BIOMASS PRODUCTION, CARBON SEQUESTRATION AND NUTRIENT FLUX IN *AILANTHUS TRIPHYSA* (DENNST.) ALSTON.

BY

SUKANYA, S

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Biomass production, carbon sequestration and nutrient flux in *Ailanthus triphysa* (Dennst.) Alston."** is a bonafide record of research done by me during the course of research and that the thesis has not previously formed the basis for the award of any degree, diploma, fellowship or other similar title, of any other University or Society

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CERTIFICATE

We, the undersigned members of the advisory committee of **Miss. Sukanya, S (2011-17-108)** a candidate for the degree of **Master of Science in Forestry** agree that this thesis entitled **"Biomass production, carbon sequestration and nutrient flux in *Ailanthus triphysa* (Dennst.) Alston."** may be submitted by **Miss. Sukanya, S** in partial fulfillment of the requirement for the degree.

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Dedicated to My Family

INTRODUCTION

INTRODUCTION

The global demand of wood and forest products is escalating and the associated demographic pressure on the natural forests are all time high especially in the tropics. This indiscriminate exploitation of natural forests has lead to large scale deforestation and forest degradation especially in the tropics. But accelerated rate of deforestation had lead to increasing carbon concentration in atmosphere, which in turn contributes to global warming and related climate change, an important environmental issue of this century. Forest ecosystems plays a vital role in sequestering carbon in their biomass there by directly involving in reducing atmosphere C emission and helping in climate change mitigation. Hence natural forests are essential for the ecological and social well being of a nation whose conservation is of paramount importance. In the recent times, there has been a worldwide initiative to conserve tropical natural forest in this pursuit. Hence expansion of plantation forestry has been major agenda of all nations to meet diverse forest products where by relieving pressure on the ecologically important primary forests. Plantation forestry is steadily expanding around the world under diverse biophysical, social and economic environments, and is providing a range of products. Massive planting programmes are being initiated in India also to meet the ever increasing domestic demand and to reduce the widening gap between demand and supply of forest products. Forest plantation areas under major countries are China, 24 %; India, 17 %; Russia, 9 %; USA, 9 %; Japan, 6 %; Brazil, 3 %; Ukraine, 2 % and Iran, 1 % (FAO, 2009).

Apart from premier timber based round wood production which are long rotation based, the fast growing plantations have received wider acceptance on account of the faster rates of biomass production and quicker returns. Such fast growing plantation species mainly cater the paper and pulp, small wood, plywood, matchwood and packing case industries. Well managed plantation of such species offer attractive economic returns even at small and marginal farming sector. However there is genuine lack of scientific information about the cultivation of tree crops to optimum productivity levels.

Apart from those direct economic benefits, planted forests attain considerable attention in the ecological front in view of their role as potential carbon sinks there by directly involving in green house gas (GHG) abatement and climate change mitigation. Fast growing trees in general sequester atmospheric CO_2 and lock in their biomass at faster rates and hence function as cheaper GHG abatement strategy. Hence from the management objective all tree plantations qualify in generating carbon credits which could yield substantial additional benefits to the farmers. Thus forest plantations have significant role as a global carbon sink (Rahman *et al.*, 2012; Teerawong *et al.*, 2012). Carbon storage potential of trees considerably varied with tree species. Carbon sequestration potential of some of the tropical multipurpose trees (MPT's) are as follows: *Acacia auriculiformis*, 139.20 kg C $tree^{-1}$; *Grevillea robusta*, 152.32 kg C $tree^{-1}$ and *Casuarina equisetifolia*, 136.35 kg C $tree^{-1}$ (Aneesh, 2014). Young plantations can sequester relatively larger quantities of carbon while a mature plantation can act as a reservoir. Thus ability to strike a workable balance between productive and protective roles of forest plantations will determine investment returns as well as public acceptance.

Furthermore, fast growing trees contribute substantially to soil carbon sequestration which is the largest pool of terrestrial carbon. Soils store 2.5 to 3.0 times as much carbon that is stored in plants and 2 to 3 times more than the atmospheric carbon as CO_2 (Davidson *et al.*, 2000). Tree dominated systems characterized by higher amounts of litter fall and root activity compared to solo crop agriculture systems makes trees more efficient in promoting soil carbon sequestration (Brady and Weil, 2007). Vertical distribution of soil organic carbon in these wooded system vary depending on the tree species involved, pattern of root growth and development and tree management practices (Saha *et al.*, 2010).

Thus economic, environmental, and social concerns are important factors in shaping the future role of plantations. High biomass production obviously is an important consideration in all tropical tree planting programmes. Proper estimation of biomass gives an overall picture of the function of ecosystem (Leith and Whittaker, 1975). Biomass studies are important for assessing the productivity, nutrient dynamics and deciding the stand management schedules in time and space. Thus biomass studies are essential for efficient management of forest plantation on sustained basis. Estimation of the essential mineral elements in plants is yet another important aspect in the study of biomass and nutrient dynamics. This is especially true in the case of fast growing MPT's which incorporate considerable amounts of nutrients in their biomass over relatively short period of time and export major share of nutrient from the system through harvest. Yet another significance of biomass study is its direct functionality with carbon sequestration. Primarily C sequestration is a function of biomass production and allocation pattern.

In the light of the growing concerns over the economic and the environmental advantage of fast growing short rotation tree plantations there is a greater need to gather information on the biomass allocation and carbon sequestration potential of fast growing tropical forest plantations. Also, the rising demand of energy from renewable resources has generated a shift in attention towards woody biomass production systems. At present, data on biomass and nutrient accumulation of tropical broad leaved tree species are less available.

Ailanthus triphysa is a prominent fast growing multipurpose tree in the homegardens of Kerala (Kumar, 2001) and an important plantation species in the peninsular India (Kumar *et al.*, 2001). It belongs to the family Simaroubaceae. In Kerala, *A. triphysa* occurs in all physiographic provenances except in the high ranges and tolerate a wide range of soils (Kumar, 2000). The light and soft wood is utilised for plywood, packing cases etc and is a prominent matchwood species used for both splints and boxes. The bark, gum, roots and leaves are used for medicinal purposes (Indira, 1996). The tree yields a highly viscous aromatic resin that is widely used in perfumery and in indigenous medicine (PID, 1948). *A. triphysa* is a popular support tree for black pepper vines and is an important component of silvopastoral and agrisilviculture systems of Kerala (Kumar *et al.*, 1994; Kumar, 2001). The relative frequency of *A. triphysa* in the homesteads of Kerala is highest (13.2%) compared with other homegarden tree components (Kumar *et al.*, 1994).

Due to its quick rate of growth and physical suitability, *A. triphysa* is recommended as a plantation species for producing match wood over shorter rotations. Fast growth, deep root system, amenability to lopping etc. make *A. triphysa* an excellent tree species for agroforestry purpose too. Despite this general understanding on the growth of *A. triphysa*, details on the performance of this species in terms of growth and biomass production are less available. Such information on biomass production and nutrient accumulation in *A. triphysa* as affected by stand management strategies such as planting density regulation are also limited. Few available reports suggest considerable variation in biomass production for young *A. triphysa* (8.8 years) in response to variable stand density and fertilizer regimes (Shujauddin and Kumar, 2003). However, such information is limited for mature rotation aged *Ailanthus triphysa* stands. Moreover, information such as biomass partitioning, aboveground and belowground C-sequestration, nutrient storage in the biomass, changes in the soil nutrient and C pool etc are very much limited to mature *A. triphysa* stands. Hence this study aims at estimating the biomass and C- sequestrated in aboveground and belowground components, associated nutrient flux in the biomass and soil for a 22-year- old *A. triphysa* stand primarily as a function of variable planting densities. The specific objectives include. 1) assessment of aboveground and belowground biomass production and carbon sequestration potential in *A. triphysa* stand (22-year-old) established at various planting densities 2) develop allometric equations for total biomass, bole biomass, total tree volume and bole volume 3) biomass partitioning and nutrient storage of above and belowground tissue components and also soil nutrients under various planting densities for *A. triphysa*.

REVIEW OF LITERATURE

REVIEW OF LITERATURE

Tropical plantations can serve diverse productive, economic, social, political and ecological functions. With their relatively high yields, tropical and sub-tropical plantations can make substantial contributions to world timber and pulp production (Wadsworth, 1983; Evans, 1992). They may help to stabilize rural populations in regions where shifting agriculture is the predominant land use. Industrial plantations can make developing countries producers of wood based commodities (Dabas and Bhatia, 1996). In combination with subsistence and commercial crops (agroforestry) or cattle (agrosilvopastoral systems), plantations have also been used as tools in rural development projects worldwide. Besides its ecological and economic functions plantations can also act as terrestrial carbon pool. Winjum and Schroeder (1997) suggested that 11.8 Pg C stock could be credited to tropical plantations at the global level.

Moreover, fast growing tropical tree plantations incorporate considerable amounts of nutrients in their biomass over a relatively short period of time. However, site fertility decline 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 or site preparation (Jorgensen and Wells, 1986; Perry and Maghembe, 1989). This can be particularly serious when plantations are established on soils that are inherently poor. Therefore, examination of the role of tropical plantations necessitates integrative approaches to evaluate not only the rates of biomass accumulation and C sequestration by different tree species, but also their design and management to minimize potential deleterious effects on ecosystem nutrients and to make plantations economically, socially, and environmentally sound land use options.

2.1 BIOMASS

Biomass is defined as "organic material both aboveground and below ground, and both living and dead, eg: trees, crops, grasses tree litter, roots etc" (FAO, 2004). Biomass assessment is important for many purposes aimed at resource use and environmental management (Parresol, 1999; Zheng *et al.*, 2004). There are two methods to calculate forest biomass, one is direct method and the other is indirect method. Direct method also known as destructive method, involves felling of trees to determine biomass. Indirect means of estimation of stand biomass are based on allometric equations using measurable parameters (Salazar *et al.*, 2010). Biomass is also an important indicator for carbon cycle studies (Cairns *et al.*, 2003; Ketterings *et al.*, 2001).

2.1.1 Biomass production

The biomass production is the reflection of plant communities' capacity to assimilate solar energy under certain environmental conditions. High biomass production is an important consideration in all tropical tree planting programmes. This is particularly significant in view of the rising CO_2 levels and the growing need to sequester it. Biomass production potential of trees varies considerably with species, age and spacing. Many reports from the tropics suggested that biomass accumulation potential varied with tree species. Landseberg *et al.* (1995) observed that biomass production potential of trees varies considerably owing to variation of species-site relationships, rotation age stand density interactions and cultural treatments.

Different plant communities also have different rate of biomass production based on their efficiency. Higher production observed for both above and belowground biomass in shaded coffee system compared to open grown coffee system in Southwestern Togo and the shade tree *Albizia adianthifolia* contributed 87 % of total aboveground biomass and 55 % of total root biomass in the shaded coffee system (Dossa *et al.*, 2008). Swamy *et al.* (2006) conducted similar study in six-year-old clones of *Populus deltoides* based agrisilviculture system in sub-humid tropics of Central India reported total biomass production value ranging from 48.5 to 62.2 Mg ha^{-1} under different clones. Biomass accumulation study conducted in a 20-year-old *Grevillea robusta* plantation showed variation among three diameter classes, highest in intermediate diameter class (15-25 cm) 34.26 Mg ha^{-1} (Paul, 2013).

2.1.2 Factors affecting biomass production

2.1.2.1 Species

The productive capacity of many fast growing species exhibits substantial variability. A comparison study on aboveground biomass production of four MPT's in silvopasture system including *Ailanthus triphysa* in humid tropics of Kerala reported highest biomass for *Acacia auriculiformis* (183.54 Mg ha^{-1}) and the lowest value recorded for *Ailanthus triphysa* (19.38 Mg ha^{-1} ; Kumar *et al.*, 1998). Lugo *et al.* (1988) found that aboveground net primary productivity for tropical species ranged from 16 to 29.8 Mg $ha^{-1}yr^{-1}$ of dry matter. Likewise, considerable variation in biomass production has been observed among various MPTs. Singh and Toky (1993) observed that biomass was markedly higher for *Leucaena leucocephala* (112 Mg ha^{-1}) and *Eucalyptus tereticornis* (96 Mg ha^{-1}) compared to *Acacia nilotica* (53 Mg ha^{-1}). Similarly another study showed that the stand biomass varied considerably among *Gliricidia sepium* (85.6 t ha^{-1}), *Gmelina arborea* (85.6 t ha^{-1}) and *Leucaena leucocephala* (46.2 t ha^{-1}; Fuwape and Akindele, 1997). Ming *et al.* (2010) observed the aboveground biomass in *Phyllostachys makinoi* was 105.33 Mg ha^{-1}. Another study conducted in a 2.5-year-old plantation in North West India with six semi-arid species showed considerable variation in biomass production with *Melia azedarach* (38.4 t ha^{-1}) produced high biomass per hectare followed by *Ailanthus excelsa* (27.2 t ha^{-1}) and lowest recorded by *Populus deltoides* (5.2 t ha^{-1}) (Toky *et al.*, 2011). Similarly, Arora and Chaudhry (2014) reported highest biomass production in *Eucalyptus tereticornis* (169.44 Mg ha^{-1}) followed by *Tectona grandis* (153.31 Mg ha^{-1}) and *Syzygium cumini* (132.59 Mg ha^{-1}) at Haryana.

Rao *et al.* (2000) compared the biomass production potential of eleven multipurpose tree species growing on sandy loam soils in Andhra Pradesh and 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}). Similarly another study on biomass production potential of six multipurpose tree species on black pepper based production system revealed that there is considerable variation in biomass production where, *Grevillea robusta* recorded highest biomass production (366 Mg ha^{-1}) followed by *Acacia auriculiformis* (331 Mg ha^{-1}) and the lowest was recorded in *Ailanthus triphysa* of 155 Mg ha^{-1} (Aneesh, 2014). Another study related with the comparison of biomass production of 20-year-old MPTs in South Gujarat showed that aboveground biomass production is higher for *Albizia procera* (380 Mg ha^{-1}) and lowest for *Gmelina arborea* (229 Mg ha^{-1}; Sreedevi *et al.*, 2011).

2.1.1.2 Rotation age

Biomass production in general increases with increasing age and stabilize at maturity. Thus rotation period of the species markedly influenced the biomass yield (Evans, 1982). It was revealed through many studies conducted in different species globally. Jayaraman *et al.* (1992) reported that *Casuarina equisetifolia* plantations growing in the west coast areas of Kerala are highly productive and can produce biomass of 190 Mg ha^{-1} at age of 4.5 years. The study conducted in 2 to 8 year-old plantations of *Eucalyptus tereticornis* growing in Tarai region of central Himalaya showed a considerable increase in biomass ranging from 7.7 Mg ha^{-1} in the 2nd year to 126.7 Mg ha^{-1} in the 8-year-old plantation (Bargali *et al.*, 1992). Likewise, Vidyasagaran (2003) reported biomass production of *Casurina equisetifolia* at an age of 2 year as 42.3 Mg ha^{-1} and at 9 years, as 366.82 Mg ha^{-1}, suggesting that the aboveground biomass increased nine times from 2 years to 9 years in the plantations of central Kerala. Total biomass accumulation of *Grevillea robusta* plantation at Karnal of 25-year-old is found to be 324.198 Mg ha^{-1} (Jangra *et al.*, 2010). Above ground biomass production estimated for 5-21 years of *Gmelina arborea* (Roxb) plantations in Nigeria registered high biomass yield, ranging from 83.2 Mg ha^{-1} (5 years) to 394.9 Mg ha^{-1} (21 years) and the mean annual biomass increment varied from 16.2 to 20.9 Mg ha^{-1}yr^{-1} (Onyekwelu, 2004). A study conducted on differentially aged Eucalyptus and Acacia plantations in the Pearl River delta of South China found that the accumulation of biomass increased with stand age reaching 207.45 and 189.35 Mg ha^{-1} in mature Eucalyptus and Acacia plantations (Zhang *et al.*, 2012). Likewise, another study conducted in *Grevillia robusta* plantation revealed that biomass production potential increased considerably with age and found to be 345.27

Mg ha^{-1} (Gopichand and Sing, 2011). Similarly Kumar *et al.* (1998) conducted biomass estimation study involving nine fast growing MPTs in the humid tropics of Kerala observed considerable variation in biomass production in nine taxa. The above-ground biomass yield on per hectare basis was highest for *Acacia auriculiformis* (326 Mg ha^{-1}) and lowest for *Leucaena leucocephala* (22.81 Mg ha^{-1}) at 8.8 years of age.

2.1.1.3 Spacing / Planting density

A variety of planting arrangements and planting densities are used while planting programmes are carried out which have varying effects on individual tree growth and total system yield. Stand density manipulation through thinning and initial planting density control are powerful tools for developing desired stand structures (Smith, 1986). Many reports suggested that close initial spacing favors the initial height growth. In general total stand biomass was higher for denser stand however low density stand had higher mean tree biomass.

Study conducted in 8.8 year old *Ailanthus triphysa* planted at four different spacings shows considerable differences among spacings in mean tree and stand biomass yield fractions. Biomass production was higher in the closer spacing (2m x 2m) than wider spacing (Shujauddin and Kumar, 2003). Likewise, biomass study conducted in a Eucalyptus based agroforestry system in Andhra Pradesh with five spacing arrangements showed significant difference in biomass production with spacing (Prasad *et al.*, 2010). Swamy *et al.*, (2003) observed a variation in tree growth and above and belowground biomass in *Gmelina arborea* planted at three different densities (4mx4m, 4mx6m and 4mx8m) in an agrisilviculture system. After 5 years, total biomass ranged from 6.96 to 13.75 Mg ha^{-1} and highest biomass was recorded in trees planted under 4mx4m spacing and lowest in 4mx8m spacing. Biomass accumulation and partitioning studied in an age series of three Eucalyptus species, reported a strong individual tree growth response to increased spacing and declined in stand biomass production with increased spacing (Bernardo *et al.*, 1998). Another study conducted in a 5-year-old Leucaena plantation planted at six different spacings showed that spacing had a significant effect on biomass yield. The narrowest spacing (1m x 0.25m) exhibited highest biomass yield (Chotchutima *et al.*, 2013).

The relative allocation of biomass to different plant parts also varies with spacing. Henskens *et al.* (2001) observed variation in growth and form of 3 to 4-year-old *Eucalyptus globulus* planted in farm forestry in response to spacing and planting arrangement. The proportion of above ground biomass found in stems declined with increasing spacing as the mass in foliage and branches increased. Stems accounted for 65 % of above-ground biomass in block planted trees but only 35 % in isolated trees. The contributions of leaves and branches correspondingly rose from 19 to 35 % and from 16 to 29 %, respectively.

2.2 PARTITIONING OF BIOMASS

2.2.1 Aboveground biomass partitioning

Biomass partitioning among various tree components vary considerably with species and age. The relative allocation of biomass to various above ground parts is a decisive factor that reflects the productivity of any wooded system. Generally, bole fraction accounts bulk of the total tree biomass.

The biomass accumulation in different tree components of 25-year-old *Grevillea robusta* plantation at Karnal was 216.943 Mg ha^{-1} bole > 41.380 Mg ha^{-1} branches > 7.590 Mg ha^{-1} foliage (Jangra *et al.*, 2010). The percentage contribution of different tree components to the total aboveground biomass was: bole (66.91 %), branches (12.76 %), and foliage (2.34%). Similarly biomass partitioning analyzed in 7-year-old *Acacia mangium* in Kerala registered component yield on per ha basis at a rate of 152.12 Mg ha^{-1} for stemwood, 37.72 Mg ha^{-1} for branchwood, 11.92 Mg ha^{-1} for foliage and 8.48 Mg ha^{-1} for twigs (Kunhamu *et al.*, 2011). For all the size classes, stemwood accounted for bulk of the aboveground biomass (65 to 75%) followed by branchwood (12.5 to 25.2 %), foliage (5.0 to 6.5%) and twigs (4.1 to 6.5%).

Biomass partitioning 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 branchwood and stemwood biomass (Kumar, 2009). In an age series of *Gmelina arborea* (Roxb) plantations in Nigeria, stemwood accounted for an average of 83.6 % (range: 81.8 to 85.7 %) of total above ground biomass, while branch and foliage biomasses accounted for an average of 13.2 (range: 11.5 to 14.7%) and 3.3% (range: 2.4 to 4.2%) respectively (Onyekwelu, 2004). Tandon *et al.*, (1996) reported a percentage increase in bole biomass from 28 percent to 86 percent over a period of 3 to 9 years in and *Eucalyptus grandis* plantation from Kerala. Similarly, Paul (2013) observed maximum biomass allocation to the stemwood portion followed by branchwood and the lowest for twig portion in a 20- year-old *Grevillea robusta* plantation. A study in black pepper based polyculture system involving six multipurpose tree species showed that stemwood constituted the bulk of the aboveground biomass in all species and the percentage contribution follows the order stemwood> branchwood> twig> leaves (Aneesh, 2014).

The relative proportions of growth allocated to different plant parts were also influenced by tree species and spacing levels. Increased spacing levels decreased the relative amount of growth allocated to the bole of the tree and increased allocation to the root system (Bernardo *et al.*, 1998). In *Ailanthus triphysa* stands, branchwood and foliage biomass per tree were, 38 and 84 % more in 3mx3m spacing than that of 3mx1m; yet, the highest total stand biomass of 135 Mg ha^{-1} and MAI of 13.6 Mg ha^{-1} per year were obtained in 3mx1m spacing (Shujauddin and Kumar, 2003). The above ground biomass ranged from 264 Mg ha^{-1} (*Grevillea robusta*) to 122 Mg ha^{-1} (*Macaranga peltata*) in a pepper based biomass production system. The stemwood constituted the bulk of the aboveground biomass in all species and the percentage contribution follows the order stemwood> branchwood> twig> leaves (Aneesh, 2014).

2.2.2 Belowground root biomass

Belowground biomass accumulation by tree roots can generally vary from 3 to 6 Mg $ha^{-1}yr^{-1}$ (Sanchez, 1995). This biomass can make a substantial contribution to soil organic matter, carbon and nutrient cycling. However, the belowground biomass production is influenced by many factors such as tree species, stand age, management regimes etc. Despite the vast literature available on the aboveground biomass production, such information on belowground are by far scarce.

Root biomass estimated in 8.8 year old MPTs in a woodlot experiment of the humid tropics of Kerala 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 (Kumar *et al.*, 1998). Belowground coarse root biomass in four year old *Gmelina arborea* planted at four different spacing in agrisilviculture system in the sub-humid 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. Root biomass study conducted in a 22-year-old pepper based production system with six MPTs showed significant difference in root biomass production with *Grevillea robusta* (63.29 Mg ha^{-1}) showed higher root biomass followed by *Acacia auriculiformis* (62.26 Mg ha^{-1}) and *Ailanthus triphysa* (24.26 Mg ha^{-1}) recorded the lowest (Aneesh, 2014). Similarly, Samritika (2014) found that mean tree root biomass production based on diameter class ranged from 12.94 to 59.81 kg $tree^{-1}$ in 21-year-old *Grevillea robusta* plantation and the mean stand level root biomass accumulation were found to be 18.45 Mg ha^{-1}.

Coarse roots generally contribute more to total biomass than fine roots in terrestrial systems (Eamus *et al.*, 2002). Das and Chaturvedi (2008) found that root biomass accounted for 18.2 to 37.9 % of total tree biomass in five agroforestry species at Pusa, Bihar. Among the species, there were a wide range of variation in biomass accumulation in the main roots, lateral roots and fine roots. 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.

Root biomass studied in an age series of five multipurpose tree species at Doon valley showed that root biomass increases with age in all the species and it was directly related to aboveground biomass and dbh of the plants. However, the percentage contribution of roots to the total biomass decreases gradually with increasing age (Dhyani *et al.*, 1990).

2.2.3 Root: Shoot ratio

The root to shoot ratio is commonly used to estimate below ground living biomass in trees (Nair, 2011). The ratios differ considerably among species (eg., higher in palms than in dicot trees) and across ecological regions (eg., higher in cold than in warm climates).

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 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 with mean of 0.16 (Kraenzel *et al.*, 2003). However 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 root: shoot ratio of 21-year-old *Grevillea robusta* vary considerably with diameter classes with mean of 0.29 (Samritika *et al.*, 2014).

Various factors are thought to determine the relative biomass allocation between roots and aboveground plant parts (Klepper, 1991). For example, Mangroves often accumulate large amounts of biomass in their roots, and the aboveground biomass to belowground biomass ratio of mangrove forests is significantly low compared to that of upland forests (Komiyama *et al.*, 2008).

2.3 CARBON SEQUESTRATION

Carbon sequestration is the process of removing carbon from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric C, especially CO_2, and its secure storage in long-lived pools (UNFCCC, 2007). Such Carbon pools in terrestrial systems include the aboveground plant biomass, durable products derived from biomass (timber and roots), soil microorganisms, and the relatively stable forms of organic and inorganic C in soils and deeper subsurface environments.

2.3.1 Carbon sequestration in plantation

The importance of trees as potential C sinks has been reported by many. Sequestration of atmospheric carbon by trees is by and large a function of biomass production. Trees play an important role in the global carbon cycle and they are important as potential carbon pools and sinks (Schimel *et al.*, 2001). Reports suggest that tree incorporation in cropland and pasture would result in great net aboveground as well as belowground C-sequestration (Halie *et al.*, 2008). Land cover changes, particularly 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 changes on ecosystem functioning and human wellbeing are driving the development of mitigation initiatives at local to international levels (eg., UNEP, 1992; UNFCC,1992; MEA, 2005)

For calculation of carbon accumulation by each plantation species, only stem biomass values were used, because most leaves and a great portion of branches are expected to turnover every year, i.e., 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). However, belowground carbon contributions are also very much important in wooded systems.

2.3.1.1 Aboveground carbon sequestration

Aboveground carbon sequestration is the direct manifestations of aboveground biomass production (Nair *et al.*, 2010). A large number of ecological and management factors influence the rate at which this fundamental process proceeds. Tree plantations, especially in the tropics, play an important role in carbon sequestration through the accumulation of carbon in the wood and in soil. In a study of nine native and exotic taxa in the humid tropics of peninsular India Kumar *et al.* (1998) found that the aboveground 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 observed higher concentration of carbon in the boles and branches followed by leaves and roots (Jangra *et al.*, 2010). 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}. Likewise, carbon sequestration study conducted in 20-year-old *Grevillea robusta* plantation at Kerala observed a carbon sequestration of 74.30 kg C tree^{-1}and the higher concentration of carbon observed in stemwood followed by branchwood and leaves (Paul, 2013).

Comparative study conducted on 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 showed 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 to 42.55 %, 41.06 to 43.3 % and 40.74 to 46.5 % and 44.4 to 45.3% in leaves, branches, stems and roots respectively. The total carbon storage ranged from 1354.7 to 3079.86 kg ha^{-1}.

Aboveground carbon sequestration was also influenced by stand management regimes. Kunhamu, *et al.* (2011) observed that a significant reduction in vegetation carbon pool of 6.5-year-old *Acacia mangium* stands planted at four different spacing in response to pruning. The planting density and pruning significantly influenced the C stocks. Widely spaced stands of 6.5 year old *Acacia mangium* showed greater reductions in C stocks consequent to pruning compared to the denser or closely spaced stands. Comparative study on above ground carbon sequestration potential of pepper based production system including six MPTs shows considerable variation. *Grevillea robusta* shows maximum carbon sequestration with 139.60 kg C $tree^{-1}$ and lowest recorded for *Ailanthus triphysa* 58.99 kg C $tree^{-1}$. Bole shows the maximum fraction followed by branch, leaves and twigs (Aneesh, 2014).

Variations in environmental conditions can also affect carbon sequestration potential even within a relatively small geographic area (Montagnini and Nair, 2004). Carbon stock estimated in the aboveground biomass of three dominant mangrove species of Sunderbans 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).

2.3.1.2 Belowground biomass carbon sequestration

The amount of carbon sequestered in the tree root is substantial but it is unknown for many species. In a 20-year-old teak plantation at panama an average of 13.1 % of the tree carbon was stored in their roots (Kraenzel *et al.*, 2003).

Samritika (2014) reported stand level C sequestered in below ground biomass of 20 year old *Grevillea robusta* plantation was 8.04 Mg ha^{-1}. Similar study conducted in a pepper based system revealed that the belowground carbon production varies considerably among different MPTs with *Acacia auriculiformis* (30.13Mg C ha^{-1}) showed maximum belowground carbon production followed by *Grevillea robusta* (29.64 Mg Cha $^{-1}$) and the lowest was recorded for *Ailanthus triphysa* (11.13Mg 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 (Kunhamu *et al.*, 2011).

2.3.1.3 Soil carbon sequestration

The term "soil C sequestration" implies net removal of atmospheric CO_2 by plants and its storage as soil organic matter. Processes of Soil organic carbon sequestration include humification, aggregation, deep incorporation of C in the subsoil, and calcification. Soil plays a major role in global C sequestration (Lal, 2002) and has a higher capacity to store C compared to vegetation and atmosphere (Bellamy *et al.*, 2005). 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 pool (610 Pg; Lal, 2004). 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).

Tree based land use systems have greater potential of soil carbon sequestration than agronomic crops. A comparison study of soil carbon stock under different land use system in Kerala reported higher soil organic carbon stocks under tree based system like Forest (177 Mg ha^{-1}), Homegarden (119 Mg ha^{-1}), Rubber plantation (119Mg ha^{-1}), and Coconut (91 Mg ha^{-1}) compared to Rice (54 Mg ha^{-1}; Saha *et al.*, 2010).

The Influence of tree on soil C storage differs among different tree species, which differ in biomass production, tissue nutrient concentrations and their effects on soil quality (Post and Kwon, 2000). 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 registered greater levels of soil organic carbon in the rhizosphere of *G. sepium* (26.5 g kg^{-1}), and the lowest level was registered under *A. triphysa* (21.6 g kg^{-1}; Dinesh *et al.*, 2010).

Study conducted to estimate the soil carbon stocks under three MPTs interplanted coconut plots showed maximum soil carbon levels under *Leucaena* followed by Casuarina and Ailanthus interplanted plots (Sreenivasan *et al.*, 2010). Moreover surface soil showed highest organic carbon percentage as compared to soil from deeper layers. Arora and Chaudhry (2014) studied total SOC upto 1 m depth was found that carbon stocks was maximum under *Syzygium cumini* (77.72 Mg C ha^{-1}) followed by *Eucalyptus tereticornis* (74.69 Mg C ha^{-1}) and *Tectona grandis* (55.46 Mg C ha^{-1}). Depth wise distribution of soil carbon varies in different land use system. 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 improving soil organic carbon through their decomposition (Brady and Weil, 2008) and supply C to soil through the process known as rhizo-deposition. Roots are the sources of soil organic carbon 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 *et al.*, 2007).

Tree management practices like thinning, pruning and litter fall removal also influence the extent of soil carbon storage in an agroforestry system. Study conducted in 6.5 year old *Acacia mangium* with four planting density with or without 50% pruning level shows significant difference in soil organic carbon production. The soil carbon stocks range from 24 to 35 Mg ha^{-1}and soil carbon stock under denser stand is higher (2500 trees ha^{-1}) than the stand with wider spacing. The importance of organic matter input from tree prunings and litterfall, to help maintain or increase the soil organic carbon pool, has been demonstrated by several studies in tropical and temperate agroforestry systems. Soil organic carbon study conducted in a 21-year-old *Grevillea robusta* plantation found to be 77.45 Mg C ha^{-1} within 1 m depth (Samritika, 2014). Similar study conducted 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}, *Ailanthus triphysa* recorded a value of 65.56 Mg ha^{-1} and lowest recorded for *Grevillea robusta* 61.26 Mg ha^{-1} (Aneesh, 2014).

2.4 Nutrient concentration in Biomass

The nutrient absorption and distribution by plants and the efficiency of nutrient utilization by the plant are important factors in the management of cultivated forests due to the exportation of significant amounts of nutrients in the stem (the harvested portion, preferentially) and the consequent nutrient depletion of the soils which in the tropics have, naturally, low fertility (Balieiro *et al.*, 2002).

Biomass and nutrient concentration in different tree components are used for estimation of tree nutrient uptake and nutrient removal by harvest and are crucial for understanding of nutrient circulation in 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 nutrient concentration in different parts of biomass depends mainly on tree species, phenological stage, management and site factors (Schroth, 2003). 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). Furthermore, nutrient absorption in forest plantations is closely associated with the increase in biomass and attains its maximum in the initial stage of rotation period (Miller, 1989).

Deciduous species generally have higher N concentrations in the leaves than evergreen species (Eamus, 1999). In general, nutrient concentration was in the order: leaves> bark> branches> stem (Lugo and Murphy, 1986). Similar results are shown by many authors. For instance, a study involving nine tropical fast growing MPT's revealed marked variations in nutrient concentration of tissue fractions among different species which followed in the order foliage> branches> roots> bole and also noticed markedly higher levels of foliar nitrogen in N- fixing leguminous trees (Kumar *et al.*, 1998). Similarly, the young leaf frequently have higher nutrient concentrations in pruned trees than the more woody biomass of infrequently pruned trees, although the quantity of biomass produced decreased with pruning frequency (Duguma *et al.*, 1988).

Likewise a study involving six multipurpose trees shows a decreasing trend of nutrient concentration in the order leaves> twigs> branches> roots> bole (Aneesh, 2014). 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). 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>boles. Shujauddin and Kumar (2003) showed that N, P, K concentration was highest in leaf followed by branchwood, course root and stem wood.

Concentration of certain nutrients showed a definite trend with increase in 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.

2.4.1 Nutrient accumulation and harvest related loss

The amount of nutrient absorbed from the soil differs from species to species. Neither all plants have similar nutrient requirement nor do they compete similarly for nutrients. 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 ie., biomass production leads to considerable amount of nutrient accumulation in the aboveground plant parts. Age, species, soil conditions, spacing and climate are some factors that influence the accumulation and distribution of nutrients in the plant part (Ovington, 1968).

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.* (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. 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.

A Study on nutrient analysis conducted in a 12-year-old *Eucalyptus tereticornis* plantation planted at high density spacings of 60cmx60cm showed, 1532.85 kg ha^{-1}, 196.40 kg ha^{-1} and 885.93 kg ha^{-1} of N, P and K respectively. Among different tree components, the bole accumulated maximum nutrients followed by leaves and branch + twig in all the spacing treatments (Bhardwaj *et al.*, 2000). Shujauddin and Kumar (2003) observed a higher foliar N, P and K concentrations followed by branchwood, coarse roots and stemwood 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 nutrient concentrations in response to tree spacing were also noticed.

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.*, 1991; Kumar *et al.*, 1998). 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.

2.4.4 Soil enrichment by trees

The capacity of trees to maintain or improve soil properties are shown by many. Trees in managed species mixtures have a great potential to bring about 'micro-site enrichment' through processes such as efficient cycling of plant nutrients and nutrient pumping (Huxley, 1985; Nair, 1983). Tree species also influence soil biogeochemical processes through differences in functional traits, such as tissue nutrient concentrations, and stand properties, including the amount of nutrients stored in wood (Mueller *et al.*, 2012). Tree crop based land use systems are more efficient in maintaining soil fertility than annual cropping system. Plots with Leucaena and Casuarina registered higher concentration of available N as compared to sole coconut and coconut + ailanthus and recorded significantly higher levels of soil available nutrients (N, P and K) under MPTs interplanted coconut than sole coconut in the humid tropics of Kerala (Sreenivasan *et al.*, 2010).

Nitrogen fixing trees have the additional potential of bringing in substantial quantities of atmospheric nitrogen into the combined form. A significant portion of the nitrogen fixed by the nitrogen fixing tree is probably released into the rhizosphere and is utilized by field crops (current nitrogen transfer). Many studies reported an increase in available nitrogen content of soils under different multipurpose trees (Puri *et al.*, 1994; Bheemaiah *et al.*, 1998). Another study using N-fixing red alder (*Alnus rubra*) in a maize alley cropping system in Oregon 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 (Seiter *et al.*, 1995).

2.5 ROOT ARCHITECTURE AND DISTRIBUTION PATTERN

Root architecture refers to the spatial configuration of the root system, i.e. the explicit geometric deployment of root axes. Usually, studies of root architecture do not include fine structural details such as root hairs, but are concerned typically with an entire root system of an individual plant (Lynch, 1995). From the root architecture both the topology (a description of how individual roots are connected through branching) and the distribution (the presence of roots in a spatial framework) can be derived, whereas neither topology nor distribution can be used to derive root architecture.

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). Based on the dimensions of the EFS, the perennial plant species are grouped into 16 classes ranging from plants with very compact-very shallow active root system (less than 100 cm lateral extension and less than 30 cm deep) to very extensive – very deep root system (more than 300 cm lateral spread and more than 90 cm deep) (Wahid, 2000). Root architecture conducted in 6-year-old trees of 9 indigenous and 3 exotic species growing in arid region of north-western India observed large variation in horizontal and vertical spread of roots (Toky and Bisht, 1992).

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). A study involving six multipurpose trees in Kerala showed maximum root depth in *Ailanthus triphysa* and minimum in *Grevillea robusta.* However the root spread of *Ailanthus triphysa* and *Casuarina equisetifolia* recorded the minimum (Aneesh, 2014). 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).

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. Another observation by Das and Chaturvedi, (2008) was on a large variation in root depth and horizontal root spread in 4-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 maximum root depth was recorded in *W. exserta* (2.10 m) and minimum in *B. variegata* (1.00 m). Horizontal root spread was 2.05 m in *Bombax ceiba* and 8.05 m in *Acacia auriculiformis.* Root spread exceeded crown cover for all species. The primary roots were more horizontal than the secondary roots. Rooting characteristics studied in a 10-year-old Tea-*Grevillea robusta* based system in the Western Ghats of Munnar showed a spatial segregation of coarse and fine roots in *Grevillea robusta.* Root distribution of *G. robus*ta was characterized by the occurrence of less number of feeder (fine) roots and an abundance of coarse roots near the soil surface., *G. robusta* 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. *G. robusta* roots also penetrated deeper into the soil profile (2.4 m) compared to that of tea bushes, which were confined within a limit of 1.5 m (Niranjana and Viswanath, 2008).

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 x 2 m and 2 x 3 m stands. However in the case of wide spaced stands the spread extended beyond the canopy. The average depth of coarse roots increased from 35 cm (2mx 2m) to 75 cm (2mx 5m).

Tree management 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) or irrigation (Fernandez *et al.*, 1991). 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 of supply of assimilates from the leaves and retranslocating sugars to aboveground organs. Similarly Fownes and Anderson (1991) reported reduction in the root length following pruning in the case of *Sesbania sesban* and *Leucaena leucocephala*.

Root activity pattern studied in 2-year-old *Acacia mangium* using ^{32}P soil injection technique observed spatial variations in the distribution pattern of physiologically active roots under varying planting density and pruning regimes (Kunhamu *et al.*, 2010). 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. Also, trenching technique study revealed that the distribution of 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 (Samritika, 2014).

2.6 ALLOMETRIC EQUATION

Allometric regressions developed by measuring biomass or production of either trees or their components and regressing these data against some easily measured variable, such as DBH (diameter at breast height) form the most important method for determining stand biomass production (Kumar *et al*., 1998). Allometric equations are developed for many species including fast growing tropical species (Dudley and Fownes, 1992). Allometric equations uses functions such as plant height and trunk diameter at breast height that are easily and non-destructively measured which allow the estimation of plant biomass from variables (Perez-Quezada *et al.,* 2011). Estimates of C pools in the vegetation component of forest ecosystems can be obtained by using allometric functions (Navar *et al*., 2002; Perez-Quezada *et al*., 2011).

2.6.1 Biomass prediction equation

Biomass quantification is a time consuming activity therefore there is a need to develop useful indirect methods for estimating the difficult to measure variables. The development and application of allometric equations is the standard methodology for above ground tree biomass estimation (Brown *et al.,* 1989; Chave *et al.,* 2004; 2005; Navar, 2009). Allometric regression equations developed by measuring biomass or production of either trees or their components and regressing these data against some easily measured variable, such as DBH (diameter at breast height), forms the most accurate biomass estimates (Litton and Kauffman, 2008). These biomass equations can be applied directly to develop tree level and stand level inventory data (Lehtonen *et al.*, 2004)

Biomass prediction equation can be developed for trees using known growth variables. For the prediction of the biomass of tree regression equations were widely used. Location specific allometric equations of large number of tree species have been developed across age sequence. Multiple regression models were found to be suitable for predicting biomass of many species including *Casurina equisetifolia* as reported by Dash *et al.*, (1991). 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; Claesson *et al.*, 2001). Location specific allometric equations for large number of tree species have been developed across age sequence. 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).

Number of variables representing prediction equations is often important for tree species. Tree diameter at breast height is often found to have a strong linkage with aboveground biomass and volume. However, equations based on one variable ie., dbh can make fair prediction with high R^2values (Dudley and Fownes, 1991). Allometric equation in a 22-year-old pepper based stand containing six MPTs were attempted by linking aboveground biomass, total aboveground 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 (Aneesh, 2014).

Likewise, Kunhamu *et al.* (2005) attempted regression equations linking aboveground biomass, tree volume with DBH (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*. Ceulemans (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. 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 $\{In\ Y = a_o + a_1 * InD + a_2 * InH1\}$ 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. A study conducted in *Eucalyptus pilularis*, it was observed that dbh alone as the predictor variable produced the most stable relationship (Montagu *et al.*, 2005). 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, 1991)

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. 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 where as relationship of foliage was strong with D^2 and D^2H only.

MATERIALS AND METHODS

MATERIALS AND METHODS

3.1 LOCATION

The experimental site is located at Vellanikkara, Thrissur. The area has an elevation of 40.29 m above sea level and located at 10° 13' N latitude and 76° 13' E longitude. Vellanikkara experienced a warm and humid climate, having mean annual rainfall of 2390 mm (average past 21 years from 1991-2012), most of which is received during SW monsoon (June to August). The mean max temperature ranges from 29.10° C to 35.49° C in the month of July and March respectively while the mean minimum temp varied from 22.19°C to 24.83°C in the months of December and April respectively. Soil is ultisol having average pH 5.1. The study plantation was established in 1991, in split plot design with a view of studying the effect of planting density and effect of fertilizers on the growth of *Ailanthus triphysa.*

3.2 EXPERIMENTAL DETAILS

Present study was undertaken in pre-existing *Ailanthus triphysa* stand established during 1991. The experimental plots were laid out in split plot design with four planting densities and four fertilizer regimes in three replications. The various planting density regimes included 3333 trees ha^{-1} (3mx1m), 2500 trees ha^{-1} (2mx2m), 1600 trees ha^{-1} (3mx2m) and 1111 trees ha^{-1} (3mx3m). Three month old Ailanthus seedlings were planted at specified planting densities during June 1991. Over a period of 22-years the *A. triphysa* stands were subjected to selective logging as part of previous biomass studies and mortality due to longer periods of suppression, brining changes in initial spacing and planting density. The present stand density is 2360 trees ha^{-1}, 1560 trees ha^{-1}, 900 trees ha^{-1} and 560 trees ha^{-1} as against the initial planting density of 3333 trees ha^{-1}, 2500 trees ha^{-1}, 1600 trees ha^{-1} and 1111 trees ha^{-1} respectively.

Plate 1. A view of the experimental plot at Aramkalu, Thrissur, Kerala

3.3 TREE GROWTH OBSERVATIONS

Prior to the biomass studies growth observations of 22-year-old *A. triphysa* stand were taken that included total tree height, dbh and crown width. Border plants were excluded from the measurement in order to minimize the edge effect. Tree height was measured by means of Haga Altimeter. Coupled with this exercise the trees to be felled were numbered and ringed at 1 m height from the ground level using paint. This exercise facilitates the subsequent girth measurements at 2 m intervals from 1m height after felling of the trees and also helped in distinguishing the trees earmarked for felling from that of the border trees.

3.3.1. Sampling procedure

After taking the growth parameters of all the trees in the experimental area the trees in each stand density levels were classified into three girth classes viz., 0-40 cm, 40-80 cm, 80-120 cm. Frequency of trees under different girth classes in each stand density levels are shown in Table 1.

Table1. Frequency and number of trees sampled in each stand density regime under different girth classes for 22-year-old *A. triphysa*

Girth class (cm)	2360 trees ha^{-1}		1560 trees ha^{-1}		900 trees ha^{-1}		560 trees ha^{-1}	
	Total no: of trees	No: of trees sampled	Total no: of trees	No: of trees sampled	Total no: of trees	No: of trees sampled	Total no: of trees	No: of trees sampled
0-40	73	10	26	7	14	5	9	4
40-80	47	6	36	9	22	12	14	13
80-120	9	4	12	4	5	3	4	3
Total	129	20	74	20	41	20	27	20

Sample trees were selected by using proportionate sampling method, ie., maximum numbers of trees were selected from the higher frequency class. Proportionate number of trees were randomly selected from each girth class for a given stand density such that the total trees sampled for density levels is twenty. Accordingly a total of 80 trees were selected for aboveground biomass study. Immediately after felling, the bole height and total height of the trees were recorded. After this the girth at 2 m intervals from the 1 m height were recorded for volume calculation. The growth data were tabulated and statistically analyzed following analysis of variance technique.

3.3.2. Limitations

The original experimental area was laid out in split plot design, in three replications with planting density as main plot and fertilizer regime as subplots. However, frequent logging in due course and natural mortality due to longer periods of suppression lead to poor stocking in replication 2 and 3 in the previous experiment. However, they were omitted from the present study due to lack of sufficient number of trees.

3.4 VOLUME ESTIMATION OF FELLED TREES

For estimating the volume of felled trees, the trees were divided into 2 m sections up to the tip of the tree and midgirth of each 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 by multiplying the mean tree volume with number of trees per ha.

3.5 BIOMASS ESTIMATION

3.5.1 Aboveground biomass estimation

The total number of 80 trees selected for biomass study under variable density regimes were marked using red paint. After recording the total height and diameter at breast

Plate 2. Weighing of different biomass components in the field using digital spring balance

height (dbh), the trees were felled at ground level by using power saw (Oleo mac, Italy). The aboveground portions of the felled trees were separated into stem wood, branch wood, 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, branch wood, twigs and foliage were collected from all the felled trees and transferred to laboratory in double-sealed polythene bags and fresh weights 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, branch, twig and leaf) and from their corresponding moisture contents. Biomass of tree parts was summed up to obtain the total aboveground biomass per tree (dry weight biomass). 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.

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

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

3.5.2 Belowground biomass estimation

The belowground biomass (coarse roots) was estimated following root excavation technique. Sample trees to be excavated were determined by using proportionate sampling method and a total of 24 trees were excavated for biomass study using powered earth mover

Plate 3. Root excavation using Earthmover for belowground biomass estimation

Plate 4. Soil profile for collecting samples for organic carbon and nutrient analysis

Plate 5 and 6. Root system of *A. triphysa* excavated for root morphometric and biomass study

(Tata Hitachi). The fresh weights were recorded after thorough cleaning. Triplicate samples (250 g each, coarse roots) were collected for moisture and chemical analyses. Dry weight of roots was derived from the fresh weights and their corresponding moisture contents.

3.6 BIOMASS C- SEQUESTRATION

Organic carbon content in the plant samples were determined by using dry ash method in a muffle furnace. 10 g of the sample was weighed in a crucible. The crucibles were then placed inside the muffle furnace and heated at 506^0C for 6 hours. The crucibles were then taken out and the residual weight was calculated to determine the carbon content. Triplicate samples of each tissue types (stem, branch, twig, leaf and coarse 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 biomass with the corresponding carbon concentration. Total for whole tree were obtained by summing results for component parts. Stand level biomass C stock were estimated by multiplying the average C stock per tree with the number of trees per ha.

3.7 PHYTOCHEMICAL ANALYSIS

In order to estimate the nutrient accumulation in the aboveground and belowground biomass, triplicate samples of tissue types (stem, branch, twig, leaf and coarse root) were analyzed for N, P and K. Three sub samples were drawn from the composite samples for phytochemical analysis. Nitrogen and phosphorus were analysed using continuous flow analyzer (SKALAR) method and potassium by flame photometry (Jackson, 1958). 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 results for component parts. Average nutrient accumulation per tree were then multiplied by the number of trees per ha to estimate per ha accumulation.

Plate 7. Digestion chamber for soil and plant sample digestion

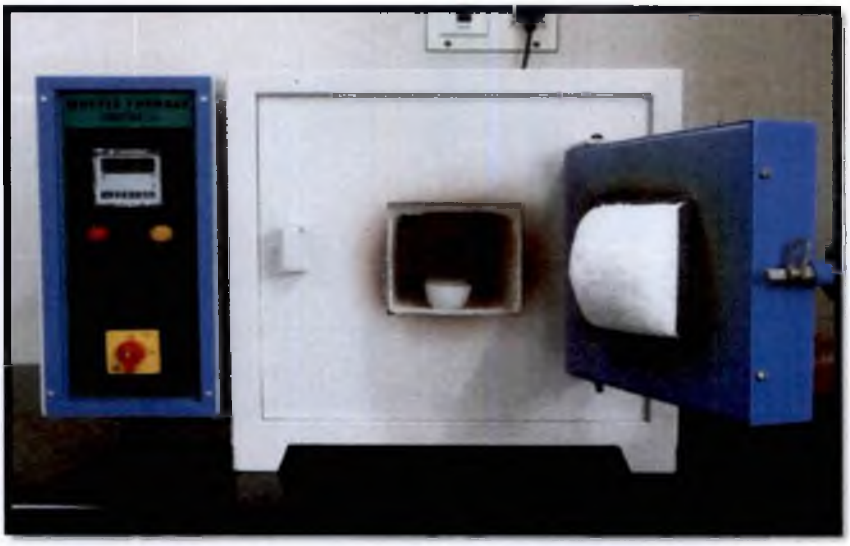

Plate 8. Muffle furnace for elemental carbon analysis

3.7.1 Estimation of nitrogen

Total nitrogen content in plant samples was determined by continuous flow analyzer (skalar) method. The automated procedure for the determination of ammonia/total nitrogen is based on the modified Berthelot reaction: after dialysis against a buffer solution of pH 5.2 the ammonia in the sample is chlorinated to monochloramine which react with salicylate to 5 aminosalicylate. After oxidation and oxidative coupling a green coloured complex is formed. The absorption of the formed complex is measured at 660nm. The various reagents used include Potassium sodium tartrate solution, Sodium salicylate solution, Sodium nitroprusside solution, Sodium dichloroisocyanurate solution, Rinsing liquid sampler, Distilled water + Brij 35.

Sulphuric acid and Se powder mixture – 3.5g Se powder was weighed. 1 litre of conc. H_2SO_4 was carefully and slowly poured into a two litre beaker. Se powder 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 slowly changed to deep blue colour and then light yellow. The solution was then cooled.

Digestion mixture – 10.8g salicylic acid was weighed and added to 150 ml of H_2SO_4 and Se mixture already prepared.

Procedure

0.2 g of the plant sample (leaves, stem wood, branches and twigs) was weighed in the digestion tube. 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 digestion was completed. The digest was made upto 75 ml in a standard flask. The nitrogen content of the plant sample was then analysed using skalar.

Plate 9. Continuous flow analyser (SKALAR) for estimation of N and P

Plate 10. Flame photometer for estimation of K

3.7.2 Estimation of Phosphorous

One gram of the plant sample was weighed and digested with diacid mixture (HNO_3 and $HClO_4$ in 9:4 ratio) in a digestion chamber until the solution became colourless. After that the digest was made upto 50 ml. About 5ml of the liquid was used to determine the phosphorous content using skalar method using reagents. The various reagents used include Sulphuric acid solution, distilled water + FFD6, Ammonium heptamolybdate solution, Ascorbic acid solution, distilled water + FFD6 (required for predilution), Rinsing liquid solution

The automated procedure for the determination of phosphate/Total phosphate is based on the following reaction; after dialysis against distilled water, ammonium heptamolybdate and potassium antimony (III) oxide tartarate react in an acidic medium with diluted solutions of phosphate to form an antimony-phospho-molybdate complex. This complex is reduced to an intensely blue-coloured complex by L(+) ascorbic acid. This complex is measured at 880 nm.

3.7.3 Potassium

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

3.8 SOIL ANALYSIS

3.8.1 Soil sampling

Soil samples were collected from the interspaces between the rows of trees. Four profile pits were taken from the experimental plot each corresponding to a density level and triplicate samples were collected from five depths viz. 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Similarly soil profile was also taken in treeless control plot. Soil samples for bulk density measurement were done using specially designed steel cylinder (Jackson, 1958). Bulk density was estimated by taking out a core of undistributed soil by using steel cylinder. The core was taken out without pressing the cylinder too hard on soil so that the natural bulk density of soil is disturbed. The soil samples were oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder (πr^2h). The bulk density was calculated by dividing the oven dry weight of soil samples (g) by volume of soil. Soil samples collected at different soil depth were air dried and passed through 2 mm sieve and stored in polyethylene containers. Triplicate samples were taken for analyzing N, P, K and organic carbon. Similar analyses were followed for soil in the treeless control plot.

3.8.2 Soil C- sequestration

For estimating the soil C stock under 22-year-old *A. triphysa* stands, triplicate soil samples were collected from five soil depths. The soil were stored in plastic zip lock bags, sealed for transport and re-opened within 24 h. Samples were air-dried in a drying room and sieved to 2 mm prior to further analysis. The soil organic carbon was analyzed using Wakley and Black method using continuous flow analyzer (SKALAR). Soil mass for each soil depth were computed from the corresponding bulk density and soil C-sequestration were 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 control.

3.8.2.1 Soil carbon estimation using continuous flow analyzer

The automated procedure for the determination of carbon is based on the Walkely and Black method. Soil organic matter is oxidized at a temperature of approximately 120° C with a mixture of potassium dichromate and concentrated sulphuric acid and the absorption is measured at 620nm.

3.8.3 Soil nutrient analysis

Composite soil samples were collected replication wise from each tree plot from five soil depths. They were air-dried and ground to pass through a 2 mm sieve. Triplicate samples drawn from the composite samples were analyzed for total nitrogen, total phosphorus and total potassium using skalar method (Continuous flow analyzer) for nitrogen and phosphorus and flame photometry for potassium. Also, representative triplicate soil samples were collected from contiguous treeless plots as control.

3.9 ALLOMETRIC EQUATIONS

The biomass, biomass C sequestration and volume data obtained from all the sampled trees were pooled and used to develop the allometric equations. Simple linear and quadratic equations were developed 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.

3.10 STATISTICAL TREATMENT OF DATA

Attempts were made to analyze the combined effect of size class and density regimes on tree growth. However, the effects were confounding and confusing. On further statistical consultations, considering the complexity involved in interpreting the results, the treatment comparisons were limited to stand density levels only disregarding the tree size classes. Biomass, photochemical and soil data (means of three sub-samples) were analysed with one-way ANOVA technique (using SPSS). LSD and DMRT test was used to compare mean biomass yield, nutrient concentration, nutrient content of tree parts and whole trees and the soil parameters.

RESULTS

RESULTS

The present study involved assessment of aboveground and belowground biomass, carbon sequestration, allometric equations and nutrient dynamics in a 22-year-old *Ailanthus triphysa* stands managed at variable stand densities. The salient results of the study are discussed hereunder.

4.1 TREE GROWTH CHARACTERISTICS OF 22-YEAR-OLD *A. TRIPHYSA* STAND

Aboveground morphometric data of 22-year-old *A. triphysa* trees managed at various planting densities viz., 2360 trees ha^{-1}, 1560 trees ha^{-1}, 900 trees ha^{-1} and 560 trees ha^{-1} are presented in Table 1. Stand density exerted significant variation in growth parameters such as total height and bole height. The mean total height ranged from 15.28 m (1560 trees ha^{-1}) to 11.14 (900 trees ha^{-1}) which is on par with mean height of 560 trees ha^{-1} stand (11.28 m). The effect of stand density on diameter growth was found to be inconspicuous. However, maximum mean diameter was registered for 560 trees ha^{-1} stand (20.03 cm) which was followed by stand at 900 trees ha^{-1} (18.80 cm; Table 2).

Table 2. Tree growth characteristics of 22-year-old *A triphysa* stand managed at variable stand densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Dbh (cm)**	**Total height (m)**	**Bole height (m)**
2360	18.15 (1.92)	13.66^{a} (0.82)	9.24^{a} (0.66)
1560	18.15 (1.83)	15.28^{a} (1.05)	9.38^{a} (0.98)
900	18.80 (1.49)	11.14^{b} (0.59)	6.92^{b} (0.58)
560	20.03 (1.59)	11.28^{b} (0.76)	7.23^{b} (0.55)
F-test	ns	*	*
P-value	0.848	0.008	0.002

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means.*

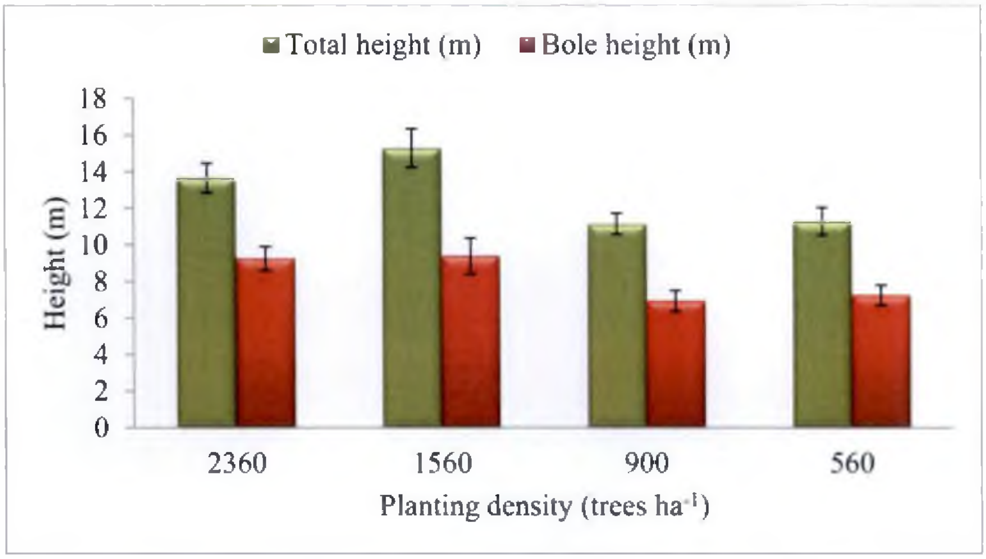

Figure 1. Tree growth characteristics of 22-year-old *A triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

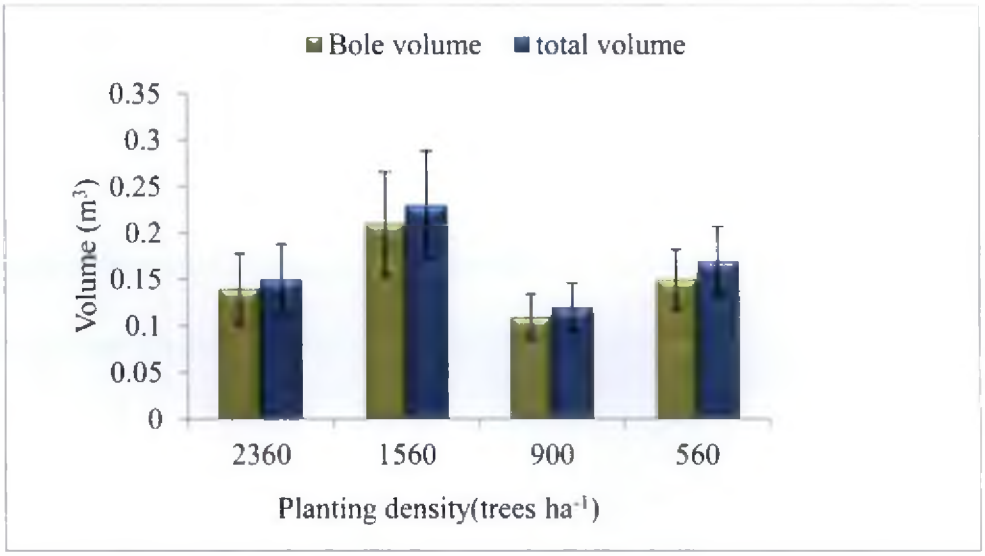

Figure 2. Mean tree total volume and bole volume for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

The mean bole height ranged from 6.92 m to 9.38 m. The maximum bole height was recorded by stand density, 1560 trees ha^{-1} (9.38 m) which was closely followed by stand density, 2360 trees ha^{-1} (9.24 m) and then by stand density, 560 trees ha^{-1} (7.23 m). The minimum value was recorded for stand at 900 trees ha^{-1} (6.92 m).

4.1.1 Volume

The mean tree total volume and bole volume production of *A. triphysa* trees of 22-year-age are shown in Table 3. Variable plant densities did not show any significant difference on bole volume and total volume production among *A. triphysa* trees. Despite the poor statistical significance, there occur modest variation among the mean values with maximum mean tree bole volume recorded for 1560 trees ha^{-1} stand (0.21 m^3) followed by 560 trees ha^{-1} stand (0.15 m^3) and 2360 trees ha^{-1} stand (0.14 m^3) and minimum mean tree bole volume was recorded for 900 trees ha^{-1} stand (0.11 m^3). As regards mean tree total volume also, the same trend was followed with 1560 tree ha^{-1} stand recording the maximum (0.23 m^3) which was closely followed by 560 trees ha^{-1} stand (0.17 m^3) and 2360 trees ha^{-1} stand (0.15 m^3) while minimum was for 900 trees ha^{-1} stand (0.12 m^3).

Table 3. Mean tree total volume and bole volume for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Bole volume (m^3)**	**Total volume (m^3)**
2360	0.14 (0.038)	0.15 (0.038)
1560	0.21 (0.058)	0.23 (0.056)
900	0.11 (0.026)	0.12 (0.024)
560	0.15 (0.037)	0.17 (0.032)
F-test	ns	Ns
P value	0.318	0.248

ns-non significant; Values shown in parenthesis are standard error of means

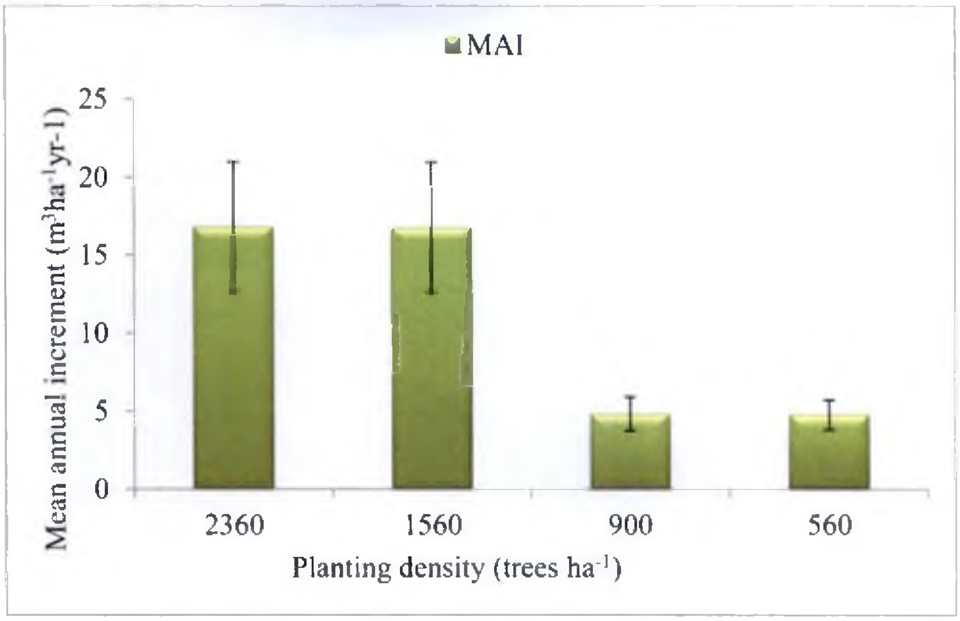

Figure 3. Mean annual increment for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

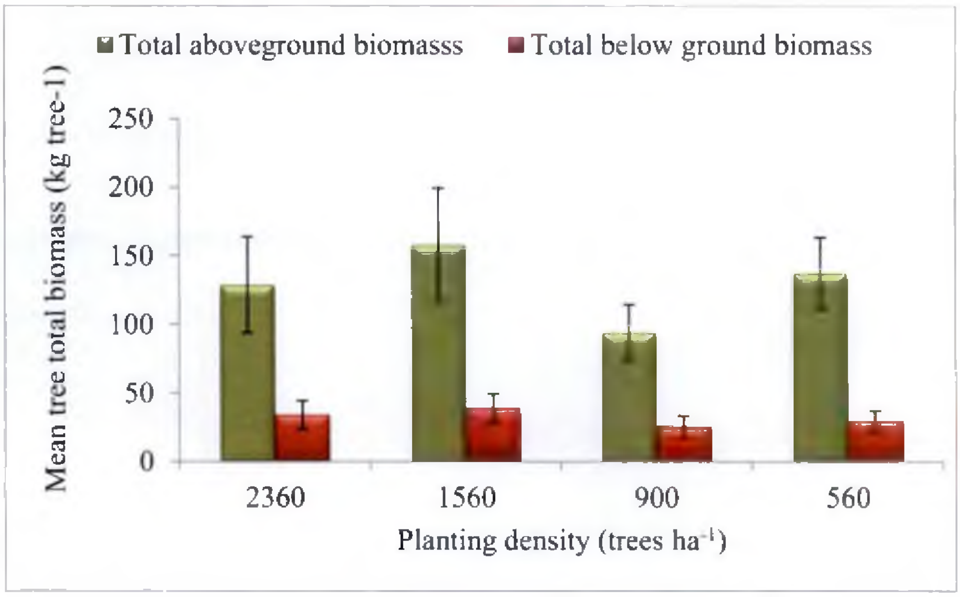

Figure 4. Mean tree total aboveground and total belowground biomass for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

4.1.2 Stand volume and mean annual increment (MAI)

Table 4 shows the stand volume and corresponding mean annual increment (MAI) for 22- year-old *A. triphysa* stand. The stand volume production and MAI showed significant variation among the densities tried. The maximum stand volume production was observed for 2360 trees ha^{-1} stand (370.04 m^3 ha^{-1}) which was on par with that of 1560 trees ha^{-1} stand (369.01 m^3 ha^{-1}). The minimum mean stand volume value was observed in 560 trees ha^{-1} stand (105.05 m^3 ha^{-1}) and stand at 900 trees ha^{-1} recorded a value of 106.38 m^3 ha^{-1}. The mean annual stand volume production also shows the same trend with maximum value to the tune of 16.82 $m^3ha^{-1}yr^{-1}$ recorded by 2360 trees ha^{-1} stand which was closely followed by 1560 trees ha^{-1} stand (16.77 $m^3ha^{-1}yr^{-1}$). The minimum value was again recorded for 560 trees ha^{-1} stand (4.77 $m^3ha^{-1}yr^{-1}$).

Table 4. Stand volume and MAI volume for 22-year-old *A. triphysa* stand managed at variable densities, Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Stand volume (m^3 ha^{-1})**	**MAI (m^3 $ha^{-1}yr^{-1}$)**
2360	37.04^a (91.52)	16.82^a (4.16)
1560	369.01^a (91.87)	16.77^a (4.17)
900	106.38^b (24.01)	4.83^b (1.09)
560	105.05^b (21.24)	4.77^b (0.96)
F-test	*	*
P-value	0.003	0.003

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means.*

4.2 Biomass accumulation

The biomass production in a 22-year-old *A. triphysa* stand is shown in Table 5. Variation in aboveground biomass (AGBM), belowground biomass (BGBM) and total biomass production is explicit for various stand density regimes.

Table 5. Mean tree biomass accumulation for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Total aboveground biomass (kg tree^{-1})**	**Total belowground biomass (kg tree^{-1})**	**Total biomass (kg tree^{-1})**	**Percentage aboveground biomass (%)**	**MAI (biomass) (kg ha^{-1}yr^{-1})**
2360	129.05^{ab} (35.09)	33.94 (10.58)	162.99^{a}	79.17	7.41
1560	158.12^{a} (41.13)	39.02 (10.32)	197.13^{a}	80.21	8.96
900	94.34^{b} (20.48)	25.65 (7.74)	119.99^{b}	78.62	5.45
560	137.74^{a} (26.17)	29.91 (7.05)	166.85^{a}	82.55	7.5
Average	129.81	27.13	161.74	80.13	7.3
F-test	*	Ns	*	-	-
P-value	0.002	0.241	0.002	-	-

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means*

The total mean tree biomass production among the various stand densities for *A. triphysa* ranged from 119.99 kg tree^{-1} to 197.13 kg tree^{-1}. The total biomass production in medium density (900 trees ha^{-1}) was characteristically lower (119.99 kg tree^{-1}) compared with other density regimes. Despite lower statistical significance, the total biomass production, showed apparent difference in the mean value with 1560 trees ha^{-1} stand (197.13 kg tree^{-1}) recording maximum value followed by 560 trees ha^{-1} stand (166.85 kg tree^{-1}) and 2360 trees ha^{-1} stand (162.99 kg tree^{-1}).

Similar to total biomass production, the aboveground biomass production also followed the same trend with stand at lower density (900 trees ha^{-1}) showing significantly lower biomass (94.34 kg $tree^{-1}$) compared with other density regimes. The maximum aboveground biomass production was registered by 1560 and 560 trees ha^{-1} stands with a value of 158.12 kg $tree^{-1}$ and 137.74 kg $tree^{-1}$ respectively. However, the high density stand (2360 trees ha^{-1}) showed intermediate values. Belowground biomass production also showed marginal changes with stand density. However, the high density stands appear to have accumulated more biomass to the belowground (33.94 and 39.02 kg $tree^{-1}$ for 2360 and 1560 trees ha^{-1} stand respectively). The mean tree belowground biomass production among lower density regimes were 25.65 kg $tree^{-1}$ (900 trees ha^{-1} stand) and 29.91 kg $tree^{-1}$ (560 trees ha^{-1} stand) respectively.

4.2.1 Biomass partitioning

Allocation of biomass to different components viz. stem, branch, twig, leaf and root and their percentage contribution to total biomass are furnished in Table 6. Clearly, the largest component of biomass yield in all density treatment was stemwood which varies from 129.04 kg $tree^{-1}$ (65.50 %) to 74.03 kg $tree^{-1}$ (61.92 %). Root biomass accounted for the second largest share to the total biomass for most of the density regimes. The twig portion contributed the least to biomass production.

Considerable variation in biomass partitioning has been observed with stand density. Maximum mean tree stemwood production was observed for *A. triphysa* at 1560 trees ha^{-1} stand density with a value of 129.04 kg $tree^{-1}$ followed by 2360 trees ha^{-1} stand with 104.21 kg $tree^{-1}$ and 560 trees ha^{-1} stand having a value of 102.08 kg $tree^{-1}$. Stand at 900 trees ha^{-1} registered the minimum value for stemwood biomass production (74.03 kg $tree^{-1}$). Root biomass contributed the second largest share to the total biomass production. The allocation of mean tree biomass to the roots followed the order 39.02 kg $tree^{-1}$ (1560 trees ha^{-1}), 33.94 kg $tree^{-1}$ (2360 trees ha^{-1}), 29.91 (560 tree ha^{-1}) and 25.56 kg $tree^{-1}$ (900 trees ha^{-1}). However the percentage allocation of roots compared to total biomass were variable among the stand density regimes. For instance, the highest allocation towards roots was

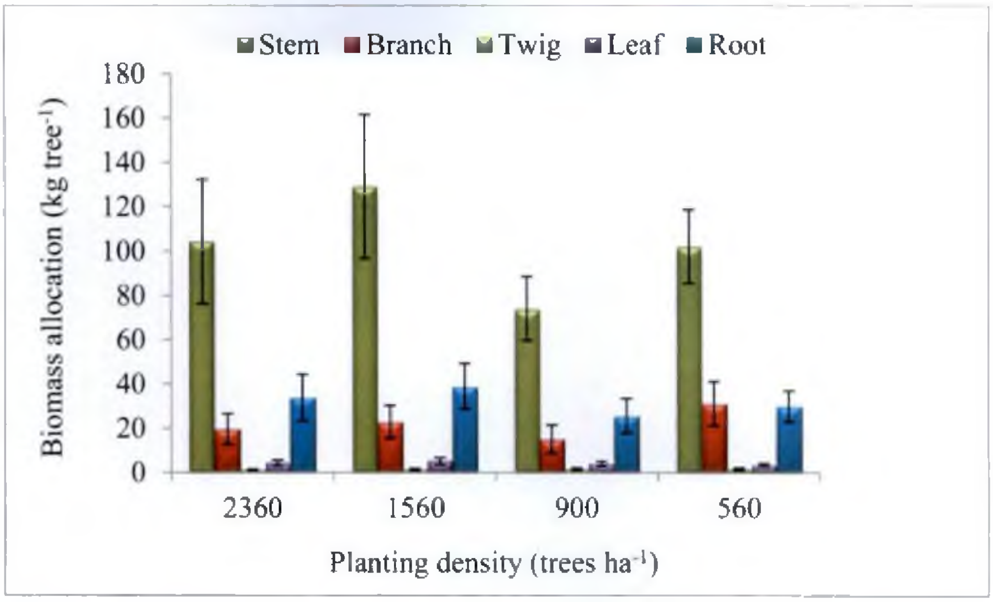

Figure 5. Contribution of different components to the total biomass of 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

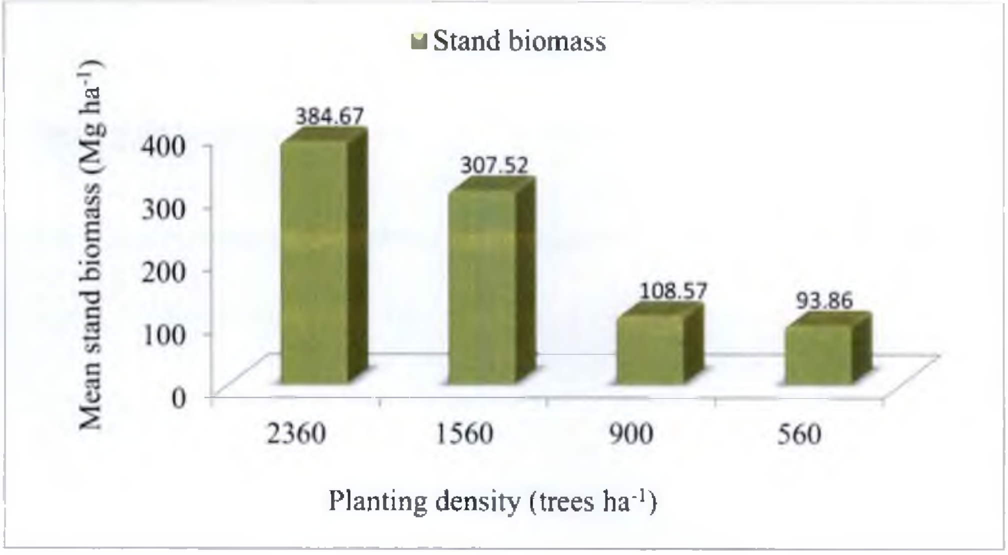

Figure 6. Stand biomass accumulation for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Table 6. Partitioning of mean tree biomass for 22-year-old *A. triphysa* stand managed at variable densities, Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Stem**		**Branch**		**Twig**		**Leaf**		**Root**		**Total**
	Kg	**%**	**Kg**	**%**	**Kg**	**%**	**kg**	**%**	**kg**	**%**	
2360	104.21^{ab} (28.01)	63.93	19.62 (7.07)	12.04	1.05 (0.41)	0.64	4.17 (1.35)	2.55	33.94 (10.58)	20.82	162.99^{a}
1560	129.04^{a} (32.51)	65.50	22.78 (7.51)	11.55	1.24 (0.47)	0.62	5.04 (1.46)	2.55	39.02 (10.32)	19.79	197.13^{a}
900	74.03^{b} (14.47)	61.92	14.96 (6.43)	12.46	1.43 (0.58)	1.19	3.90 (1.03)	3.2	25.56 (7.74)	21.37	119.99^{b}
560	102.08^{a} (16.66)	61.18	31.12 (10.07)	18.65	1.43 (0.59)	1.44	3.38 (0.71)	2.02	29.91 (7.05) -	17.92	166.85^{a}
Average	102.34	-	22.12	-	1.28	-	4.12	-	32.11	-	161.74
F-test	*	-	ns	-	Ns	-	ns	-	ns	-	*
P-value	0.002	-	0.160	-	0.59	-	0.793		0.241	-	0.002

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means* given by 900 trees ha^{-1} stand (21.37 %) followed by 2360 trees ha^{-1} stand (20.82 %), 1560 trees ha^{-1} stand (19.79%) and lowest of 17.92 % by 560 trees ha^{-1} density regimes.

With regard to branches, maximum percentage allocation was observed in 560 trees ha^{-1} density (18.85 %) and minimum for 1560 trees ha^{-1} (11.55%). The percentage contribution of leaf and twig was generally very low. Leaf biomass contribution ranged from 3.38 % to 5.04 % of total biomass. Twig invariably recorded the least biomass yield for all the density regimes (0.54% -1.35%).

4.2.2 Biomass production on stand basis

Stand level biomass production is a function of factors such as species composition, age, planting density and tree management practices. The present study showed considerable variation in stand biomass accumulations with stand density (Table 7). In general, the total stand biomass production increased with increasing stand density. For example, stand at highest density (2360 trees ha^{-1}) recorded higher value to the tune of 384.67 Mg ha^{-1} followed by 1560 trees ha^{-1} stand having a value of 307.52 Mg ha^{-1}, which were however statistically on par. The lowest stand biomass production was shown by 560 trees ha^{-1} stand (93.86 Mg ha^{-1}) while stand at 900 trees ha^{-1} showed intermediate value (108.57 Mg ha^{-1}) which were on par. In general, biomass productions by higher density regimes (2360 and 1560 trees ha^{-1}) were significantly higher than the lower densities.

Table 7. Stand biomass accumulation and MAI for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Stand biomass accumulation (Mg ha^{-1})**						**MAI (Mg ha^{-1}yr^{-1})**
	Stem	**Branch**	**Twig**	**Leaf**	**Root**	**Total**	
2360	245.93^{a} (66.08)	46.31 (16.70)	2.48 (1.30)	9.84^{a} (3.19)	80.11^{a} (24.97)	384.67^{a}	17.48^{a}
1560	201.30^{a} (50.73)	35.54 (11.71)	1.93 (0.58)	7.87^{a} (2.28)	60.88^{ab} (16.10)	307.52^{a}	13.97^{a}
900	66.62^{b} (13.02)	13.46 (5.78)	1.29 (0.42)	3.51^{b} (0.93)	23.08^{b} (6.96)	108.57^{b}	4.93^{b}
560	57.16^{b} (9.33)	17.42 (5.64)	0.64 (0.12)	1.89^{b} (0.39)	16.75^{b} (3.94)	93.86^{b}	4.26^{b}
F-test	*	ns	ns	*	*	*	*
P-value	0.003	0.124	0.215	0.009	0.024	0.002	0.009

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means.*

As regards allocation of total biomass among the various tissue fractions, stemwood again accounted the highest proportion for all the density regimes which ranged from 245.93 Mg ha^{-1} to 57.16 Mg ha^{-1}. A consistent reduction in stemwood biomass has been observed with reduction in stand density (Table 7). For example, highest stemwood biomass was registered by stand at 2360 trees ha^{-1} density (245.93 Mg ha^{-1}) followed by stand at 1560 trees ha^{-1} (201.30 Mg ha^{-1}), 900 trees ha^{-1} (66.62 Mg ha^{-1}) and lowest for 560 tree ha^{-1} stand (57.16 Mg ha^{-1}).

The root portion constituted the second highest portion which varied significantly among various stand densities. The value ranged from 16.75 Mg ha^{-1} in lower density stand (560 trees ha^{-1}) and 80.11 Mg ha^{-1} in higher density stand (2360 trees ha^{-1}). Despite the apparent variation, branch wood and twig portion didn't show significant change with stand density. Changes in leaf biomass were prominent among extreme density regimes which ranged from 9.84 Mg ha^{-1} (2360 trees ha^{-1}) to 1.89 Mg ha^{-1} (560 trees ha^{-1}).

Mean annual increment in stand biomass also closely changed with stand density with maximum value attached to highest density stand (17.48 Mg ha^{-1} yr^{-1}; 2360 trees ha^{-1}) while the lowest density stand giving lowest MAI (4.26 Mg ha^{-1} yr^{-1}; 560 trees ha^{-1}). Other densities gave intermediate results.

Table 8. Biomass accumulations at stand level in 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Total above ground stand biomass (Mg ha^{-1})**	**Total belowground stand biomass (Mg ha^{-1})**	**Total stand biomass (Mg ha^{-1}) (AGB+BGB)**	**Root: shoot ratio**	**Percentage of total aboveground biomass (%)**
2360	304.57^{a} (82.61)	80.11^{a} (24.97)	384.67^{a}	0.26	79.17
1560	246.64^{a} (64.17)	60.88^{ab} (16.10)	307.52^{a}	0.24	80.20
900	84.90^{b} (18.43)	23.08^{b} (6.96)	108.57^{b}	0.27	78.65
560	77.13^{b} (14.66)	16.75^{b} (3.94)	93.86^{b}	0.21	82.15
Average	178.31	45.21	223.65	0.24	-
F-test	*	*	*	-	-
P-value	0.004	0.024	0.002	-	-

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means*

Table 8 shows the partitioning of total biomass production to the aboveground and belowground portion of 22-year-old *A. triphysa* stand. Maximum aboveground biomass production was registered in 2360 trees ha^{-1} stand with a value of 304.57 Mg ha^{-1} and minimum registered at 560 trees ha^{-1} stand with 77.13 Mg ha^{-1}. The belowground biomass production was also higher in the high density stand (2360 trees ha^{-1}) having a value of 80.11 Mg ha^{-1} and lowest in low density stand (560 trees ha^{-1}) with a value of 93.86 Mg ha^{-1}. The percentage contributions of aboveground biomass to total biomass vary from 78.5 %

For instance, the carbon concentration in stemwood ranged from 45.08 % (1560 trees ha^{-1}) to 44.89 % (560 trees ha^{-1}). Among density treatments, 1560 trees ha^{-1} showed higher concentration for all components except branchwood. C concentration in branchwood was highest for 560 trees ha^{-1} (45.91%) and lowest value was for 1560 trees ha^{-1} (45.61%). Twig portion lacked significant variation among density levels. Leaves recorded the highest carbon concentration among all the tissue types and the maximum concentration was shown by 1560 trees ha^{-1} density regime (48.97%). In case of roots, C concentration showed marginal variation (46.81% to 46.25%).

4.3.2 Mean tree C sequestration

Mean tree total biomass C stock for 22-year-old *A . triphysa* are depicted in Table 10.

Table 10. Mean tree total biomass C stock for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Total (kg C tree^{-1})**
2360	75.02 (15.81)
1560	91.11 (18.65)
900	55.23 (9.31)
560	76.83 (11.88)
Average	74.55
F test	ns
P value	0.257

Values shown in parenthesis are standard error of means

Variations in mean tree C stocks were not prominent ($P>0.05$) across density regimes for *A. triphysa* at 22 year of stand age. Also, a predictable trend with C stocking was not

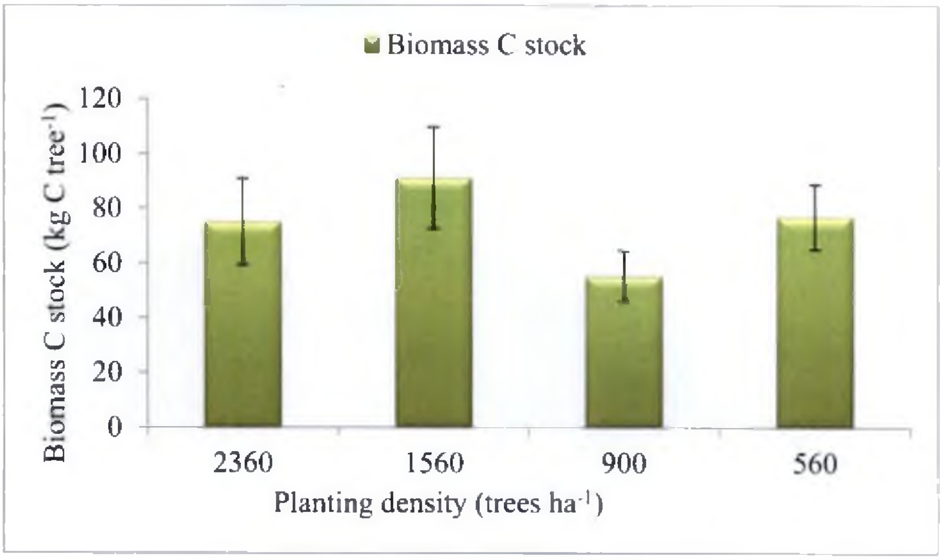

Figure 7. Mean tree total biomass C stock for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

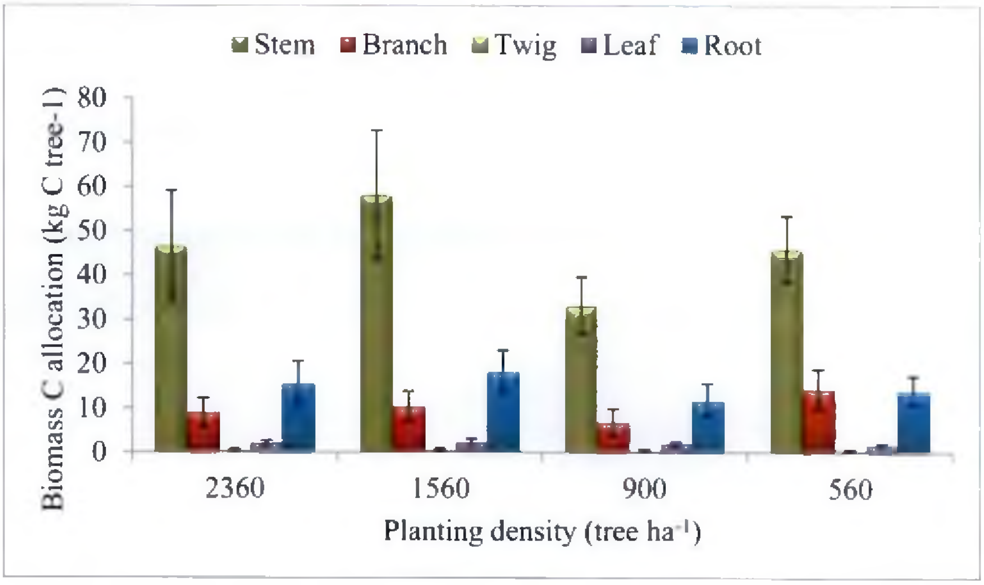

Figure 8. Mean tree total biomass C allocation for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

discernible with density. For example, the highest mean tree C content was given by medium density stand (91.11 kg C tree^{-1}; 1560 trees ha^{-1}) while the lowest value was attached to stand at 900 trees ha^{-1} (55.23 kg C tree^{-1}). Lowest stand density (560 trees ha^{-1}) however, showed fairly high C stock (76.83 kg C tree^{-1}).

4.3.3 Partitioning of mean tree C stock

Partitioning of biomass C stock in different components of *A. triphysa* for 22-year-old stand were furnished in Table 11. Among different tissue fractions, stemwood accounted for largest proportion to the total biomass C among the density regimes (63.84 % to 59.70%). Interestingly, roots account for second largest contributor to the mean tree biomass C stock among density regimes. Predictable trends were not visible across density regimes. However, stand at moderate density (1560 trees ha^{-1}) showed higher mean tree C storage for stemwood, leaf and root.

4.3.4 Stand level biomass C sequestration

Stand level biomass C stock analyzed for *A. triphysa* trees at 22 year stand age are presented in Table 12. Contrary to the inconsistency in mean tree C allocation, there existed a linear trend in C stocking and stand density. Among different density levels highest total aboveground biomass C stock was recorded by high density stand (2360 trees ha^{-1}) with a value 139.94 Mg C ha^{-1} which was closely followed by 1560 trees ha^{-1} stand (111.96 Mg C ha^{-1}). The lowest total aboveground C stocks (35.51 Mg C ha^{-1}) were shown by the lowest stand density (560 trees ha^{-1}).

Table 11. Partitioning of biomass C stock in different tissue fractions for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Mean tree C stocks (kg tree^{-1})**									
	Stem		**Branch**		**Twig**		**Leaf**		**Root**	
	Kg	**%**	**kg**	**%**	**kg**	**%**	**Kg**	**%**	**kg**	**%**
2360	46.64 (12.55)	62.17	9.05 (3.26)	12.05	0.55 (0.18)	0.62	2.04 (0.66)	2.71	15.71 (4.91)	20.93
1560	58.17 (14.62)	63.84	10.40 (3.43)	11.41	0.64 (0.21)	0.61	2.41 (0.72)	2.72	18.28 (4.84)	20.06
900	33.20 (6.51)	60.11	6.88 (2.96)	12.45	0.47 (0.26)	1.16	1.91 (0.51)	3.45	11.90 (3.61)	21.55
560	45.87 (7.51)	59.70	14.29 (4.62)	18.59	0.51 (0.22)	0.60	1.66 (0.34)	2.16	13.98 (3.31)	18.19
F-test	ns		ns		ns		ns		ns	
P – value	0.447		0.534		0.590		0.182		0.241	

ns- non significant; Values shown in parenthesis are standard error of means

Table 12. Partitioning of stand level biomass C stock and MAI for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Stand level biomass C sequestration (Mg C ha^{-1})**								**MAI (Mg C ha^{-1} yr^{-1})**
	Stem	**Branch**	**Twig**	**Leaf**	**Total above ground**	**Percentage of total aboveground C**	**Root**	**Total (aboveground + roots)**	
2360	110.08^{a} (29.61)	23.93^{a} (7.81)	1.10 (0.42)	4.83^{a} (1.57)	139.94^{a} (32.11)	79.06	37.06^{a} (9.34)	177.00^{a}	8.04
1560	91.02^{a} (22.86)	16.22^{a} (5.35)	0.86 (0.33)	3.86^{ab} (1.12)	111.96^{a} (22.45)	79.70	28.51^{ab} (4.23)	140.47^{a}	6.38
900	29.88^{b} (5.85)	6.19^{b} (2.67)	0.57 (0.23)	1.71^{ab} (0.45)	38.35^{b} (8.57)	78.16	10.71^{b} (1.54)	49.06^{b}	2.23
560	25.69^{b} (4.20)	8.61^{b} (2.59)	0.28 (0.12)	0.93^{b} (0.19)	35.51^{b} (8.21)	81.95	7.82^{b} (1.21)	43.33^{b}	1.97
F-test	*	*	ns	*	*	-	*	*	-
P-value	0.002	0.014	0.372	0.009	0.002		0.004	0.002	

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means*

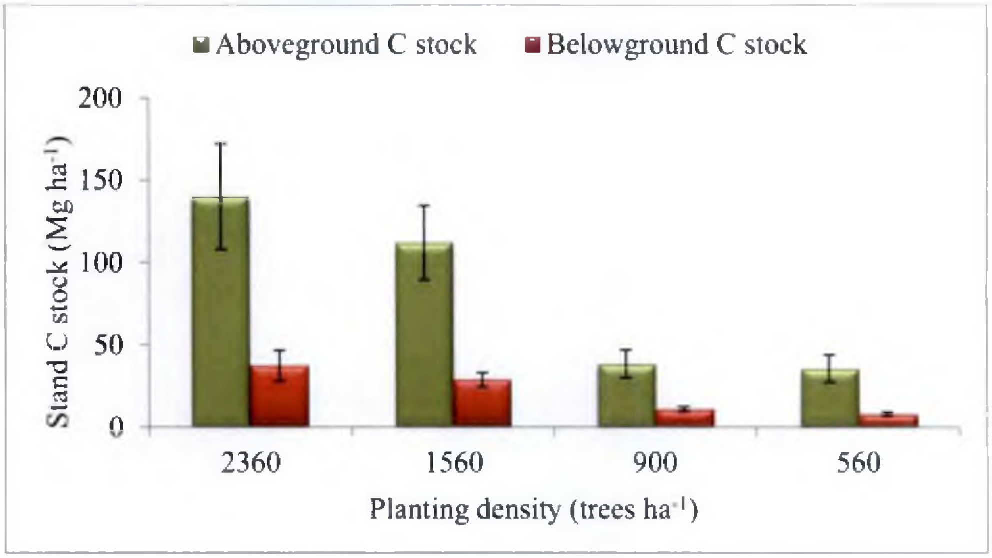

Figure 9. Mean stand biomass C sequestration for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

As observed for stand level biomass partitioning, stemwood portion constituted highest stand level C stock followed by root portion (18.31 to 21.83 %). Stand level total biomass C stock for stemwood portion varied significantly among different density regimes. The highest value was registered for stand at 2360 trees ha^{-1} (110.08 Mg C ha^{-1}) while minimum value (25.69 Mg C ha^{-1}) was registered for stand at lowest density (560 trees ha^{-1}). The changes in branchwood and twig C stock were not appreciable across density regimes. However, among the tissue fractions leaf and twigs showed the lowest C stocks. Leaf C stock ranged from 0.93 to 4.83 Mg C ha^{-1} and twig C stock ranges from 0.28 to 1.10 Mg C ha^{-1}.

Carbon stocks in the belowground biomass (coarse roots) also followed a similar trend with higher value attributed to higher stand density (37.06 Mg ha^{-1}; 2360 trees ha^{-1}). The root C content consistently declined with decreasing stand density giving a lower value of 7.82 Mg ha^{-1} at lowest stand density (560 trees ha^{-1}). The table also clearly demonstrates the changes in the C stocks for total stand biomass (total aboveground + roots). The total standing biomass carbon at stand level varied from 177.00 Mg ha^{-1} (2360 trees ha^{-1}) to 43.33 Mg ha^{-1} (560 trees ha^{-1}). The MAI in stand level C storage also followed a similar trend with a range of 8.04 Mg C ha^{-1}yr^{-1} (2360 trees ha^{-1}) to 1.97 Mg C ha^{-1} yr^{-1} (560 trees ha^{-1}). Of the total C stock, aboveground fraction in general was the highest which constituted roughly 79-81 % of total stand C stocks. Belowground biomass also contributed well to the carbon storage that ranged across density levels from 18-22 % of total standing C stock.

4.4 NUTRIENT CONCENTRATION

Table 13, 14 and 15 shows the nutrient concentration (N, P and K) in the various tissue fractions for 22-year-old *A. triphysa* stand.

4.4.1 Nitrogen

Nitrogen concentration was found to vary markedly among various stand densities for different tissue types. In general among tissue types, N concentration followed the general order of leaves > twigs > branches > root > bole.

Table 13. Nitrogen concentration in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Nitrogen (%)**				
	Stem	**Branch**	**Twig**	**Leaf**	**Root**
2360	0.75^{a} (0.003)	1.09^{a} (0.035)	1.39 (0.035)	2.84^{a} (0.038)	0.90^{c} (0.008)
1560	0.73^{b} (0.004)	0.96^{b} (0.006)	1.38 (0.033)	2.81^{a} (0.003)	0.91^{b} (0.004)
900	0.67^{d} (0.003)	0.98^{b} (0.017)	1.35 (0.028)	2.74^{b} (0.002)	0.90^{bc} (0.001)
560	0.69^{c} (0.004)	0.97^{b} (0.004)	1.34 (0.045)	2.72^{b} (0.002)	0.93^{a} (0.002)
F test	*	*	ns	*	*
P-value	0.000	0.000	0.154	0.025	.002

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means*

High density *A. triphysa* stands (2360 trees ha^{-1}) registered highest nitrogen percentage in leaves, twigs, branch and bole which was closely followed by other density regimes viz., 1560 trees ha^{-1}, 900 trees ha^{-1}, 560 trees ha^{-1}. Interestingly root N concentration was highest for stand at lowest density (560 trees ha^{-1}). Leaves registered the maximum nitrogen concentration (2.72 % to 2.74 %) while the lowest nitrogen concentration registered for bole (0.69 % to 0.75 %). Among the density levels highest leaf nitrogen concentration was recorded by stand at 2360 trees

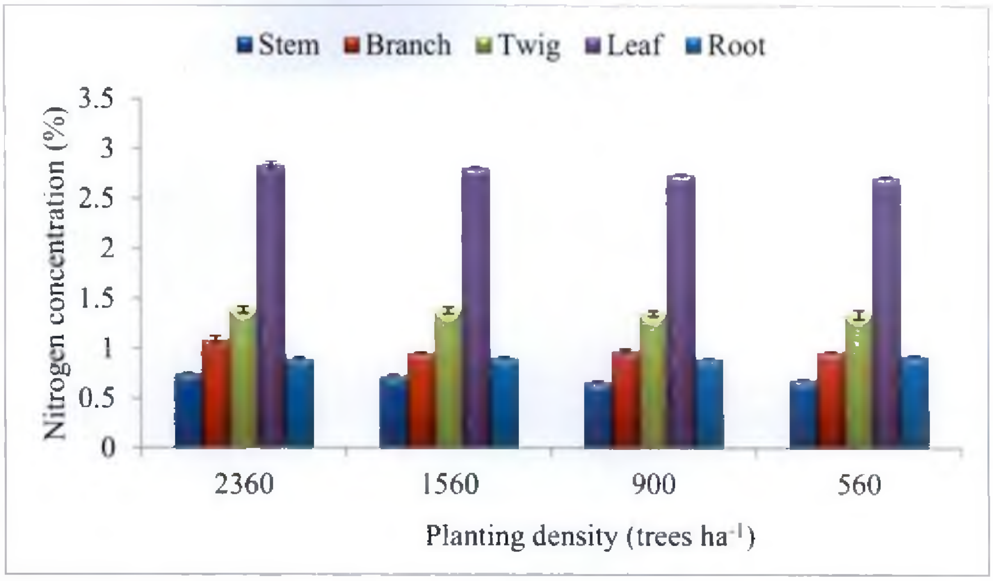

Figure 10. Nitrogen concentration in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

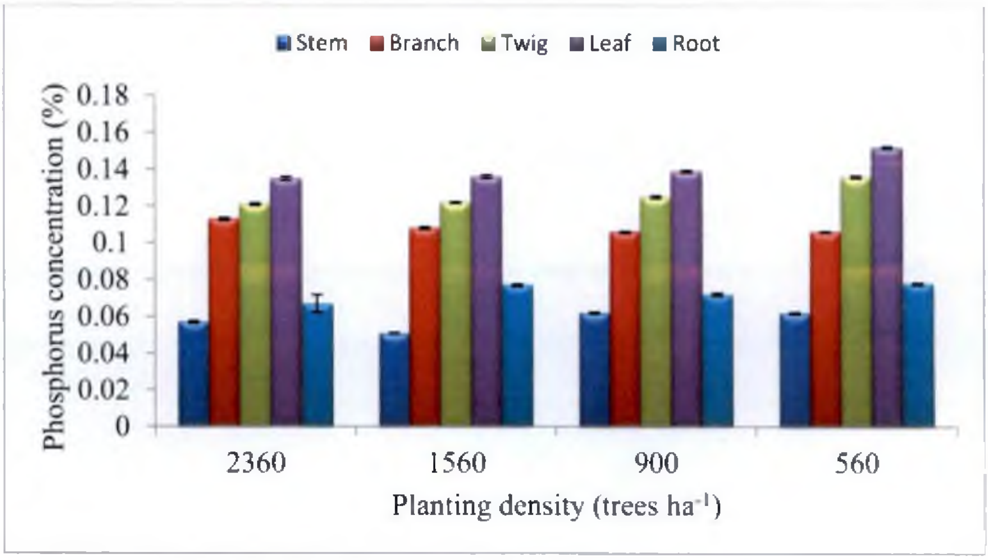

Figure 11. Phosphorus concentration in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

ha^{-1} (2.83 %) and lowest by stand at 560 trees ha^{-1} (2.72 %). The nitrogen concentration in other components also followed the same pattern. Twig nitrogen concentrations were on par across density regimes.

4.4.2 Phosphorus

Phosphorus concentration varied modestly among the *A. triphysa* of different density regimes for different tissue types. Phosphorus concentration in general decreased in order of leaf>twig>branch>bole.

Table 14. Phosphorus concentrations in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Phosphorus (%)**				
	Stem	**Branch**	**Twig**	**Leaf**	**Root**
2360	0.057^{b} (0.0007)	0.113^{a} (0.0007)	0.121^{c} (0.0006)	0.135^{c} (0.0009)	0.067^{c} (0.0004)
1560	0.051^{c} (0.0005)	0.108^{b} (0.0006)	0.122^{c} (0.0004)	0.136^{c} (0.0009)	0.077^{a} (0.0007)
900	0.062^{a} (0.0006)	0.106^{c} (0.0005)	0.125^{b} (0.0007)	0.139^{b} (0.0006)	0.072^{b} (0.0008)
560	0.062^{a} (0.0005)	0.106^{c} (0.0002)	0.136^{a} (0.0006)	0.152^{a} (0.0006)	0.078^{a} (0.0005)
F-test	*	*	*	*	*
P-value	0.000	0.001	0.001	0.001	0.002

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means*

Following nitrogen concentration trends, phosphorus also registered the maximum value for leaves (0.135 % to 0.152%) while the lowest concentration was registered for bole (0.051 % to 0.062%). Unlike N and K, tissue P concentration was highest for low density stand (560 trees ha^{-1}) and lowest recorded for high density (2360 trees ha^{-1}) except for branchwood. In leaves highest phosphorus concentration was recorded by 560 trees ha^{-1} density (0.152%) and lowest recorded by 2360 trees ha^{-1} density level (0.135 %). The phosphorus content in other components also follows the same order.

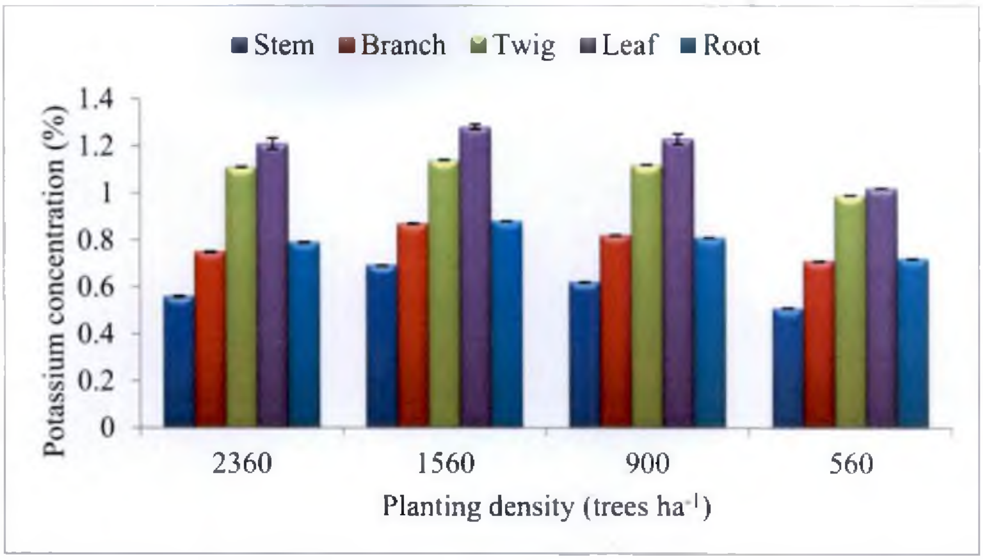

Figure 12. Potassium concentration in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

4.4.3 Potassium

The potassium concentration in different biomass fraction showed marked variability (Table 15). As in the case of N and P, concentration of K in the aboveground portion followed the order leaf> twig> branch> bole.

Table 15. Potassium concentration in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	Potassium (%)				
	Stem	**Branch**	**Twig**	**Leaf**	**Root**
2360	0.55^{c} (0.003)	0.78^{c} (0.002)	1.11^{b} (0.001)	1.21^{b} (0.023)	0.79^{c} (0.002)
1560	0.59^{a} (0.002)	0.85^{a} (0.001)	1.14^{a} (0.001)	1.28^{a} (0.012)	0.88^{a} (0.001)
900	0.57^{b} (0.001)	0.82^{b} (0.001)	1.12^{b} (0.001)	1.23^{ab} (0.022)	0.81^{b} (0.001)
560	0.51^{d} (0.001)	0.72^{d} (0.001)	0.99^{d} (0.001)	1.02^{c} (0.009)	0.72^{d} (0.001)
F-test	*	*	*	*	*
P-value	0.000	0.001	0.001	0.002	0.002

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means*

The potassium concentration of tree components also varied considerably among different density levels. The medium density stand (1560 trees ha^{-1}) showed higher value and the lowest was shown by the low density stand (560 trees ha^{-1}). As stated above, K concentration was higher for leaves that ranged from 1.02 % (560 trees ha^{-1}) to 1.28 % (1560 trees ha^{-1}). Lowest K concentrations were registered for stemwood that ranged from 0.51 % (560 trees ha^{-1}) to 0.59 % (1560 trees ha^{-1}). The twig K concentration ranges from 0.99 % (560 trees ha^{-1}) to 1.14 % (1560 trees ha^{-1}) and the branch K concentration ranged from 0.71 % (560 trees ha^{-1}) to 0.87 % (1560 trees ha^{-1}). The root K concentration was highest for 1560 trees ha^{-1} stand (0.88 %) while 560 trees ha^{-1} stand recorded the lowest (0.72%).

4.5. NUTRIENT ACCUMULATION

Accumulations of N, P and K in various tree components of 22- year-old *A. triphysa* stand are depicted in table 16, 17 and 18. The relative proportion of nutrients tied up in various tissue fractions, showed significant variation among density regimes.

Table 16. Nitrogen accumulations in different tissue components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Nitrogen accumulation (kg ha^{-1})**					
	Stem	**Branch**	**Twig**	**Leaf**	**Root**	**Total**
2360	1849.63^{a} (500.79)	514.66^{a} (187.75)	36.65^{a} (15.11)	282.51^{a} (92.14)	718.37^{a} (223.67)	3401.82
1560	1492.40^{a} (381.31)	340.27^{ab} (112.29)	26.38^{ab} (10.01)	221.37^{ab} (64.31)	556.96^{a} (149.33)	2637.38
900	447.43^{b} (87.20)	170.63^{b} (57.07)	9.19^{b} (2.71)	96.90^{ab} (25.75)	208.89^{b} (63.13)	933.04
560	394.97^{b} (63.02)	132.42^{b} (55.38)	3.68^{b} (0.68)	57.43^{b} (11.05)	155.18^{b} (36.68)	743.68
F-test	*	*	*	*	*	-
P-value	0.001	0.002	0.002	0.009	0.004	

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means*

Nitrogen accumulation recorded highest value for the denser stand (2360 tree ha^{-1}) for all tissue types while lowest value recorded in the low density stand (560 tree ha^{-1}). The stemwood recorded the highest nitrogen accumulation followed by roots among all the density regimes. The accumulation of N in the stemwood was maximum for higher density stand with a value to the tune of 1849.63 kg ha^{-1} (2360 trees ha^{-1}) while minimum value was recorded for the lower density stand of 560 trees ha^{-1} (394.97 kg ha^{-1}). Invariably, root constituted the second highest in N accumulation, the highest value being recorded by 2360 trees ha^{-1} density (718.37 kg ha^{-1}) which was closely followed by density levels 1560 trees ha^{-1} (556.96 kg ha^{-1}) and 900 trees ha^{-1} (447.43 kg ha^{-1}). The lowest value was recorded for 560 trees ha^{-1} stand (394.97 kg ha^{-1}).

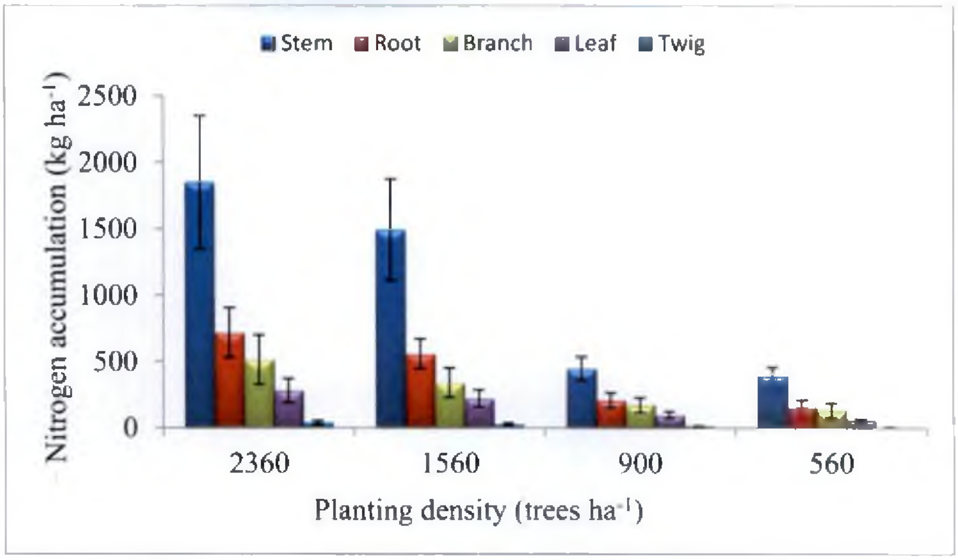

Figure 13. Nitrogen accumulation in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

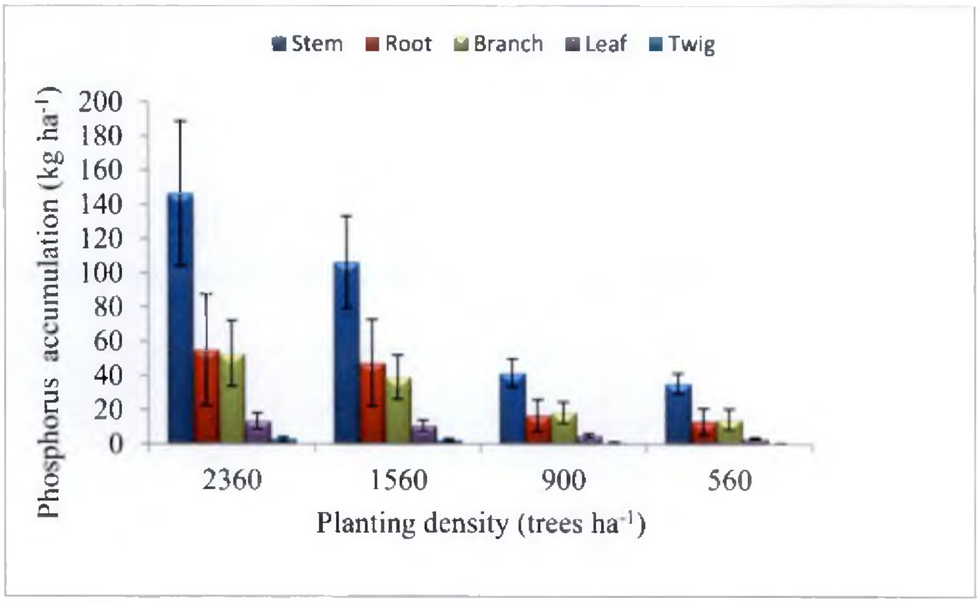

Figure 14. Phosphorus accumulation in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Branchwood N accumulation didn't vary significantly among the density regimes and the value ranged from 514.66 kg ha^{-1} (2360 trees ha^{-1}) to 132.42 kg ha^{-1} (560 trees ha^{-1}). In other tissue types also, the higher density stand (2360 trees ha^{-1}) showed the maximum value and the minimum value recorded by the lower density stand (560 trees ha^{-1}). The twigs constituted the lowest proportion in N accumulation and the value ranged from 3.68 kg ha^{-1} (560 trees ha^{-1}) to 36.65 kg ha^{-1}(2630 trees ha^{-1}). The N accumulation in the leaf varied with highest value recorded in the 2360 trees ha^{-1} stand (282.51 kg ha^{-1}) while lowest value was recorded in 560 trees ha^{-1} stand (57.43 kg ha^{-1})

4.6.2 Phosphorus accumulation

Phosphorus accumulation of different tissue types among variable density regimes studied are shown in Table 17. Stemwood accounted for maximum share of P in all the density regimes under study (50.24 to 54.11 %).

Table 17. Phosphorus accumulation in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Phosphorus accumulation (kg ha^{-1})**					
	Stem	**Branch**	**Twig**	**Leaf**	**Root**	**Total**
2360	146.43^{a} (42.25)	52.81 (19.19)	3.02^{a} (1.17)	13.56^{a} (4.53)	54.82^{a} (42.54)	270.64
1560	106.18^{ab} (27.11)	38.99 (12.90)	2.39^{ab} (0.92)	10.83^{a} (3.20)	47.39^{a} (31.51)	205.78
900	41.50^{b} (8.13)	18.48 (6.25)	0.85^{ab} (0.25)	4.90^{b} (1.29)	16.72^{b} (12.43)	82.45
560	35.48^{b} (5.76)	14.48 (5.99)	0.37^{b} (0.07)	3.24^{b} (0.63)	13.12^{b} (7.68)	66.69
F-test	*	ns	*	*	*	
P-value	0.004	0.079	0.001	0.041	0.031	

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly ; Values shown in parenthesis are standard error of means*

Similar to N, P accumulation was also higher in the high density stand (trees ha^{-1}) and lowest in the lower density stand (560 trees ha^{-1}). Among the different tissue types, stemwood constituted the highest portion which ranged from 35.48 kg ha^{-1} (560 trees ha^{-1})

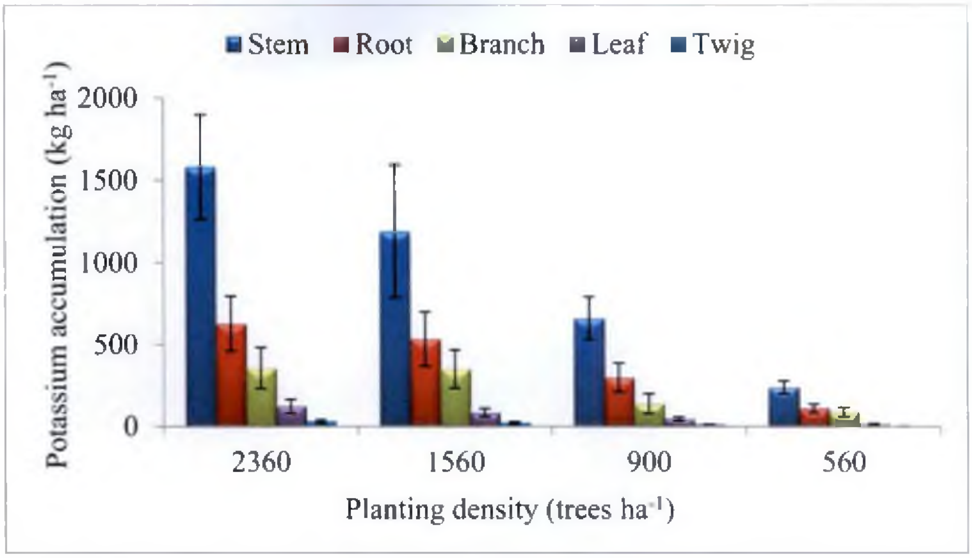

Figure 15. Potassium accumulation in different biomass components for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

to 146.43 kg ha^{-1} (2360 trees ha^{-1}). Twigs contributed the lowest portion for phosphorus accumulation and the values ranged from 0.37 kg ha^{-1} (560 trees ha^{-1}) to 3.02 kg ha^{-1} (2360 trees ha^{-1}). Root constituted the second highest in P accumulation the highest value recorded by 2360 trees ha^{-1} stand (54.28 kg ha^{-1}). Low density stand (560 trees ha^{-1}) registered minimum value of 13.12 kg ha^{-1}.

4.6.3 Potassium accumulation

The potassium accumulation of different tissue components of 22-year-old *A. triphysa* stand is given in Table 18.

Table 18. Potassium accumulation in the biomass components of 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Stand density (trees ha^{-1})	**Potassium accumulation (kg ha^{-1})**					
	Stem	**Branch**	**Twig**	**Leaf**	**Root**	**Total**
2360	1579.90^{a} (318.79)	356.03 (126.76)	27.64^{a} (10.72)	123.36^{a} (41.53)	627.01^{a} (168.63)	2713.97
1560	1188.32^{ab} (402.64)	351.19 (117.42)	19.8^{ab} (7.61)	83.77^{ab} (24.35)	533.77^{a} (166.46)	2176.85
900	661.20^{bc} (129.41)	137.81 (59.25)	7.70^{b} (2.29)	43.79^{b} (11.59)	297.16^{ab} (89.78)	1147.66
560	237.73^{c} (38.83)	86.59 (28.14)	1.45^{b} (0.27)	13.12^{b} (2.54)	108.78^{b} (118.09)	447.67
F test	*	ns	*	*	*	-
P-value	0.004	0.081	0.031	0.015	0.001	

** mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly; Values shown in parenthesis are standard error of means*

Potassium accumulation also followed the same order as that of N and P with stemwood and root fractions accounting major share for all the density regimes under study. The maximum stemwood K accumulation shown in denser stand 2360 trees ha^{-1} (1579.90 kg ha^{-1}) followed by 1560 trees ha^{-1} stand (1188.32 kg ha^{-1}) and 900 trees ha^{-1} stand (661.20 kg ha^{-1}) while the lowest value recorded in 560 trees ha^{-1} stand (237.73 kg ha^{-1}). The root portion constituted the second highest in K accumulation with 2360 trees ha^{-1} density stand recording maximum that ranged from 627.01 kg ha to 108.18 kg ha^{-1} (560 trees ha^{-1}).

The branch K accumulation ranged from 356.03 kg ha^{-1} (2360 trees ha^{-1}) to 86.59 kg ha^{-1} (560 trees ha^{-1}). The leaves K accumulation was highest for 2360 trees ha^{-1} stand (123.36 kg ha^{-1}) then by 1560 trees ha^{-1} stand (83.77 kg ha^{-1}) and 900 trees ha^{-1} stand (43.79 kg ha^{-1}). The twigs contributed the lowest for K accumulation among different density regimes (Table 18).

4.7 ALLOMETRIC EQUATIONS

Allometric relationships were attempted in the present study linking aboveground biomass, bole biomass, total aboveground carbon sequestration, total volume and bole volume with DBH and / or total height/bole height of the trees which gave reasonably good predictions (Table 19). Among the models tried, simple linear and quadratic equations showed better fit with reasonably high R^2 values.

Most of the cases equations with dbh alone as predictor variable gave good predictions. For total aboveground biomass ($B_1=0.765D^2-15.46D+118.05$) and bole biomass $B_2=0.518D^2-9.26D+72.41$) quadratic equation with single variable (dbh alone as a predictor variable) gave good R^2 value (0.91 and 0.85 respectively; Table 19). In case of carbon sequestration also the quadratic equation with single variable (dbh) has emerged as better model; $CS=0.345D^2-6.93D+52.607$, with high R^2 value (0.91) (Table 19). In case of aboveground biomass and aboveground carbon sequestration the prediction equation recorded the same R^2 value of 0.91.

Similar trend occurred in case of volume prediction also. Quadratic equation with single variable alone (dbh as a predictor variable) gave most fitted equation in case of total volume ($V_1=0.001D^2-0.015D+0.109$) and bole volume ($V_2=0.001D^2-0.016D+0.116$) with high R^2 value of 0.85 and 0.83 respectively (Table 18).

Table 19. Allometric prediction equations developed for 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Dependent Variable	**Independent variable**	**Equation**	**R^2 Value**	**Standard Error of estimate**	**F value**
Total aboveground Biomass	DBH Height	B_1=17.277D-182.61 B_1=15.26+5.01H_1-210.29 B_1=0.765D^2-15.46D+118.05	0.81 0.82 0.91	60.58 59.57 43.38	350.10 182.87 378.87
Bole biomass	DBH Bole height	B_2=12.92D-131.302 B_2=10.84D+7.64H_2-156.38 B_2=0.518D^2-9.26D+72.41	0.78 0.82 0.85	50.22 46.51 41.38	284.83 173.02 228.68
Total aboveground carbon sequestration	DBH Height	CS=7.843D-83.091 CS=6.94D+2.247H-95.49 CS=0.345D^2-6.93D+52.607	0.82 0.82 0.91	27.18 26.73 19.36	358.22 187.04 391.53
Total Volume	DBH Height	V_1=0.023D-0.242 V_1=0.019D+0.011H_1-0.301 V_1=0.001D^2-0.015D+0.109	0.79 0.81 0.85	0.088 0.084 0.074	286.40 160.85 224.06
Bole Volume	DBH Bole height	V_2=0.021D-0.220 V_2=0.016D+0.017H_2-0.275 V_2=0.001D^2-0.016D+0.116	0.75 0.81 0.83	0.088 0.088 0.076	238.72 135.25 180.81

B_1=Aboveground biomass, B_2=Bole biomass, CS=Carbon sequestration, V_1=Total volume, V_2=Bole volume, H_1=Total height, H_2= Bole height

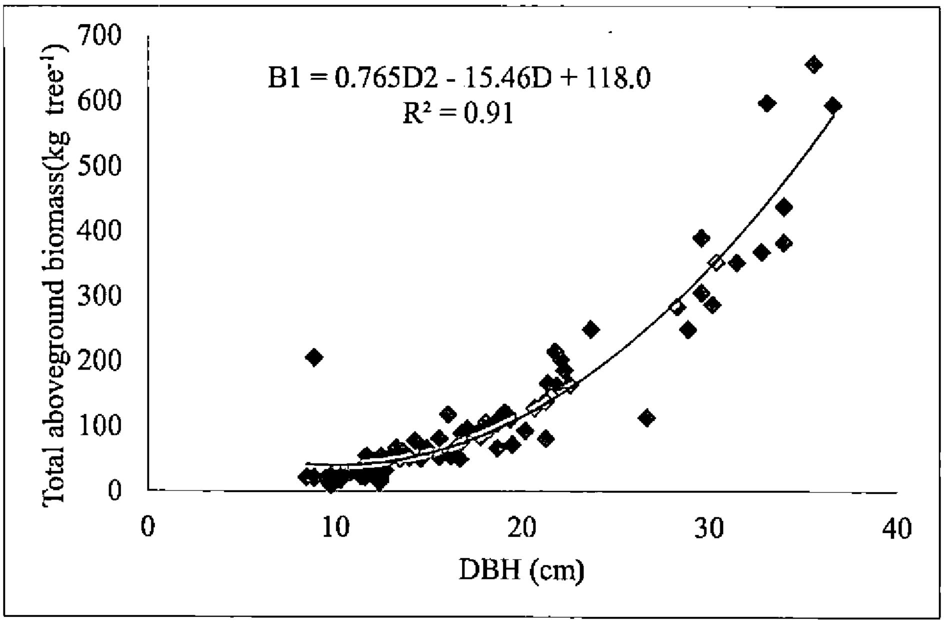

Figure 16. Prediction model for total aboveground biomass of *A. triphysa* of 22-year-old stand managed at variable densities at Aramkallu, Thrissur, Kerala

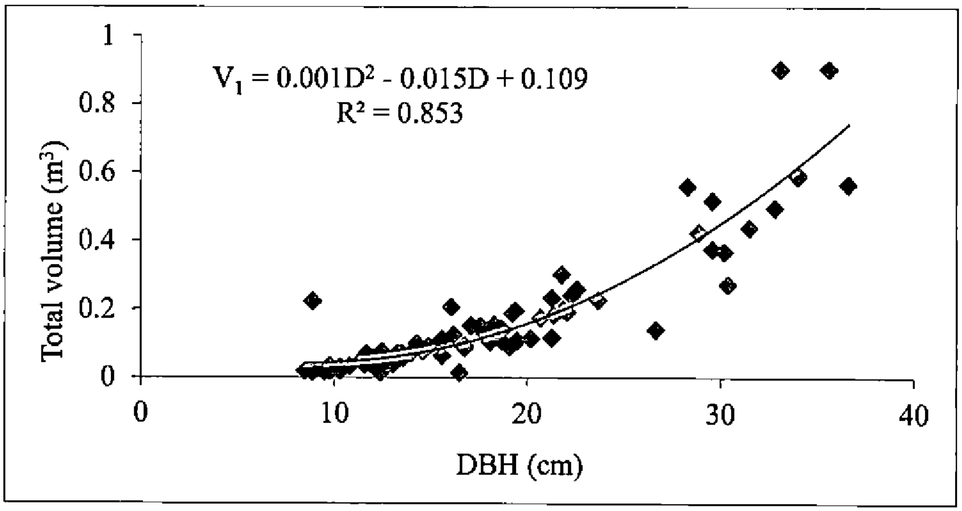

Figure 17. Prediction model for total volume of *A. triphysa* of 22-year-old stand managed at variable densities at Aramkallu, Thrissur, Kerala

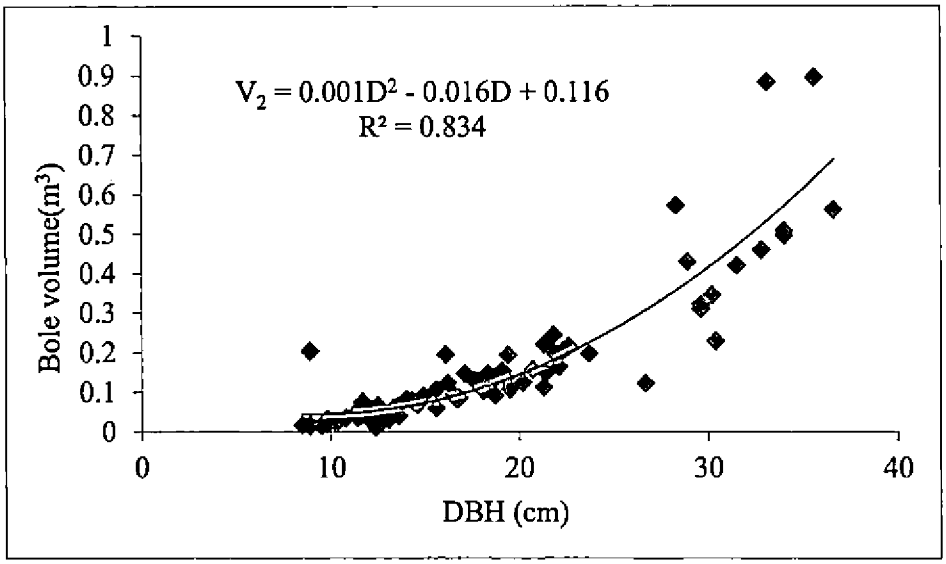

Figure 18. Prediction model for bole volume of *A. triphysa* of 22-year-old stand managed at variable densities at Aramkallu, Thrissur, Kerala

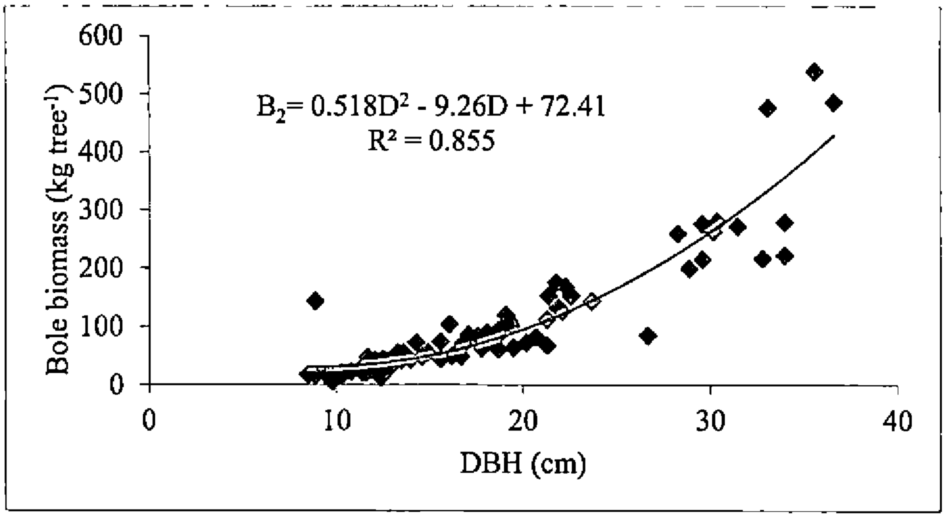

Figure 19. Prediction model for bole biomass of *A. triphysa* of 22-year-old stand managed at variable densities at Aramkallu, Thrissur, Kerala

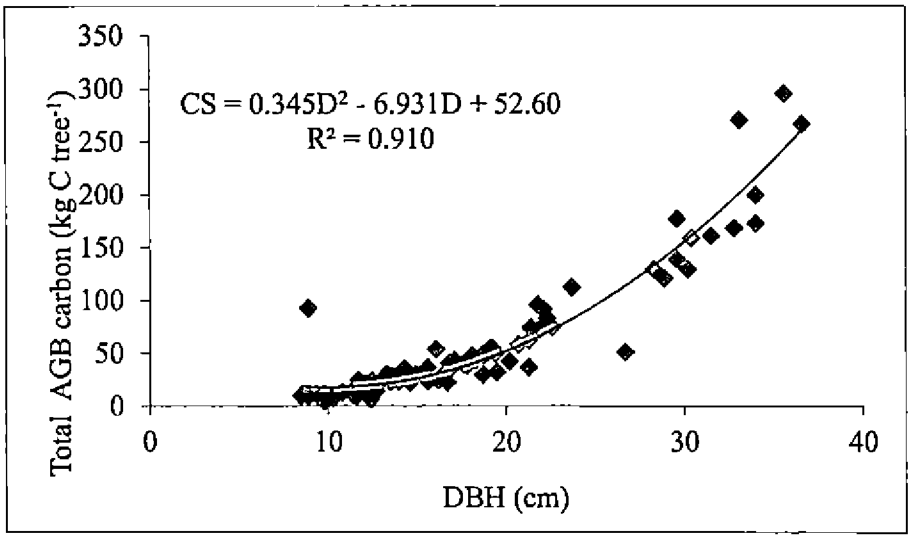

Figure 20. Prediction model total aboveground carbon sequestration of *A. triphysa* of 22-year -old stand managed at variable densities at Aramkallu, Thrissur, Kerala

4.8 SOIL CARBON SEQUESTRATION

Total soil carbon stock up to 1m soil depth for *A. triphysa* trees of 22-year stand age at Aramkallu are presented in Table 21. The *A. triphysa* stand registered significantly higher soil carbon stock compared to the treeless control plot. The soil organic carbon was significantly different across different density regimes.

4.8.1 Soil organic carbon concentration

Depth-wise representation of mean soil organic carbon concentration is depicted in Table 20. The mean SOC concentration ranged from 0.61 % (treeless control) to 0.97 % (1560 trees ha^{-1}). There has been a consistent reduction in mean SOC concentration with increasing soil depth. For instance, the mean SOC concentration declined from 0.96% (0-20 cm) to 0.26% (80-100 cm) in 2360 trees ha^{-1} stand. Similar is the case with almost all the density regimes. Invariably the SOC concentration was relatively lower in treeless plot compared with *A. triphysa* at different density regimes.

4.8.2 Bulk Density and organic carbon

Depth-wise distribution of mean soil organic carbon content and bulk density of 22-year- old *A. triphysa* with adjacent treeless plot as control is furnished in Table 21 and 22. The mean soil carbon content decreased with soil depth for all density regimes and in general tree stand recorded higher carbon content at all depths compared to treeless control.

Table 20. Depth wise distribution of Mean Soil carbon (SOC) concentration in 22-year old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Soil depths (cm)	Mean soil organic carbon (SOC) concentration (%)					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees**	**Control (Treeless)**	**Mean**
0-20	0.96	0.97	0.90	0.93	0.61	0.94^{a}
20-40	0.76	0.77	0.71	0.76	0.41	0.75^{b}
40-60	0.56	0.58	0.53	0.55	0.22	0.55^{c}
60-80	0.37	0.37	0.31	0.33	0.17	0.34^{d}
80-100	0.26	0.27	0.23	0.23	0.13	0.24^{e}
Mean	0.58^{a}	0.59^{a}	0.50^{b}	0.56^{a}	0.31^{c}	

Table 21. Depth wise distribution of Mean soil carbon (SOC) content in 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala

Soil Depths (cm)	Mean soil organic carbon (SOC) content (Mg ha^{-1})					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	21.39	21.40	20.74	21.23	21.19^{a}	14.24
20-40	17.37	17.47	16.55	17.26	17.16^{b}	9.86
40-60	13.22	13.26	12.63	13.14	13.06^{c}	5.37
60-80	8.73	8.78	7.74	8.43	8.42^{d}	4.25
80-100	6.27	6.31	6.13	6.23	6.23^{e}	3.17
Total	66.98	67.22	63.79	66.29		36.89
Mean	13.39^{b}	13.44^{a}	12.76^{d}	13.25^{c}		7.38^{e}

Table 22. Depth wise distributions of Mean Bulk density in 22-year-old *A. triphysa* stand managed at variable densities at Aramkallu, Thrissur, Kerala.

Soil Depths (cm)	**Mean soil bulk density (g cm^{-3})**					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	1.12	1.13	1.14	1.12	1.12^{e}	1.15
20-40	1.13	1.14	1.16	1.13	1.14^{d}	1.19
40-60	1.17	1.17	1.18	1.17	1.17^{c}	1.21
60-80	1.22	1.21	1.24	1.21	1.22^{b}	1.30
80-100	1.25	1.26	1.28	1.23	125^{a}	1.32
Mean	1.17	1.18	1.20^{b}	1.17^{c}		1.23^{a}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

The soil samples from the treeless control pit registered maximum bulk density (1.15 g cm^{-3} to 1.32 g cm^{-3}) for all soil depths compared with *A. triphysa* plots. In general, bulk density showed a marginal increase with increasing soil depth. The present study also registered such a trend with bulk density increasing with increasing soil depth. For example, in 2360 tree ha^{-1} stand the bulk density value registered in the surface layer was 1.12 g cm^{-3} and it increased and reached a value of 1.25 at the deeper layer.

In all five soil depths, total soil organic carbon were highest for 1560 trees ha^{-1} stand and 900 trees ha^{-1} stand. In general, the SOC content was highest in the 0-20 cm soil depth for all the density regimes (Table 23), while individually varied from 14.24 Mg ha^{-1} (control) to 21.40 Mg ha^{-1} (1560 trees ha^{-1}). There has been a consistent decline in SOC with increasing soil depth.

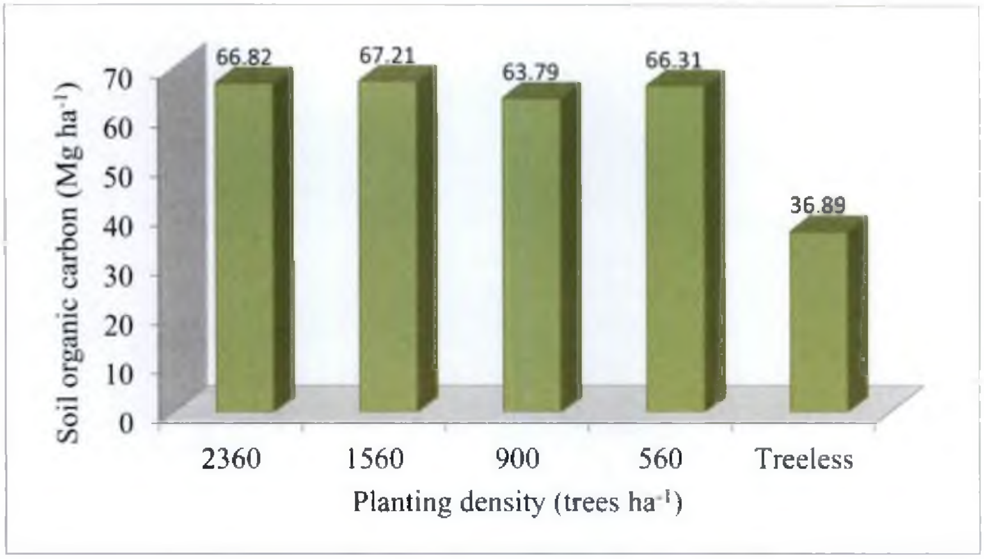

Figure 21. Total soil organic carbon (SOC) content in whole soil upto 1 m depth in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala.

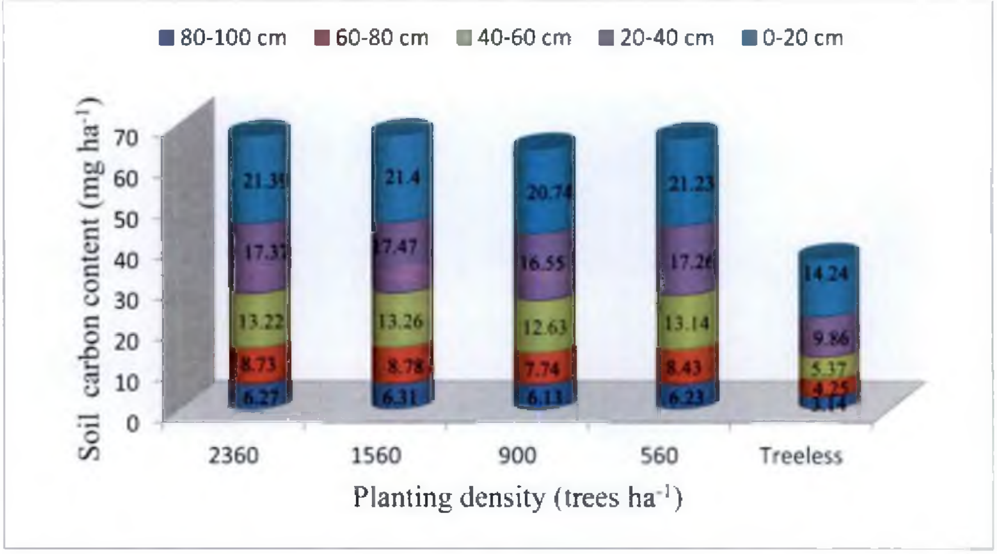

Figure 22. Soil organic carbon (SOC) in different depth classes in 22-year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

For instance, the SOC declined from 21.39 Mg ha^{-1} at 0-20 cm to 6.27 Mg ha^{-1} at 80-100 cm soil depth for stand at 2360 trees ha^{-1}. Similar is the case with almost all the *A. triphysa* density regimes. Invariably the treeless control showed the lowest SOC for all the soil depths. Interestingly, the proportion of SOC at deeper soil (80-100 cm) is higher in the *A. triphysa* plots compared to treeless control. For example, the SOC at 80-100 cm soil depth for stand density 2360 tree ha^{-1} is approximately 30% of the SOC at top soil (0-20 cm) while the corresponding SOC value for treeless control is less than 22% (Table 23).

Table 23. Total soil organic carbon (SOC) content in the whole soil up to 1m depth in 22-year- old *A. triphysa* stand at variable stand densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Total (Mg ha^{-1})**
2360	66.82^{b}
1560	67.21^{a}
900	63.79^{d}
560	66.31^{c}
Average	66.03
Control (treeless)	36.89^{e}
F-test	*
P value	0.000

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

Among the different density regimes, the medium stand (1560 trees ha^{-1}) registered maximum C stocks of 67.21 Mg ha^{-1}, followed by 2360 trees ha^{-1} stand (66.82 Mg ha^{-1}) and 560 trees ha^{-1} stand (66.31 Mg ha^{-1}). The lowest soil organic carbon value was registered in treeless control plot (36.89 Mg ha^{-1}).

4.9 SOIL NUTRIENT

4.9.1 Soil Nitrogen

Soil Nitrogen concentrations at five depth intervals in *A. triphysa* stand with adjacent treeless plot as control has been depicted in Table 24 and 25. The 1560 and 560 trees ha^{-1} stands registered higher soil nitrogen concentration with a value 0.149% to 0.147% respectively. There was a consistent reduction in the soil nitrogen concentration with increasing soil depth. For eg: the 2360 trees ha^{-1} stand registered 0.139% N concentration in upper layer (0-20 cm) and the value gradually reduced to 0.046% in the deeper layer (80-100 cm). Similar trend were followed in all other density regimes. Invariably, the treeless control plots recorded the lowest soil nitrogen in all the depth classes among the density regimes.

Table 24. Depth wise distributions of mean soil nitrogen concentration in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala.

Soil Depths (cm)	**Soil Nitrogen (%)**					
	2360 trees ha^{-1}	1560 trees ha^{-1}	900 trees ha^{-1}	560 trees ha^{-1}	Mean	Control (Treeless)
0-20	0.139	0.149	0.135	0.147	0.142^{a}	0.078
20-40	0.085	0.089	0.083	0.087	0.086^{b}	0.069
40-60	0.062	0.064	0.062	0.064	0.063^{c}	0.046
60-80	0.055	0.057	0.052	0.056	0.055^{d}	0.033
80-100	0.046	0.048	0.045	0.048	0.046^{e}	0.031
Mean	0.077^{b}	0.081^{a}	0.075^{c}	0.080^{a}		0.051^{d}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

Table 25. Depth wise distributions of mean soil nitrogen content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala.

Soil Depths (cm)	**Soil Nitrogen (kg ha^{-1})**					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	312.16	340.50	305.54	335.49	323.42^{a}	181.20
20-40	196.45	204.54	192.89	200.22	198.52^{b}	165.93
40-60	146.25	151.05	141.56	156.44	148.82^{c}	110.51
60-80	133.76	142.24	128.14	143.56	136.92^{d}	86.66
80-100	115.82	120.74	114.10	115.93	116.64^{e}	75.17
Mean	180.57^{b}	189.92^{a}	178.66^{b}	187.52^{a}		123.89^{c}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly.*

4.9.2 Soil Phosphorus

Soil phosphorus concentrations in *A. triphysa* stand at five depth intervals are furnished in Table 26 and 27. Phosphorus concentration in soil recorded maximum in the wider stand (560 trees ha^{-1}).

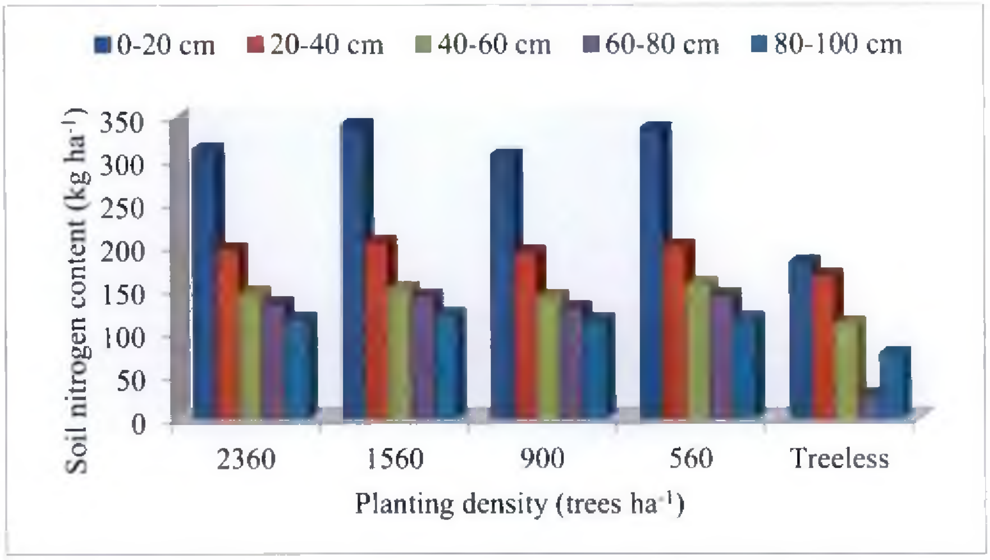

Figure 23. Depth wise distributions of soil nitrogen content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

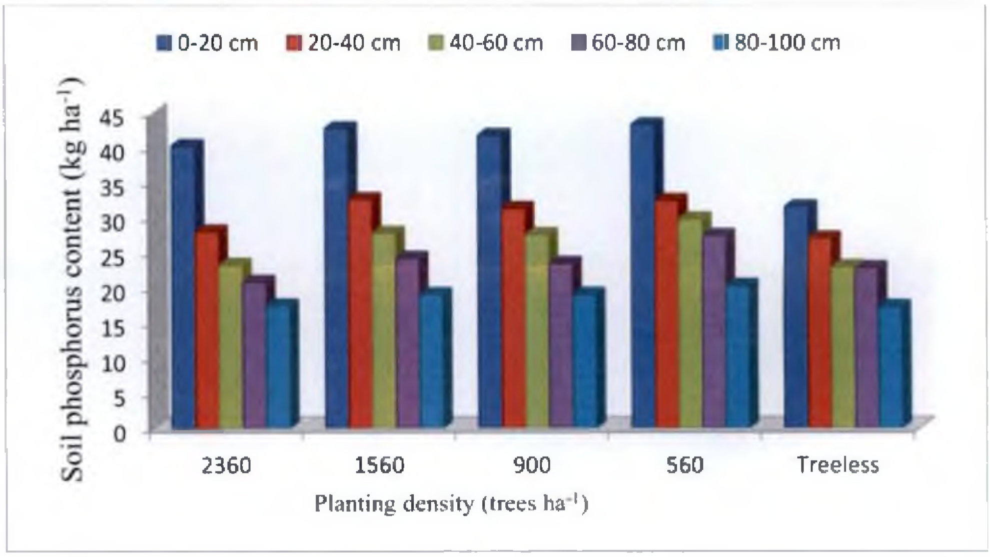

Figure 24. Depth wise distributions of soil phosphorus content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Table 26. Depth wise distribution of mean soil phosphorus concentration in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Soil Depths (cm)	**Soil Phosphorus (%)**					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	0.0017	0.0018	0.0018	0.0019	0.0018^{a}	0.0013
20-40	0.0012	0.0013	0.0013	0.0014	0.0011^{b}	0.0011
40-60	0.0009	0.0011	0.0011	0.0012	0.0010^{c}	0.0009
60-80	0.0008	0.0009	0.0009	0.0011	0.0008^{d}	0.0008
80-100	0.0006	0.0007	0.0007	0.0008	0.0006^{e}	0.0006
Mean	0.0011^{c}	0.0012^{b}	0.0012^{b}	0.0013^{a}		0.0009^{d}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

P content was registered to be higher in the lower density stand (560 trees ha^{-1}) stand with value ranged from 43.13 kg ha^{-1} to 20.26 43.13 kg ha^{-1}. While lowest value recorded for the higher density stand (2360 trees ha^{-1}) ranged from 40.12 kg ha^{-1} to 17.44 kg ha^{-1}. Phosphorus concentration was also higher in the surface layer (0-20 cm) and gradually reduced with increasing soil depth. For instance, in 2360 trees ha^{-1} stand the upper layer (0-20 cm) registered a value of 40.12 kg ha^{-1} to 17.44 kg ha^{-1} in the deeper layer (80-100 cm). This trend was followed in all other density regimes under study. In case of Phosphorus also, the treeless control registered the minimum value compared with the all density regimes for all soil depths.

Table 27. Depth wise distribution of mean soil phosphorus content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala.

Soil Depths (cm)	**Soil Phosphorus (kg ha^{-1})**					
	2360 trees ha^{-1}	1560 trees ha^{-1}	900 trees ha^{-1}	560 trees ha^{-1}	Mean	Control (Treeless)
0-	40.12	42.59	41.63	43.13	41.86^{a}	31.40
20-40	27.92	32.51	31.20	32.34	30.99^{b}	26.94
40-60	23.13	27.64	27.44	29.66	26.96^{c}	22.89
60-80	20.77	24.10	23.37	27.32	23.89^{d}	22.78
80-100	17.44	18.99	19.02	20.26	18.92^{e}	17.30
Mean	25.88^{d}	28.87^{b}	28.54^{c}	30.54^{a}		24.26^{e}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

4.9.3 Soil Potassium

Soil K concentration in *A. triphysa* stand and associated tree less control plot at five depth classes are shown in Table 28 and 29.

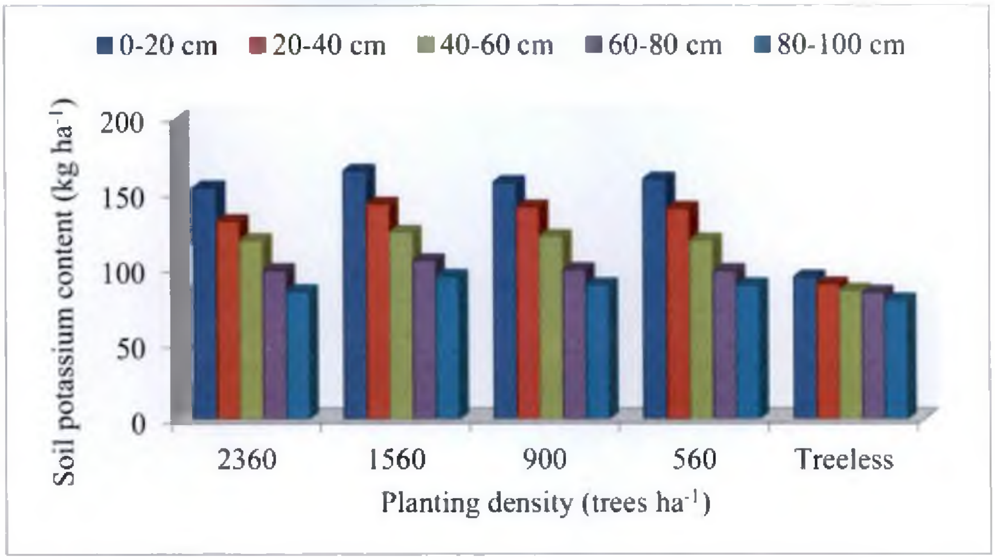

Figure 25. Depth wise distributions of soil potassium content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Table 28. Depth wise distributions of mean soil potassium concentration in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Soil Depths (cm)	**Soil Potassium (%)**					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	0.0068	0.0072	0.0068	0.0067	0.0068^{a}	0.0044
20-40	0.0057	0.0061	0.0060	0.0061	0.0059^{b}	0.0040
40-60	0.0050	0.0052	0.0051	0.0050	0.0050^{c}	0.0037
60-80	0.0040	0.0042	0.0039	0.0040	0.0040^{d}	0.0034
80-100	0.0033	0.0037	0.0034	0.0034	0.0034^{e}	0.0030
Average	0.0050^{d}	0.0053^{a}	0.0051^{c}	0.0052^{b}		0.0033^{e}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

Table 29. Depth wise distributions of mean soil potassium content in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Soil Depths (cm)	**Soil Potassium (kg ha^{-1})**					
	2360 trees ha^{-1}	**1560 trees ha^{-1}**	**900 trees ha^{-1}**	**560 trees ha^{-1}**	**Mean**	**Control (Treeless)**
0-20	153.35	164.25	156.65	158.80	158.26^{a}	93.78
20-40	131.04	142.37	140.38	139.47	138.31^{b}	89.23
40-60	118.37	123.65	120.77	118.25	120.26^{c}	85.00
60-80	98.44	104.81	98.81	98.03	100.02^{d}	83.86
80-100	84.46	94.34	88.65	88.58	89.01^{e}	78.62
Mean	117.13^{c}	124.29^{a}	121.00^{b}	120.68^{b}	-	81.70^{d}

**mean value significant at 0.05 level; ns-non-significant; The values with same superscript do not differ significantly*

Similar to N, potassium content in *A. triphysa* stand also follows same trend with highest value recorded in 1560 trees ha^{-1} stand and lowest value registered in 2360 trees ha^{-1} stand. Potassium content in 1560 trees ha^{-1} stand were 164.25 kg ha^{-1} (0-20cm) and in 2360 trees ha^{-1} were 153.35 kg ha^{-1} (0-20 cm). Likewise N and P, K concentration also reduced gradually with increasing depth of the soil layer. For instance, the potassium content in the surface layer (0-20 cm) of 2360 trees ha^{-1} were 153.35 kg ha^{-1} and it decreased to 84.46 kg ha^{-1} in the deeper layer (80-100 cm) layer. Similar trend observed in all other density regimes. Invariably the treeless control plot registered lowest potassium concentration in all depths compared with all the density regimes.

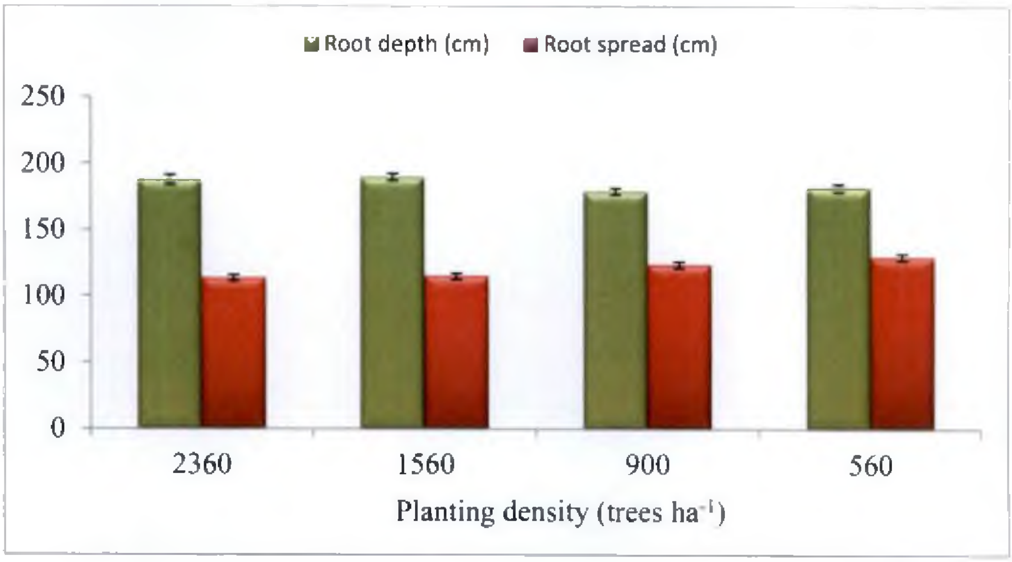

Figure 26. Average depth and lateral spread of roots in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

4.10 ROOT MORPHOMETRIC OBSERVATION

Root morphometric observation of 22-year-old *A. triphysa* trees managed at variable stand densities are furnished in Table 30. No marginal variation exists among various density regimes for root depth and spread.

Table 30. Average depth and lateral spread of roots in 22- year-old *A. triphysa* stand at variable densities at Aramkallu, Thrissur, Kerala

Stand density (trees ha^{-1})	**Root depth (cm)**	**Root spread (cm)**
2360	187.82 (3.82)	113.50 (2.45)
1560	189.67 (2.37)	114.83 (2.37)
900	178.83 (2.52)	123.67 (2.52)
560	181.83 (3.11)	129.50 (3.11)
Average	184.53	120.37
F-test	ns	ns
P-value	0.295	0.069

Despite poor statistical variation, high density stands (2360 and 1560 trees ha^{-1}) registered a higher value for root depth to the tune of 187.82 cm and 189.67 cm respectively. The root spread also didn't show any variation with various density regimes. However, the value ranged from 113.50 cm (2360 trees ha^{-1}) to 129.50 cm (560 trees ha^{-1}).

DISCUSSION

DISCUSSION

The present experiment was focused on assessing the changes in growth parameters, biomass productivity, carbon sequestration and nutrient dynamics as a function of stand density in a 22-year-old *A. triphysa* stand. The salient findings are discussed here under.

5.1 TREE GROWTH CHARACTERISTICS

The growth and yield of a stand is primarily controlled through decisions regarding initial spacing and/or subsequent thinning. Field studies on the influence of initial spacing on tree growth and plantation development has a long history (Jorgensen, 1967; Evert 1984), although few studies were reported in the case of *A. triphysa.*

In the present study, irrespective of density *A. triphysa* recorded an average total height growth of 12.84 m and bole height of 8.19 m. The mean tree diameter (DBH) recorded during the present study was 18.78 cm. This growth performance is fairly good at 22 years of stand age for *A. triphysa* when compared to other stands of the same species and other fast growing tree species. For instance, the growth of *A. triphysa* as support tree in a black pepper based production system showed average height of 10.78 m and DBH of 20.24 cm at 22-years of stand age. However, other fast growing species like *Acacia auriculiformis* (height: 13.08 m; DBH: 20.32 cm) and *Grevillea robusta* (height: 14.42 m; DBH: 23.06 cm) with same stand age registered higher mean height and DBH growth (Aneesh, 2014). The results converges to the generalization that tree growth is mostly influenced by factors such as specie selection and management regimes.

Present study showed interesting observations in tree growth among variable density regimes. The tree height growth (total and bole height) observed to be higher in the high density stand (13.66 m; 2360 trees ha^{-1} and 15.28 m; 1560 trees ha^{-1}) than in the wide stand (11.14 m; 900 trees ha^{-1} and 11.28m; 560 trees ha^{-1}) (Table 2). This type of response in height growth with increasing stand density was observed in a 6.5 year *Acacia mangium* stand in Kerala (Kunhamu *et al.*, 2005). A reasonable explanation for this pattern could be the crown competition, higher vertical competition for light and space makes trees in the denser stand to grow more in height (Long and Smith, 1984). However, a non-significant pattern for height growth was observed in the same stand at 8.8-years of stand age implying the dominant role of growth phase on height growth behavior of stand (Shujauddin and Kumar, 2003).

Tree diameter growth usually increases with reduction in planting density (Harper, 1977). The wide spacing may induce rapid crown expansion so that the diameter growth accelerates at the expense of height growth (Jonestone, 1985). The present study however, observed an inconsistency in diameter growth with changing planting densities. Such trend in tree growth parameters as a function of tree density has also been reported earlier for *A. triphysa* at 4-years of age (Kumar *et al.*, 2001). The differential pattern in height and diameter growth is due to the diverse behavior of lateral and apical meristems (Lanner, 1985). Despite modest variation in diameter growth with stand density there appeared a higher diameter at lowest stand density (Table 2). While a significant variation in diameter growth with different density regimes obtained in the same stand at the age of 8.8 years (Shujauddin and Kumar, 2003), the insensitivity in radial growth with stand density during present study could be partly on account of the old age and stagnation in stand growth and associated mortality through self thinning. This could be the reason for the similar trend observed for mean tree total volume and bole volume production observed in the present study (Table 3). Despite the inconsistency observed in mean tree growth patterns, the growth behavior at stand level (on hectare basis) however followed a general trend with increase in volume production with increasing tree density (Table 4).

5.2 BIOMASS PRODUCTION

The total mean tree aboveground biomass production potential of 22-year-old *A. triphysa* stand irrespective of density regimes was 129.81 kg tree^{-1} and the corresponding MAI was 5.9 kg tree^{-1} yr^{-1}. The mean tree aboveground biomass production and corresponding MAI for *A. triphysa* in the same stand at an earlier age (8.8 years) was 49.33 kg tree^{-1} and corresponding MAI was 5.6 kg tree^{-1} yr $^{-1}$. Considerable increase in the biomass production over a period of 13.2 years has been observed.

This shows that the age of the stand exerts significant influence on biomass production of tree species. However, the MAI in biomass production for the stand at different ages remain more or less same. The mean tree aboveground biomass obtained during present study was also higher than the value obtained for the same species grown under pepper based polyculture system (117.46 kg tree^{-1}, 5.33kg tree^{-1}yr^{-1}) (Aneesh, 2014). Probably, the intensive tree lopping practiced in the pepper production systems might have limited the tree growth. In general, the production potential of *A. triphysa* could be attributed to the genetic characters and partly to the congenial humid site conditions of Kerala. However, the present investigation registered lower total aboveground biomass production compared with other fast growing species (*Casuarina equisetifolia*: 259.46 kg tree^{-1}; *Acacia auriculiformis*: 241.76 kg tree^{-1}, *Grevillea robusta*: 272.19 kg tree^{-1}) with similar growth habit and stand age (Aneesh, 2014). Similar study conducted in a *Grevillea robusta* stand of 21- year-old reported to have higher mean tree aboveground biomass compared with the present value registered by *A. triphysa* (Paul, 2013). These highlight the wide range of species differences on biomass production.

Total mean tree belowground biomass (coarse roots) regardless of density regimes was 32.12 kg tree^{-1}and corresponding MAI was 1.46 kg tree^{-1}yr^{-1}. However the same stand at 8.8 years showed a considerably lower value (Shujauddin and Kumar, 2003). *A. triphysa* of similar stand age (22 years) in a polyculture system involving black pepper showed a mean tree belowground biomass production to the tune of 22.16 kg tree^{-1} (Aneesh, 2014) which was lower than the present value. Considering other fast growing multipurpose trees with same stand age, the present value was comparatively lesser (*Macaranga peltata*: 38.33 kg tree^{-1}; *Acacia auriculiformis*: 56.03 kg tree^{-1}; *Grevillea robusta*: 56.96 kg tree^{-1}) owing to the fact that root production was highly influenced by tree species and management conditions. The mean tree belowground biomass production in 21-year-old *Grevillea robusta* stand in a nearby location was 39.46 kg tree^{-1} which was slightly higher than the present reported value (Samritika, 2014) again highlighting the influence of tree species in belowground biomass production.

Present study registered fairly good mean tree total biomass production (aboveground+belowground) which was 161.74 kg tree^{-1} and 7.3 kg tree^{-1} yr^{-1} (MAI) irrespective of density regimes. The present value for mean tree total biomass was higher when compared with value registered in a black pepper based polyculture system (139.62 kg tree^{-1}; MAI: 6.3 kg tree^{-1} yr^{-1}) involving *A. triphysa* with same stand age (Aneesh, 2014) may be due to the variable stand density (560 trees ha^{-1}) and tree management influences on biomass production. However, a higher biomass production obtained in a 20-year-old *Grevillea robusta* (197.87 kg tree^{-1}; MAI: 9.4 kg tree^{-1} yr^{-1}) and in a 25-year old *Acacia auriculiformis* stand (288.32 kg tree^{-1}; MAI: 11.53 kg tree^{-1} yr^{-1}) further imply the variability in biomass production potential among tree species and management conditions (Paul, 2013; Sajeer, 2010).

Stand management practices like spacing and planting density strongly influence the biomass production in a stand. Usually, wider spacing produces more biomass and better performance of the individuals than the closer spacing (Wilkinson *et al.*, 2007; Hegazy *et al.*, 2008). However such a predictable trend was hardly discernible in the present study. All the four density regimes produced considerable amount of mean tree total biomass (Table 5 and Fig. 4) with medium density stand registering maximum production. The mean tree biomass was on par for all density levels except 900 trees ha^{-1} which incidentally was the lowest, implying the possible homogeneity in tree biomass production with longer periods of stagnation and related mortality.

The average total biomass production on per hectare basis irrespective of density regimes was 223.61 Mg ha^{-1} and corresponding MAI was 10.16 Mg ha^{-1} yr^{-1}. Stands of similar age however has exhibited much lower values (155.13 Mg ha^{-1}; MAI: 7.05 Mg ha^{-1} yr^{-1}) from an adjacent location (Aneesh, 2014). The mean aboveground stand biomass production in this study was 192.41 Mg ha^{-1} (MAI: 8.74 Mg ha^{-1} yr^{-1}). This was lower compared to stands of other species of similar age. For instance, a 25-year-old of *Grevillea robusta* stand (324.19 Mg ha^{-1}; MAI: 12.96 Mg ha^{-1} yr^{-1}; Jangra *et al.*, 2010) and 25-year-old *Acacia auriculiformis* (494.73; Mg ha^{-1}; MAI: 19.78 Mg ha^{-1} yr^{-1}; Sajeer, 2010) reported higher aboveground biomass values. Fast growing trees usually exhibit higher MAI in biomass production during younger age. For instance, Kunhamu *et al.* (2005) observed an MAI to the tune of 30.03 Mg ha^{-1} yr^{-1} for *Acacia mangium* at seven years of stand age. Considerable MAI (24.55 Mg $ha^{-1}yr^{-1}$) for aboveground biomass obtained for 3-year-old *Gmelina arborea* in Costa Rica (Arias *et al.*, 2011), again implies the role of tree species and management conditions in controlling the biomass production.

Yet another observation in the present study was higher belowground stand biomass (45.20 Mg ha^{-1}; 2.05 mg ha^{-1} yr^{-1}) (coarse roots) compared to other *A. triphysa* stands. For example, 22-year-old *A .triphysa* in a black pepper based production system showed much lower value (24.26 Mg ha^{-1}; 1.01 Mg ha^{-1} yr^{-1}) probably due to intensive tree lopping and variation in stand density. Such lower belowground biomass production has been observed for fast growth trees of similar growth habit. For example, Samritika (2014) reported belowground biomass of 18.45 Mg ha^{-1} for 21- year- old *Grevillea robusta* in a nearby area (460 trees ha^{-1}). Further reports on such lower belowground biomass has been reported elsewhere that include in 21-year-old *Acacia catechu* (11.87 Mg ha^{-1}; 0.56 Mg ha^{-1} yr^{-1}), *Albizia procera* (41.53 Mg ha^{-1}; 1.97 Mg ha^{-1} yr^{-1}), *Eucalyptus tereticornis* (35.51 Mg ha^{-1}; 1.69 Mg ha^{-1} yr^{-1}) plantations in north western Himalaya, India (Devi *et al.*, 2013).

Stand biomass production potential of *A. triphysa* (per ha) also showed considerable variation among density regimes (Table 8 and Fig. 6). Present study followed a consistent decline in stand biomass production with maximum value in denser stand (384.67 Mg ha^{-1}; 2360 trees ha^{-1}) and minimum in low density stand (93.86 Mg ha^{-1}; 560 trees ha^{-1}). The total stand biomass per ha in the denser stand (2360 trees ha^{-1}) was about 2.8 times higher than that of the low density stand. Similar trend was followed in the same stand at younger age (8.8 year; Shujauddin and Kumar, 2003). The above and belowground stand biomass production in present stand also followed the same trend. Therefore, when the stand management objective is to produce large biomass on a unit area basis, it would be probably better to follow closer spacings such as 2360 or 1560 trees ha^{-1}. This, in turn focuses on need for appropriate silvicultural manipulations, especially in respect of stocking levels, to meet specific stand management objectives.

Comparison of biomass production by *A. triphysa* with other multipurpose trees at different stand ages and management regimes showed considerable variation in biomass production (Table 31 and 32). *A. triphysa* in the present woodlot study showed higher biomass production compared to other management regimes as observed by higher MAI in biomass production. The prominent contribution of stand density to total biomass production is visible in the present study. For instance, the MAI in stand biomass production at lower density were moderate (900 and 560 trees ha^{-1}) both when the stand was at 8.8 year and 22 year age. Usually, fast growing trees show higher MAI in biomass during vigorously growing young age (Kumar et al., 1998; Shujauddin and Kumar, 2003). However, the trends suggest that the 'grand growth phase' extends beyond 8.8 years for *A. triphysa.* Rather, the MAI for biomass production for *A. triphysa* would stabilize at age between these reference years.

Biomass accrual potential is again species specific. For instance, in woodlot trial *Acacia auriculiformis* showed higher rates of biomass production at 8.8-years-old stand (MAI: 37.09 Mg ha^{-1} yr^{-1}) suggesting that peak production for the species is at a lower age as compared to *A. triphysa.* Also, woodlot experiment involving *Casuarina equisetifolia* and *Leucaena leucocephala* at 8.8 year age suggest that the grand growth phase extends beyond 8.8 years (Table 32). Results of the present investigation suggest that tropical fast growing tree species have high annual biomass accumulation with aboveground net primary productivity ranged from 16 to 29.8 Mg ha^{-1} yr^{-1} (Lugo *et al.*, 1988).

5.3 BIOMASS PARTITIONING

Biomass allocation among various tissue types in trees are controlled by many factors such as genetics, rate of growth, light demand and management conditions (Keeling *et al.*, 2008; Fonseca *et al.*, 2012). Generally, aboveground biomass production account highest share of the total biomass production. In the present study also nearly

80% of the total biomass is allocated to the aboveground portion in all the density regimes (Table 5). Similar results were achieved in many fast growing tropical species like *Acacia catechu*, *Eucalyptus tereticornis*, *Albizia procera*, *Betula pendula* (Kumar *et al.*, 1998; Uri *et al.*, 2012; Devi *et al.*, 2013). Following the general pattern root biomass contributed the second largest share to the total biomass production. In the present study, the contribution to root biomass was nearly 20 % of total biomass (Table 6). *A. triphysa* in a black pepper based polyculture system at same age showed root contribution towards total biomass as only 15 % (Aneesh, 2014). Probably the intensive tree lopping followed in black pepper production system may have limited the belowground biomass production. However, other multipurpose trees such as *Casuarina equisetifolia*, *Acacia auriculiformis* and *Grevillea robusta* in a black pepper based system of same stand age registered a moderate value towards root biomass that ranged from 11.19 to 17.3 % (Aneesh, 2014). In a 21-year-old *Grevillea robusta* roots registered 16.6 % towards total biomass production in a nearby area (Samritika, 2014), implying the strong variability in biomass production with species. Irrespective of density regimes the stemwood fraction contributes bulk of the aboveground biomass (63.13 %). The corresponding values for other components were branchwood (10.94 %), foliage (2.58 %) and Twig (0.97 %; Table 6). Comparable trends were observed in same stand at the age of 8.8 years, with percentage allocation of stemwood fraction to the biomass as nearly 70% (Shujauddin and Kumar, 2003).

Similarly, the allocation of stemwood biomass was reported to be 70-85% of total biomass in *A. triphysa* under woodlot as well as silvopastoral experiment at younger ages (8.8, 7 and 5 years; Kumar *et al.*, 1998). Similar trend also was observed in *A. triphysa* based on a pepper production system in Kerala, where stemwood fraction was reported to be 68% (Aneesh, 2014). Likewise, many tropical tree species like *Acacia nilotica*, *Bombax ceiba*, *Dalbergia sisso*, *Gmelina arborea*, *Populus deltoides* etc. were reported to produce higher stemwood biomass (Grier *et al.*, 1992; Onyekwelu, 2004; Chauhan *et al.*, 2009; Fonseca *et al.*, 2012). Furthermore, stocking levels are seen to influence the accumulation of stemwood significantly.

Table 31. Comparative biomass production by *Ailanthus triphysa* at different stand ages and management regimes

Species	**Land use**	**Age** (years)	**AGB** (kg tree^{-1})	**Total biomass** (kg tree^{-1})	**Total biomass** (Mg ha^{-1})	**MAI** (m^3 ha^{-1} yr^{-1})	**Source**
Ailanthus triphysa	Woodlot	8.8	16.21	19.17	47.94	4.61	Kumar *et al.*, 1998
	Silvopasture	7	7.75		-	2.77	Kumar *et al.*, 1998
	Silvopasture	5	7.87	9.57	24.00	3.96	Kumar *et al.* 1998
	Woodlot	8.8	35.603	40.587	135.28	13.64	Shujauddin and Kumar (2003)
	Woodlot	8.8	46.887	52.701	131.75	13.47	Shujauddin and Kumar (2003)
	Woodlot	8.8	44.513	50.594	80.95	8.19	Shujauddin and Kumar (2003)
	Woodlot	8.8	47.848	53.458	59.30	6.11	Shujauddin and Kumar (2003)
	Pepper based	22	117.46	139.62	155.13	7.05	Aneesh, 2014
	Woodlot	22	129.05	162.99	384.67	17.48	Present study
	Woodlot	22	158.1	197.13	307.52	13.97	Present study
	Woodlot	22	94.34	119.99	108.57	4.93	Present study
	Woodlot	22	137.74	166.85	93.86	4.26	Present study

Table 32. Comparative biomass production by MPT's at different stand ages and management regimes

Species	**Land use**	**Age (years)**	**AGB (kg tree^{-1})**	**Total biomass (kg tree^{-1})**	**Total biomass (Mg ha^{-1})**	**MAI (Mg ha^{-1} yr^{-1})**	**Source**
Acacia auriculiformis	Woodlot	8.8	130.57	137.66	344.16	39.10	Kumar *et al.*, 1998
	Silvopasture	7	74.32				Kumar *et al.*, 1998
	Silvopasture	5	56.13	62.68	156.80	31.36	Kumar *et al.*, 1998
	Pepper based	22	241.76	297.79	330.87	15.03	Aneesh, 2014
Casuarina equisetifolia	Woodlot	8.8	38.23	40.47			Kumar *et al.*, 1998
	Silvopasture	7	-	-			Kumar *et al.*, 1998
	Silvopasture	5	-	39.30			Kumar *et al.*, 1998
	Woodlot	20	-	-			Sreedevi *et al.*, 2010
	Pepper based	22	259.46	292.16	288.30	13.10	Aneesh, 2014
Grevillea robusta	Woodlot	25	-	-	324.20	14.73	Jangra *et al.*, 2010
	Pepper based	22	272.19	329.15	365.72	16.62	Aneesh, 2014
	Woodlot	21	197.89	-			Paul, 2013
Leucaena leucocephala	Woodlot	8.8	9.12	26.04			Kumar *et al.*, 1998
	Silvopasture	7	25.40	-			Kumar *et al.*, 1998
	Silvopasture	5	26.28	77.8			Kumar *et al.*, 1998
Acacia mangium	Woodlot	7	-		210.24	35.04	Kunhamu *et al.*, 2005

Stemwood accounted for 63-65% of the total aboveground biomass in 2360 and 1560 trees ha^{-1}, whereas it accounted for 61% of the total aboveground biomass in 900 and 560 trees ha^{-1} stand (Table 6). Similar trend were observed in the same stand at the age of 8.8 years, with stemwood contribution to aboveground biomass higher in high density stand than in the low density stand (Shujauddin and Kumar, 2003). Since, stemwood being the most important component of commercial value for most tree plantations, results of the present study explain the significance of stand density manipulation on stemwood production. The changes in relative amounts of material allocated to different tree parts as a function of spacing showed that trees in the wider spacings do not compete each other atleast during the early phase of the growth period and can extend their crown. This expansion is mostly at the expense of height growth leading to more allocation towards branchwood compared to allocation in closely spaced stands. Harrison *et al.*, 2000 and Hegazy *et al.*, 2008 studied the effect of spacing on biomass production also showed that biomass allocation towards branchwood was more wide spaced stands.

5.4 CARBON SEQUESTRATION

Accumulation of atmospheric CO_2 and entrapment in tree tissues has a strong correspondence with biomass production pattern. In the present study, *A. triphysa* showed substantial amount of carbon storage potential. Irrespective of density regimes, *A. triphysa* recorded average carbon storage of 74.55 kg $tree^{-1}$ and corresponding MAI was 3.38 kg $tree^{-1}yr^{-1}$. However, lower values were observed for the same species at an earlier age (1.08 kg yr^{-1}: 8.8 years) (Kumar *et al.*, 1998). The present value was fairly higher compared with black pepper based polyculture system involving same species at the same stand age (63.3 kg $tree^{-1}$; MAI: 2.87 kg $tree^{-1}$ yr^{-1}). However, compared with other fast growing tree species at same age such as *Casuarina equisetifolia* (6.19 kg $tree^{-1}$ yr^{-1}), *Acacia auriculiformis* (6.32 kg $tree^{-1}$ yr^{-1}) and *Grevillea robusta* (6.92 kg $tree^{-1}yr^{-1}$) (Aneesh, 2014), present stand reported substantially lower carbon sequestration potential, again reiterating the capacity of different species in carbon sequestration potential. This study showed substantial difference in carbon storage with density regimes. Total tree C stocks on per tree basis (stemwood+branchwood+twig+foliage+roots) ranged from 55.23 kg tree^{-1} to 91.11 kg tree^{-1} among various density levels. However, the insensitivity in mean tree biomass production with stand density is evident with carbon sequestration as well. As explained earlier the carbon accumulation among the trees might stabilize over time especially when the stand is subjected to longer periods of suppression and mortality (Table 11).

The present study registered an average total stand carbon storage of 160.89 Mg ha^{-1} and corresponding MAI of 7.31 Mg ha^{-1} yr^{-1} (Table 12). This is in conformity with the earlier recorded values for tropical forests, that varied from 132-174 Mg ha^{-1} (Dixon *et al.*, 1994). Kunhamu *et al.*, (2005) reported C sequestration potential of 7- year-old *Acacia mangium* stand to be 110 Mg ha^{-1}(15.71 Mg ha^{-1} yr^{-1}). However, a lower carbon sequestration (31.37 Mg ha-1; 5.22 Mg ha^{-1}yr^{-1}) was reported in a 6-year-old *Gmelina arborea* based agri-silviculture system (Swamy *et al.*, 2003). Yet another observation during the present study is the fairly high carbon storage in the belowground parts. Irrespective of density regimes, *A. triphysa* stand produced belowground carbon (33.15 Mg C ha^{-1}) which was comparable with other fast growing species like *Acacia auriculiformis* (26.87 Mg C ha^{-1}) and *Grevillea robusta* (29.64 Mg C ha^{-1}) of same stand age in a black pepper based polyculture system (Aneesh, 2014). The belowground carbon sequestration potential of 21-year-old *Grevillea robusta* plantation in a nearby site was reported to be 8.04 Mg C ha^{-1} (Samritika, 2014) which was much less compared to the present study. This stand however was maintained at a lower stand density (460 trees ha^{-1}) further implying that stand density play a pivotal role on stand biomass production.

On a stand basis carbon stocks showed consistent increase with increasing stand density that followed the order 2360 >1560>900>560 trees ha^{-1} (Table 12). About 4 times increase in carbon stocks was observed in denser stand (177.00 Mg ha^{-1}; 2360 trees ha^{-1}) compared to that of low density stand (43.33 Mg ha^{-1}; 560 trees ha^{-1}). The above and belowground carbon stocks also followed this order. This is in accordance with the findings of Shujauddin and kumar (2003) who reported 2.2 times increase carbon stocks in denser stand (59.33 and 26.58 Mg ha^{-1} for 2360 and 560 trees ha^{-1}respectively). Similar trend were observed in a 6.5-year-old *Acacia mangium* stand in Kerala where total carbon stocks increased with increasing stand density and reported almost twofold increase in carbon stocks (Kunhamu *et al.*, 2011).

Present observations also revealed that the elemental carbon concentration was higher in the soft tissues like leaf, than other woody tissue like root and branches. Same trend was followed in temperate species (Zhang *et al.*, 2009), *Acacia crassicarpa* and *Xylia xylocarpa* (Meupong *et al.*, 2010). The mean carbon concentration obtained in the present study was 46.03 %-46.22 % and found very closer to the 50 % value often used for estimation of carbon storage from dry biomass (Chhabra and Dadhwal, 2004).

Carbon accumulation in the tree biomass is a function of total biomass production. In this study the carbon sequestered by tree components were in the order stem> root> branch>leaves>twig. Similar trend was observed for many studies elsewhere (Swamy *et al.*, 2003; Coleman *et al.*, 2004; Keeratiurai *et al.*, 2012). Component wise carbon sequestration differed with stemwood registering highest carbon accumulation for all the density regimes (Table 11). The second highest share was accounted by the root portion and similar observations were reported by many authors (Norris *et al.*, 2001; Kaur *et al.*, 2002). Belowground biomass production and associated carbon sequestration is a cardinal factor in both monoculture and polyculture system involving trees. This ensures substantial enrichment in soil carbon content even after the harvesting of trees. Many studies highlighted the role of trees in improving the below ground carbon sequestration (Haile *et al.*, 2008; Saha *et al.*, 2010) and thereby ascertaining the long term productivity of the soils.

5.5 ALLOMETRIC EQUATIONS

Allometric equations are widely used to predict the standing biomass/volume of trees. They relate easily measurable variables such as tree diameter and height with the tree biomass/volume. The prediction model attempted in the present study tried to link the aboveground biomass, bole biomass, total aboveground carbon sequestration and volume with dbh and/or height as the predictor variables. Different models such as simple linear, quadratic, cubical, logarithmic were tried. Among the various equations the simple linear equation with single variable (dbh), linear equation with diameter coupled with height and single variable (dbh) quadratic equation showed better prediction with higher R^2 value. For all the dependent variables tried, prediction equation withsingle variable quadratic equation (DBH) showed high R^2 value compared with linear equations. The incorporation of height as a variable did not show appreciable improvement in the model. The advantage of dbh alone as independent variable is that they are simple, practical and easy to use and provide more rapid and less costly biomass/carbon estimates (Whitesell *et al.*, 1983). Several studies also found that tree biomass is primarily a function of dbh and is relatively less sensitive to tree height (Kadeba, 1991; Naidu *et al.*, 1998; Verwijst and Telenius, 1999).

Comparing the present allometric equation obtained for *A. triphysa* with those equations developed for the same species in a pepper based stand in Kerala showed the similar trend (Aneesh, 2014). However, logarithmic equations proved better fit for *A. triphysa* at 8.8, 7 and 5 years of stand age (Kumar *et al.*, 1998).

5.6 NUTRIENT CONCENTRATION

The concentrations of nutrients in tissues depend mainly on species, environmental factors (climate and soil availability) and plantation management (Moya *et al.*, 2013). Tissue nutrient concentrations, especially those in foliage, are considered to be an efficient management tool for evaluating the nutritional status of planted trees (Drechsel and Zech, 1991; Lehto *et al.*, 2010). It is evident that most of the nutrients were concentrated in the leaves (2.84 % N; 0.135 % P and 1.21 % K) for all density regimes followed by twigs, branchwood, roots and stemwood (Table 13, 14 and 15). Higher foliar nutrient concentrations were reported in the same stand at earlier age (4 and 8.8 years; Shujauddin and Kumar, 2003). Elevated nutrient concentrations in leaves were also reported by many authors (Wang *et al.*, 1991; Mohsin *et al.*, 2005; Ren and Yu, 2008; Arias *et al.*, 2011). The higher nutrient concentration in the leaves offer efficient nutrient return to the soil in wooded ecosystems. Leaf being the seat of maximum photosynthetic activity, it is logical that the highest nutrient concentration was always found in leaves as compared to other components (Kumar *et al.*, 2009). The elevated nutrient concentration in the leaves (especially N) makes this tree component an important reserve of bio elements, although it represents only a small percentage of the whole tree biomass. The lower nutrient concentrations in the tree trunk and branches assume a conservative measure against the huge harvest related nutrient losses from the site through stemwood and branchwood (Kumar *et al.*, 2009).

Elemental nutrient concentration in various tissue fractions was moderately higher than previously reported value in the same stand at the age of 8.8 years (Shujauddin and Kumar, 2003). It suggests that site and soil conditions together with stand growth phase may have a strong influence on tissue nutrient concentrations. Among various nutrients nitrogen recorded the highest value (2.77 to 0.71 %), followed by potassium and phosphorous for all tissue types (Table 13) probably due to the significance of this element in plant growth. This trend was supported by many studies (Rao *et al.*, 2000; Devine *et al.*, 2013). Same observation was registered in 5-year-old *Acacia auriculiformis* (George, 1993), *Acacia auriculiformis*, *Ailanthus triphysa*, *Casurina equisetifolia*, *Emblica officinalis* (Kumar *et al.*, 1998), *Dalbergia sissoo* (Lodhiyal *et al.*, 2002) and in *Acacia mangium* (Kunhamu *et al.*, 2005). The present study also analysed changes in nutrient concentration as a function of stand density. However, the trends were insignificant. Probably, stand density and associated changes in biomass accretion may not inflict appreciable changes in tissue nutrient concentration (Laclau *et al.*, 2000).

5.7 NUTRIENT ACCUMULATION AND EXPORT

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

As regards the nutrient accumulation on hectare basis, the stand with 2360 and

560 trees ha^{-1} showed maximum accumulation for N, P and K (Table 17, 18 and 19) and minimum in 1560 and 900 trees ha^{-1} stand indicating that nutrient accumulation highly influenced by biomass production and stand density. Likewise, the same stand at 8.8 years followed the same trend (Shujauddin and Kumar, 2003). Most of the nutrients were accumulated in the stemwood followed by roots, branchwood, foliage and twig (Table 17, 18 and 19) in all density regimes suggesting that nutrient accumulation in different tree components are related to the production of aboveground and belowground biomass. Results indicate that huge quantity of nutrients could be lost from the systems through harvest and removal. Such heavy loss leads to heavy drain of soil nutrients in a long run. Many studies followed similar trends that include *Dalbergia sissoo* (Das and Chaturvedi, 2003), *Gmelina arborea* (Swamy and Puri, 2005), *Grevillea robusta* (Paul, 2013). Interestingly, roots accounted for the second largest share, nearly 20% to nutrient accumulation in all the density regimes. Nitrogen accumulation in root portion ranged from 718.37 kg ha^{-1} to 155.18 kg ha^{-1} (Table 16). Belowground biomass is often not subjected to removal as part of harvest and hence may contribute to enrich the soil physico-chemical attributes. Despite the higher proportion of biomass attached to the stemwood their lower tissue nutrient concentrations probably help to regulate the harvest related nutrient losses from the site. Interestingly, the leaf, though contributes the lower biomass production, maintain highest nutrient concentration and thereby contribute significantly to enrich soil nutrient pool. Leaf biomass can bring substantial nutrient turnover to soil mainly through litterfall. Hence during harvest operations, if the branches and stemwood alone are removed leaving other tissue fraction in the site itself, the nutrient loss could be substantially reduced.

5.8 SOIL C-SEQUESTRATION

The soil carbon sequestration in wooded ecosystem depend upon many factors, like climate, soil type, vegetation and management practices (Saha *et al.*, 2010). In the present investigation, soil organic carbon concentrations at different soil depths were monitored. The average soil carbon concentration was found to be 0.94% irrespective of density regimes at 0-20 cm depth and thereafter showed a decline with soil depth to

0.24 % at 80-100 cm depth. The present values are moderate compared to other wooded ecosystems in the same ecoregions. For instance, the soil carbon concentration at 0-20 cm was 0.84 % for *A. triphysa* stand in a MPT-pepper system (Aneesh, 2014). Higher values are also reported from a 21-year-old *Grevillea robusta* stand (1.01 %) in an adjacent location (Samritika, 2014). Soil carbon content in natural forests is usually higher compared to captive plantations (Kumar and Deepu, 1992). This is primarily due to the more efficient turn over and conservation in natural forests. Managed stands are often subjected to frequent removals limiting the nutrient and carbon build up in the soil. However, the contributions from the trees are substantially higher compared to the soil from treeless open area. For example, the average carbon concentration in the *A. triphysa* stand was 0.94 % at 0-20 cm and corresponding value in the treeless open was 0.61 %.

Yet another observation is the consistent decline in soil carbon concentration with increasing soil depth. The average C concentration at 0-20 cm was 0.94% while the value at 80-100 cm soil depth was 0.24 % (approximately 75 % reduction). The top soil being the repository of organic inputs, always maintain a higher carbon and nutrient level. However this organic activity declines with increasing soil depth. Plenty of reports are there in support of this trend. For instance, the top soil carbon (0.84 %) recorded a heavy decline (0.29 %) in yet another *A. triphysa* stand at same age (Aneesh, 2014). Likewise, a study conducted in a nearby 21-year-old *Grevillea robusta* stand registered SOC concentration of 1.01 % in the 0-20 cm soil layer and 0.38 % in 80-100 cm depth (Samritika, 2014). The changes in soil carbon concentration across the stand density regimes were however, not convincing implying that soil organic carbon build up fairly uniform in the *A. triphysa* stands.

In the present study, the total average soil organic carbon stock for 22-year-old *A. triphysa* stand corresponding to 1 m soil depth irrespective of stand density was found to be 66.03 Mg C ha^{-1}. This value was comparable with SOC (65.56 Mg C ha^{-1}) content registered in a pepper based polyculture system with *A. triphysa* of same stand age (Aneesh, 2014). However, the present study showed lower value when compared with SOC content in a nearby 21-year-old *Grevillea robusta* stand (Samritika, 2014), indicating differences in root biomass production and root activity for different tree species. Soil carbon stocks may also vary with land use practices. For instance, the soil carbon study within 1m profile depth conducted in tropical homegardens registered a value of 101.5 Mg ha^{-1} to 127.4 Mg ha^{-1} (Saha *et al.*, 2008). This higher SOC content could be probably due to the higher tree density and species diversity in homegardens (Schwartz *et al.*, 2000; Tilman *et al.*, 2001, Kumar and Nair, 2004).

The overwhelming significance of wooded ecosystem are relevant as regards the carbon build at various soil depths. In the present study, C sequestration at 0-20 cm soil depth in was found to be 21.19 Mg ha^{-1} (nearly 32%) and reduced to 6.23 Mg ha^{-1} (nearly 9 %) in 80-100 cm soil depth. Kunhamu *et al.* (2011) reported higher soil carbon storage ranged from 24 to 35 Mg ha^{-1} in the 0-15 cm soil layer for 6-year-old *Acacia mangium* managed at various stand densities. The present value was lower when compared to total soil organic carbon (0-20 cm) pool of four land use systems in Kerala, viz., coconut (*Cocos nucifera* L.) plantations, homegardens, rubber (*Hevea braziliensis* H.B.K.M.-Arg.) plantations, rice (*Oryza sativa*) paddy that ranged from 28 to 37 Mg C ha^{-1} (Saha *et al.*, 2010). The congenial edapho climatic conditions of Kerala support higher belowground biomass production and soil carbon in tree based systems. However, they vary considerably with tree species and management conditions. Carbon build up in the soil for wooded system is primarily determined by factors such as litterfall, fine root biomass turn over, decomposition which vary considerably with species and soil attributes.

The present study showed average soil carbon stock for *A. triphysa* stand as 66.03 Mg C ha^{-1} and in the treeless control, 36.89 Mg C ha^{-1}. This study indicates that the soil organic carbon stocks within 1 m profile depth under 22-year-old *A. triphysa* plantation exceeded that of contiguous treeless plot by 29.14 Mg C ha^{-1} (44 % increase) and the rate of sequestration was found to be 1.32 Mg C ha^{-1} yr^{-1}. The rate of carbon sequestration in a nearby *Grevillea robusta* stand was reported to be 0.53 Mg C ha^{-1} yr^{-1} (Samritika, 2014). The soil carbon content in the 0-20 cm depth was 21.19 Mg ha^{-1} while the corresponding value in the treeless control was 14.24 Mg ha^{-1} (nearly 67 % reduction). Likewise, soil carbon content in the 80-100 cm depth was 6.27 Mg ha^{-1} while the corresponding value in the treeless control was 3.17 Mg ha^{-1} (nearly 50 % reduction). This throws light to the prominent role of tree based production system in improving the organic carbon and nutrient status of the soil. Other studies also highlight the advantage of trees in improving the C content in the soil. Studies supporting the present results were shown by many (Thevasathan and Gordon, 2004; Gupta *et al.*, 2009; Venkateswaralu, 2010). The SOC was reported to be considerably higher than the adjoining treeless plot due to litterfall and addition of tree roots in the soil under tree cover. The decomposition of dead roots causing constant addition of organic matter in plantation soil may be described as primary reason for improved soil carbon status in wooded systems (Young, 1997; Rai *et al.*, 2001).

While considering different density regimes, highest soil carbon stock was observed in the denser stands (2360 and 1560 trees ha^{-1}; Table 23). Similar results were observed from a 6.5 year old *Acacia mangium* stand with higher soil carbon sequestration attached to denser stand (Kunhamu *et al.*, 2011). This was probably due to the high litter production and associated carbon turn over in high density stands. Such higher soil organic carbon content in denser stand was reported from the same stand at 17-year-old (Rakesh, 2009). However, compared to the soil carbon content reported at earlier ages (8.8 and 17) for the same stand, the present result indicate a general decline in soil carbon stock suggesting that carbon turn over efficiency has been declined over time.

5.9 SOIL NUTRIENT CONTENT

The knowledge of soil nutrient stock is of fundamental importance to the understanding wooded ecosystems. The nutrient content registered in 1 m profile depth were 920.83 kg ha^{-1} N, 142.28 kg ha^{-1} P and 603.87 kg ha^{-1}. The N and P in the present study were comparatively higher than N and P (667.90 kg ha^{-1} and 57.66 kg ha^{-1}) reported in nearby *Grevillea robusta* stand (Samritika, 2014). Similarly the present value for N, P and K for 0-40 cm depth (260.97 kg ha^{-1} N; 26.99 kg ha^{-1} P; 148.27 kg ha^{-1}K) recorded higher value when compared with *A. triphysa* (207.38 kg ha^{-1} N; 13.88 kg ha^{-1} P; 72.74 kg ha^{-1} K) under coconut based system (Srinivasan *et al.*, 2010). Consistent decline in nutrient content with soil depth was observed in the present study also. The soil nutrients (N, P and K) declined with increasing the soil depth for both the tree stand and treeless control. A greater proportion of nutrients were found accumulated in the surface soil reflecting the massive inputs of nutrients to the soil surface layer through litterfall. Furthermore, the biological activity will be more intense in the surface layer that ensures higher mineralization and plant available nutrient release. This pattern of nutrient distribution was in agreement with studies conducted elsewhere (Jobbagy and Jackson, 2001; Starr *et al.*, 2005; Kumar *et al.*, 2009). The fairly high nutrient status in the soil emphasis the desirable effect of *A. triphysa* on the physico-chemical properties of the soil under study when compared with the treeless control.

Study revealed modest change in soil nutrient concentration among the variable density regimes (Table 24, 25 and 26). Similar trend in nutrient concentration was shown by the same stand at an earlier age (8.8) except for soil N (Shujauddin and Kumar, 2003). The widely spaced stand (560 trees ha^{-1}) showed higher soil nutrient content when compared with the denser stand (2360 trees ha^{-1}) (Table 24, 25 and 26). A plausible explanation for this is the accelerated removal of nutrients by the trees in denser stands. *A. triphysa* is a fast growing species and may absorb nutrients rapidly. The magnitude of nutrient extraction is presumably a function of tree density. Similar results have been reported at the present stand in earlier age (Kumar, 2001; Shujauddin and Kumar, 2003). However, the decisive role of tree cover has been fairly demonstrated from the present study in improving the overall productivity of the soil.

The results of the present study finally converges to the conclusion that *A. triphysa* has fair amount of biomass and carbon storage potential. Also, silvicultural manipulation and management aspects can alter the biomass production and nutrient efficiency. Hence, *A. triphysa* can be considered as a promising fast growing MPT species in the small and marginal farming sector of Kerala that ensure sound economic and ecological benefits.

SUMMARY

SUMMARY

Ailanthus (*Ailanthus triphysa* Dennst Alston.) is an important multipurpose tree in the peninsular Indian. It show high growth rates and can be used for multiple uses such as matchwood, plywood making and medicinal uses besides being a support tree for black pepper vines. Despite its wide acceptability as a plantation species and potential component in agroforestry, relatively little is known about the stand density regimes for optimum biomass production and growth of *A. triphysa*. The objectives of the present study involved the assessment of growth characteristics, total aboveground and belowground biomass production, carbon sequestration, besides estimating the nutrient dynamics through whole tree harvesting under various density regimes. The four population density levels studied includes 2360 trees ha^{-1}, 1560 trees ha^{-1}, 900 trees ha^{-1}, 560 trees ha^{-1}.

Salient findings of the study are summarized below

a. Differing levels of stand densities had a marked effect on total height and bole height of 22-year-old *A. triphysa* stand with higher densities (2360 and 1560 trees ha^{-1}) showed higher value for total and bole height. The highest mean tree total height was 15.28 m (1560 trees ha^{-1}) followed by 13.66 m for stands at 2360 trees ha^{-1}. Diameter (DBH) growth however showed modest variation with planting density with highest value (20.03 cm) corresponding to density of 560 trees ha^{-1}.
b. Biomass accumulation studies on per tree basis revealed that stand with 1560 trees ha^{-1} showed maximum mean tree total biomass (aboveground+belowground) with a value of 197.13 kg tree^{-1}. The mean tree biomass production could not follow a predictable trend with density. For instance, the 560 and 2360 trees ha^{-1} stands recorded values of 162.99 kg tree^{-1} and 166.85 kg tree^{-1} respectively which were statistically on par with 1560 trees ha^{-1} stand. The minimum value for mean tree biomass was recorded by 900 trees ha^{-1} stand which was to the tune of 119.99 kg tree^{-1}. However, on stand basis, consistent variation occurred with high density stands such as

2360 and 1560 trees ha^{-1} showing substantially higher biomass accumulation with mean values of 384.67 Mg ha^{-1} and 307.52 Mg ha^{-1} respectively. The lower density level recorded minimum stand biomass accumulation with mean value to the tune of 93.86 Mg ha^{-1} (560 trees ha^{-1}) and 108.57 (900 trees ha^{-1}).

c. The percentage contribution of various components to the total biomass followed the order: stemwood>root>branchwood>leaves>twig in all the density regimes. Among different components, stemwood constituted the major portion of the biomass in all the density regimes that ranging from 65.50 % (1560 trees ha^{-1}) to 61.92 % (900 trees ha^{-1}). Root biomass accounted for the second largest share with percentage contribution ranging from 21.37 % (900 trees ha^{-1} stand) to 17.92% (560 trees ha^{-1}) stand and twigs represented the lowest share (1.1 % to 0.64%).

d. Among the density regimes highest MAI for stand biomass was recorded for 2360 trees ha^{-1} stand (17.48 Mg ha^{-1} yr^{-1}) which is on par with 1560 trees ha^{-1} stand having a value of 13.97 Mg ha^{-1}yr^{-1}. The lowest MAI values were recorded for low density stands with a value of 4.93 Mg ha^{-1}yr^{-1} and 4.26 Mg ha^{-1}yr^{-1} for 900 trees ha^{-1} and 560 trees ha^{-1} stands respectively.

e. Mean tree average carbon stocks was 74.55 kg C tree^{-1} irrespective of stand density for 22- year-old *A. triphysa* stand. Biomass carbon sequestration also, didn't show appreciable variation among the density regimes. The corresponding carbon stocks were 75.02 kg C tree^{-1} (2360 trees ha^{-1}), 91.12 kg C tree $^{-1}$ (1560 trees ha^{-1}), 55.23 kg C tree^{-1} (900 trees ha^{-1}) and 76.83 kg C tree^{-1} (560 trees ha^{-1}).

f. Component wise contribution to carbon sequestration on per tree and per hectare basis showed similar trends as biomass partitioning. The stemwood registered highest carbon accumulation on per tree basis that ranged from 33.20 to 58.17 kg C tree^{-1}. Root portion stores the second largest C storage (11.90 to 18.28 kg C tree^{-1}) followed by branchwood (6.88 to 14.29 kg C tree^{-1}), leaves (1.66 to 2.41 kg C tree^{-1}) and twigs (0.47 to 0.64 kg C tree^{-1}).

g. Stand level biomass C stock showed a trend well in tune with stand biomass accretion with maximum C stock for 2360 trees ha^{-1} stand (177.00 Mg C ha^{-1}) which was on par with C stock for 1560 trees ha^{-1} stand. Lowest levels of C stocks were registered for 560 and 900 trees ha^{-1} stands which were 43.33 Mg C ha^{-1} and 49.06 Mg C ha^{-} respectively.

h. Nutrients removed through whole tree harvesting are a function of tissue nutrient concentrations and biomass accumulation. High density stands in general recorded greater potential for nutrient export from the site.

i. Compared to the woody tissues, leaves registered the highest concentration of N (2.84 to 2.72 %), P (0.13 to 0.15 %) and K (1.02 to 1.28 %) followed by twigs, branchwood, roots and stemwood respectively. Among the nutrients, N concentration was higher followed by potassium and phosphorus.

j. The nutrient accumulation was also calculated and the maximum accumulation was observed in stemwood portion (54 %) and minimum value in twig portion (2.06 %).

k. Since foliage represented sizable share of the aboveground nutrient accumulation, it is suggested that simple stand management practices such as leaving foliage and twigs in the plantation field can reduce the harvest related nutrient export from the site.

l. Prediction model developed for total aboveground biomass, bole biomass, total aboveground carbon sequestration, total volume and bole volume using DBH and height as predictor variables showed that simple linear and quadratic equations showed better fit with high R^2 value. In general, single variable (dbh) equations yielded reliable results compared to multiple variables. These equations benefit by way of saving time spent on tree height measurements without compromising the accuracy.

m. The soil carbon was registered highest in the tree based system (66.03 Mg ha^{-1}) than the treeless control plot (36.89 Mg ha^{-1}). With regarding the soil carbon 1560 trees ha^{-1} stand recorded a value of 66.82 Mg ha^{-1} and lowest value recorded in 900 trees ha^{-1} stand with a value of 63.79 Mg ha^{-1}. Soil nutrient concentration (N, P and K) was also registered higher value under tree based system than the adjacent treeless control plots.

n. The study in general suggest that *A. triphysa* is MPTs with high biomass production potential and can improve the soil properties through carbon and nutrient build up. Hence, it can be a better candidate in small and medium farming sector when managed under desirable densities that suits the management objectives.

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BIOMASS PRODUCTION, CARBON SEQUESTRATION AND NUTRIENT FLUX IN *AILANTHUS TRIPHYSA* (DENNST.) ALSTON.

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ABSTRACT OF THE THESIS

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ABSTRACT

A field study was carried out to evaluate the biomass production, carbon sequestration and nutrient dynamics in a 22-year-old *Ailanthus triphysa* stand managed at variable densities viz., 2360 trees ha^{-1}, 1560 trees ha^{-1}, 900 trees ha^{-1} and 560 trees ha^{-1}. Total number of 80 trees (20 from each density regime) was destructively sampled for the biomass and carbon stock assessment. Also nutrient stocks (N, P and K) in various tissue types were assessed following standard procedures. The soil carbon and nutrient contents were assessed for one meter soil depth at regular depth intervals.

The average stand height and bole height were 12.84 m and 8.19 m respectively which varied significantly with stand density with maximum value recorded for 1560 trees ha^{-1}. The average dbh, mean tree volume and bole volume put in by the 22- year-old *A. triphysa* stand was 18.78 cm, 0.15 m^3 and 0.16 m^3 respectively which however could not yield a predictable trend with stand density. Despite this, the stand volume exhibited a proportional increase with stand density. The mean tree biomass production by the stand was 129.81 kg tree^{-1} that varied with stand density. Biomass production at stand level showed a consistent increase with increasing stand density with highest produced corresponding to 2360 trees ha^{-1} stand (384.67 Mg ha^{-1}) and lowest for 560 trees ha^{-1} stand (93.86 Mg ha^{-1}). Component wise biomass allocation was highest for stemwood (63 %) followed by roots (20 %) for all the density regimes while twig portion registered the least (0.97 %).

The mean tree C stocks and corresponding MAI for *A. triphysa* at 22 years of stand age were 74.54 kg tree^{-1} and 3.38 kg tree^{-1} yr^{-1} respectively which was comparable with many fast growing MPT's similar growth habit in humid tropics. Elemental carbon storage at stand level showed proportionate increase with density (177.00 Mg ha^{-1}, 2360 tree ha^{-1}; 140.47 Mg ha^{-1}, 1560 tree ha^{-1}; 49.06 Mg ha^{-1}, 900 trees ha^{-1} and 43.33 Mg ha^{-1}, 560 trees ha^{-1}). Allometric models were developed for total aboveground biomass, bole biomass, aboveground carbon sequestration, total volume and bole volume using dbh and height as predictor variables. Among various models tried single variable (dbh) quadratic equations were best fitting with high R^2 value. The nutrient concentration varied

substantially among various biomass components with foliage registering highest N, P and K concentration (%). Tissue nutrient concentration followed the general order: leaves> twig> branch> root> stemwood. Biomass nutrient stocks at stand level varied considerably with stand density which was closely following biomass production trends. Nutrient storage followed the order N > P > K with highest stocks corresponding to stemwood followed by roots, branchwood, leaves and twigs. High nutrient accumulation in the stemwood suggests possible higher levels of nutrient export from the site through harvest. Transfer of nutrient rich leaf biomass into the soil at harvest would be a viable strategy in this context that replenish the nutrient loss through harvest. Carbon and nutrient contents in the soil were substantially higher in all sampled depths implying the dominant role of trees in improving the soil productivity in wooded systems. Study converges to the generalization that *A. triphysa* trees have a good potential for volume and biomass production under proper silvicultural management regimes.