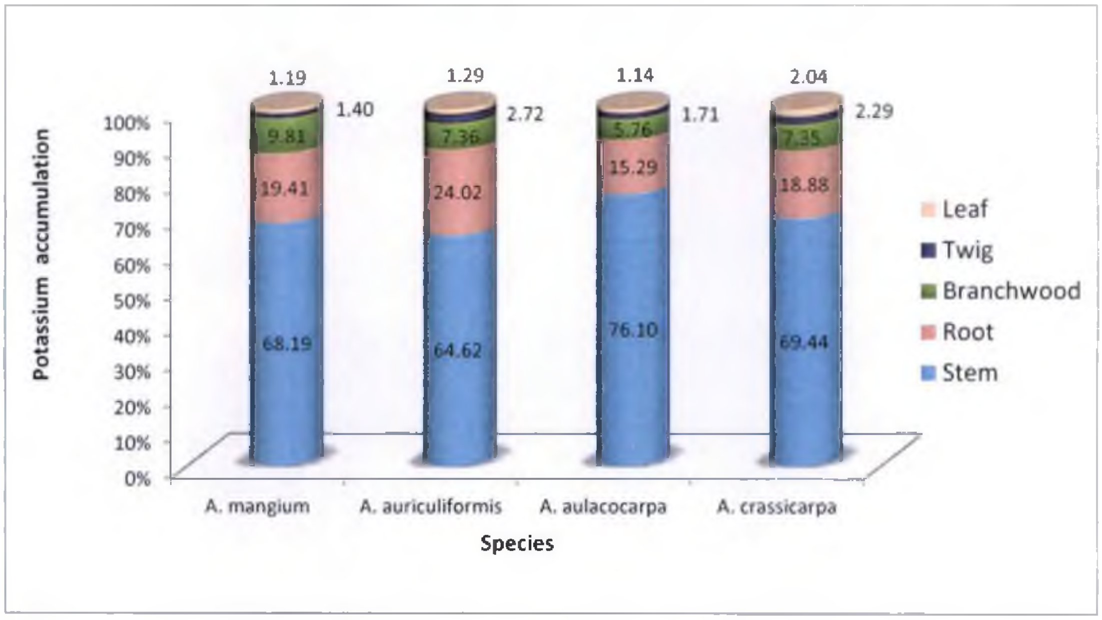


Figure 17. Percentage potassium accumulation in different biomass components of 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

4.7 Soil carbon sequestration under four different acacia species

The total soil carbon of soil under four different acacia species are presented in Table 22. Soil organic carbon (SOC) content was calculated by using the estimated soil carbon content and bulk density of soil under study. Among the species *A. auriculiformis* recorded the highest total soil organic carbon of 77.96 Mg ha^{-1} followed by *A. mangium* (74.75Mg ha^{-1}), while the treeless control plot has recorded the lowest carbon stock (46.64 Mg ha^{-1}).The acacia plantations registered significantly higher soil carbon stock compared to the treeless control plot (Fig. 18). With regard to SOC, all the four acacia species show statistically significant variation.

Table 22. Total soil organic carbon content of different acacia speciesat Vellanikkara at18-years of age.

Species	Total SOC(Mg ha^{-1})
A. mangium	74.75^{b}
A. auriculiformis	77.96^{a}
A. aulacocarpa	72.76^{c}
A. crassicarpa	66.92^{d}
Control (Treeless plot)	46.64^{e}
F test	*
P value	0.000

** significant at 0.05 level*

4.7.1 Vertical distribution of SOC

Depth-wise distribution of mean soil organic carbon content of acacia species with adjacent treeless plot as control is furnished in Table 23. In the uppermost soil layer (0-20 cm depth) maximum mean soil organic C content was recorded for *A. mangium* (24.33 Mg ha^{-1}) followed by *A. aulacocarpa* with C content of 21.95 Mg ha^{-1}. In the 20-40 cm depth, maximum value was recorded for *A. auriculiformis* (16.84 Mg ha^{-1}) followed by *A. aulacocarpa* (16.47 Mg ha^{-1}). In the 40-60 cm and 60-80 cm soil depth classes, *A. mangium* recorded the maximum mean organic C content (13.73 Mg $ha^{-1}$and 13.69 Mg ha^{-1}respectively). At 80-100 cm depth the maximum mean SOC content was registered for *A. auriculiformis* (13.05 Mg ha^{-1}). The highest SOC of 20.94 Mg $ha^{-1}$was recorded in the surface soil (0-20cm).The SOC content in all the depth, varied significantly and it followed an inverse relation with increase in depth (Fig. 18). Treeless control plot recorded a lower value of SOC in all the depth zones.

The bulk density of soil calculated from the undisturbed soil cores collected from the field under different acacia species are presented in Table 24. Generally, for all the species the bulk density shows a direct relationship with increase in depth. The highest bulk density was reported for *A. auriculiformis* (1.22 g cm^{-3}) followed by *A. auriculiformis* (1.22 g cm^{-3}), *A. aulacocarpa* (1.20 g cm^{-3}), *A. mangium* (1.19 g cm^{-3}) and *A. crassicarpa* (1.17 g cm^{-3}). In all the depth zones, treeless control plot recorded the highest bulk density.

Table 23. Depth-wise distribution of Mean soil organic carbon (SOC) content in 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Depth	Mean soil organic carbon content in Mg ha^{-1}					Depth mean
	A. mangium	*A. auriculiformis*	*A. aulacocarpa*	*A. crassicarpa*	Control	
0-20 cm	24.34 (0.013)	21.38 (0.010)	21.95 (0.011)	21.90 (0.011)	15.12 (0.008)	20.94^{a}
20-40 cm	15.00 (0.008)	16.84 (0.009)	16.47 (0.013)	15.63 (0.013)	10.54 (0.013)	14.90^{b}
40-60 cm	13.73 (0.011)	13.28 (0.012)	12.72 (0.011)	10.23 (0.004)	8.39(0.003)	11.67^{c}
60-80 cm	13.69 (0.010)	13.06 (0.004)	11.59 (0.013)	9.48 (0.011)	7.22 (0.013)	11.01^{d}
80-100 cm	8.79 (0.003)	13.41 (0.013)	10.04 (0.004)	9.68 (0.013)	5.68 (0.003)	9.52^{e}
Treatment mean	15.11^{B}	15.59^{A}	14.55^{C}	13.38^{D}	9.38^{E}	

** significant at 0.05 level*

Values in the parenthesis are standard error to the mean

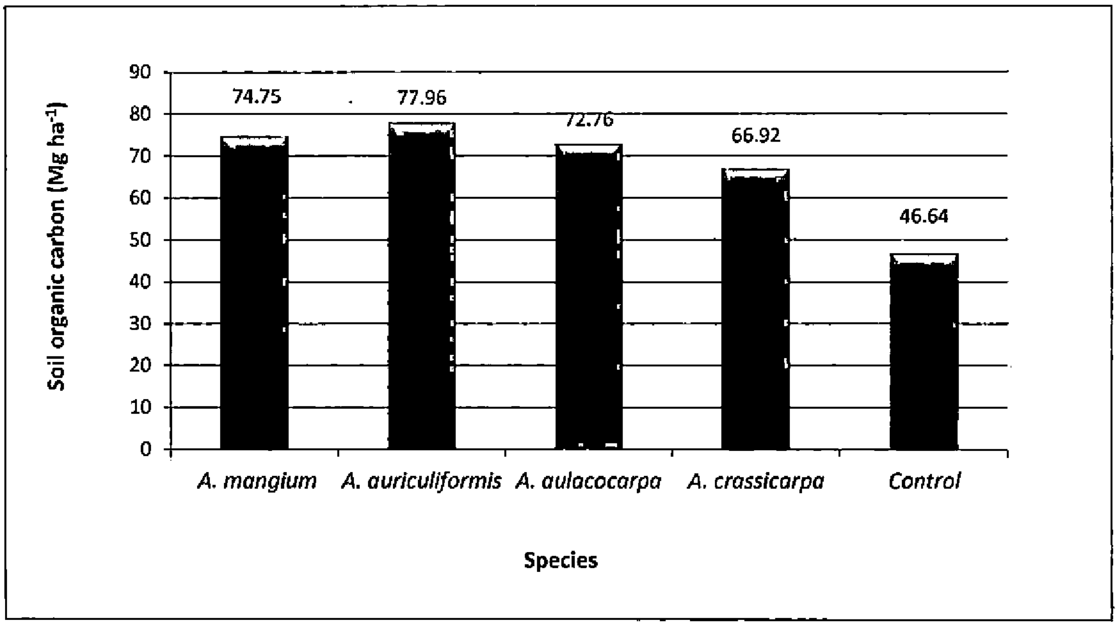


Figure 18. Total soil organic carbon content (Mg ha^{-1}) upto 1m soil depth under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

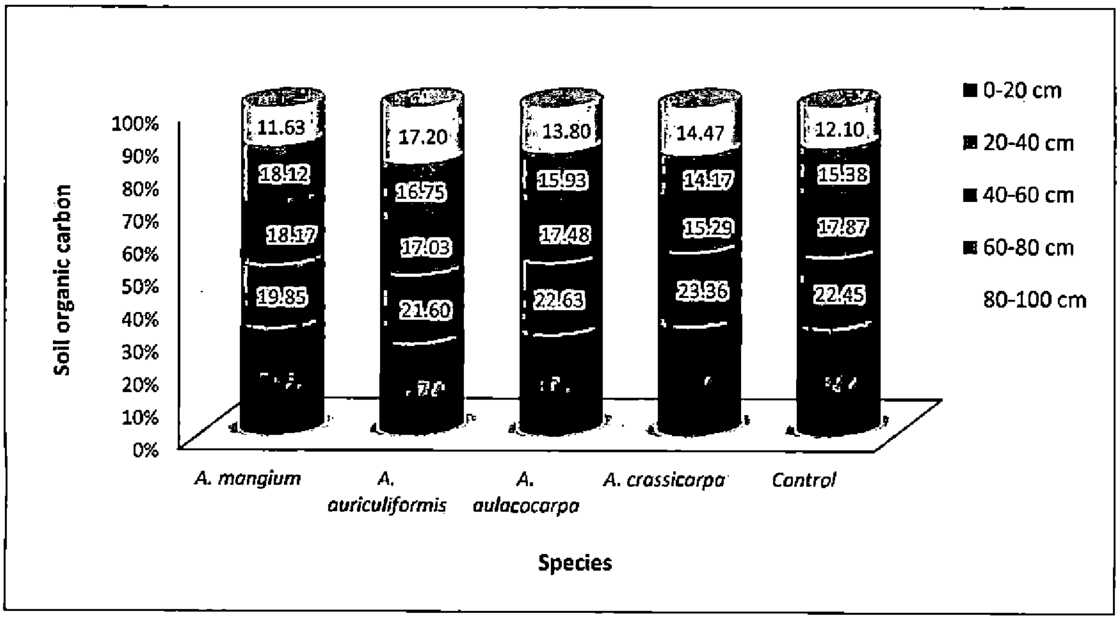


Figure 19. Percentage distribution of soil organic carbon (SOC) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Table 24. Depth-wise pattern of Mean Bulk density of soil under different acacia species of 18-years age at Vellanikkara.

Species	Bulk density of the soil (g cm^{-3})					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	1.13	1.14	1.19	1.21	1.26	1.19^{BC}
A. auriculiformis	1.16	1.7	1.23	1.26	1.30	1.22^{A}
A. aulacocarpa	1.15	1.16	1.19	1.24	1.28	1.20^{B}
A. crassicarpa	1.12	1.14	1.17	1.19	1.24	1.17^{C}
Control	1.17	1.20	1.25	1.28	1.31	1.24^{A}
Depth mean	1.15^{d}	1.16^{d}	1.21^{c}	1.24^{b}	1.28^{a}	

4.8 Soil nutrients

The soil nutrients such as N, P and K upto 1m depth of soil under different acacia species are presented below.

4.8.1 Soil Nitrogen concentration

Soil Nitrogen, at 1m depth over five depth classes of 20cm interval under four acacia species and the treeless plot as a control plot is presented in Table 25. The highest soil nitrogen concentration was observed for *Acacia mangium,* with 0.135% in the surface soil depth (0-20cm) followed by *Acacia auriculiformis* with a value of 1.26%.No particular trend was observed among species at different depth classes. In soil depth zones 20-40 cm and 40-60 cm, highest nitrogen content was recorded for *Acacia aulacocarpa* with values 0.093% and 0.082% respectively. And *Acacia auriculiformis* recorded the highest nitrogen concentration in soil depth zones of 60-80 cm and 80-100 cm with values 0.083% and 0.086% respectively. Invariably, the treeless control plot recorded the lowest nitrogen in all soil depth zones (Fig. 19).

Table 25. Depth-wise distribution of Mean soil nitrogen concentration under different acacia species of 18-years age at Vellanikkara.

Species	Soil Nitrogen (%) at different depths					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	0.135	0.062	0.050	0.026	0.029	0.060[C]
A. auriculiformis	0.126	0.092	0.040	0.083	0.086	0.085[A]
A. aulacocarpa	0.092	0.093	0.082	0.073	0.050	0.078[B]
A. crassicarpa	0.078	0.058	0.028	0.058	0.059	0.056[D]
Control	0.053	0.038	0.026	0.022	0.016	0.041[E]
Depth mean	0.099[a]	0.072[b]	0.049[d]	0.053[c]	0.049[d]	

4.8.2 Soil Phosphorous concentration

Soil phosphorous concentration at five depth classes in four different acacia species stand with adjacent treeless plot as a control plot is presented in Table 26. Soil phosphorous concentration also followed a similar trend as soil Nitrogen. Maximum P concentration was recorded for *A. auriculiformis,* with 0.075% and 0.068% for both 0-20cm and 20-40 cm depth zones respectively. The highest total P concentration at 1m depth was recorded for *A. aulacocarpa.* The second highest value at the surface soil of 0-20 cm depth zone was recorded for *A. mangium* with value 0.068%. Comparatively very low P concentration was recorded for all the depth classes in treeless control plot (Fig. 20).

Table 26. Depth-wise distribution of Mean soil Phosphorous concentration under different acacia species of 18-years age at Vellanikkara.

Species	Soil Phosphorous (%) at different depths					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	0.068	0.044	0.038	0.026	0.030	0.041^{D}
A. auriculiformis	0.075	0.068	0.038	0.055	0.065	0.060^{B}
A. aulacocarpa	0.053	0.065	0.069	0.068	0.050	0.061^{A}
A. crassicarpa	0.048	0.043	0.028	0.059	0.063	0.048^{C}
Control	0.037	0.032	0.026	0.017	0.019	0.033^{E}
Depth mean	0.057^{a}	0.051^{b}	0.042^{e}	0.047^{c}	0.046^{d}	

4.8.3 Soil Potassium concentration

Soil potassium concentration upto 1m depth in four acacia species plot are presented in Table 27. Soil potassium concentration followed a different trend from soil N and P. Maximum K concentration was recorded for *A. mangium,* with 0.007% and 0.007% for both 0-20cm and 20-40 cm depth zones respectively. The highest K concentration at 1m depth was reported for *A. mangium* (o.oo6%) closely followed by *A. crassicarpa* (0.005%). The second highest value at the 0-20 cm depth zone was recorded for *A. crassicarpa, A. auriculiformis, A. aulacocarpa* with value 0.006%. Comparatively very low K concentration was recorded for all the depth classes in treeless control plot (Fig. 21).

Table 27. Depth-wise distribution of Mean soil Potassium concentration under different acacia species of 18-years age at Vellanikkara.

Species	Soil Potassium (%) at different depths					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	0.007	0.007	0.005	0.005	0.006	0.006^{A}
A. auriculiformis	0.006	0.006	0.006	0.005	0.005	0.0055^{B}
A. aulacocarpa	0.006	0.006	0.006	0.005	0.005	0.0054^{C}
A. crassicarpa	0.006	0.007	0.005	0.006	0.006	0.0059^{A}
Control	0.004	0.004	0.003	0.004	0.003	0.0036^{D}
Depth mean	0.006^{a}	0.0057^{b}	0.0049^{d}	0.0049^{d}	0.005^{c}	

4.9 Soil nutrient accumulation

Accumulation of N, P and K in different soil depth classes under different acacia species are presented below (Table 28-30).

4.9.1 Nitrogen accumulation

In all the four acacia species, N accumulation was reported highest in the 0-20 cm depth zone and the value varied from 174.76 kg ha^{-1} to304.9 kg $ha^{-1}$for *A. crassicarpa*and *A. mangium* respectively. *A. auriculiformis* recorded the maximum value in 20-40 cm, 60-80 cm and 80-100 cm with values 214.55 kg ha^{-1}, 207.95 kg ha^{-1} and 223 kg ha^{-1}respectively. Maximum N accumulation in 40-60 cm depth was reported for *A. aulacocarpa* (195.99 kg ha^{-1}). Nitrogen accumulation was reported highest for *A. auriculiformis* followed by *A. aulacocarpa* in the 1m soil depth. The lowest N accumulation was observed consistently in the treeless control plot (Fig. 22).

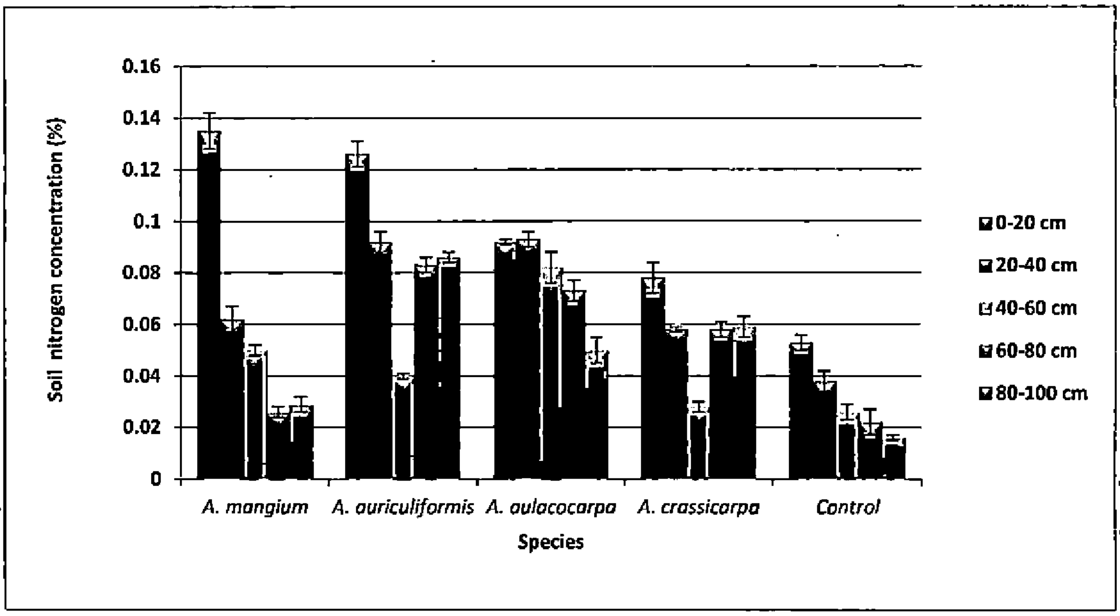


Figure 20. Soil nitrogen concentration (%) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

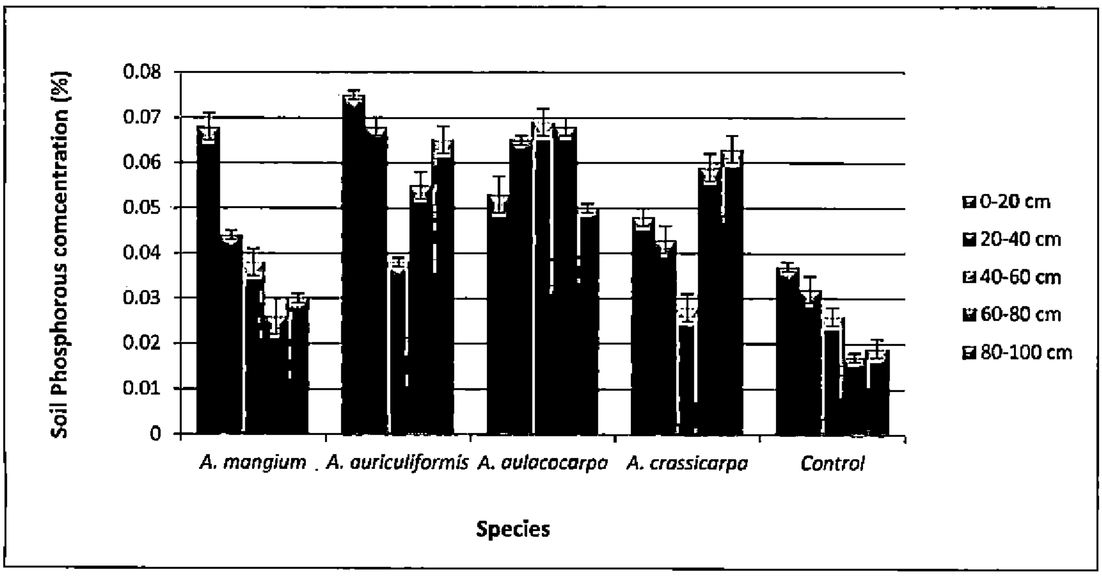


Figure 21. Soil phosphorous concentration (%) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

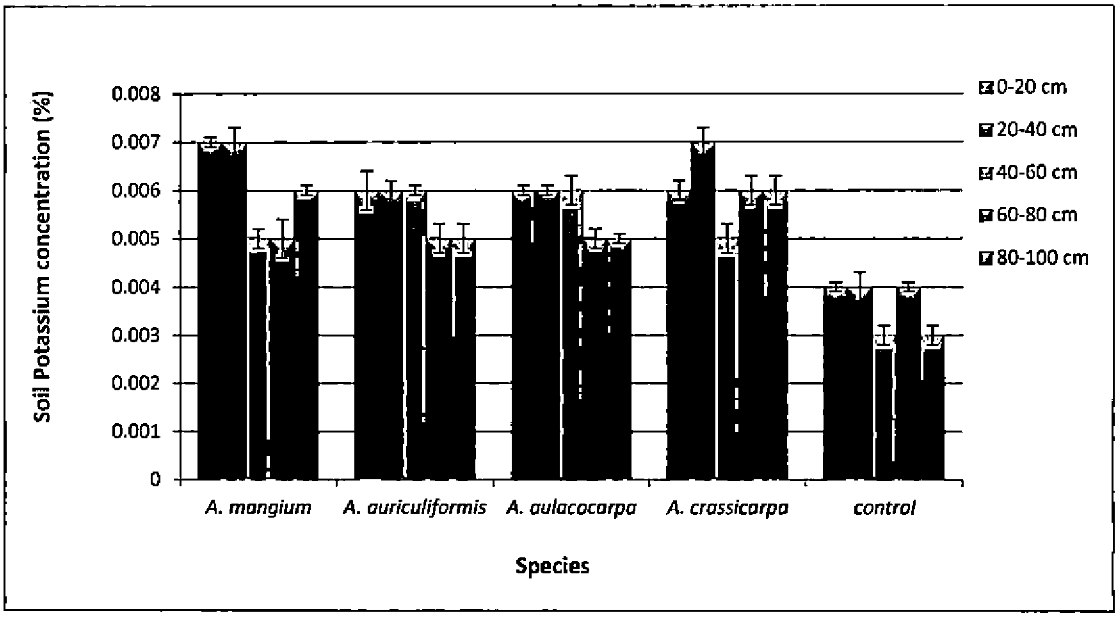


Figure 22. Soil potassium concentration (%) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Table 28. Depth-wise mean soil nitrogen accumulation (kg ha^{-1}) under different acacia species of 18-years age at Vellanikkara.

Species	Soil Nitrogen accumulation (kg ha^{-1})					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	304.90	141.52	118.57	62.03	72.06	139.81^{C}
A. auriculiformis	293.05	214.55	97.74	207.95	223.89	207.43^{A}
A. aulacocarpa	211.61	126.56	195.99	180.65	127.01	186.37^{B}
A. crassicarpa	174.76	132.18	65.07	138.74	147.13	131.58^{D}
Control	150.18	126.27	110.72	58.42	52.71	99.66^{E}
Depth mean	226.90^{a}	166.22^{b}	117.62^{e}	129.56^{c}	124.56^{d}	

4.9.2 Phosphorous accumulation

In all the four acacia species, P accumulation was reported highest in 0-20 cm depth zone and the value varied from 107.52 kg $ha^{-1}$to 174.17 kg ha^{-1} for *A. crassicarpa* and *A. auriculiformis* respectively. *A. auriculiformis* recorded the maximum value in 20-40 cm depth and in 40-60 cm and 60-80 cm highest P accumulation was recorded for *A. aulacocarpa* with values 163.91kg ha^{-1} and 169.40 kg ha^{-1} respectively. Maximum P accumulation in 80-100 cm depth was reported for *A. auriculiformis* (169.26kg ha^{-1}). Phosphorous accumulation was reported highest for *A. auriculiformis* closely followed by *A. aulacocarpa* in the 1m soil depth. The lowest P accumulation was observed consistently in the treeless control plot (Fig. 23).

Table 29. Depth-wise mean soil phosphorous accumulation (kg ha^{-1}) under different acacia species of 18-years age at Vellanikkara.

Species	Soil Phosphorous accumulation (kg ha^{-1})					Treatment mean
	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm	
A. mangium	152.63	101.40	90.63	63.62	75.17	96.69^{D}
A. auriculiformis	174.17	159.57	92.53	139.62	169.26	147.03^{A}
A. aulacocarpa	122.60	149.68	163.91	169.40	128.30	146.78^{B}
A. crassicarpa	107.52	97.90	66.56	141.33	155.82	113.82^{C}
Control	95.87	85.23	93.75	66.29	61.75	80.58^{E}
Depth mean	130.56^{a}	118.76^{b}	101.48^{e}	116.05^{d}	118.06^{c}	

4.9.3 Potassium accumulation

In all the four acacia species, K accumulation was reported highest in 0-20 cm depth zone and the value varied from 142.87 kg ha^{-1} to 156.77 kg $ha^{-1}$for *A. crassicarpa* and *A. mangium* respectively. In the 20-40 cm and 80-100cmdepth maximum K accumulation was reported for *A. mangium* with values151.06kg $ha^{-1}$and 156.50 kg ha^{-1} respectively. Maximum K accumulation in 40-60 cm depth was reported for *A. auriculiformis* (136.50kg ha^{-1}). Potassium accumulation was reported highest for *A. mangium* followed by *A. crassicarpa* in the 1m soil depth. The lowest K accumulation was observed consistently in the treeless control plot (Fig. 24).

Table 30. Depth-wise mean soil potassium accumulation (kg ha^{-1}) under different acacia species of 18-years age at Vellanikkara.

Species	**Soil Potassium accumulation (kg ha^{-1})**					**Treatment mean**
	0-20 cm	**20-40 cm**	**40-60 cm**	**60-80 cm**	**80-100 cm**	
A. mangium	156.77	151.06	114.97	131.18	156.50	142.09^{A}
A. auriculiformis	146.41	135.87	136.50	120.37	134.51	134.73^{C}
A. aulacocarpa	144.61	133.98	131.15	116.97	130.45	131.43^{D}
A. crassicarpa	142.87	149.49	123.70	139.93	146.02	139.93^{B}
Control	99.93	92.67	79.39	92.07	84.47	89.72^{E}
Depth mean	138.13^{a}	132.62^{b}	117.14^{e}	119.63^{d}	130.39^{c}	

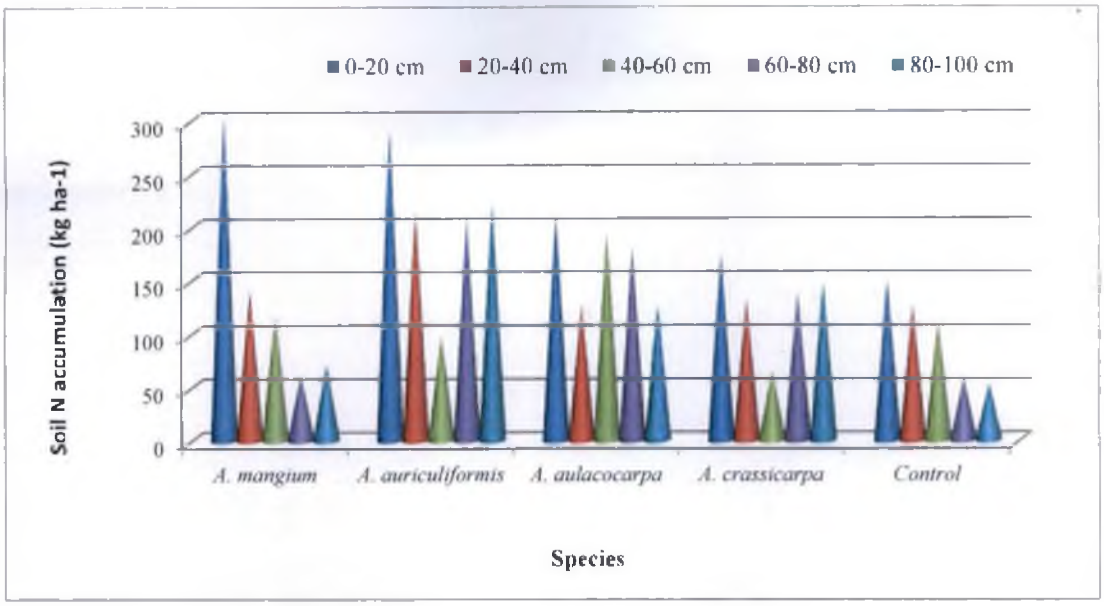


Figure 23. Soil nitrogen accumulation (kg ha^{-1}) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

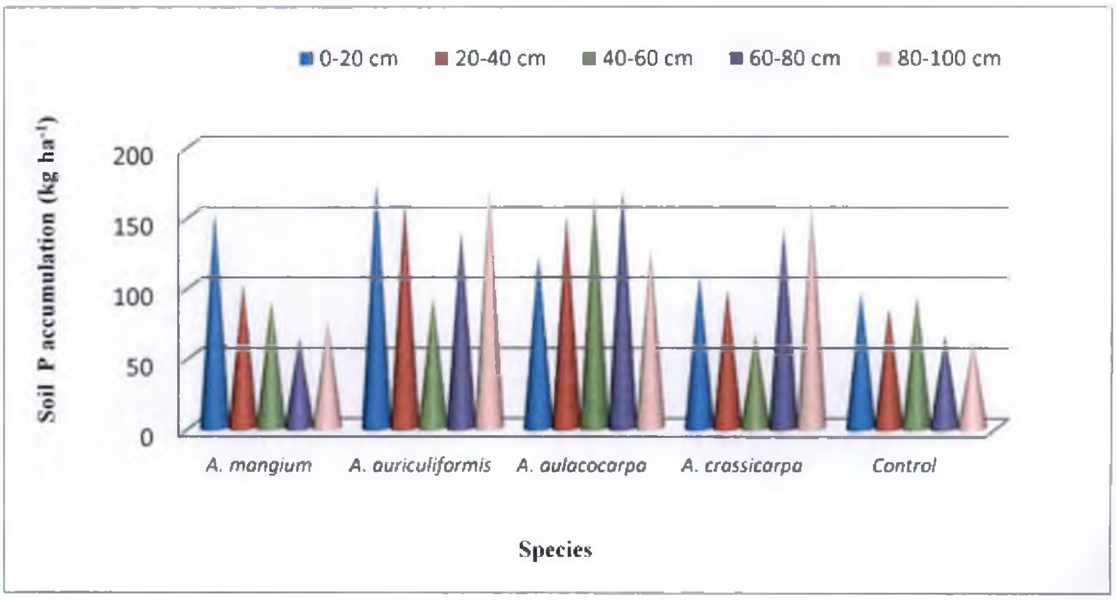


Figure 24. Soil phosphorous accumulation (kg ha^{-1}) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

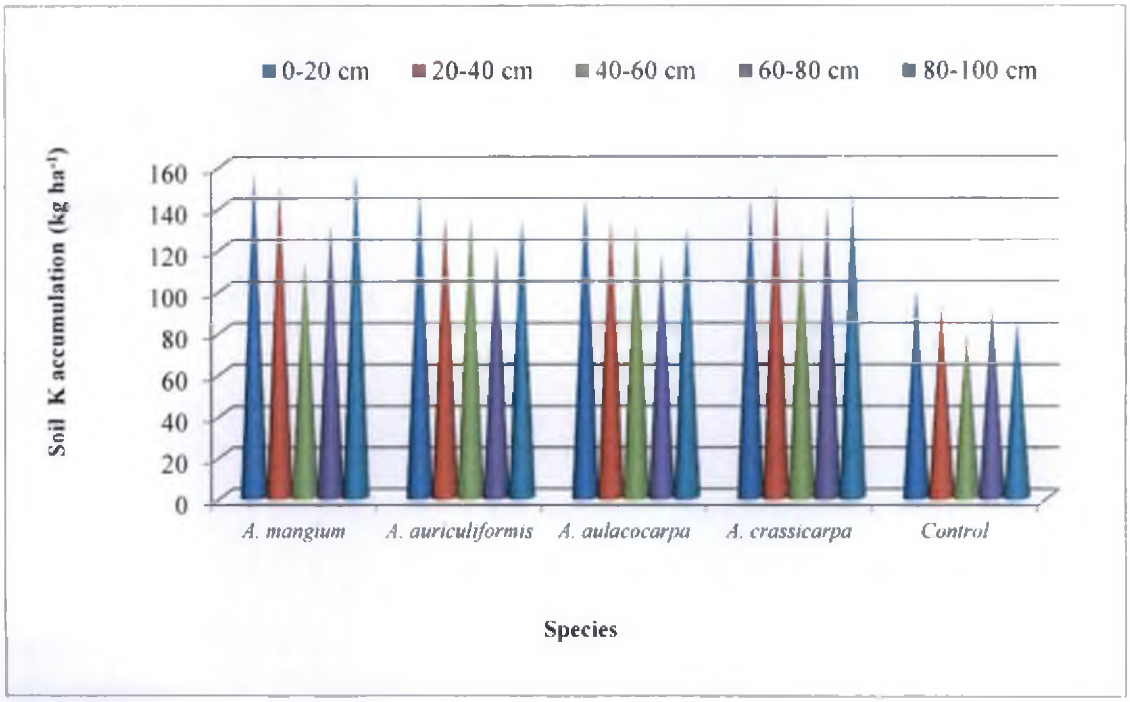


Figure 25. Soil potassium accumulation (kg ha^{-1}) in different soil depths under 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

4.9 Root morphometric studies

Results of the root morphometric observations such as root depth and root spread were taken for all the four species from the field are presented in Table 31. A total of 16 trees were excavated from the acacia stand. Maximum root spread was recorded for *A. mangium* with value 5.23 m followed by *A. crassicarpa* (4.59 m), *A. auriculiformis* (3.98 m) and *A. aulacocarpa* (3.26 m). Maximum root depth was registered for *A. crassicarpa* (1.49 m) followed by *A. auriculiformis* (1.29 m), *A. aulacocarpa* (1.17 m)and lowest value was recorded for *A. mangium* (1.10 m).

Table 31. Root morphometric data of the 18-year-old acacia species at Vellanikkara, Thrissur, Kerala.

Species	Mean Root spread (m)	Mean Root length (m)
A. mangium	5.23	1.10
A. auriculiformis	3.98	1.29
A. aulacocarpa	3.26	1.17
A. crassicarpa	4.59	1.49
F test	*(ns)*	*(ns)*
P value	0.277	0.266

ns - non significant at 0.05 level

Plate 11. Root system of *Acacacia mangium.*

Plate 12. Root system of *Acacacia auriculiformis*.

Plate 13. Root system of *Acacacia aulacocarpa.*

Plate 14. Root system of *Acacacia crassicarpa*

Discussion

DISCUSSION

The findings of the study entitled "Biomass production and root distribution pattern of selected acacias" are discussed hereunder.

5.1 Tree growth pattern of acacias

The tree species vary considerably in their growth patterns. The present study looked into the growth pattern of different acacia species. Tree height varied significantly among species with *A. aulacocarpa* showing maximum height closely followed by *A. auriculiformis* and *A. mangium*. Tree height is one of the growth variables that is strongly influenced by the site conditions. But in the present study the site conditions and management practices provided for all the acacia species are same. In general with the same site the differential growth given by tree species is again strongly influenced by genetic and physiological factors and therefore the growth rate of *A. crassicarpa* may be inherently inferior compared to the other three acacias observed.

The increase in height growth with stand age revealed that growth phase has a major role in the height growth behavior of a stand. Maximum height growth of *A. auriculiformis* was also reported by Jamaludheen *et al.* (1997), Sajeer (2010) and Aneesh (2014). Similarly Kunhamu *et al.* (2005), on seven year old *A. mangium,* reported the MAI in height and DBH (2.51m yr^{-1} and 2.47 cm yr^{-1} respectively) with values higher than the present study (1.17m yr^{-1} and 1.5 cm yr^{-1} respectively). Comparative growth observations by the above species at different stand age and management regimes are given in Table 32 and 33.

Among the acacia species, DBH have no significant difference, with *A. mangium* showing maximum DBH closely followed by *A. aulacocarpa, A. auriculiformis* and *A. crassicarpa* at 18-years of stand age. This may be because of the overstocking (same spacing of 3m×3m) of the stand, old age and the consequent stagnation in radial growth. High diameter growth in *A. auriculiformis* was also reported by Kumar *et al.* (1998), Sajeer (2010) and Aneesh (2014) in woodlot experiments. Similarly Jamaludheen (1994), while studying nine fast growing MPTs in wood lot experiment at Peninsular India, reported that the MAI in DBH at 8.8-years of stand age (1.55 cm yr^{-1}) were comparable in the case of *A. auriculiformis* (1.47 cm yr^{-1}) in the present study. However, the diameter growth of *A. auriculiformis* (26.51 cm) in the present study were comparable with the similar study in a pepper based production system (20.32 cm) using six MPTs (Aneesh, 2014) and study by Sajeer (2010) in three MPTs (20.51) with 22-years and 25-years of stand age respectively.

Such diverse nature in tree growth parameters with species has also been reported earlier. For instance, Kumar *et al.* (1998), on nine fast growing MPTs in wood lot and four fast growing MPTs in silvopastoral experiment at Peninsular India, also reported that *A. auriculiformis* showing the highest height and diameter growth followed by *Casuarina eqisetifiloa, Paraserianthes facultaria* and *Leucaena leucocephala* at 5, 7 and 8.8 years of stand age.

Acacia species also showed significant variation in terms of bole height with *A. aulacocarpa* showing maximum bole height followed by *A. mangium*. The lowest bole height was reported for *A. crassicarpa* which is on par with *A. auriculiformis.* Overall growth was reported highest for *A. aulacocarpa* followed by *A. mangium* and *A. auriculiformis* and the lowest for *Acacia crassicarpa.* Acacia species also showed marked variation in mean tree bole volume production. Tree volume, being a function of diameter and height, followed similar trend with *A. aulacocarpa* showing the highest bole volume followed by *A. auriculiformis.*

Table 32. Comparative growth performance of acacia species at different stand age and management regimes in the humid tropics of Kerala.

Species	Land use	Age (years)	Spacing	Height (m)	DBH (cm)	MAI in Height (m yr^{-1})	MAI in DBH (cm yr^{-1})	**Source**
Acacia auriculiformis	Woodlot	8.8	2m×2m	17.84	13.63	2.03	1.55	Kumar et al., 1998
	Silvopasture	7	4m×1m	12.45	11.64	1.78	1.67	Kumar et al., 1998
	Silvopasture	5	-	10.91	9.28	2.18	1.86	Kumar et al., 1998
	Pepper based	22	3m×3m	13.08	20.32	0.59	0.92	Aneesh, 2014
	Woodlot	25	2m×2m	22.01	20.51	0.88	0.82	Sajeer, 2010
	Plantation	18	3m×3m	21.55	26.51	1.2	1.47	Present study
Acacia mangium	Woodlot	7	2.5m×2.5m	17.6	17.29	2.51	2.47	Kunhamu et al., 2005
	Plantation	18	3m×3m	21.05	27.15	1.17	1.5	Present study

Table 33. Comparative growth performance of MPTs at different stand age and management regimes in the humid tropics of Kerala.

Species	Land use	Age (years)	Spacing	Height (m)	DBH (cm)	MAI in Height (m yr^{-1})	MAI in DBH (cm yr^{-1})	Source
Ailanthus triphysa	Woodlot	8.8	2m×2m	5	8.42	0.57	0.96	Kumar et al., 1998
	Silvopasture	7	4m×1m	5.11	6.68	0.73	0.95	Kumar et al., 1998
	Silvopasture	5	-	4.18	5.64	0.84	1.13	Kumar et al., 1998
	Pepper based	22	3m×3m	10.78	20.24	0.49	0.92	Aneesh, 2014
Casuarina equisetifolia	Woodlot	8.8	2m×2m	12.13	7.50	1.38	0.85	Kumar et al., 1998
	Silvopasture	7	4m×1m	9.43	5.69	1.35	0.81	Kumar et al., 1998
	Silvopasture	5	-	8.24	5.54	1.65	1.1	Kumar et al., 1998
	Pepper based	22	3m×3m	13.67	13.67	0.62	0.80	Aneesh, 2014
Grevillea robusta	Pepper based	22	3m×3m	14.42	23.06	0.65	1.05	Aneesh, 2014

5. 2 Biomass production potential

Biomass production potential of trees vary considerably with tree species. Different plant communities have different rate of biomass production based on their efficiency. In the present study, even though the growth parameters are reported high for *A. aulacocarpa* followed by *A. mangium*, a varying trend was observed in case of biomass production. The mean tree total biomass and stand biomass per hectare was highest for *A. auriculiformis* (388.91Mg $tree^{-1}$ and 432.08 Mg ha^{-1} respectively) followed by *A. crassicarpa* this shows the superiority of *A. auriculiformis* (MAI= 24 Mg ha^{-1} yr^{-1}) over the other acacias. Similar trend was reported for the stand mean below ground biomass also. For instance, the total biomass estimated in 22-year old *Acacia auriculiformis* stand at Thiruvazhamkunnu was 330.87 Mg ha^{-1} (Aneesh, 2014) and which were lower than the present study and that may be due to the intensive tree lopping followed in the black pepper production system and which may limit the above and belowground biomass production.

In general, considerable variation in biomass production among the species occurs with respect to tree age, management system and stand density (Kumar *et al.*, 1998; Shujauddin and Kumar, 2003). Tropical fast growing MPTs in general have high annual biomass accumulation rate. In the present study the, highest stand MAI was recorded in *A. auriculiformis* (24 Mg ha^{-1} yr^{-1}) followed by *A. crassicarpa* (23.25 Mg ha^{-1} yr^{-1}), *A. aulacocarpa* (22.56 Mg ha^{-1} yr^{-1}) and *A. mangium* (20.43 Mg ha^{-1} yr^{-1}). The values obtained in the present study are in true with the MAI of fast growing MPTs of the same age. For example higher MAI in biomass to the tune of 22-27 Mg ha^{-1} yr^{-1} has been reported for *A. auriculiformis* from Varanasi, India (Kumar, 2008). Also Jangra *et al.* (2010) reported an MAI of 24.42 Mg ha^{-1} yr^{-1} in 25-year old *G. robusta* plantation. Similarly Sreedevi (2011) reported an MAI of 18.99 Mg ha^{-1} yr^{-1} in *A. procera* and 18.59 Mg ha^{-1} yr^{-1} in *C. equisetifolia* at 20 years of age at Navasari, Gujrat. With increase in age, after a particular time the MAI also decreases because of the stagnation in growth. For example Aneesh (2014) reported an MAI of 16.62 Mg ha^{-1} yr^{-1} in *G. robusta,* 15.04 Mg ha^{-1} yr^{-1} in *A. auriculiformis* and 14.76 Mg ha^{-1} yr^{-1} in *C. equisetifolia* at 22 years of age at Thiruvazhamkunnu, Kerala. In younger ages, the growth rate was very high, for example Jamaludheen (1994), reported a MAI of 39.11 Mg ha^{-1} yr^{-1} in *A. auriculiformis* at an age of 8.8-years. Comparative biomass production by the above species at different stand age and management regimes are given in Table 34 and 35.

With respect to stand above ground biomass production no significant difference was seen in the acacias. The maximum value was reported for *A. auriculiformis* closely followed by *A. aulacocarpa, A. mangium* and *A. crassicarpa.* The reports suggest that aboveground net primary productivity for tropical species ranged from 16 to 29.8 Mg ha^{-1} yr^{-1} of dry matter (Lugo *et al.*, 1988). For instance, *Acacia auriculiformis* showed comparable biomass production for 25 year old woodlots (20.18 Mg ha^{-1} yr^{-1}; Sajeer, 2010) with the present study (18.68 Mg ha^{-1} yr^{-1}). Similarly, Halenda (1989) reported a comparable MAI of 17.6 Mg ha^{-1} yr^{-1} in *A. mangium* with the present study (16.58 Mg ha^{-1} yr^{-1}). The higher rate of biomass production (28.1 Mg ha^{-1} yr^{-1} and 37.09 Mg ha^{-1} yr^{-1}) for younger *Acacia auriculiformis* may be attributed to the grand growth phase and the intensive management regimes under woodlots as reported by Jamaludheen (1994) and Kumar *et al*, (1998) at the age of 5 and 8.8-years of stand age. Similarly Kumar *et al.*, (1998) on 7-year-old *Acacia auriculiformis* reported comparable biomass production (MAI= 26.22 Mg ha^{-1} yr^{-1}). Similarly, Kunhamu *et al.*, (2005) reported an MAI of 35.04 Mg ha^{-1} yr^{-1} in 7-year-old *A. mangium* stand and which were more than double the value of the present study (16.58 Mg ha^{-1} yr^{-1}). With increasing age after the grand growth phase, the growth rate decreases and thereafter stagnant phase is reached. The biomass production in the present study corresponds to 18-year old stand which has surpassed rotation age and obviously it gives a lower MAI.

Table 34. Comparative biomass production by acacias at different stand age and management regimes in the humid tropics of Kerala.

Species	Land use	Age	Spacing	AGB (kg tree^{-1})	Total biomass (kg tree^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Total biomass (Mg ha^{-1})	MAI (Mg ha^{-1} yr^{-1})	Source
Acacia auriculiformis	Woodlot	8.8	2m×2m	130.57	137.66	326.43	17.73	344.16	39.11	Kumar et al., 1998
	Silvopasture	7	4m×1m	73.42	-	183.54	-	-	-	Kumar et al., 1998
	Silvopasture	5	-	56.13	62.68	140.5	16.3	156.8	31.36	Kumar et al., 1998
	Pepper based	22	3m×3m	241.76	297.79	268.62	62.26	330.87	15.04	Aneesh, 2014
	Plantation	18	3m×3m	302.69	388.91	336.29	95.79	432.08	24.00	Present study
Acacia mangium	Woodlot	7	2.5m×2.5m	-	-	-	-	210.24	35.04	Kunhamu et al., 2005
	Woodlot	7	-	-	-	-	-	123.2	17.6	Halenda, 1989
	Plantation	18	3m×3m	270.78	331.01	298.43	69.33	367.76	20.43	Present study

Table 35. Comparative biomass production by MPTs at different stand age and management regimes in the humid tropics of Kerala.

Species	Land use	Age	Spacing	AGB (kg tree^{-1})	Total biomass (kg tree^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Total biomass (Mg ha^{-1})	MAI (Mg ha^{-1} yr^{-1})	Source
Ailanthus triphysa	Woodlot	8.8	2m×2m	16.21	19.17	40.54	7.40	47.94	5.45	Kumar et al., 1998
	Silvopasture	7	4m×1m	7.75	-	19.38	-	-	2.2	Kumar et al., 1998
	Silvopasture	5	-	7.87	9.57	19.8	4.2	24	4.8	Kumar et al., 1998
	Pepper based	22	3m×3m	117.46	139.62	130.51	24.62	155.13	7.05	Aneesh, 2014
	Woodlot	8.8	3m×3m	47.85	53.46	53.16	6.14	59.30	6.74	Shujauddin and kumar, 2003
Casuarina equisetifolia	Woodlot	8.8	2m×2m	38.23	40.47	95.58	5.6	101.18	11.5	Kumar et al., 1998
	Silvopasture	7	4m×1m	13.47	-	-	33.68	-	4.8	Kumar et al., 1998
	Silvopasture	5	-	14.31	15.65	35.9	3.4	39.3	7.86	Kumar et al., 1998
	Pepper based	22	3m×3m	259.46	292.16	288.30	36.33	324.63	14.76	Aneesh, 2014
	Woodlot	20	-	-	-	371.70	-	-	18.59	Sreedevi et al., 2010
Leucaena leucocephala	Woodlot	8.8	2m×2m	9.12	10.41	22.81	3.23	26.04	2.96	Kumar et al., 1998
	Silvopasture	7	4m×1m	25.40	-	63.51	-	-	9.07	Kumar et al., 1998
	Silvopasture	5	-	26.28	33.04	65.8	12	77.8	15.56	Kumar et al., 1998

The MAI also vary depending on the nature of growth of species. For fast growing species the growth rate or MAI will be higher than slow growing species. For example the MAI in aboveground biomass of *Acacia auriculiformis* in a 25-year old stand was 20.18 Mg ha^{-1} yr^{-1} while MAI was 6.93 Mg ha^{-1} yr^{-1} for *Artocarpus heterophyllus* and 4.02 Mg ha^{-1} yr^{-1} in the case of *Artocarpus hirsutus* stand (Sajeer, 2010).

5.3 Biomass allocation pattern

Biomass partitioning among various tree components namely, bole, branchwood, twigs, leaf, reproductive parts and roots vary considerably with species, age, spacing, growth rate, light demand and management practices (Keeling *et al.*, 2008; Fonseca *et al.*, 2012). In the present study the order of biomass accumulation to the various tree components were bole> root> branchwood> twig> leaf. Interestingly, more than 80 % of the total biomass was accounted in the aboveground biomass portion for all the acacia species (Table 5). Similar trends were shown by many fast growing tropical tree species (Jamaludheen, 1994; Paul, 2013; Aneesh, 2014).

Bole fractions accounted highest allocation to (65-72%) the total and total above ground biomass and least by leaf portion (0.85-1.5%) for all the species under the present study at 18-year age (Figure 4). Contribution of bole fraction in the total biomass was highest in *Acacia aulacocarpa* followed by *Acacia mangium* and *Acacia auriculiformis.* Lowest percentage of bole biomass was recorded for *Acacia crassicarpa,* however contribution of root biomass was highest for *Acacia crassicarpa* (22.94%). High percentage of bole biomass is also reported in many tropical fast growing MPTs (Grier *et al.*, 1992; Karmacharya and Singh and Toky, 1993; Kumar *et al.*, 1998; Kunhamu *et al.*, 2005; Sajeer, 2010; Fonseca *et al.*, 2012; Paul, 2013 and Aneesh, 2014). Kunhamu *et al.* (2011) reported 65-75% of biomass allocation to the bole portion of all the classes of 7-year old *Acacia mangium* in Kerala. Similar trend (56-69%) was reported by Aneesh (2014) for 22-year old six MPTs in a polyculture system involving black pepper support at Thiruvazhamkunnu, Kerala. The contribution of bole portion to the total biomass in the case of *A. auriculiformis* was 62.6% while in the present study it was 67.73%. In the present study contribution of bole portion to the total biomass vary with different species of same age and same density. Aneesh (2014) reported a similar finding of difference in contribution of bole portions in different species of same age and same density. For instance, the percentage contribution of bole fraction to the total biomass recorded in *G. robusta* (68.85%), *A. auriculiformis* (62.60%), *C. equisetifolia* (65.76%) and *A. triphysa* (68.38%) in a 22-year-old pepper support tree system. The value also varied for same species at different age. For instance, the contribution of bole portion to total biomass for *A. auriculiformis* were 79.88% (Jamaludheen, 1994), 62.60% (Aneesh, 2014), 72.35 (Kunhamu, 2005) and 69.67% (present study) at an age series of 8.8, 22 and 18-year of stand age.

Root biomass contributed the second largest share to the biomass production. In the present study, at 18-year of age, the percentage root concentration ranged from 18-23%. The highest root fraction was recorded for *A. crassicarpa* (22.94%) followed by *A. auriculiformis* (22.17%). Similar trend was reported by Aneesh (2014) in 22-year old MPTs (black pepper support trees) with 23.87% in *M. peltata,* 19.34% in *A. heterophyllus,* 18.82% in *A. auriculiformis* and 17.3% in *G. robusta* stand. A disagreeing trend to the above statement were recorded by Jamaludheen (1994) in 8.8 year old nine MPT stand with second largest contribution of tree components to the biomass were by branchwood portion at an younger age of growth.

5. 4 Carbon sequestration potential of acacias

Carbon sequestration by trees or in a wooded system is by and large a function of their biomass production (Schimel *et al.*, 2001). Approximately 88 per cent of the total tree biomass in plantation and agroforestry system is stored in tree trunks as aboveground biomass, and the remaining as belowground (Sharrow and Ismail, 2004). The present study involving four acacia species shows the enormous carbon sequestration potential of these trees. The carbon sequestrated by tree components followed similar trend as biomass allocation. The order of carbon sequestrated by tree components were bole > root > branchwood> twig > leaves. Similar result was also reported by Norris *et al.* 2001; Kaur *et al.* 2002 and Swamy *et al.* 2003. In the present study high mean tree carbon sequestration was showed by *Acacia auriculiformis* (176.38 kg C tree^{-1}) followed by *Acacia aulacocarpa* (165.54 kg C tree^{-1}) (Figure 5). Carbon sequestration values for 22 year old *Acacia auriculiformis, Grevillea robusta* and *Casuarina equisetifolia* (Aneesh, 2014) showed comparatively lower values than the present study (139.20, 152.32 and 136.35 kg tree^{-1} respectively). The difference in growth pattern with increasing age could explain the wide variation in mean tree C production. However the MAI in mean tree C sequestration of 9.80 kg tree^{-1} yr^{-1} in the present study was high as that of 8.8 year old (Kumar *et al.*, 1998) and 22 year old (Aneesh, 2014) *Acacia auriculiformis* with values 7.82 kg tree^{-1} yr^{-1} and 6.32 kg tree^{-1} yr^{-1} respectively. The lowest mean tree C sequestration was recorded for *Acacia crassicarpa* (147.28 kg tree^{-1}) among the acacia species examined in the present study.

Carbon sequestration on stand basis also followed similar trend with *Acacia auriculiformis* and *Acacia aulacocarpa* showing higher C sequestration to the tune of 195.94 Mg ha^{-1} and 183.93 Mg ha^{-1} respectively (Table 11). This is in conformity with the earlier reported values for tropical forests, which varies from 132-174 Mg ha^{-1} (Dixon *et al.*, 1995). MAI in carbon sequestration rate of 22-year-old and 25-year-old *Acacia auriculiformis* stand was reported to be 6.19 Mg ha^{-1} yr^{-1} and 10.09 Mg ha^{-1} yr^{-1} and which was comparable with the MAI in C sequestration of the present study (10.89 Mg ha^{-1} yr^{-1}). Yet another interesting factor is that the roots account for second largest contributor to the mean tree C stock in all the species studied with values ranging from 33.59 Mg C ha^{-1} (*A. mangium*) to 44.49 Mg C ha^{-1} (*A. auriculiformis*) (Table 10). Many studies emphasis the role of trees in improving the belowground C sequestration (Saha *et al.*, 2010; Haile *et al.*, 2008) and there by ascertaining the long-term productivity of the soils. Aneesh (2014) on 22-year-old *Acacia auriculiformis* reported 1.37 Mg ha^{-1} yr^{-1} rate belowground C sequestration, which were less than the 18-year-old stand with value 2.47 Mg ha $^{-1}$ yr^{-1} in the present study. Similarly Kunhamu *et al.*, (2011) reported the belowground C sequestration of 34.62 Mg ha $^{-1}$ (MAI= 5.33 Mg ha $^{-1}$ yr^{-1}) for *Acacia mangium* at 6.5-years of age and which were higher than the value obtained in the present study (1.87 Mg ha $^{-1}$ yr^{-1}). Observations indicate that belowground carbon sequestration also varies quite well with stand age management practices. This may be because of the old age and stagnation in stand growth. The decrease in rate of below ground C sequestration with stand age revealed that growth phase has a major role in the biomass production. Root carbon sequestration was higher in the present study compared to younger stands.

Elemental carbon concentration was higher in the woody tissues like bole, root and branchwood than soft tissues like leaves (Kraenzal *et al.*, 2003). In the present study also all the species showed similar trend and the order of elemental carbon on the tissue components as bole > root > branchwood > twigs > leaves. The C sequestration can be effective only if increased photosynthetic C fixation occurs in long-lived pools. Present study showed maximum C sequestration in bole (63.61%-71.28%) followed by root (19.10%-23.78%) (Figure 6). Bole and branchwood usually maintain higher tissue carbon concentration primarily on account of the proportionate lower content of other nutrients (Fonseca *et al.*, 2012). This higher carbon concentration in the bole and branchwood permits higher sequestration of elemental carbon for longer periods. The mean carbon concentration obtained in the present study (46.17% - 46.72%) was found very close to the 50 per cent value often used for estimation of carbon storage from dry biomass (Chhabra and Dadhwal, 2004).

5. 5 Allometric equations

Estimates of aboveground biomass are required for better planning, sustainable management and monitoring of changes in C stocks in agroforestry systems. Biomass prediction models are considered to be a nondestructive method for the estimation of biomass of tree stands. Since total estimation of the tree stand is usually impracticable, the biomass estimation from easily measurable tree growth variable is commonly used for prediction. Prediction equations attempted in the present study tried to link the total aboveground biomass, total aboveground carbon sequestration, total volume and bole volume with dbh and/or height of the trees as predictor variables. Various equations were developed for predicting the above mentioned parameters. The best fit models for the parameters for the given growth variables were assessed based on the predictability in terms of coefficient of determination (R^2 value). Models with higher R^2 values were selected for aboveground biomass, aboveground biomass carbon sequestration, total volume and bole volume predictions.

Biomass prediction equations generally vary with species, age, stand density, genetic differences and environmental conditions (Cambell *et al.*, 1985). In the present study, linear prediction equation with two variable showed higher R^2 values for the aboveground biomass of *Acacia mangium* and *Acacia auriculiformis*, but for *Acacia aulacocarpa* and *Acacia crassicarpa* best fitted equations were cubic equations with single variable ie., diameter. Kumar *et al.*, (1998) predicted the allometric equations for above ground biomass of *Acacia auriculiformis* at different age (8.8, 7 and 5 years) and agroforestry systems and reported that best fit equations are logarithmic equations with two variables (DBH and height). Aneesh (2014) predicted equations for 22-yer old *Acacia auriculiformis* stand and linear equations with two variables reported as best fit equation. In the case of *Ailanthus triphysa, Casuarina equisitifolia,* for biomass prediction the best fit equation was logarithmic with two variables (Kumar *et al.*, 1998). Kunhamu *et al.* (2005) developed regression equations linking above ground biomass with GBH and height of seven-year-old *Acacia mangium* and regression models viz. power, quadratic and cubic with one variable (GBH) gave good fit.

Similar trend was reported for the aboveground C sequestration for all the four acacia species. In 22-year old *Acacia auriculiformis,* linear equation (with two variables) found as best fit one. However, a different trend was reported for total volume. Linear equation with two variables for *Acacia mangium,* quadratic equation with diameter as dependent variable for *Acacia auriculiformis* and *Acacia aulacocarpa* and cubic equation with single variable (DBH). Quadratic equations with one variable (DBH) gave good prediction model for the total volume of seven year old *Acacia mangium* stand (Kunhamu *et al.*, 2005). With respect to bole volume all species except *Acacia crassicarpa* recorded linear equation with two variables as the best fit. For *Acacia crassicarpa,* the prediction equation with high R^2 value was cubic with diameter as variable.

5. 6 Nutrient concentration in tree components

The nutrient concentration in various tissues vary depending on species, environmental factors and management strategies (Moya *et al.*, 2013). In the present study among the various tree components, leaf had registered the highest concentration of all nutrients, followed by twig, branchwood, root and bole (Table 16, 17 and 18). Higher nutrient concentration in leaves was also reported for many species (Wang *et al.*, 1991; Lodhiyal *et al.*, 2002; Shujahudin and Kumar, 2003; Mohsin *et al.*, 2005; Geo, 2013; Sajeer, 2010 and Aneesh, 2014). Tissue nutrient concentration, especially in leaves are considered to be an efficient tool for evaluating nutrient status of the trees. Leaf being the centre of maximum photosynthetic activity; it is logical that the highest nutrient concentration is always found in leaves as compared to other components (Sreemannarayanan *et al.*, 1994; Kumar *et al.*, 2009). The elevated nutrient concentration in the leaves makes this tree component an important reserve of bio elements, although it represents only a small percentage of the whole tree biomass. High nutrient concentration in the leaves will avoid the nutrient loss from the site through harvest because of its low commercial value and it will actively participate in the nutrient cycling and enrich soil. The lower nutrient concentration on the tree trunk and branchwood assume a conservative measure against the huge harvest related nutrient loss from the site. Kumar *et al.* (1998) on 8.8-year-old *A. auriculiformis* reported the highest nutrient concentration in the leaf portion (N=2.47%, P=0.08% and K=0.73%) compared to the other biomass components and which were comparable with the present study (N=2.41%, P=0.11% and K=0.57%). Same trend was recorded by the species at 22 and 25-year old stands. The nutrient concentration in the biomass components of the same species were low at 7 and 5-years of age showing that nutrient concentration increases with increase in age and after the grand growth phase a stagnant phase is developed.

In the present study, highest nutrient (N, P and K) concentration were reported for *Acacia auriculiformis* for all most all tissue types. Significantly different nutrient concentrations were recorded for almost all the nutrients and tissue type. Among the nutrients nitrogen concentration was highest, followed by potassium and phosphorous in all tissue types of the tree. Similar trend was reported for many species (Jamaludheen, 1994; Geo, 2013; Sajeer, 2010 and Aneesh, 2014). Similarly, George (1993) reported higher N concentration in a 5-year-old *Acacia auriculiformis* (2.32%) stand than P and K. Similar observation has been reported in *Acacia auriculiformis, Artocarpus heterophyllus, Ailanthus triphysa, Artocarpus hirsutus, Emblica officinalis, Leucaena lecocephala, Paraserianthus facultaria, Pterocarpus marsupium* and *Casuarina equisetifolia* (Kumar *et al.*, 1998) and in *Acacia mangium* (Kunhamu *et al.*, 2005).

5. 7 Nutrient accumulation

Nutrient accumulation and export from the site have become an important consideration in fast growing MPT based system, where nutrient removed through frequent harvest may exceed the natural rate of nutrient input such as mineral weathering, atmospheric inputs and biological fixation (Kumar *et al.*, 1998; Pare *et al.*, 2013). The key factors that control the nutrient accumulation in various biomass components is the rate of biomass production and the nutrient concentration in the respective components.

In the present study, irrespective of nutrient concentration in biomass components maximum nutrient accumulation of N, P and K was found in the bole fraction for all the acacia species because of the high biomass accumulation in the bole. Among the species, N accumulation followed the order of *Acacia auriculiformis* > *Acacia aulacocarpa* > *Acacia mangium* > *Acacia crassicarpa.* Same trend was repeated for both P and K accumulation. Maximum nutrients are accumulated in the bole fraction and the order of accumulation was bole > root > branchwood > twig > leaf and is same for all the species and for all the nutrients. This indicates the huge quantity of nutrients that could be lost from the system through harvest. Such heavy losses in the subsequent rotations can bring substantial reduction in the soil nutrient base in the long run. Similar trend has been reported in *Acacia auriculiformis, Artocarpus heterophyllus, Ailanthus triphysa, Artocarpus hirsutus, Pterocarpus marsupium* and *Casuarina equisetifolia* (Kumar *et al.*, 1998), in *Dalbergia sissoo* (Das and Chaturvedi, 2003) in *Acacia mangium* (Kunhamu *et al.*, 2005) and in *Grevillea robusta* (Geo, 2013). Such issues can be made up by bring in back the nutrient rich tops to the system and removing only the commercially utilizable bole fractions (Kumar *et al.*, 1990)

In the present study root portion accounted for the second largest share of nutrient accumulation in all the species. The highest N accumulation in the root biomass was for *Acacia auriculiformis* (582.25 kg ha^{-1}) and lowest for *Acacia mangium* (395.97 kg ha^{-1}) (Table 19). All the species under study were being a N fixer, may retain more root nitrogen and may lead to better nitrogen turnover in the system. As regards P and K accumulation in the root biomass, *Acacia auriculiformis* showed the highest values and lowest was reported for *A. aulacocarpa* and *Acacia mangium* respectively (Table 20 and 21). The portion of various nutrients tied up in the root portion was in the order of Nitrogen, Potassium and Phosphorous for different acacia species. The nutrient tied up in the root portion is normally not removed from the system and thus helps in contributing to the renewal of soil nutrient and ensuring the sustainability of production in the long term. Despite the lower nutrient accumulation, the higher nutrient concentration in the bole was primarily on account of the higher biomass productions compared to foliage and twigs. Leaves, on the other hand, despite their higher nutrient concentration could accumulate lower quantity nutrients mainly due to lower leaf biomass production. However, it is important to observe that leaf biomass can bring substantial nutrient turnover to the soil through leaf litter and periodic pruning. Comparable nutrient accumulations were reported for same and other MPTs of same age.

5. 8 Soil Carbon sequestration

The soil C sequestration in a stand depends on factors such as climate, soil type, species and management practices (Saha *et al.*, 2010). In the present study the stand characterized by high amount of litterfall, root activity and nutrient cycling under present study recorded significantly higher C stock compared to treeless control plot. The average C sequestration in acacia species ranged from 66.92 Mg ha^{-1} (*A. crassicarpa)* to 77.96 Mg ha^{-1} (*Acacia auriculiformis*) (Table 22) and these values were significantly different. Study conducted by Aneesh (2014) in a 22-year-old pepper based production system involving six MPTs revealed that soil organic carbon content decreases with depth and the highest value recorded for *Acacia auriculiformis* (71.39 Mg ha^{-1}) and lowest for *Grevillea robusta* (61.26 Mg ha^{-1}). Kunhamu *et al.*, (2009) reported the soil carbon sequestration by the annual litterfall in 9 year old *Acacia mangium* as 11.18 Mg ha^{-1} (1.24 Mg ha^{-1} yr^{-1}) in an unthinned stand (1600 trees ha^{-1}) and reported the variation in litter production in relation to stand density. The values obtained were less than the present study (4.15 ha^{-1} yr^{-1}). Higher litter production potential and its fast turnover, being a nitrogen fixing tree, may explain the higher SOC status under four acacia stand compared to the treeless control plot.

Tree based production systems are reported to augment the soil C stock in a number of situations. This is quite evident in the present study with treeless control plot showing significantly lower soil C (46.64 Mg ha^{-1}) than the other acacia stand. Similarly Aneesh (2014) reported lowest SOC for the treeless control in a pepper based production system involving six MPT species. Similar trend was reported by Kunhamu *et al.* (2011) on 6.5-year-old *Acacia mangium* stand with SOC value ranging from 27.02 to 34.64 Mg ha^{-1} and the treeless control plot with 24.7 Mg ha^{-1} SOC. Another study by Singh and Singh (1993) on alkali soil indicates that rising of trees will increase the SOC from 0.12% to a maximum of 0.58% in 20 years.

The consistent reduction in the SOC with depth is evident in the present study with highest C content corresponding to 0-20 cm for all the four acacias (21.38-24.33 Mg ha^{-1}) (Table 23). This represents the organic layer where maximum accumulation of all nutrient takes place. The soil organic C content of *Acacia auriculiformis* (0-15 cm soil depth) at age, 8.8, 7, 5 year-old stand were 1.68%, 4.51% and 4.23% respectively and which is greater than that of the present study (1.08%). Among the species studied high soil organic carbon contentment was reported for *Acacia auriculiformis*, which will reflect the role of leguminous trees in improving the soil carbon and nutrient status (Kumar *et al.*, 1998). Similarly Kunhamu *et al.*, (2011) reported a higher soil C storage of 24 Mg ha^{-1} to 35 Mg ha^{-1} in the 0-15 cm soil layer for 6 year-old *Acacia mangium* managed at varying stand densities in the same location at Thiruvazhamkunnu, Kerala. In all the land use systems the mean soil organic C content decreases with soil depth. This is obviously due to the decrease in organic matter content in the lower soil depths.

5. 9 Soil nutrient content

All the four acacias showed higher soil nutrient concentrations compared to treeless areas emphasizing their potential to influence the long term productivity of the soil. Among the nutrients, nitrogen concentration was highest in all the species followed by phosphorous then potassium. Higher litter production potential and its fast turnover, being a nitrogen fixing tree, may explain the higher nitrogen concentration under four acacia stand compared to the treeless control plot. The biologically fixed N is released into the rhizosphere (La Rue and Patterson, 1981). In the present study, the highest soil nitrogen concentration was reported for *A. auriculiformis* followed by *A. aulacocarpa, A. mangium* and lowest for *A. crassicarpa* which followed the order of nitrogen concentration in the above ground biomass components.

The nutrient concentration of soil, in general, decreased with increase in depth and higher values are recorded in the upper layer. Similar trend was reported in *A. auriculiformis, A. triphysa, G. robusta and C. equisetifolia* (Kumar *et al.*, 1998; Aneesh, 2014). Same trend was reported for P and K also with significantly low concentration in the treeless control plot. The concentration of P and K also followed the similar trend of nutrient concentration in the aboveground portion.

5. 10 Root distribution pattern

The distribution of root systems through space and time is usually influenced mainly by the genetic character of a species, silvicultural management, and localized soil conditions (Huck, 1983). Root distribution pattern is important in understanding the extent of soil space explored by component species in polyculture systems in view of the possible competition or complimentary root level interactions taking place among them (Willey, 1979). Information on the root distribution of active roots is a pre-requisite for formulating a rational method for fertilizer application (Wahid *el al.*, 1989).

In the present study all the species had well developed lateral root systems but differed in the relative abundance in lateral root and root length (Table 31). Tap root development are not that much prominent. Number of roots and root biomass of all the species were concentrated in the top one meter of the soil profile spreading parallel to the ground and penetrating vertically to the ground.

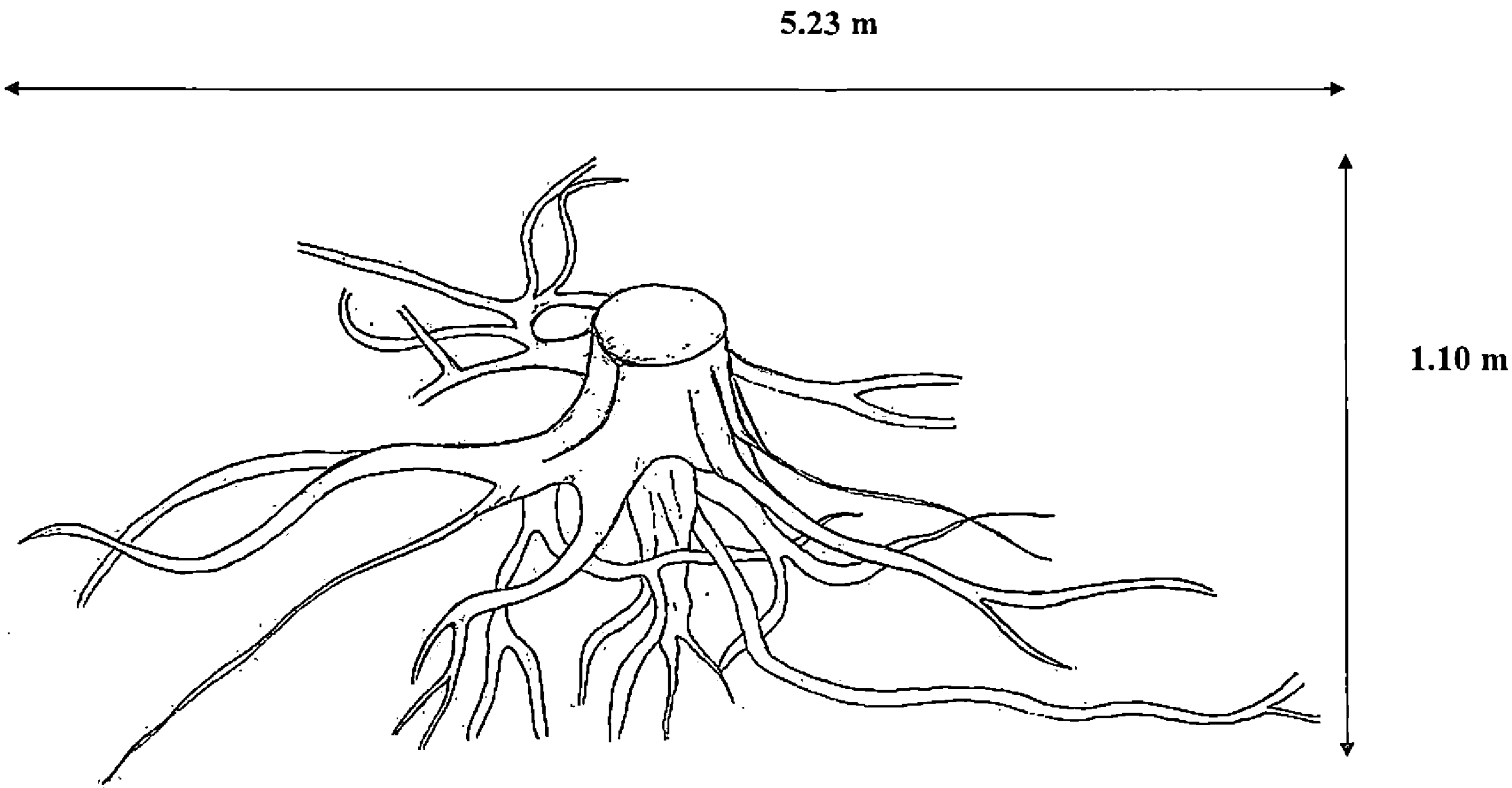


Plate 15. Diagrammatic representation of the root system of *Acacia mangium*

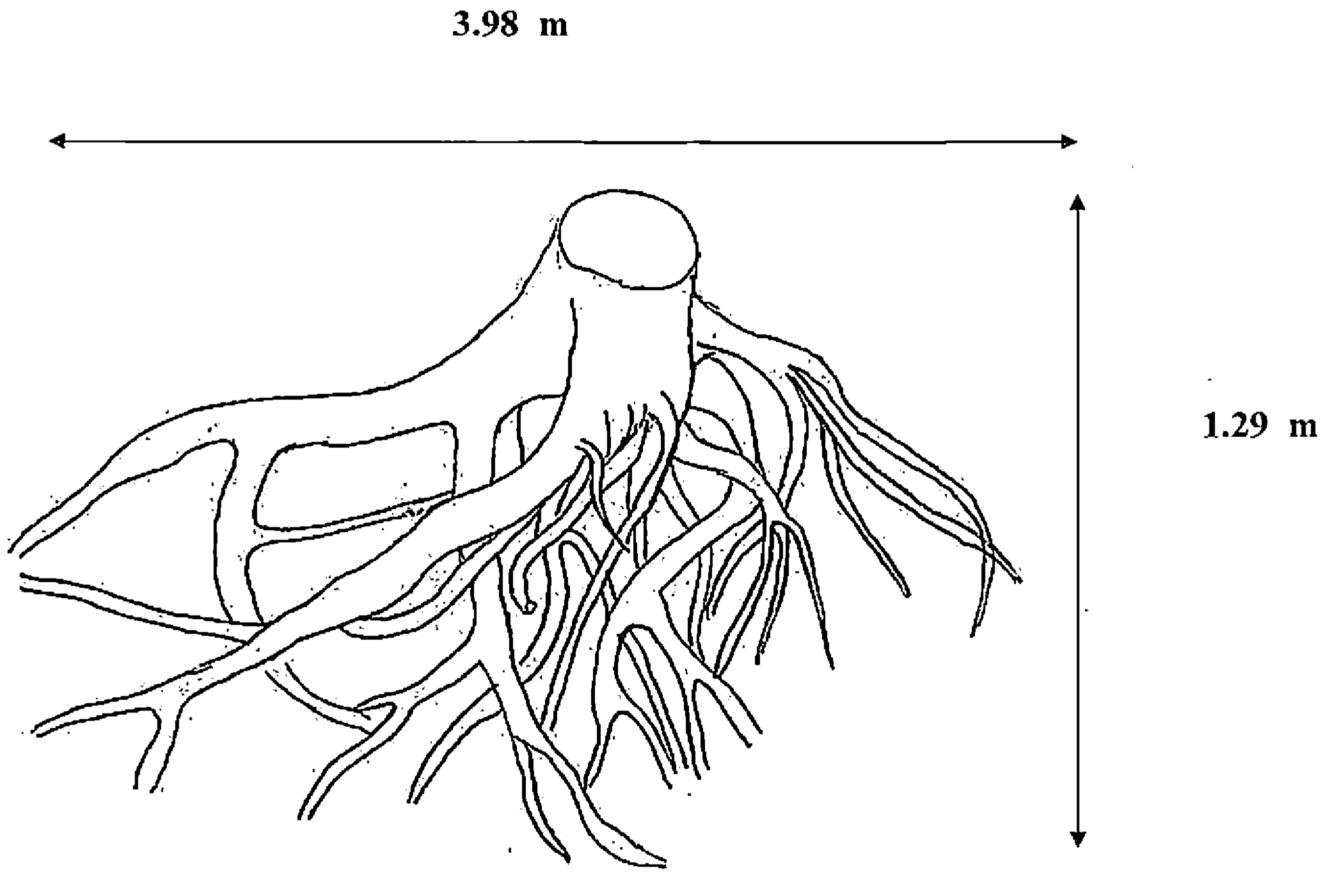


Plate 16. Diagrammatic representation of the root system of *Acacia auriculiformis*

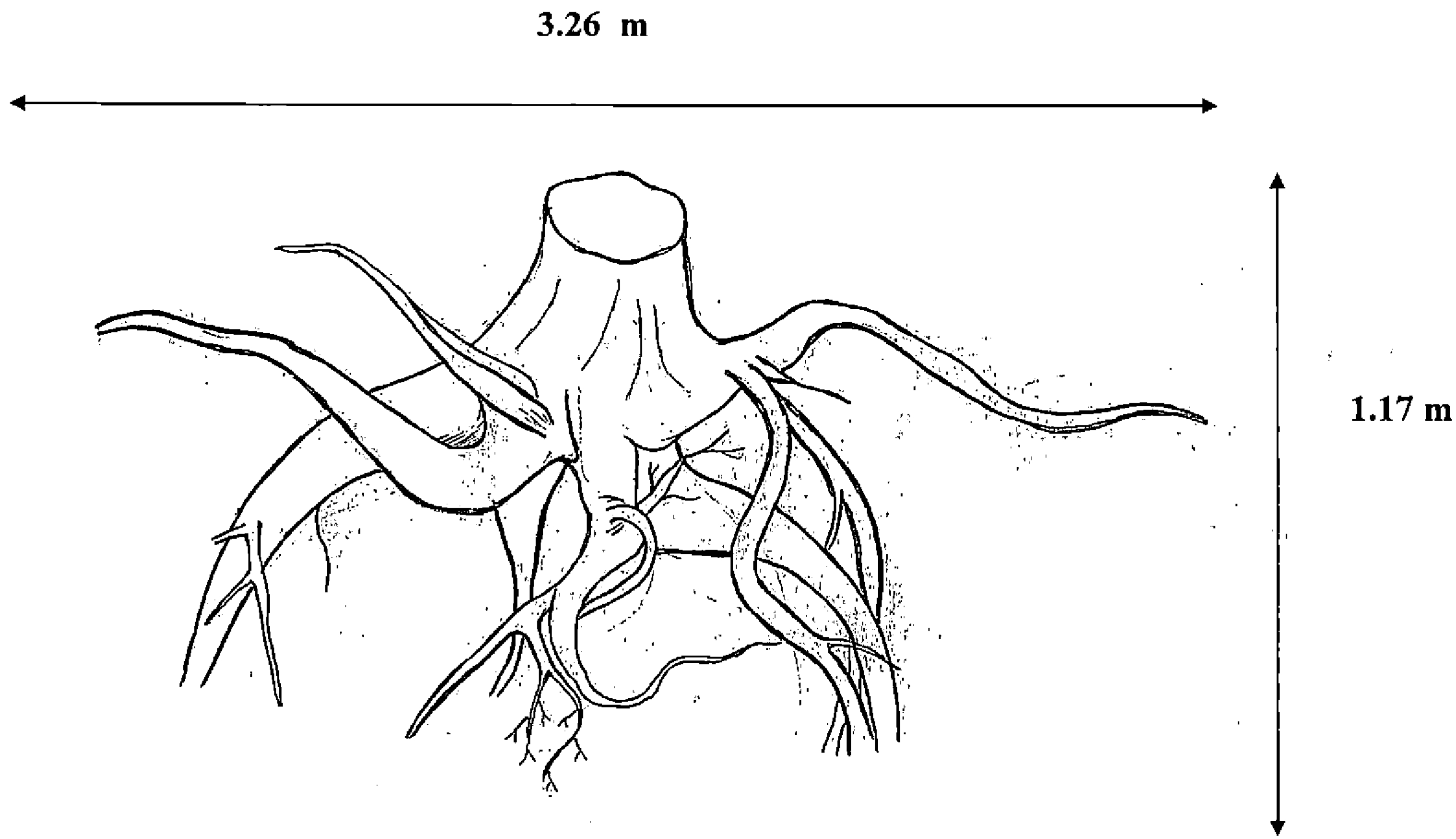


Plate 17. Diagrammatic representation of the root system of *Acacia aulacocarpa.*

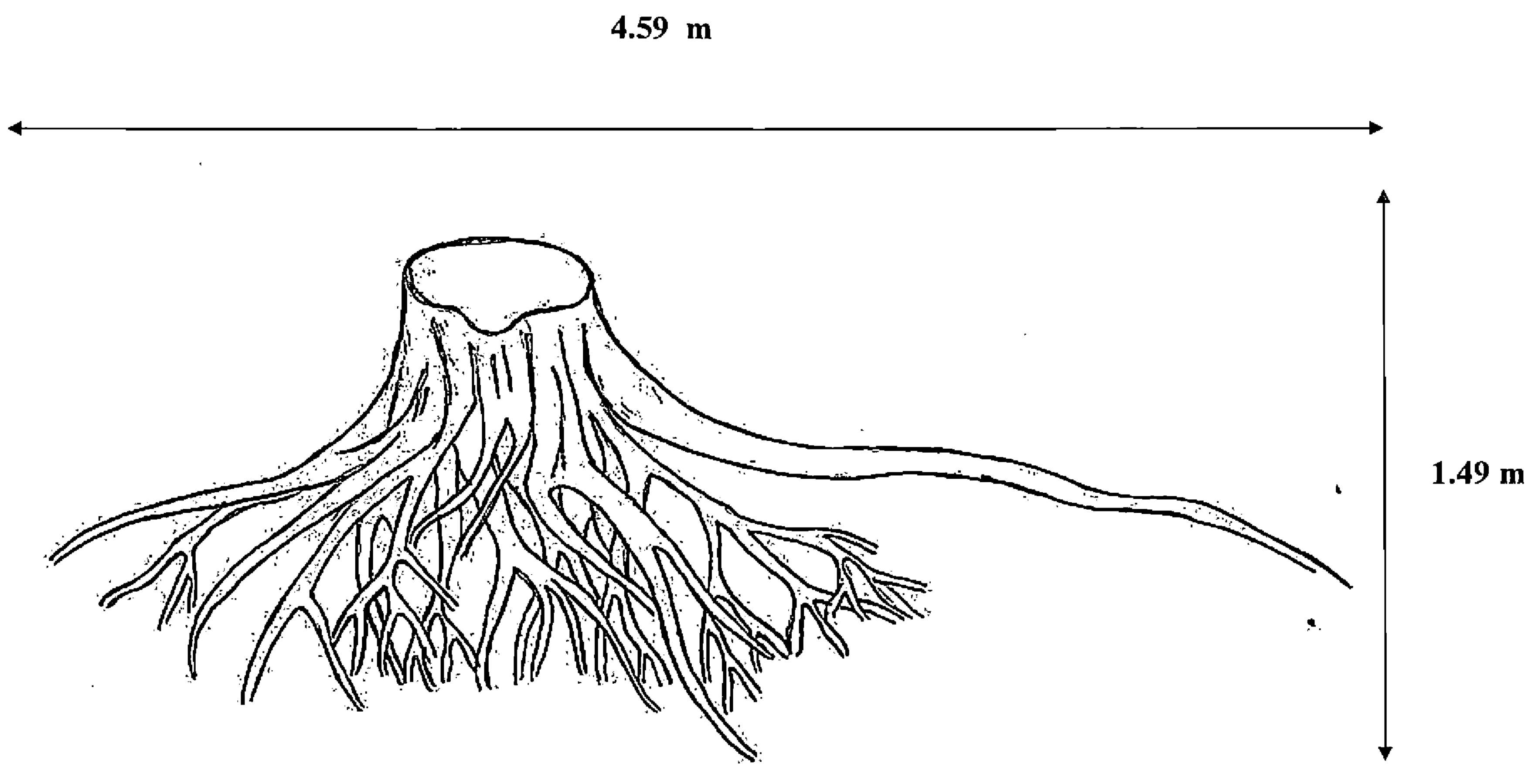


Plate 18. Diagrammatic representation of the root system of *Acacia crassicarpa.*

Among the acacias maximum lateral root spread was recorded for *A. mangium* (5.23 m) and the maximum root length for *A. aulacocarpa* (1.49 m) respectively. A study conducted by Schumacher *et al.* (2003) in a 18-month-old *Acacia mearnsii* plantation in Rio Grande do Sul, Brazil revealed that as the soil depth increases, root biomass and root density increases. Similar study involving direct excavation method by Aneesh, (2014) on 22-year old six MPTs, *A. heterophyllus* reported maximum lateral root spread and the root length (3.53 m and 1.90 m respectively) and the values reported for *A. auriculiformis* were 1.33m for rooting depth and 0.79 m for the lateral root spread.

Summary

SUMMARY

The study entitled "Biomass production and root distribution pattern of selected acacias" was carried out in an eighteen year old acacia plantation established during 1996 at the arboretum of College of Forestry, Vellanikkara, Kerala. The study involved assessment of growth, biomass production, carbon sequestration, nutrient accumulation and soil nutrient and carbon stock of four acacia species, viz *A. mangium*, *A. auriculiformis*, *A. aulacocarpa* and *A. crassicarpa*. The salient findings are summarised below.

1. **Tree growth characteristics of acacias**

   1.1 Among the acacia species, maximum DBH was recorded in *Acacia mangium* (27.15 cm) closely followed by *A. aulacocarpa* (27.07 cm). No significant difference was observed in radial growth among the species.

   1.2 Mean tree height was recorded maximum for *A. aulacocarpa* (22.40 m) and which was on par with *A. auriculiformis* (21.55 m) and *A. mangium* (21.05 m).

   1.3 With respect to clean bole height also, *A. aulacocarpa* (13.85 m) recorded maximum and minimum for *A. crassicarpa* which were on par with *A. auriculiformis* (11.05 m).

2. **Mean tree volume and MAI**

   2.1 Mean tree volume does not show any significant variation among species.

   2.2 With regard to mean tree volume and bole volume, *A. aulacocarpa* (0.625 m3; 0.516 m3) recorded maximum and the lowest for *A. crassicarpa* (0.413 m3; 0.334 m3).

2.3 *A. mangium* (0.407 m3) and *A. auriculiformis* (0.414 m3) recorded moderate bole volume and were statistically on par.

2.4 The highest mean annual increment was recorded for *A. aulacocarpa* (38.56 m^3 $ha^{-1}yr^{-1}$) and the lowest for *A. crassicarpa* (25.11 m^3 $ha^{-1}yr^{-1}$).

3. Biomass accumulation

3.1 Mean tree aboveground biomass production was highest for *A. auriculiformis* (302.69 kg $tree^{-1}$) followed by *A. aulacocarpa* (297.41 kg $tree^{-1}$) and *A. mangium* (270.78 kg $tree^{-1}$).

3.2 *A. auriculiformis* (86.22 kg $tree^{-1}$) was followed by *A. crassicarpa* (73.95 kg $tree^{-1}$) and the minimum value for *A. mangium* (62.41kg $tree^{-1}$) with respect to the mean tree below ground biomass.

3.3 With respect to mean tree biomass, *A. auriculiformis* (388.91 kg $tree^{-1}$) recorded the maximum value followed by *A. aulacocarpa* (297.41 kg $tree^{-1}$).

4. Biomass partitioning

4.1 Bole fraction constituted the bulk of the biomass in all the species ranging from 64.52% for *A. crassicarpa* to 71.86% for *A. aulacocarpa.*

4.2 Root biomass accounted for the second largest share to the total biomass which varied from 18.69% for *A. aulacocarpa* to 22.94% for *A. crassicarpa*

4.3 The order of percentage contribution of various components to the total biomass was bole> root> branchwood> twigs> leaves.

5. **Stand biomass accumulation and MAI**

5.1 Highest biomass production registered for *A. auriculiformis* (432.08Mg ha^{-1}) followed by *A. crassicarpa* (418.45 Mg ha^{-1}), *A. aulacocarpa* (406.11 Mg ha^{-1}) and *A. mangium* (367.76 Mg ha^{-1}).

5.2 Among the acacia species, highest MAI was recorded for *A. auriculiformis* (24 Mg ha^{-1} yr^{-1}) closely followed by *A. crassicarpa* (23.25 Mg ha^{-1} yr^{-1}) and the lowest MAI for *A. mangium* (20.43Mg ha^{-1} yr^{-1}).

6. **Biomass carbon sequestration**

6.1 Mean tree C concentration was registered highest for *A. crassicarpa* (46.72%) followed by *A. mangium* (46.69%), *A. auriculiformis* (46.44%) and *A. aulacocarpa* (46.17%).

6.2 Mean tree biomass C stock also followed similar trend as the biomass accumulation among the species. The maximum C stock was recorded for *A. auriculiformis* (176.38 kg C $tree^{-1}$) followed by *A. aulacocarpa* (165.54 kg C $tree^{-1}$) and *A. mangium* (151.35 kg $tree^{-1}$). The lowest value was registered for *A. crassicarpa* (147.28 kg C $tree^{-1}$).

6.3 The highest bole C stock was observed for *A. auriculiformis* (118.35 kg C $tree^{-1}$) closely followed by *A. aulacocarpa* (118.07 kg C $tree^{-1}$). Contribution of roots to the mean tree C stock varies from 19.10% in *A. aulacocarpa* to 23.78% in *A. crassicarpa.*

6.4 Stand level biomass C stock shows trend well in line with the mean tree biomass C stock. *A. auriculiformis* recorded the highest total biomass C stock (131.48Mg C $tree^{-1}$) and the lowest for *A. crassicarpa* (104.08Mg C $tree^{-1}$).

7. **Allometric equations**

7.1 Allometric relationships were attempted linking aboveground tree biomass, total aboveground biomass carbon sequestration, total volume and bole volume with DBH and/or total height

7.2 For all the above mentioned parameters, in *A. mangium* and *A. auriculiformis*, linear equations with two variables gave high R^2 value.

7.3 For *A. aulacocarpa* and *A. crassicarpa* quadratic, cubical equations with single variable (DBH) fitted as best equations.

8. **Tree nutrient concentration**

8.1 Nutrient concentration varied among tree tissue types and the highest concentration was recorded for leaf fraction and the lowest for bole fraction in all the species.

8.2 The order of nutrient concentration in all the species of acacia were N> K> P.

8.3 The mean tree N concentration was reported highest for *A. auriculiformis* followed by *A. mangium* and the lowest for *A. crassicarpa.*

8.4 The highest amount of nutrients (kg ha^{-1}) was accumulated in the bole fraction because of the highest biomass accumulation in the bole fraction.

8.5 Nutrient accumulation on the stand basis was highest for *A. auriculiformis* followed by *A. aulacocarpa, A. mangium* and lowest for *A. crassicarpa* for all the three nutrients.

9. Soil carbon sequestration

9.1 Among the species, *A. auriculiformis* recorded the highest total organic carbon stock of 77.96 Mg ha^{-1} followed by *A. mangium* (74.75Mg ha^{-1}). The treeless control plot recorded the lowest carbon stock (46.64 Mg ha^{-1}).

9.2 Significant difference seen in the SOC content in different soil depths. In 0-20 cm depth, the highest soil organic C content was recorded for *A. mangium* (24.33 Mg ha^{-1}) followed by *A. aulacocarpa* (21.95 Mg ha^{-1})

10. Soil nutrients

10.1 The highest soil nitrogen concentration was observed for *Acacia mangium,* with 0.135% in the surface soil (0-20cm) depth. The highest total nitrogen concentration at 1m depth was reported for *A. auriculiformis.*

10.2 The treeless control plot recorded the lowest concentration for all the nutrients in all the soil depth zones.

10.3 Maximum P concentration was recorded for *A. auriculiformis,* with 0.075% and 0.068% for both 0-20cm and 20-40 cm depth zones respectively. The highest phosphorus concentration at 1m depth was reported for *A. aulacocarpa.*

10.4 Potassium concentration was recorded highest for *A. mangium* (0.006%) which were par on *A. crassicarpa* (0.0059%) followed by *A. auriculiformis* (0.0055%). The lowest soil K concentration was recorded for *A. aulacocarpa* (0.0054%).

10.5 The nutrient accumulation for all the nutrients followed the same trend as soil nutrient concentration.

11. Root distribution pattern

11.1 Maximum root spread of 5.23 m was recorded for *A. mangium* and minimum for *A. aulacocarpa* (3.26 m).

11.2 Highest root length was registered for *A. crassicarpa* (1.49 m) followed by *A. auriculiformis* and the lowest for *A. mangium* (1.10 m).

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BIOMASS PRODUCTION AND ROOT DISTRIBUTION PATTERN OF SELECTED ACACIAS

BY

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ABSTRACT OF THE THESIS

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ABSTRACT

A field study was conducted with acacia species on an 18-year-old stand with 3m×3m spacing at the arboretum of College of Forestry, Thrissur, Kerala to evaluate the growth, biomass production, carbon sequestration and nutrient accumulation in four acacia species viz. *Acacia auriculiformis*, *Acacia mangium*, *Acacia crassicarpa* and *Acacia aulacocarpa*. The objective of the study included quantifying the biomass production potential, harvest related nutrient export from the site, characterising the root distribution pattern of these trees and to develop allometric equations for aboveground biomass, aboveground C sequestration, volume and bole volume.

The above ground biomass was estimated from 20 destructively sampled trees from each species and the belowground biomass was estimated following root excavation of average sized trees of each species. Significant differences were observed for the tree growth parameters except DBH. *Acacia aulacocarpa* recorded the highest growth rates in terms of height closely followed by *Acacia auriculiformis*. Among the species, *Acacia auriculiformis* recorded the highest stand total biomass (432.08 Mg ha^{-1}) and the lowest by *Acacia mangium* (367.76 Mg ha^{-1}). The most important component of total biomass undoubtedly, was the bole while foliage contributed least to biomass yield. Maximum aboveground and belowground biomass was recorded for *Acacia auriculiformis* (336.29 Mg $ha^{-1}$and 95.79 Mg ha^{-1}respectively).

Carbon sequestration potential was estimated for both aboveground and belowground biomass. Maximum mean tree C sequestration was recorded for *Acacia auriculiformis* (176.38 kg C $tree^{-1}$) followed by *Acacia aulacocarpa* (165.54 kg C $tree^{-1}$). The bole portion sequester major portion of C (63.61% to 71.28%) followed by root portion (19.1% to 23.78%). MAI in total stand C sequestration was maximum for *Acacia auriculiformis* (10.89 Mg C $ha^{-1}yr^{-1}$) closely followed by *Acacia aulacocarpa* (10.22 Mg C $ha^{-1}yr^{-1}$). Stand level biomass C sequestration in the leaf and twig portion varied significantly among the acacias. Soil C sequestration

under each species was estimated upto one meter depth. Maximum soil organic carbon (SOC) was accumulated in the surface soil (0-20 cm) for all the species. *Acacia auriculiformis* (77.96 Mg C ha^{-1}) recorded the highest total SOC followed by *Acacia mangium* (74.75 Mg C ha^{-1}). The treeless plots consistently recorded the lowest value of SOC in all the depth zones.

Nutrient concentrations (N, P and K) in the biomass components were recorded highest for the leaf portion and the highest stand nutrient accumulation was recorded for the bole portion. The order of nutrients in the plant were N> K> P. The nutrient accumulation in the stand level was also recorded highest for *Acacia auriculiformis.* The order of nutrient accumulation in the soil was N> P> K. No significant variation was observed in root distribution pattern of different acacia species. However, the maximum root spread was recorded for *Acacia mangium* (5.23 m) and root length for *Acacia crassicarpa* (1.49 m).