FINE ROOT DYNAMICS AND ASSOCIATED CARBON AND NUTRIENT FLUX IN 12 YEAR OLD *ACACIA MANGIUM* AT VARYING STAND DENSITIES

By

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(2012-27-101)

THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Fine root dynamics and associated carbon and nutrient flux in 12 year old *Acacia mangium* at varying stand densities"** 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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Certified that this thesis entitled **"Fine root dynamics and associated carbon and nutrient flux in 12 year old *Acacia mangium* at varying stand densities"** is a record of research work done independently by **Ms. Delphy Rocha (2012-27-101)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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EXTERNAL EXAMINER

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Delphy Rocha

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Dedicated to my loving family

Introduction

INTRODUCTION

The demand for timber and other forest produce is escalating at unprecedented rate throughout the world. However, the supply is grossly limited owing to various reasons. The forest plantation cover in the world constitute about 140 million ha (M ha) that represent only a meagre 4% of the global forest area (FAO, 2005). Natural forests have been the primary source of timber and forest produce since long time that lead to massive decline of these precious natural resources especially in the tropics. In this pursuit, promotion of forest plantations has been a welcome strategy on account of their vast production potential in meeting the demand for diverse forest products and more importantly in alleviating pressure on the pristine natural forests that are indispensable for maintaining the ecological balance and environmental stability.

In the production front, tropical forest plantations have distinct advantages that they accrue high mean annual increment, on an average 5-10 times higher than natural forests. Furthermore, the product quality for various end-uses can be achieved through prudent management strategies in planted forests. For instance, of the total 322 million m^3 round wood production in the tropics, almost 47.5% was from the tropical plantations. Estimates suggest that roughly half of the global industrial roundwood demand will be met by plantations and planted forests by the year 2040 (Jürgensen *et al.*, 2014). Hence, there has been renewed interest in the recent times on the expansion of area under plantation forests especially in the tropics.

The limitations on the availability of land for large scale expansion of forest plantations and the ever rising demand for forest products has led to greater focus on scientific interventions in plantation forestry sector in the tropics. Since 1980s, there have been consistent efforts for developing

plantation management strategies for improving the productivity and product quality of the goods and services (Kelty, 2006; Paquette and Messier, 2010). The promotion of plantation forestry has attained added significance in the context of their vast potential to sequester elemental carbon and thereby in the abatement of green house gas emissions that are responsible for the global climate change. Plantations also play a key role in restoration of degraded and unproductive lands through cycling of nutrients and improvement of organic carbon content and overall productivity of the soils (Montagnini, 2000). It is assumed that, the relative importance of such provisional and ecological services rendered by forest plantations will increase in the future.

Forests are the main source of energy, livestock grazing and construction materials of about 60% of the Indian population (FSI, 2003). In this context, fast growing trees are of vital importance in meeting the wood and tree derived products. They constitute approximately 45% of the 32.6 million hectares plantation stock of the country. Fast growing short rotation tree species such as *Eucalyptus grandis, E. tereticornis, Acacia auriculiformis, A. mearnsii* and *A. nilotica* (FAO, 2001) dominate the sector. Among the slow growers, teak (*Tectona grandis*) accounts for about 8% of the total plantation area. Pines and other conifers constitute roughly 10% of the total forest plantation area. Commercial forest plantations in the private sector represent about 8.18 million hectares (ITTO, 2005).

Among the fast growing tree species, exotics play a prominent role in India, primarily on account of their enormous growth potential and ability to supply large quantum of wood within short periods. Further, they conform to the quality standards for various industrial purposes such as pulpwood, structural wood and plywood. They also respond to good management practices and are capable of producing higher biomass and volume in addition to provision of ecosystem services. Consequentially,

exotic fast growers dominate the plantation sector in the tropics. Cossalter and Pye-Smith (2003) estimated that in the early 2000s, the total area of fast-growing plantations was about 10 M ha, growing at the pace of about 1M ha per year.

Woody perennials enjoy the benefit of self-nourishment by efficient cycling of nutrients from deeper soil and making them available for re-absorption. The productivity of forest plantations are by and large a cumulative result of the efficiency with which these ecosystem processes support biomass production through the fundamental photosynthetic pathway. The photosynthetic efficiency in woody ecosystems is primarily species dependent and their resource acquisition potential is greatly controlled by the biophysical environment in which they grow (Melillo *et al.,* 1993). Similarly, tree management environment can modify the biomass production and allocation patterns in woody ecosystems. Both the aboveground and belowground factors contribute to the productivity of plantation ecosystems.

Among the aboveground factors, the stand density plays a pivotal role in regulating the biomass production and allocation patterns. Stand density manipulation through thinning and initial planting density regulation are powerful tools for developing desired stand structures (Smith, 1986). Trees sequester substantial quantity of elemental carbon through biomass production and reduce global warming and climate change (IPCC, 2000). Stand management strategies such as density regulation in tree crops may also influence the carbon sequestration rates. Considerable amount of nutrients are accumulated in the tree biomass which could be lost from the plantation soils, when subjected to total harvest (Kumar *et al.,* 1998). However, such quantitative information on biomass production and allocation, carbon sequestration and nutrient accumulation rates and their functional relation with the stand density regulation and pruning are unclear for several fast growing plantation species in the tropics.

Litter production and their turnover into the soil as nutrients and organic matter constitute the primary pathway of self nourishment in plantation ecosystems which is influenced by stand density management. However, such information on the definite role of stand density regulations on these fundamental nutrient replenishment strategies is poorly known in tropical plantation ecosystems. Despite the vast literature available on the role of litter dynamics in the exchange of carbon and nutrient across the vegetation and soil and their potential to maintain soil carbon and nutrient reserves in woody ecosystems, limited studies are available that link the litter production in relation to stand management strategies (Diaz *et al.,* 2004; Gusewell, 2004; McGroddy *et al.,* 2004; Reich and Oleksyn 2004; Wright *et al.,* 2004). These assume greater relevance in tropics where the soils are fragile and nutrient deficient and productivity of the woody ecosystems are primarily linked with efficiency with which the carbon and nutrient transfers occur across the soil-plant system (Fearnside, 1985; Lugo *et al.,* 1990).

Yet another strong determinant of the resource use efficiency in plantation productivity is the belowground fine root dynamics. These tiny short lived apparatus play a unique role in nutrient and carbon transfer in the soil-tree system through their brilliant turnover process. Despite the carbon and nutrient losses by the total harvest in short-rotation stands, return of carbon and nutrients through leaf litter and fine roots offer a potential strategy for compensating the losses from the woody ecosystems. A functional relationship probably exists between aboveground litter dynamics and belowground fine root dynamics in plantation ecosystems. There could be large similarity in the dynamics and functioning of these two processes and its cumulative effect might decide the overall productivity of woody ecosystems (McClaugherty *et al.,* 1982; Vogt *et al,* 1986; 1996). According to Aerts *et al.* (1992) and Sanford and Cuevas (1996), nutrient inputs to soils from root litter equal or surpass the return from the

aboveground counterpart. Estimates suggest that fineroots can contribute up to 27% of the annual NPP in tropical forests (Malhi *et al.,* 2011). Further, estimates of fineroot production from the pan tropics range from 75 to 2193 g dry matter (DM) $m^{-2}y^{-1}$ (Hertel and Leuschner, 2010). Despite the vast knowledge accumulated on the aboveground leaf litter dynamics, very less is known on the contributions from fine roots. Quantitative information on the fine root production, their longevity, turnover and rates of their decomposition especially on tropical plantation species are very much limited (Majdi and Andersson, 2005; Hertel and Leuschner 2010; Finér *et al.,* 2011). Also, our understanding on the various factors that control the carbon and nutrient fluxes associated with fine roots is poor. Just as aboveground litter, the fine root turnover and decomposition processes may be influenced by stand density regulation and tree pruning in plantation ecosystems. However, such information on belowground traits is unclear especially for tropical plantation species.

Major deterrent in pursuing studies on tree fine roots is the methodological challenges in sampling and analysis (Vogt *et al.*, 1998; Bledsoe *et al.,* 1999; Makkonen and Helmisaari, 1999; Majdi *et al.,* 2005). Divergent opinion exists on the best method for measuring fine root production and assessing their turnover (Vogt *et al.,* 1998; Hertel and Leuschner, 2002 and Hendricks *et al.,* 2006; Yuan and Chen, 2012; AddoDanso *et al.,* 2016). For instance, the most accepted methods such as ingrowth core and sequential sampling have limitations when applied individually. Thus use of a combination of techniques may yield better results (Yuan and Chen, 2012). In the ensuing study, we have tried such multipronged strategy to evaluate the tree fine root production.

The complex, laborious and time-consuming nature of fine root assessments led to the development of models for predicting root biomass (Danjon *et al.,* 2005). Simple allometric equations linking fine roots and easily measurable aboveground growth variables such as diameter/basal

area may be of great practical advantage in fine root assessment. But only few studies are available on prediction models developed for fine roots especially from the tropics (Santantonio, 1989; Vogt *et al.*,, 1996; Cairns *et al.*,, 1997; Vanninen and Mäkelä, 1999; Li *et al.*, 2003; Chen *et al.*, 2004; Ammer and Wagner, 2005). In the present study, effort has been made to develop allometric models for fine root quantification, biomass production and carbon sequestration from tree diameter/ height as predictor variables.

Acacia mangium Willd., a fast growing evergreen Australian tree introduced to India in the 1980s, has gained acceptance as a plantation species and as a component of the multistrata agroforestry systems in the southern and eastern regions of this country (Kumar, 2005). In South India, *A. mangium* has become a favourite choice of large farmers who cultivate it on plantation basis as well as of marginal farmers who prefer this tree as a component in their small holdings and homegardens (Kumar, 2005). The key factors that endear *A. mangium* are, superior wood qualities with acceptable physical and mechanical properties such as basic density, shrinkage and hardness (Shanavas and Kumar, 2006), faster rate of growth and shorter rotation (Awang and Taylor, 1993). On very good sites, *A. mangium* is reported to have a mean annual increment in volume of 46 m^3 ha^{-1} (Tham, 1976). The wood makes attractive furniture, door frames, window parts, cabinets and sliced veneer. In addition, it is an excellent fuel wood (calorific value 4800-5000 kcal/kg; Yanthasath *et al.*, 1986). The wood is also used in pulp and paper production. Despite the widespread use of *A. mangium* in the humid tropics (Kunhamu *et al.*, 2005), species-specific information on the aboveground and belowground biomass production and allocation, their carbon and nutrient storage potential, leaf litter and fine root production and turnover, soil carbon and nutrient status and the overall plantation productivity as influenced by planting density regulation are lacking. Inventory of the various biomass components such as stemwood, branchwood, leaves, twigs, coarse roots

and fine roots and assessment of their contribution to the soil carbon and nutrient pools and their functional relation to stand management practices such as density regulation and pruning will provide valuable information on strategies to be evolved for optimization of productivity in *Acacia mangium* plantations.

In this context a comprehensive field study was carried to investigate the biomass production potential, biomass allocation patterns, carbon and nutrient accumulation in the biomass, litter production and its turnover and fine root dynamics and changes in the soil carbon and nutrient pools as influenced by planting density regulation in a 12-year-old *A. mangium* plantation.

The specific objectives of the study are:

1. To study the fine root production, turnover and seasonality as function of planting density and pruning in a 12-year-old *Acacia mangium* plantation.

2. To investigate the total biomass production and allocation patterns and their functional relationship with fine root production as influenced by stand density and pruning in 12-year-old *Acacia mangium* plantation.

3. To estimate the aboveground litter production, decomposition and seasonality as function of planting density and pruning in the 12-year-old *Acacia mangium* plantation

4. To estimate the fine root and litter contribution to carbon and nutrient flux in tree-soil system as affected by tree density and pruning for *Acacia mangium*.

Review of literature

REVIEW OF LITERATURE

Fine roots are important structural and functional components of woody ecosystems which contribute 2–5% to the total forest biomass (Helmisaari *et al.*, 2002). They contribute significantly to forest soil carbon and nutrient flux because of their rapid production, death and decomposition, (Brunner and Godbold, 2007). Silvicultural interventions in forest stand impact aboveground component as well as the entire root system, including the fine roots. An understanding of the stand management practices such as planting density regulation and pruning on fine roots and above ground litter dynamics are important in gaining better understanding of global carbon (C) and nutrient cycling. Yet, data on changes in fine root production and turnover with different stand management practices are rare mainly due to difficulties associated with collecting belowground data. This review deals with fine root dynamics, growth and biomass production, litter dynamics, carbon and nutrient stocks and their associated fluxes in plant and soil systems with special reference to *Acacia mangium*. It also contains review of functional relationship between these growth variables and stand management attributes such as planting density and pruning. Also, above ground and belowground biomass allocation potential of forest stands are also reviewed.

2.1. ROOT SYSTEM AND PRODUCTIVITY

In terrestrial ecosystems, net primary production (NPP) is an essential component for energy, carbon and nutrient budget models (Fahey and Knapp, 2007). Even though there is a long account of net primary productivity (NPP) studies in the ecological literature, current understanding of ecosystem-level production is skewed towards aboveground NPP (ANPP). A significant portion of C assimilated by plants through photosynthesis is transferred to roots (Litton *et al.*, 2007;

McCormack *et al.*, 2015); this may even surpass the quantity allocated to aboveground components (Moser *et al.*, 2011). Fine and coarse roots are major contributors to the total biomass pools of the woody ecosystems, and play critical roles in the cycling and allocation of carbon (C) and nutrients (Malhi *et al.*, 2011; Smyth *et al.*, 2013; Raich *et al.*, 2014). In forests, belowground net primary productivity accounts for 30–50% of total net primary production (Gill and Jackson, 2000). Litton *et al.* (2007) reports that the carbon transferred to belowground is 22–63% of the total gross primary productivity of forests. This large flux of C exerts a profound influence on the regulation of major soil processes that affect productivity and biogeochemical cycling in these woody ecosystems (Prescott, 2010; Clemmensen *et al.*, 2013; Raich *et al.*, 2014 and Zhang and Wang, 2015).

The proportion of the total tree biomass represented by fine roots and mycorrhizas is in the range of 10–20% (Makkonen and Helmisaari, 1999), whereas Vogt *et al.* (1996) give a conservative estimate of fine root biomass under 5% of total tree biomass but their growth and maintenance use a major part, perhaps as much as 67–70%, of total net primary production. In western forest ecosystems, a large variation (8-73%) in fine root production has been reported (Welke *et al.*, 2003).

2.1.1 Fine root studies in tropics

In the tropical forests fine roots generally occur as root mats on the soil surface or in the first few centimeters of the soil (Stark and Spratt, 1977) and can change rapidly due to perturbations (Yin *et al.*, 1989). Fine roots take up nutrients and water and thus support aboveground forest productivity, to an extent that is far in excess of their mass. These functions are energetically expensive; half or more of forest soil respiration frequently is attributed to root respiration (Hanson *et al.*, 2000). Fine roots also are important sources of detritus within forest soils that sustain soil

biological activity (Pollierer *et al.*, 2007) and influence soil organic matter and nutrient dynamics (e.g., Gill and Jackson 2000; Hendricks *et al.*, 2006). In the predominantly nutrient poor tropical soils, fine root and litter play a key role in their productivity through efficient cycling of nutrients. However, despite widespread recognition of the importance of fine roots, their production and decay dynamics remain poorly quantified in the tropics in particular. For instance, a 2001 review by Silver and Miya included only three studies of fine root decay of tropical broad-leaved tree species.

2.1.2 Fine root spatial distribution

Generally, fine roots are defined as roots less than 2 mm in (Gill and Jackson, 2000). Fine roots are considered as non-woody, absorbing organs which together with their mycorrhizal associates account for the bulk of nutrient and water uptake and are the most dynamic component of the forest ecosystem (Ruess *et al.*, 2006). Fine roots have a much shorter lifespan than coarse roots, as a consequence, their biomass varies both seasonally and due to changing environmental conditions.

Generally, fine roots are often abundant in the soil organic horizon. Tingey *et al.* (2000) and Jackson *et al.* (1996) mention that in forests about 50–80% of roots are found in the upper 30 cm of soil. According to Jackson *et al.* 1996, average rooting distribution for all trees with 60% roots in the top 30 cm and 78% in the top 50 cm across all relevant biomes. Similar trend is also found in the conifer forests of temperate zone. They reported about 52% of the total root biomass in the top 30 cm in coniferous forest of temperate biome. However, Brazilian eucalypts are found to have low fine root biomass in the 0–30 cm soil layer in comparison with the amounts measured down to a depth of 3 m during the first year of its growth (Jourdan *et al.*, 2008). A similar pattern was found in Congo, where

eucalypt fine roots were observed down to a depth >3 m in one year old stands (Bouillet *et al.*, 2002). However, reports are also available on highest densities of fine roots in the topsoil in eucalypt plantations (Fabia˜o *et al.*, 1995; Mello *et al.*, 2007).

2.1.3 Fine root biomass production

Fine root biomass constitutes the weight of fine roots per unit area of woody ecosystem. Very little reliable information is available on fine root production from various forest ecosystems which however is highly variable. Published information on fine root biomass of the world tropical moist deciduous forest was in the range 8.30–8.90 (Mg ha^{-1} $year^{-1}$), semi-evergreen forest 7.90–8.04 Mg ha^{-1} $year^{-1}$ and evergreen forest 6.30–9.40 Mg ha^{-1} $year^{-1}$ (Shan *et al.*, 1993) while the value for subtropical forests ranged between 1.1 to 10.6 Mg ha^{-1} (Li *et al.*, 1998; Liao, 1995; Vogt, 1996; Wen, 1999 and Yang *et al.*, 2002).

As compared to temperate conditions, information on the fine root production for tropical plantations and agroforests are very much limited. Studies on Brazilian Eucalyptus estimated a fine root production of 2.4–2.8 Mg ha^{-1} $year^{-1}$ (Jourdan *et al.*, 2008) which was close to the values from tropical dry region of India (Singh and Singh, 1981) or that reported in agroforestry systems of Acacia with Sorghum in Kenya (2.1 Mg $ha^{-1}year^{-1}$; Lehmann and Zech, 1998) but was higher to alley cropping system with Gliricidia in Ivory Coast (1.1 Mg ha^{-1} $year^{-1}$; Schroth and Zech, 1995) or in Acacia monoculture stands (0.95 Mg ha^{-1} $year^{-1}$) in northern Kenya (Lehmann and Zech, 1998). By contrast, their results were much lower than those reported (6.5–8.1 Mg ha^{-1} $year^{-1}$) in North America for sugar maple trees (Aber *et al.*, 1985; Hendrick and Pregitzer, 1993), or that found for oak trees (9.9 Mg ha^{-1} $year^{-1}$; McClaugherty *et al.*, 1982).

In the temperate biomes, temperate deciduous and temperate coniferous forests reported fine root production of 440 and 500 mg m^{-2} respectively (Jackson *et al.*, 1997). Interestingly, higher production of 500 mg m^{-2} (cold temperate evergreen needle leaf forests), 700 mg m^{-2} (warm temperate deciduous broad leaf forests), and 654 mg m^{-2} (cold temperate deciduous forests) has been reported (Vogt *et al.*, 1986, 1996). Finer *et al.* (2007) estimated 389 and 303 mg m^{-2} in the temperate species *Fagus sylvantica* and *Picea abis*. However, a characteristically lower production has been observed for boreal forests, with values 135–152 mg m^{-2} in boreal evergreen needle leaf and 129 mg m^{-2} in boreal deciduous forests (Vogt *et al.*, 1986, 1996). However, still higher values have been reported for boreal forests in the range 230-290 mg m^{-2} (Jackson *et al.*, 1996, 1997).

2.1.4 Fine root turn over and longevity

Root turnover is the process by which roots die and are replaced by a new crop of active roots. It is often quantified with respect to annual fine root production and mortality and defined as the amount of fine root that have been produced or have died each year in relation to the mean annual fine root biomass (Gill and Jackson, 2000; West *et al.*, 2004). Fine root turnover can also be defined as the inverse of median lifespan (Coleman, 2003), and conceptually reflects the number of cycles per year roots are produced and then senesce. The lifespan of fast-cycling roots is a critical parameter determining a large flux of plant carbon into soil through root turnover and is a biological feature regulating the capacity of a plant to capture soil water and nutrients via, root-age-related physiological processes. Few assessments are available on fine root longevity, or seasonal patterns in root production and senesce. Root lifespan has important inferences for plant growth, competition and below-ground carbon and nutrient cycling (Anderson *et al.*, 2003).

According to Gill and Jackson (2000), fine root turnover rates of world forests were in the range of 0.02 to 2.64 yr^{-1}, with an average of 0.56 yr^{-1}. Turnover rates usually reported for tropical forest species are of the same order. For example, turnover rates for Larix in central Korea amounted to 2.2–2.5 yr^{-1} in unfertilized and fertilized plots, respectively (Son and Hwang, 2003), similar values were found for Acacia in Kenya (2.0 yr^{-1}; Lehmann and Zech, 1998), for Terminalia in Ivory Coast (2.4 yr^{-1}; Schroth and Zech, 1995). In general, these values were higher than the turnover rates previously reported for deciduous (0.1–2.0 yr^{-1}) or coniferous (0.5–0.7 yr^{-1}) forests in temperate ecosystems (Burke and Raynal, 1994; Ruess *et al.,* 1996). Gill and Jackson (2000) reviewed studies dealing with fine root dynamics and concluded that fine root turnover decreased from tropical to high-latitude ecosystems for all plant functional groups. Some exceptions still remain and fine root turnover rates of 2– 2.5 yr^{-1} for non-mycorrhizal fine roots of 8-year-old fertilized loblolly pine stands were reported in United States (King *et al.*, 2002).

Estimates of fine root longevities range from a few months to several years in both deciduous and coniferous stands (Burke and Raynal, 1994; Fahey and Hughes, 1994; Schoettle and Fahey, 1994). Tree fine root longevity depends on species, climate, and soil conditions and can range from weeks to several years (Hendrick and Pregitzer, 1992). Several studies have employed root cohort analysis to determine root longevity, including Kosola *et al.* (2001) and Black *et al.* (1998), who measured a mean fine root lifespan of 30 days in *Populus camaldensis* seedlings. Likewise, Block (2004) reported mean longevity in hybrid poplar (*P. deltoids, P. petrowskyana*) fine root cohorts to range from 36 to 120 days. A study by Coleman *et al.* (2000) measured a greater mean lifespan in 10–12 year-old *Populus tristis* of 149 days. Root longevity in an aspen (*Populus tremuloides*) stand in Saskatchewan's boreal forest was approximately 50–100 days, as indirectly calculated from mortality and turnover data

presented by Steele *et al.* (1997). Other studies on poplar root longevity support this time period (Pregitzer *et al.*, 1993; Pregitzer and Friend, 1996). Wells and Eissenstat (2001) recorded apple tree root longevities between 36 and 114 days. In case of Brazilian eucalyptus Jourdan *et al.* (2008) found out fine root longevity <3 months and high decomposition rates.

2.1.5 Carbon and nutrient accumulation in fine roots

Although, fine root biomass contributes relatively little to total tree biomass, they are the major contributors to carbon inputs because of their quick turnover (Norby and Jackson, 2000). Carbon allocation to the root system and eventually to the soil after its death is one of the most important but least well computed fluxes of C in the terrestrial ecosystem (Matamala *et al.*, 2003). Together with aboveground litter production and the turnover of mycorrhizal hyphae, fine root dynamics represent an important path of organic carbon input to soils. Tropical forests are characterized by a rapid fine root turnover, thereby exerting large influence on ecosystem carbon fluxes (Silver *et al.*, 2005). Fine root production and turnover are more important for the accumulation of carbon in forest soils than above-ground litter input (Lugo and Brown, 1993; Block *et al.*, 2006). Arthur and Fahey (1992) observed that the annual nitrogen cycled by fine roots may be of the same magnitude or greater than the amount of nitrogen in leaf litter in some coniferous and deciduous species. Thus, soil organic matter and root dynamics are firmly interconnected (Guo *et al.*, 2005; Rasse *et al.*, 2005).

Dead roots make up 50–80% of the fine root biomass (Usman *et al.*, 1999). The annual loss of fine roots in forest ecosystems ranges from 40-92% of standing crop (Welke *et al.*, 2003). Due to the high rate of fine root turnover, its contribution to the increase of organic matter in soil is 2–5

times higher than that of the aboveground components of the trees. Thus the pool of organic matter and nutrients released upon decomposition of fine roots could compensate the antagonistic effect of harvesting. Research directs the nature of fine root production and mortality to be highly dynamic and often simultaneous (Tierney and Fahey, 2001; Block 2004). Hendrick and Pregitzer (1993) estimated about 33% of annual fine root production and mortality occurred simultaneously in a temperate hardwood forest.

2.1.6 Environmental factors on fine root production

Discerning how various external factors influences fine root growth which is important to predict current and projected future climate and vegetation changes. Climatic variables are important regulators that affect fine root growth (Silver and Miya, 2001) as well as fresh and senesced leaves (Yuan and Chen, 2012).

2.1.6.1 Temperature

Field observations of majority of the studies across sites or through time specify that fine root lifespan decreases with increasing temperature (Kitajima *et al.*, 2010). Metabolic activity and respiration of the fine roots enhances at higher temperature (Schindlbacher *et al.*, 2009). This is associated with the regularly observed faster senescence and increased mortality of fine roots in surface soil than in mineral soil (Baddeley and Watson, 2005; Chen and Brassard, 2013). At lower temperatures, roots tend to have lower respiration rates (Burton *et al.*, 2002).

2.1.6.2 Water

Variation in the root lifespan response to the changes in water availability depends on whether water strongly limits root or whole-plant growth. Adding water and alleviating drought should increase whole-plant productivity and increase root lifespan on one side (Meier and Leuschner, 2008). Increased root longevity has also been associated with higher precipitation in some tropical systems since root production and lifespan tends to increase during wet seasons and decrease during dry periods (Green *et al.*, 2005). Yet, additional water applied to an environment that already has adequate moisture may in fact reduce lifespan (Leppälammi-Kujansuu *et al.*, 2014) as the frequency of anaerobic conditions elevates root stress and pressures from external factors including increase in soil pathogens and saprophytic fungi.

2.1.6.3 Soil nutrients

Fine root biomass has been reported to be lower in more fertile sites in both needle-leaved and deciduous stands (Keyes and Grier, 1981). A reduction in nutrient availability has been shown to lead to an increased root mass density (Ryser and Lambers, 1995). According to the carbon optimization theory by Eissenstat (1992), trees growing in nutrient-poor habitats invest large amounts of carbon in the construction of new fine roots for improved nutrient acquisition.

The impact on root growth and lifespan may go beyond simple alterations in mineral nutrition (Marschner, 2011). For instance, presence of available nitrogen is the most important factor that influences the stratification of fine roots (Hertel, 1999). Much like extreme water limitation, ecosystems that are severely limited in available phosphorus produces some of the most extraordinary adaptations in root morphology (Lambers *et al.*, 2008).

Beyond increases in total surface area, adaptations to low phosphorus conditions may also involve changes to root physiology and morphology, leading to alterations in root lifespan. For example, under low phosphorus conditions thinner roots may be produced to increase absorptive area per unit mass. Earlier studies have consistently reported that thinner roots, both within and across species, tend to have shorter lifespans than thicker roots (Baddeley and Watson, 2005 and McCormack *et al.*, 2012).

2.1.6.4 Soil pH

On the most acidic sites fine root density is lower than on the least acidic sites (Helmisaari *et al.*, 2009). Microbial activity is inhibited in acidic soil, whereas soils with a higher pH can stimulate the growth of fine roots (Francis, 1986). Plants may allocate more production to fine root growth at acidic nutrient-poor sites as a response to high nitrogen and phosphorus residence times in biologically inactive soils (Vogt *et al.*, 1996).

2.1.6.5 CO_2

Generally, the fine root production and biomass respond positively to elevated levels of CO_2 (Smith *et al.*, 2013). At elevated CO_2, there is an increase in fine root diameter (Milchunas *et al.*, 2005), fine root proliferation in deeper soil (Norby *et al.*, 2004) and root tissue density (Eissenstat *et al.*, 2000) which all correlate positively with fine root lifespan, subsequently decreasing the fine root litter carbon input into the soil. However the overall responses of fine root longevity to elevated CO_2 have been highly controversial, due to the multiple interacting factors (Pritchard, 2011). For example, in a study in Norway spruce forest in Sweden, Sigurdsson *et al.* (2013), found that low nitrogen availability progressively suppressed the positive response of plant biomass to elevated CO_2 and also elevated CO_2 concentration caused no effect on tree height

and stem increment unless extra nutrients were supplied (Sigurdsson *et al.*, 2013 and Reich *et al.*, 2006).

2.1.6.6 Soil depth

Block (2004) reported that fine root within the 30–60 cm depth lived significantly longer than those at the 0–30 cm depth. Hendrick and Pregitzer (1992) found a mean root lifespan of sugar maple (*Acer saccharum*) of 8.0 and 5.5 months in the 0-30 cm and 30–60 cm depths, respectively.

2.1.7 Stand management effect on fine root production

Fine root biomass varies with stand management practices especially with spacing but studies in this line are limited. A general increase in fine root production has been reported for many tree species. For instance, the proportion of material allocated to roots <2 mm doubled when the spacing level is increased from 3 x 1.5 m to 4 x 3 m for *Eucalyptus urophylla* (Bernardo *et al.*, 1998). A similar trend was reported for *Eucaliptus camaldulensis* and *E. pellita*. In a similar study trees at 770 stems per hectare (SPH) had 3–12 times more fine roots than those at densities of ≤ 237 SPH for tree-pasture systems (Douglas *et al.*, 2010). Probably, increase in spacing would lead to an increase in BGB: AGB (Barton *et al.*, 2006). Furthermore, the small root biomass was still larger on a per unit ground area basis for the wide spaced trees. A similar result was found for *Populus deltoides* where the average tree size and density of fine roots (<2 mm) per unit ground area increased across three levels of spacing from 2 x 2 to 4 x 4 to 6 x 6 (Puri *et al.*, 1994). They attributed the increase in fine root density at wider spacing to reduced tree to tree competition and a reduction in stress thus allowing the wider spaced trees to increase allocation to roots.

2.1.8 Influences of stand age on fine roots

Fine root biomass changes with stand development (Yuan and Chen, 2010). In the broad-leaved stands fine root biomass increased up to 70 years of stand age, whereas in needle-leaved stands, it showed a general trend of increase up to 90 years and declined thereafter. They also reported that, in the case of *Picea abies,* fine root biomass by quadratic regression analysis showed a significant increase with stand age up to 70 years, and in the case of *Pinus sylvestris* increased to 100 years, subsequently decreasing. The increase of fine root biomass with stand age appears to be a result of rapid above- and below-ground biomass accumulation associated with stand development, and this coupled with an increased nutrient concentration during stand development (Wang *et al.*, 2011 and Yuan and Chen, 2010). Hence, in young stands, the deep soil layers might be more exploited by roots to meet the nutrient requirement of the rapid aboveground growth.

Generally, fine root biomass increases to a peak at canopy closure, after which it gradually declines in maturing stands (Jagodzinski *et al.*, 2016). For example, for a *Pinus strobus* (stands 2, 15, 30, and 65 years old), Peichl and Arain (2006) found that fine root biomass increased with stand age from 0.2 Mg ha^{-1} in the youngest stand to a peak of 6.2 Mg ha^{-1} in the 30-year-old stand, after which it decreased to 3.5 Mg ha^{-1} in the oldest stand. Similarly, in *Pinus sylvestris* (stands 15, 35 and 100 years old) a peak in fine root biomass has been observed at the age of 35 and suggested that the time of canopy closure determines fine root biomass maximum (Helmisaari *et al.*, 2002). Studies on stand age influence on fine root biomass to a soil depth of 60 cm in *Picea abies* stands of 10, 30, 60, and 120 years age revealed that fine root biomass was significantly higher in the 30-yr-old stand and lower in the 10-yr-old stand (Børja *et al.*, 2008). A similar trend also found in deciduous forests. Claus and George (2005)

observed fine root biomass development in *Fagus sylvatica* and *Quercus cerris* forest. The study revealed that fine root biomass reached a maximum at an approximate age of 25, and then declined to a steady-state, as forests advanced maturity.

There exists a strong correlation between the fine root biomass and age at the tree level. For example, Finér *et al.* (2007) investigated a large dataset that included published fine root biomass data obtained by the core method for 43 *Pinus sylvestris* stands (12–131 years), 71 *Picea abies* stands (24–200 years) and 36 *Fagus sylvatica* stands (30–250 years). The mean fine root biomass of beech was 389 ± 206 g m^{-2} and this value was conspicuously higher than for spruce (297 g m^{-2}) and pine stands (277 g m^{-2}). Fine root biomass stated on the tree level correlated well with stand structural attributes than on the stand level. The fine root biomass per tree increased with basal area per tree in beech, spruce and pine stands. Authors propose that, the increase of fine root biomass with stand age appeared to be a consequence of fast above- and below-ground biomass accumulation related to stand development and also due to increased nutrient concentration in the upper soil horizons during stand development. Besides, in the older stands biomass production was lower and the foliage to non-foliage biomass ratio reduced and this might be related to reduced demands for nutrient and water supply from fine roots. As a result, this may lead to decreases in fine root biomass with age in old-growth stands.

2.1.9 Seasonal production and mortality

A significant relationship between fine root biomass and annual rainfall distribution patterns has been stated for a number of tropical forest ecosystems (Zewdie *et al.*, 2008). The pattern of seasonal variation was observed by the Sundarapandian and Swamy, (1996) in the tropical forests, this agrees with others study in the temperate forests (Khiewtam and

Ramakrishnan, 1993). During extreme summer and winter, probably due to unfavourable soil moisture and temperature, root mass deviation was at minimum. The rainy season is a favourable period for root growth in terms of soil temperature and moisture, so that, fine root mass greater in rainy than in other seasons (Zewdie *et al.*, 2008). A study conducted in a temperate forest witnessed maximum fine root mass during autumn season followed by spring and the minimum during summer and winter seasons. These temporal patterns may be ascribed to changes in soil moisture and temperature (Lopez *et al.*, 2001), nutrients and carbon allocation patterns (Pregitzer *et al.*, 2000). The turnover of fine root mass under the semi-arid climatic conditions is rapid (Bakker *et al.*, 2008). The formation of new root and subsequent death under the semi-arid ecosystems could be attributed to extreme variations of temperature, soil moisture and micro-climatic conditions.

Fine root production and mortality rate are not constant through time, though, with distinct periods of high production or mortality, leading to seasonal fluxes in live-root biomass. King *et al.* (1999) and Coleman *et al.* (2000) on *Populus tremuloides* and *Populus tristis, P. balsamifera*, respectively, showed nearly identical fine root production patterns; productivity increased rapidly in the spring until about mid-July, levelled off during August, and then began to decline through the fall season. This was also supported by the studies of Steele *et al.* (1997) and Ruess *et al.* (1996). They reported that, the majority of poplar fine root production occurred during spring and early summer (May to early July), while Block (2004) measured 10–50% of annual fine root production at depths below 30-cm after mid July in establishing hybrid poplar.

2.1.10 Methods for estimating root biomass and production

Fine root biomass and production estimation can be grouped into direct and indirect methods. Fine-root biomass and production have been estimated with direct methods that include soil-core/sequential-coring (Lauenroth, 2000), monolith (Makita *et al.*, 2011), soil-pit (Oliveira *et al.*, 2000), ingrowth-core (Vogt *et al.*, 1998) and (mini) rhizotrons (Madji, 1996), and indirectly through the use of empirical models (Kurz *et al.*, 1996).

There is no consensus in the literature on how best to estimate root biomass, production and turnover (Milchunas, 2012; Yuan and Chen, 2012). For example, Yuan and Chen (2012) in a global study that compared fine root production estimates for terrestrial ecosystems, stated significantly higher fine-root production estimates from indirect than direct methods, which is contrary to other studies where no differences between direct and indirect methods were detected (Finér *et al.*, 2011). The choice of a method may be determined by considerations such as cost, labor availability, site constraints and individual preferences rather than accuracy and precision (Levillain *et al.*, 2011; Makita *et al.*, 2011), with implications for modeling ecosystem carbon budget and allocation patterns. Therefore, this lack of consensus calls for critical evaluation of the assumptions, strengths and inherent limitations of the various methods to help researchers decide which method is best for their purposes.

It is often suggested to use various methods to quantify root dynamics (Hendricks *et al.*, 2006; Yuan and Chen, 2012), but few studies compare methods at the same sites and at the same sampling time (eg. Giardina *et al.*, 2013; Yuan and Chen, 2012; Sun *et al.*, 2015).

Soil-core: Fine-root biomass is usually estimated by the soil-core method (Oliveira *et al.*, 2000). To sample fine roots soil cores or augers are usually used. One of the most important considerations while selecting is the diameter of the corer or auger used for sampling roots (Snowdon *et al.*, 2002). The diameter of a corer should provide a good balance between sampling accuracy and intensity (Oliveira *et al.*, 2000). Commonly used core diameters range from 1.9 to 15 cm (Levillain *et al.*, 2011), but Snowdon *et al.* (2002) recommended corers of diameter >10 cm to estimate fine root biomass. Field sampling may be based on random, systematic or stratified-random designs; this is an important consideration in designing field-sampling procedures which is to avoid clumping of sampling locations so as to capture the spatial heterogeneity of root distribution. The depth to which root cores are taken is critical for accurate and reliable determination of fine root biomass. Preferably, fine roots should be sampled to the maximum root-depth limit for the site (Oliveira *et al.*, 2000). Therefore, sampling depth should be informed by a preliminary assessment of the concentration of fine roots at each depth.

The soil-core method has been widely used to estimate fine root biomass for decades (Yuan and Chen, 2012), and this is preferred by most researchers (Park *et al.*, 2007). The simplicity and its ability to capture well the spatial and temporal heterogeneity in fine root biomass distribution of the soil-core method made its utility over large scales (Makkonen and Helmisaari, 1999). Soil cores are preferred for the study of annual and seasonal variations in fine root biomass (Makkonen and Helmisaari, 2001). According to Day *et al.* (2013) root-biomass data from the soil-core method is also used to confirm the efficiency and accuracy of other methods.

The limitation of soil-core method that affect its field application and the estimates of fine root biomass, and that may over- or under-estimate fine

root biomass estimates. Soil compaction can result in over-estimation of root biomass. For example, a study in New Hampshire by Park *et al.* (2007), compaction resulted in 10% over-estimation of fine root biomass in a naturally regenerated hardwood forest ecosystem. Though, Bledsoe *et al.* (1999) suggested that using a core with a large inner diameter may reduce soil compaction and improve root-biomass estimates, but as per Park *et al.* (2007) the use of large diameter cores in rocky or stony sites may be difficult.

The difficulty in separating organic debris from fine roots may lead to over-estimation of root biomass (Snowdon *et al.,* 2002). Extracting sample cores and root processing takes substantial time, so in most studies roots are under-sampled, which affects the reliability of fine root biomass data (Berhongaray *et al.,* 2013; Taylor *et al.,* 2013). In a study of a Eucalyptus plantation in Congo, to achieve a 10% precision, Levillain *et al.* (2011) sampled 312 auger cores from the soil surface (0–10 cm). Berhongaray *et al.* (2013) found that when processing extracted cores, the time spent washing, sorting and weighing roots represented 84–93% of the total time needed to process root samples in a young short-rotation Populus plantation in Belgium. According to Bledsoe *et al.* (1999) for getting good precision a high number of core samples required to get, as well as the processing time makes soil cores expensive and impractical in highly replicated experiments. To improve field and laboratory efficiency and, to reduce root-processing time, it is recommended to carry out field sampling and laboratory techniques such as randomization, temporal prediction and diameter-class accumulation curves (Berhongaray *et al.,* 2013; Taylor *et al.,* 2013).

Ingrowth-core: The root-ingrowth core is one of the most commonly used methods to estimate fine-root production and turnover which including various modifications (e.g. Li *et al.,* 2013; Milchunas, 2012; Wang *et al.,*

2014; Van Do *et al.*, 2015). Ingrowth core method estimates the amount of fine root that grows into a defined volume of root-free soil within a specified period of time. According to Lauenroth, (2000) it is based on the assumption that disturbances of roots and the surrounding soil during core, or net installation, do not affect root production during the ingrowth period. Though, this assumption may not apply in all sites and forest types (Hendricks *et al.*, 2006). Studies found that this method provides conservative root-biomass estimates, and could under-estimate fine root production compared to sequential coring and (mini) rhizotrons. This could be due to constraints of mesh size on root ingrowth and rapid turnover of roots, which is lost before sampling (Adamek *et al.*, 2011; Milchunas, 2012). However, this method may provide fine-root production estimates comparable to other methods if the time elapsed between cores installation and root sampling is long enough to allow for maximum root colonization (Ostonen *et al.*, 2005; Jourdan *et al.*, 2008). This is a very vital consideration, mainly for sites with great seasonal fluctuations in root growth. Inexpensive and simple and straightforward field-application made this method to use extensively despite its potential limitations. According to Vogt *et al.* (1998) it is considered to be most effective in ecosystems with fast root growth such as the tropics.

The limitations of this methods includes: (i) the core installation causes great disturbance to roots and the rooting environment, (ii) when the root-free soil is placed in the cores, physical and chemical characteristics of soil are altered (iii) during most of the experiment, root growth proceeds at an artificially low root density in the cores (iv) root growth starts after a period of delay (v) root disappearance during the experiment caused by decomposition is not quantified (Vogt *et al.*, 1998; Hertel and Leuschner, 2002; Majdi *et al.*, 2005; Hendricks *et al.*, 2006).

2.1.11 Fine-root production estimates from ingrowth-core, sequential-coring methods

The mean fine root production estimate obtained from studies reviewed by Addo-Danso *et al.* (2016) was lower in the ingrowth-core method (2.06 ± 0.23 Mg ha^{-1} $year^{-1}$, n = 73) when compared to estimates provided by (mini) rhizotrons (3.81 ± 0.46 Mg ha^{-1} $year^{-1}$, n = 26) and sequential-coring methods (3.84 ± 0.93 Mg ha^{-1} $year^{-1}$, n = 59), although the differences were not significant. Earlier reviews and single studies that compared the three methods have also reported lower fine root production estimates from ingrowth-core than from other methods (e.g. Moser *et al.*, 2010; Finér *et al.*, 2011). Similarly, Finér *et al.* (2011) reported higher fine root production estimates for sequential-coring and (mini) rhizotrons methods than the ingrowth-core method, even though there were no significant differences in fine root production estimates among the three methods at the stand level (Finér *et al.*, 2011). There was a significant positive correlation between fine root production estimates obtained from sequential-coring and ingrowth-core, and ingrowth-core and (mini) rhizotrons, as well a sequential-coring and (mini) rhizotrons methods. Yuan and Chen (2012) reported parallel patterns of fine root production between sequential-coring and ingrowth-core methods in a boreal mixed forest in Ontario, Canada, but others have reported contrasting relationships between sequential-coring and other methods (e.g. Hendricks *et al.*, 2006; Moser *et al.*, 2010). The methods explained less than 50% of the variation in fine root production, specifying influences of other factors such as species, site conditions, sampling depth, fine-root size classification, resource availability, stand and environmental conditions on fine root production (Finér *et al.*, 2011; Mei *et al.*, 2010; Yuan and Chen, 2010, 2012; Smith *et al.*, 2013).

2.1.12 Fine root and tree allometry

Many investigators have employed indirect techniques to estimate fine root biomass and production due to the cost and labor requirements of direct methods. Fine root biomass of individual trees and stand can be estimated indirectly (Niiyama *et al.,* 2010). This is based on the pipe-model theory of tree form, as per this model a tree is viewed as an assemblage of pipe systems from the bottom to the top of the tree (Shinozaki *et al.,* 1964). The connecting nature of the pipes in a tree ensures that the cross-sectional area of an organ remains constant. Although it is considered as a fast, non-destructive alternative approach to estimate fine root biomass, this model has rarely been used to determine fine root biomass (Niiyama *et al.,* 2010).

Fine root biomass can also be estimated from other models based on easily measurable aboveground variables such as basal area, diameter at breast height, height and crown foliage. According to Sun *et al.* (2015), these models function on the basis of a strong relationship between fine root and aboveground variables at both tree and stand-levels. So many models have been developed and used to predict fine root biomass (e.g. Ammer and Wagner, 2002, 2005; Zerihun *et al.,* 2007; Jurasinski *et al.,* 2012). These models are cost-effective for estimating fine root biomass at large spatial scales, where aboveground variable data may be the only and dependable data available for most ecosystems. According to Lee *et al.,* 2004, unlike destructive methods, the accuracy of models does not depend on the spatial variation in root distribution in a stand. There are some limitations while using models to predict fine root biomass, which leads uncertainties in the estimates they produce (Jurasinski *et al.,* 2012). Models are unable to reflect the high temporal and spatial heterogeneity in fine root biomass distribution common in most ecosystems (e.g. Ammer and Wagner, 2005; Helmisaari *et al.,* 2007; Zerihun *et al.,* 2007). Finally, some of the assumptions used to parameterize models which may not hold true for all

tree species and ecosystems (e.g. Ammer and Wagner, 2002; Lee *et al.*, 2004).

Despite these critical roles, fine root studies are scare, and are poorly represented in many process-based ecosystem models, and limit the ability of the models to predict ecosystem responses to environmental changes and management practices (Smithwick *et al.*, 2014; Warren *et al.*, 2015). The uncertainty about root dynamics also hampers efforts to accurately estimate pool size for carbon accounting. This knowledge gap is partly attributable to methodological challenges in sampling roots to estimate biomass production and turnover (Makkonen and Helmisaari, 1999). Previous studies give support to the root–shoot functional balance theory expressed by leaf and fine root biomass (Magnani *et al.*, 2000). According to O'Grady *et al.* (2006), relationship between leaf area and fine root surface area is generally nonlinear during the growth process of seedlings. The ratios of leaf area to fine root surface area in their study were roughly constant across a range of diameter at breast heights, which reflects the pattern of uniform supply and demand for trees in the same age class.

Root biomass is closely related with aboveground biomass and stem volume are closely related with, fine roots particularly, either at individual or stand level. Hence, predicting biomass of entire root systems and fine roots with existing data for large-scale forest census of aboveground stocks should be relatively simple. Jia *et al.* (2005), found out that total and fine root biomass were significantly related to diameter at breast height and this can be used for estimating root biomass at stand level. It is clear that; root biomass is significantly associated with that of aboveground biomass, which is dependent on tree size and density.

Knowledge of root biomass and its dynamics is essential for a detailed understanding of carbon allocation and its storage in terrestrial ecosystems.

Bolte *et al.* (2004) and Petersson and Ståhl (2006) developed allometric functions for roots > 2mm diameter in German and Swedish stands of *Fagus sylvatica, Picea abies, Pinus sylvestris, Betula pendula* and *Betula pubescens*. Santantonio (1989) reported a linear relationship between fine root and leaf biomass in several conifer species; however, studies of Vanninen and Mäkelä (1999) have shown that this relationship is highly variable. Foliage biomass is usually estimated by modeling, but the limitation is that, models have not been developed for all species or regions. Only a few studies have attempted to create relationships between fine root biomass and more easily measured stand attributes (Li *et al.*, 2003; Chen *et al.*, 2004; Ammer and Wagner, 2005).

2.2 PRODUCTIVITY OF PLANTATIONS

Forest plantations are increasingly important forest resource worldwide. Owing to their higher productivity than natural forests, plantations become main source of wood products globally. A report by Forest Resource Assessment (FRA, 2010) showed that plantation forests account for 7% (264 million ha) of total global forest area. During the period from 2005 to 2010, the area of planted forests increased by about 5 million ha per year worldwide. In Asia, plantation area has increased rapidly in recent years (FOA, 2010).

2.2.4 Factors affecting plantation productivity

2.2.4.1 Species

The aboveground net primary productivity of tropical species ranged from 16 to 29.8 Mg $ha^{-1}yr^{-1}$ (Lugo *et al.*, 1988). There are significant variations in the productive capacity of the fast growing species. Kumar *et al.* (1998) compared the aboveground biomass production of four fast growing multipurpose trees in silvopasture system in humid tropics of Kerala and

reported highest biomass for *Acacia auriculiformis* (183.54 Mg ha^{-1}) and the lowest value recorded for *Ailanthus triphysa* (19.38 Mg ha^{-1}). Biomass observed in some fast growing species varies *Leucaena leucocephala* (112 $Mgha^{-1}$) and *Eucalyptus tereticornis* (96 Mg ha^{-1}) and *Acacia nilotica* (53 Mg ha^{-1}) (Singh and Toky, 1995), *Gliricidia sepium* (85.6 $Mgha^{-1}$), *Gmelina arborea* (85.6 Mg ha^{-1}) and *Leucaena leucocephala* (46.2 Mg ha^{-1}) (Fuwape and Akindele, 1997). In the case of *Phyllostachys makinoi* (105.33 Mg ha^{-1}) (Yen *et al.,* 2010), *Melia azedarach* (38.4 Mg ha^{-1}), *Ailanthus excelsa* (27.2 Mg ha^{-1}), *Populus deltoides* (5.2 Mg ha^{-1}) (Toky *et al.,* 2011), *Eucalyptus tereticornis* (169.44 Mg ha^{-1}), *Tectona grandis* (153.31 Mg ha^{-1}) and *Syzygium cumini* (132.59 Mg ha^{-1}) (Arora and Chaudhry, 2014)

Rao *et al.* (2000) compared the biomass production potential of eleven multipurpose tree species growing on sandy loam soils in Andhra Pradesh and they reported maximum biomass production (214.6 Mg ha^{-1}) in *Dalbergia sissoo* followed by *Leucaena leucocephala* (187.8 Mg ha^{-1}) and *Acacia auriculiformis* (162.4 Mg ha^{-1}). Likewise, studied conducted by Aneesh, (2014) to investigate the biomass production potential of six multipurpose tree species on black pepper based production system revealed that, there is considerable variation in biomass production: *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}. Sreedevi *et al.* (2011) recorded biomass production of 20-year-old MPTs in South Gujarat reported that aboveground biomass production is higher for *Albizia procera* (380 Mg ha^{-1}) and lowest for *Gmelina arborea* (229 Mg ha^{-1}).

2.2.4.2 Rotation age

Generally, biomass production increases, as the age advances and it stabilize when it reaches maturity. The rotation period of the species significantly influence the biomass yield (Evans, 1982). Jayaraman *et al.* (1992), reported a biomass production of 190 Mg ha^{-1} in the *Casuarina equisetifolia* plantations growing in the west coast areas of Kerala by at age of 4.5 years. Two to eight 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} (2 year old) to 126.7 Mg ha^{-1} (8-year-old) (Bargali *et al.,* 1992). This trend also reported by Vidyasagaran (2003) in biomass production of *Casurina equisetifolia* at an age of 2 year as 42.3 Mg ha^{-1} (2 year old) and 366.82 Mg ha^{-1} (9 years old). Their study suggesting that the aboveground biomass increased nine times from 2 years to 9 years in the plantations of central Kerala. *Grevillea robusta* plantation at Karnal at the age of 25 found to be 324.198 Mg ha^{-1} (Jangra *et al.,* 2010). According to Onyekwelu (2004), aboveground biomass production estimated for *Gmelina arborea* plantations of the age 5-21 years 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 increment varied from 16.2 to 20.9 Mg ha^{-1} yr^{-1}.

The accumulation of biomass increased with stand age in Eucalyptus and Acacia plantations of various ages in China was 207.45 and 189.35 Mg ha^{-1} in mature Eucalyptus and Acacia plantations (Zhang *et al.,* 2012). The biomass of nine fast growing multipurpose trees in the humid tropics of Kerala exhibited considerable variation. 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 (Kumar *et al.,* 1998). Biomass production potential of *Grevillia robusta*

plantation increased considerably with age and found to be 345.27 Mg ha^{-1} (Gopichand and Sing, 2011)

2.2.4.3 Spacing / Planting density

Forest management has a great impact on the release of nutrients from the litter, especially in short rotation forestry (O'Connell and Sankaran, 1997). The maximum impact from management practices are owing to operations associated with harvesting, site preparation, planting and early silviculture, including fertilisation and weed control (Nambiar and Brown, 1997). While planting, a variety of planting arrangements and planting densities are employed, that influences the individual tree growth and total system yield. Stand density manipulation by means of thinning and initial planting density regulations are powerful tools for achieving desired stand structures (Smith, 1986). It reported that, total stand biomass is higher for denser stand, though, low density stand have higher mean tree biomass.

Considerable differences among stands in mean tree and stand biomass yield fractions in *Ailanthus triphysa,* at the age of 8 years planted at four different densities are observed. Higher biomass production was observed in closely spaced stands than in wider spacing (Shujauddin and Kumar, 2003) similar trend observed in *Gmelina arborea* planted at three different densities in an agrisilviculture system (Swamy *et al.,* 2003). The total biomass in *Gmelina arborea* ranged from 6.96 to 13.75Mg ha^{-1} and highest biomass was recorded in trees planted under 4mx4m spacing and lowest in 4mx8m spacing, after 5 years of planting. The stands at closer spacing (1m x 0.25m) exhibited highest biomass yield observed in 5-year-old Leucaena plantation planted at six different spacings (Chotchutima *et al.,* 2013). Significant effect of spacing in biomass production in agroforestry system of Eucalyptus experimented on five spacing in Andhra Pradesh Prasad *et al.* (2010)

2.3 PARTITIONING OF BIOMASS

2.3.1 Aboveground biomass partitioning

The proportionate allocation of biomass to various above ground parts is a decisive factor that reflects the productivity of any woody ecosystem. Generally, bole fraction accounts the major portion of the total tree biomass. The percentage contribution of different tree components to the total aboveground biomass accumulation of 25-year-old *Grevillea robusta* plantation at Karnal was: bole (66.91 %), branches (12.76 %), and foliage (2.34%) (Jangra *et al.,* 2010). Likewise, 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. In this study, for all the size classes, stemwood accounted for bulk of the aboveground biomass (65 to 75%) which is followed by branchwood (12.5 to 25.2 %), foliage (5.0 to 6.5%) and twigs (4.1 to 6.5%) Kunhamu *et al.* (2011). In an age series of *Gmelina arborea* plantations in Nigeria, stemwood accounted for an average of 83.6 % of total above ground biomass, while branch and foliage biomasses accounted for an average of 13.2 and 3.3% respectively (Onyekwelu, 2004). Similarly, Paul (2013) observed similar trend in a 20 year-old *Grevillea robusta* plantation. A study in black pepper based polyculture system involving six multipurpose tree species also showed similar trend (Aneesh, 2014).

The relative proportions of growth allocated to different plant parts were also influenced by tree species and density regimes. Wider spacing reduces the relative amount of growth allocated to the bole of the tree and increased allocation to the root system (Bernardo *et al.,* 1998). Similar trend observed in *Ailanthus triphysa* stands, highest total stand biomass of 135 Mg ha^{-1} and MAI of 13.6 Mg ha^{-1} per year were obtained in closer 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 (Aneesh, 2014).

2.3.2 Belowground coarse root biomass

Belowground root biomass accumulation of tree generally vary from 3-6 Mg $ha^{-1}yr^{-1}$ (Sanchez, 1995). Even though belowground biomass makes a substantial contribution to soil organic matter, carbon and nutrient cycling, its 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, information on belowground ecosystem is by far scarce.

Root biomass estimated in 8.8 year old multipurpose trees 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}) whereas, root biomass study in silvopasture of *Acacia auriculiformis* produced highest root biomass of 16.3 Mg ha^{-1} and lowest recorded in *Casuarina equisetifolia* at 5 years (Kumar *et al.,* 1998). Belowground coarse root biomass of 4 year old *Gmelina arborea* in agrisilviculture system varied from 0.886 to 1.419 Mg ha^{-1} and it decreases when spacing increases which is accounted for 65.0 to 78.2% of total below ground biomass(Swamy *et al.,* 2003). Twenty two-year-old pepper based system with six multipurpose trees showed significant difference in root biomass production, *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). In 21-year-old *Grevillea robusta* plantation, mean tree root biomass production based on diameter class ranged from 12.94 to 59.81 kg $tree^{-1}$ and the mean stand level root biomass accumulation were found to be 18.45 Mg ha^{-1} (Samritika, 2014)

Contribution of the coarse roots to total biomass is greater 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. They observed that among the species, there was a wide range of variation in biomass accumulation in the main roots, lateral roots and fine roots. Belowground root biomass (coarse root +fine roots) accounted for 17.97 % of total tree biomass in 25-year-old plantation of *Grevillea robusta* (Jangra *et al.,* 2010). The coarse roots counted about 47 Mg ha^{-1} and the fine root biomass varied from 2.279 to 8.732 Mg ha^{-1} in different seasons in the case of *Grevillea robusta*.

2.4 LITTER DYNAMICS

Litter on the soil, or forest floor, acts as sink and source of nutrients, and the rate at which forest litter falls, and decays, regulates the energy flow, primary production and nutrient cycling in forest ecosystems (Sundarapandian and Swamy, 1999). In tropical ecosystems, maintenance of soil organic pool is achieved by high and rapid circulation of nutrients through the fall and decomposition of litter (Hobbie, 2010). As per the reports, density, basal area, age structure, latitude, season and climatic factors strongly influence litterfall in natural forests (eg. Meentmeyer, 1982; Morellato, 1992; Songwe *et al.,* 1988). Forest litter decomposition is a critical step in the formation of soil organic matter, the mineralization of organic nutrients, and the carbon balance in terrestrial ecosystems, which plays an important role in promoting the normal material cycle and nutrient balance in forest ecosystems, maintaining soil fertility and ensuring nutrient availability for plant growth.

Most of the litter dynamics studies have been confined to the forest and other natural systems. Analysis of the patterns of litter pathway in

integrated systems when subjected to stand management practices for optimization of productivity of the system, are by far, scarce. The reports available in this respect on the humid tropical agroforestry systems are summarized below.

Litter production observed in nine MPTs ranged from 3.43 Mg ha^{-1} (*Pterocarpus marsupium*) to 12.69 Mg ha^{-1} (*Acacia auriculiformis*) (Jamaludheen and Kumar, 1999). Litter production reports in natural rubber from Nigeria suggested an annual production ranging from 10.2 - 13.67 Mg ha^{-1} (Onyibe and Gill, 1992). Silvopastoral system under semi-arid conditions in *Hardwickia binata* yielded litter up to 8.1 Mg $ha^{-1}yr^{-1}$ wherein leaves contributed about 74.3% followed by branches (22.7%) and reproductive structures (3.0%) (Roy *et al.,* 1998), Kumar (2005) summarized the litter production rates for 24 tropical multipurpose tree species including three tropical pine species and reported a broad range of litter fall values from 0.27 to 14.1 Mg ha^{-1}.

Most of the studies in the natural or plantation forest ecosystems indicate a pronounced seasonality in litterfall, which generally follows a unimodal distribution pattern with a distinctive peak during the winter season or during the dry season (Shanmughavel and Francis, 1999). In some cases it coincides with the peak rainfall events (Lugo, 1992). Even though, unimodal litterfall pattern is common for most of the tropical species (Jamaludheen and Kumar, 1999), in *Acacia nilotica* plantations Gill *et al.* (1987) found that litterfall followed a bimodal trend in highly alkaline soils of north India with a principal peak in the winter and a minor one in the early summer season. Similar bimodal litterfall pattern were observed for *Populus deltoides* plantations, Dehra Dun, India with maximum litterfall during the month of October (1.93 Mg ha^{-1}) and second peak in the month of May (0.44 Mg ha^{-1}) (Raizada and Srivastava, 1986).

Litter works as a temporary sink for nutrients and it functions as a slow-release nutrient source in forest ecosystems and agroforests (White *et al.*, 1988). Litter consists of dead leaves, twigs, bark and fruits which transfer considerable quantity of nutrients to the soil when it decomposes. Lugo *et al.* (1990) observed considerable species variation in the nutrient accretion through litterfall for 10 tropical tree species including tropical pines. The nutrient return to the soil from the litter in kg ha^{-1} ranged in the order; nitrogen (55.4 to 187.2), phosphorus (2.1 to 8.9), potassium (15.0 to 45.8). George (1986) observed return of N, P, K and Ca values as 29.8, 1.63, 15.0 and 40.2 kg $ha^{-1}yr^{-1}$ from Eucalyptus hybrid litter. Jamaludheen and Kumar (1999) also reported wide species variation in N, P, K accretion through litterfall in a woodlot experiment for nine tropical multipurpose tree species that ranged from 38 (*Artocarpus hirsutus*) to 203 (*Acacia auriculiformis*) for N; 0.8 (*Artocarpus hirsutus*) to 6.0 (*Leucaena leucocephala)* for P and 3.4 (*Casuarina equisetifolia*) to 15.7 kg ha^{-1} (*Acacia auriculiformis*) for K.

Variable elemental concentrations in the litter was found to be a strong determinant of nutrient return to the soil (Jamaludheen and Kumar, 1999). In general, leaf litter accounts for a substantial portion of the total nutrients transferred to the soil followed by fine root and reproductive parts of the trees (Lugo *et al.*, 1990). Seasonal variations in the litter nutrient content have been reported by some workers. For example, Ghuman and Lal (1990) observed that nutrient turnover for *Cassia siamea* in an alley cropping system in southern Nigeria was highest during the cold season with peak nitrogen transfer of 305 kg ha^{-1} yr^{-1}, while nitrogen transfer was low (25.8 kg ha^{-1} yr^{-1}) during the rainy season. Arunachalam *et al.* (1998) also reported similar results for nitrogen whereas seasonal variation of phosphorus was narrow. Nonetheless, no distinct seasonal variation was discernible for nine tropical multiple tree species in respect of nitrogen and phosphorus concentrations of litter except that of nitrogen concentrations

which were generally lower during summer (Jamaludheen and Kumar, 1999). Although, vast information is available on the nutrient flux associated with many tropical tree species, studies on *Acacia mangium* in this respect are scarce.

2.4.1 Factors of litter production

There are many factors which influence quality and quantity of litter production which including environment, floristic composition, stand age, tree management and stocking levels (Albrektson, 1988; Vose and Allen, 1991; Finer, 1996). Also, site characteristics such as, latitude, altitude, aspect and season may strongly affect the litterfall dynamics of forests (Bray and Gorham, 1964; Luizao and Schubart, 1987; Stohlgren, 1988). Reiners and Lang (1987) observed a great decline of litter production with increase in altitude in deciduous ecosystem, whereas, coniferous leaf litterfall increased steeply with altitude. An increasing litterfall pattern towards the equatorial region is even in managed land use systems such as plantations/agroforests. According to Facelli and Pickett, (1991) soil fertility and soil-water retention are important determinants of litterfall within the same climatic range. Also, soil type influences litterfall and decay dynamics (Bernhard-reversat, (1993). Stand age exerts a profound influence on the litterfall patterns.

2.4.2 Stand management practices and litter production

Stand density management has a profound influence on litter production. Generally, litterfall increases until canopy closure and then remains constant over long periods before decreasing in old tree stands (Bray and Gorham, 1964). Singh (2000) reported higher litter production from *Alnus nepalensis* stands managed at high densities during the early part of the stand growth. However, stands with low density eventually, produced

highest litter biomass (17.6 Mg ha^{-1}). Norgrove and Hauser (2000) investigated the litter production patterns in young and old *Terminalia ivorensis* plantations thinned to 64 trees ha^{-1} and 192 trees ha^{-1}. They observed characteristic increase in litter production in stands with higher stocking which ranged from 1.83 - 2.78 Mg ha^{-1} for stands with higher stocking while in case of lower density stands ranges 0.45-0.73 Mg ha^{-1}. In general, thinning and pruning activities delays canopy closure. It is noted that, pruned trees yield less litter, albeit temporarily. Furthermore, removal of bulk quantities of foliar biomass during lopping operations may also alter the leaf fall periodicity considerably (George and Kumar, 1998).

2.4.3 Litter decomposition

In the recent years, much emphasis has been made on the nutrient dynamics associated with litterfall and its decomposition. Many workers have attempted to study litter decomposition and several reviews have been published (Singh and Gupta, 1977; Webster and Benfield, 1986). Majority of these reports are made on the monoculture stands in the temperate regions. According to Sharma *et al.* (1997) studies on the managed tropical ecosystems in general and multi species agroforestry systems in particular are rare.

Regarding litter decay rates, tropical broad-leaved litter generally decompose faster than conifers (Waring and Schlesinger, 1985; Kumar, 2005b). Kumar and Deepu (1992) observed that 5-8 months are required for complete mass loss for tropical moist deciduous litter. Jamaludheen and Kumar (1999) compared the decay rates of nine fast growing MPTs at Kerala, India and found that three species (*Leucaena leucocephala, Ailanthus triphysa* and *Paraserianthes falcataria)* decomposed completely during one-year period.

Generally, litter decay follows a bi-phasic pattern each with different rates (Palma *et al.,* 1998). For most of tropical broadleaved tree litter, the initial rapid mass loss phase correspond to about 3-4 months and nearly 30 to 50% is decomposed (Kumar and Deepu, 1992; Kunhamu and Gopikumar, 1996; Jamaludheen and Kumar, 1999). Decay rate coefficient and half-life values are helpful in comparing litter decay from diverse systems. Kumar (2005b) in his elaborate review reported that the decay coefficient for 17 species fall between 0.06 (*Eucalyptus tereticornis*) and 0.35 (*Xylia xylocarpa*) while the half life values ranges between 1.6 months (*Pterocarpus marsupium*) and 11.2 months (*Eucalyptus tereticornis*). Among the introduced MPTs, *Acacia auriculiformis* had more persistent litter (Jamaludheen and Kumar, 1999). Kunhamu *et al.* (1994) reported an inverse 'J' shaped pattern of mass decline for *Acacia auriculiformis*, which lasted till 16 months. Gopikumar *et al.* (2001) reported a bimodal pattern of litter decomposition for *Acacia mangium* with a rapid initial mass loss phase for 3 months followed by a slow phase.

Litter dynamics and associated nutrient turnover are important in agroforestry where site productivity is by and large, dependent on the nutrient return through litterfall/prunings (Kumar, 2005). In this context, leguminous trees and shrubs are reportedly having faster litter decomposition rates and hence a greater potential to improve soil fertility and productivity (Kang *et al.,* 1990). In a silvipastoral system (4-5 yr- old) involving four fast growing MPTs, George and Kumar (1998) found that nitrogen fixing *Casuarina equisetifolia* and *Leucaena leucocephala* litter decomposed completely within 6 to 7 months. Tropical homegardens are characterized by higher productivity primarily on account of the efficient litter input-output mechanisms and the associated tight nutrient cycling (Nair, 1993; Kumar and Nair, 2004). In a tropical homegarden in central Kerala, India, Kunhamu and Gopikumar (1996) reported faster decay rates

for *Terminalia paniculata* and *Bridelia retusa* while *Pongamia pinnata* was observed to be more persistent for decay.

Acacias in general, are known to be slow decomposers. For instance, poor decomposability has been reported for *Acacia auriculiformis* litter (Kumar and Deepu, 1992; Kunhamu *et al.,* 1994). However, such information on *Acacia mangium*, are by and large, limited. Gopikumar *et al.* (2001) studied the decomposition of *Acacia mangium* litter in both in homegarden and treeless open conditions during southwest monsoon and northeast monsoon seasons separately. It was observed that almost 30% of the initial mass decomposed during the first month while the mass loss was 85% by the 3rd month in the homegarden. In general, faster litter decomposition was recorded during the N-E monsoon season.

2.4.4 Factors affecting litter decomposition

It is perhaps well known that litter decay and subsequent nutrient release are determined by ecosystem characteristics (Olson, 1963), substrate quality (Swift *et al.,* 1979; Hartemink and O'Sullivan, 2001), physico-chemical attributes of the soil (Moore 1986), vegetation cover (Schoereder *et al.,* 1990) and soil faunal activity. Major factors are briefly reviewed hereunder.

Within an ecosystem, plant litter quality is the most important factor in determining the rate of decomposition (Aerts, 1997). Substrate quality as defined by physico-chemical attributes of the decomposing material has long been considered critical in determining the rate of decomposition (Swift *et al.,* 1979). Chemical indices of substrate quality include element concentrations and that of organic compounds. For instance, the strong influence of initial nitrogen content of the litter on the rate of decay has been documented for a long time (Findlay, 1934; Merrill and Cowling,

1966). Initial N content and C:N ratio were the first litter chemistry parameters used to predict the rate of decomposition (Swift *et al.,* 1979). Palm and Sanchez (1991) suggested that the polyphenols-to-N ratio of leguminous materials might serve as a useful index of mulch quality. They observed that legume leaves (*Inga edulis* and *Cajanus cajan*) with high content of soluble polyphenols decomposed and thus released N less rapidly than those with low polyphenol contents.

Although a number of chemical attributes are implicated as driving functions in the decay process, probably lignin and N concentration have attracted the most scientific attention (Melillo *et al.,* 1982; Taylor *et al.,* 1989; Jama and Nair, 1996). Lignin content in the leaf litter is regarded as an inverse index for the availability of carbon to decomposers. Consequently, higher the initial lignin concentration of litter, lower the decay rates (Palm and Sachez, 1991; Mesquita *et al.,* 1998). Strong negative correlation between initial lignin: N and mass loss has been reported by many workers (Thomas and Asakawa, 1993; Loranger *et al.,* 2002). However, Kumar and Deepu (1992) could not find any significant correlation between lignin:N ratio and decay rate coefficients (k) for six tropical species. They found that N content of detritus is a better predictor of decay rate constant than lignin.

To conclude, several structural chemistry attributes such as initial lignin, N and P concentrations, lignin:N ratio, C:N ratio, C:P ratio are suggested as indictors of litter bio degradability (Berg, 1986), however, there is no consensus as to which chemical parameter is the best predictor of decomposability (Loranger *et al.,* 2002).

2.4.5 Nutrient release patterns

The most important feature of litter decomposition is its enormous potential to release nutrients in a plant available form. Many reports suggest an increase in N content in the residues during the early phase of litter decomposition (Aber and Melillo, 1982; Berg, 2000; Alhamd *et al.,* 2004). In the silivopastoral study, George *et al.* (1998) however, observed considerable variations among species in their N release pattern. For instance, slow decomposing *Ailanthus triphysa* and *Acacia auriculiformis* exhibited a three-phase pattern (initial rapid release followed by modest accumulation phase and final release phase) while fast decomposing litter (Casuarina and Leucaena) showed only a two-phase pattern. In homegarden situations, *Acacia mangium* litter also showed net immobilization of N during the early phase of decomposition (Gopikumar *et al.,* 2001). C:N ratio of the decomposing material often decides the course of N release, which are inversely related (Alhamd *et al.,* 2004). Usually, plant residues with C/N ratios of ca. 27 mineralizes N where as those with C:N ratios of > 27 immobilize N (Seneviratne *et al.,* 2000). However, Mayers *et al.* (1994) proposed the cut-off point of the C:N ratio for N mineralisation/immobilization as around 25.

Although, much information exist on effect of plant quality on decomposition and N mineralizaion, few studies have evaluated the relationship between litter quality and P release (Palm and Sanchez, 1991). In one such study, Kwabiah and Stoskopf (2001) monitored the P flux associated with decomposing litter of six agroforestry tree species and found that P release was strongly correlated with total P and C: P ratio. Also, k values (decay coefficient), N and P release were strongly correlated with total P implying the role of total P in controlling the rate of decomposition, N and P release. Mayers *et al.* (1994) have suggested a threshold N: P ratio of 10 for mineralization of P in plant organic residue.

Many reports suggest K in the residual litter showing initial rapid release followed by a slower final release probably on account of its mobile nature (Jamaludheen and Kumar, 1999).

2.4.6 Soil properties

Litter dynamics and associated nutrient turnover improve the soil organic matter and mineral nutrient pools. Many workers have reported such improvement in soil properties on account of litter inputs in tree-based systems (Singh *et al.,* 1989; George and Kumar, 1998; Singh, 2000). However, soil fertility improvement depends on litter production, litter chemical quality and extent of nutrient mineralisation from the decomposing litter. For e.g. in a silvopastoral system involving four MPTs, George and Kumar (1998) observed that tree growth over five years had substantially improved the soil chemical properties. Also, among the four MPTs, N-fixing trees such as *Acacia auriculiformis* and *Leucaena leucocephala* showed relatively higher concentrations of soil N, available P and K. Issac and Nair (2004) made similar improvement in soil nutrient status in an *Artocarpus hirsutus* based agroforestry system.

Stand density manipulations often influence the extent of litter production and associated nutrient return to the soil and hence, may affect the soil fertility. For instance, Singh (2000) observed higher soil organic C and P for *Alnus nepalensis* trees planted at higher densities (4444 trees ha^{-1}) which obviously recorded higher litter production compared to lower densities. However, higher soil N content was observed for the lowest planting density (625 trees ha^{-1}), which may probably be on account of better N mineralisation efficiency at lower stocking levels.

2.5 CARBON SEQUESTRATION

Ecosystem carbon (C) stocks are represented by five carbon pools: carbon stored in live tree biomass (above and belowground), carbon stored in dead woody material (standing and down), carbon stored in understory biomass (live, dead, above and belowground), carbon stored in forest floor, and carbon stored in mineral soil (Bradford and Kastendick, 2010). The carbon is stored both in the form of biomass (trunks, branches, foliage, roots, etc.) and in the form of organic carbon in the soil. Tree plantations can be an efficient tool for combating climate change as they help in CO_2 sequestration in the short term and mitigating atmospheric levels of CO_2 in the long term (Silver *et al.,* 2000 and House *et al.,* 2002). Lamb *et al.,* (2005) reported that there is an increasing trend of growing tree plantations in the tropics and subtropics for green house gas mitigation, restoration of degraded soil and protection of watershed. Although several studies have been conducted for studying the C sequestration potential of temperate plantations, but those related to C sequestration potential of subtropical and tropical tree plantations are still lagging behind (Paul *et al.,* 2002; Silver *et al.,* 2004). Rytter (2012) reported the C sequestration in woody biomass and soil C sequestration to be 76 and 9.0 Mg ha^{-1} for willow and 80.1 and 10.3 Mg C ha^{-1} for poplar plantation over a period of 20-22 years. Carbon partitioning in trees often follow their biomass production patterns.

Several studies have reported agro-ecosystems to contain approximately 12 per cent of the world terrestrial C (Smith *et al.,* 1993; Dixon *et al.,* 1994; Dixon, 1995). Chauhan *et al.,* (2011) while working on biomass and C sequestration potential of poplar-wheat intercropping system found that the aboveground biomass and belowground biomass contributed the maximum (37.3 Mg ha^{-1} at the age of 6 years) towards aggregate carbon pool under agroforestry system. Thevathasan and Gordon (2004) observed that the annual carbon sequestration in a hybrid poplar based intercropping field

was four times higher compared to sole cropping agricultural fields. For smallholder agroforestry systems in the tropics, potential C sequestration rates range from 1.5 to 3.5 Mg C ha^{-1} yr^{-1} (Montagnini and Nair, 2004).

2.5.1 Aboveground C sequestration

Significant variation in C sequestration potential has been observed among different tree species. Especially this is true with fast growing tree species. As C accumulation in trees is related to biomass, it increases with stand age and the C storage is larger in older stands. The largest storage of carbon is in the wood. As the share of the branches increases in older stands also more carbon is accumulated in the branches. C concentration was found to be increasing from young stand of silver birch (47 per cent) to middle aged stand (49.30 per cent) and then decreasing in old stand (49.19 per cent) in case of stem. Similarly, C content in stem bark was found to be 51.06 per cent in young stand, 54.03 per cent in middle-aged stand and 51.88 per cent in old aged stand. Old branches were also reported to have 48.30, 50.78 and 50.73 per cent C concentration in young, middle and old stands respectively (Uri *et al.,* 2012). The values of aboveground biomass density in a study for Garhwal Himalaya ranged between 101.42 and 434.43 Mg ha^{-1} and the values of above ground C density ranged between 46.65 and 199.84 C Mg ha^{-1} (Sharma *et al.,* 2010). A comprehensive study on the production and C sequestration potential of *L. leucocephala* during the fallow phase carried out by Lasco and Suson (1999) using a 6-year-old model fallow reported above-ground *Leucaena leucocephala* biomass increased from 4 Mg ha^{-1} in the first year to 64 Mg ha^{-1} in the sixth year (end of the fallow).

Zabek and Prescott (2006) developed equations for short-rotation intensive-culture poplar plantations and predicted aboveground leafless biomass accumulation to be ranging from 9.2- 13.6 Mg ha^{-1} $year^{-1}$ and

73.7- 88.7 Mg ha^{-1} for 12 and 14 years old plantations respectively. They also predicted bole biomass accumulation to be ranging between 7.5 to 11.3 Mg ha^{-1} $year^{-1}$. Total carbon in aboveground leafless biomass at age 12 ranged from 51.2 to 75.7 Mg ha^{-1}.

2.5.2 Belowground C sequestration

Information on C stocks of belowground vegetation components are seldom reported, and those that have been reported lack the required scientific rigor. In fact intensive agroforestry research involving roots began in the 1990s (Schroth, 1995; Atkinson, 1996; van Noordwijk *et al.,* 1996). Available reports, however, suggest that as much as 33 per cent of the global annual net primary productivity (NPP) is used for fine-root production (Jackson *et al.*,1997), which is a major input to soil organic matter (SOM) pool (Nair *et al.,* 2010). Given their high biomass (Albaugh *et al.,* 2004; Samuelson *et al.,* 2004) and slow decay rates (Ludovici *et al.,* 2002), tap roots and large roots are probably much more important in contributing to belowground C sequestration. There always exists considerable variation in the belowground carbon sequestration with tree species. Roots of various MPTs have been reported to have varying carbon concentrations such as 40.26 (*Anogeissus pendula*), 41.49 (*Acacia nilotica*), 41.80 (*Dalbergia sissoo*), 41.86 (*Azadirachta indica*), 42.38 (*Emblica officinalis*), 42.90 (*Butea monosperma*), 44.43 (*Eucalyptus tereticornis*) and 44.96 per cent (*Albizzia procera*) (Prasad *et al.,* 2010). Kunhamu *et al.,* (2011) reported the mean carbon stocks in *Acacia mangium* (6.5-yr-old) roots to vary from 3.08 to 8.68 kg $tree^{-1}$ based on planting density. Similarly, MAI in a mean tree of *Acacia mangium* also showed variable trend within a range of 0.47–1.34 for planting density 625 to 5000 trees ha^{-1}. A 25-yr-old *Grevillea robusta* plantation has been found to show an appreciable carbon in aboveground biomass (130 Mg C ha^{-1}) and the allocation of carbon to belowground tree components amounted to

23.408 Mg C ha^{-1}.The partitioning of carbon concentration in different components of *Grevillea robusta* was 49.50, 48.46, 45.57, 42.18 and 43.52 per cent for bole, branches, leaves, coarse roots and fine roots respectively (Jangra *et al*, 2010). Keith *et al.,* (1997) suggested that in an unfertilized stand of *Eucalyptus pauciflora,* aboveground and belowground portions constituted about 80 and 20 per cent of the total C content of the biomass (i.e. 138 Mg ha^{-1}) respectively. Oelbermann *et al.,* (2003) observed that roots of *E. poeppigiana* in 4- and 10-year-old alley cropping systems had an annual coarse root increment of 0.4 Mg C ha^{-1} yr^{-1} for 10-yr-old trees compared to 0.2 Mg C ha^{-1} yr^{-1} for the 4-yr-old trees. This observation inferred that the ability of roots to sequester carbon will also increase with age of trees. Fang *et al.,* (2010) also observed C storage in *Populus deltoides* (Mg ha^{-1}) to be 0.628 to 0.968 in case of coarse roots and 0.050 to 0.155 in fine roots (94 to 250 trees ha^{-1}).

2.5.3 Soil C sequestration

About 75 per cent of total terrestrial C is stored in the world's soils (Henderson, 1995). The global soil carbon pool has been estimated to contain more than four times as much carbon as in the biotic pool and about three times as much as in the atmospheric pool (Lal, 2004). Bohn (1976) estimated that about 30 x 10^{14} kg of organic carbon is present in the soils. Soil organic matter (SOM) has been recognized for its role in the carbon (C) cycle as a sink for carbon dioxide (CO_2) and other greenhouse gas emissions to the atmosphere and is a key indicator of soil quality.

Amount of C diverted towards soil organic matter is greatly influenced by the amount of belowground C allocation. This pool of C in the soil is the largest storage site in the global C cycle (Mellilo *et al.,* 1990; Schlesinger, 1990). Thus increased allocation to belowground through root production, turnover and exudation is important for sequestering C under conditions of

increasing atmospheric CO_2 concentration (Curtis *et al.,* 1995; van Veen, 1991)

Reviewing the available information on SCS in agroecosystems worldwide, overall, the land-use systems were ranked in terms of their SOC content in the order: forests > agroforests > tree plantations > arable crops (Nair *et al.,* 2009). Trettin and Jurgensen, (2003) reported that SOC concentration in forest soils may range from 0 per cent in very young soils to as much as 50 per cent (w/w) in some organic or wetland soils. Tropical and sub-tropical ecosystems store about 30 per cent of global soil organic carbon (Dalal and Carter, 2000). Saha *et al.,* 2008 reported higher values of soil C content within 1 m profile that ranged from 101.5 to 127.4 Mg ha^{-1} for tropical homegardens. This higher CS could be attributed to higher tree density and species diversity (Schwartz *et al.,* 2000; Tilman *et al.,* 2001; Srivastava and Vellend, 2005). Niu *et al.,* (2009) observed that out of the total carbon sequestered in *Michelia macclurei* and *Cunninghamia lanceolata* plantations about 57.1 and 55.2 per cent respectively was found in the soil pool. In a 12-year HI trial on a Nigerian Alfisol, *G. sepium* and *Leucaena leucocephala* increased surface soil organic carbon (SOC) by 15 per cent (2.38 Mg C ha^{-1}) compared to sole crops (Kang *et al.,* 1999). Jensen (1993 a,b) reported that approximately 16 Mg C ha^{-1} could be stored if rice fields were transformed into homegardens in Java. Beer *et al.* (1990), while working with cacao–*Erythrina poeppigiana* and cacao–*Cordia alliadora* over a period of 10 years, reported an increase of SOM in the top 45 cm layer by 42 and 16 Mg ha^{-1} respectively. This would amount to about 21 and 8 Mg C ha^{-1} sequestered, respectively.

The carbon content also varies with soil depth. A 6.5 year old *Acacia mangium* stand at variable planting densities from humid Kerala showed higher SC content in the range of 27.02 to 34.64 Mg C ha^{-1} at 0–15 soil depth (Kunhamu *et al.,* 2011). However, for 6 year-old poplar (*Populus*

deltoides) based agroforestry systems in Punjab, India, Gupta *et al.,* (2009) reported a lower value of 13.3 Mg ha^{-1} (0 to 15 cm layer). Similar lower soil C content (18.2 Mg C ha^{-1}) has been reported for cacao (*Theobroma cacao* L.) based agroforestry system in West Africa (Isaac *et al.,* 2005) for 0-20 cm soil layer. For instance, Jangra *et al.,* (2010) conducted an experiment on carbon sequestration in the *Grevillea robusta* plantation on a reclaimed sodic soil in northern India and they found that about 0.96 per cent of soil organic carbon concentration occurred at 0–15 cm soil depth. There was a considerable decrease in the concentration of soil carbon with increasing depth. The soil organic carbon pool at 0-30 cm depth accounted for 56.18 per cent of the total organic carbon pool up to 1 m soil depth. They also reported the variation in soil carbon (Mg C ha^{-1}) with depths as: 17.09 (0–15 cm), 9.90 (15-30 cm), 8.00 (30-45 cm), 4.41 (45-60 cm) and 8.63 (60–100 cm). Chauhan *et al.,* (2011) observed a decreasing trend in soil organic carbon with soil depth in all the poplar plantations and control plots. The concentration was significantly high in surface soil layer (0–15 cm) than sub-surface depths of 15-30 and 30-60 cm. Similar results were also reported by Srinivasan *et al.,* (2010) and Gupta *et al.,* (2009) in coconut interplanted with MPTs and poplar based agroforestry system respectively. Tumwebaze *et al.,* (2012) also observed SOC at 0-25 cm depth to be highest and least at 50–100 cm under *Grevillea robusta*, *Casuarina equisetifolia, Maesopsis eminii* and *Markhamia lutea*. The higher SOC in the upper layers of soil may be ascribed to the higher litterfall and litter decomposition which subsequently decline with soil depth.

Materials and methods

MATERIALS AND METHODS

3.1 LOCATION

The experiment was conducted at the Livestock Research Station, Thiruvazhamkunnu, Palakkad district, Kerala. The location has an elevation of 60-70 m above mean sea level and is situated at 11°21'30''N latitude, 76°21'50'' E longitude (Plate 1).

3.1.1 Climate and soil

The site experiences a warm humid tropical climate with a mean annual rainfall of 2800 mm during the study period (June 2013–November 2014), most of which is received during the southwest monsoon season (June–August) with a secondary peak in September–October. Mean maximum temperature ranged from 28.5°C (June) to 36.7°C (March) and mean minimum temperature from 22.2°C (September) to 25.7°C (April) during the experimental period as per the meteorological records maintained at Thiruvazhamkunnu. Soil of the experimental site is Ultisol (very deep, clayey, mixed Ustic Palehumults) with an average pH of 5.4 and bulk density of 0.86 g cm^{-3} (0–15 cm; Kunhamu *et al.*, 2010).

3.2 EXPERIMENTAL DETAILS

Investigations were carried out in an existing 12-year-old *Acacia mangium* stand that was established as part of a larger experiment to study the effect of planting density and pruning on the growth and productivity. This trial was established in two- factorial randomized block design with three replications. The factors were planting densities at four levels and pruning at two levels. The planting densities selected were 650, 1,250, 2,500, and 5,000 stems ha^{-1} (4x4, 2x4, 2x2 and 2x1 m respectively) and the two pruning levels were pruning up to 50% tree height and no pruning. The plot size is 300 m^2 and the total number of plot is 24 (4x2x3).

Plate 1. Twelve- year- old *Acacia mangium* experimental plot at the Livestock Research Station, Thiruvazhamkunnu, Palakkad district, Kerala

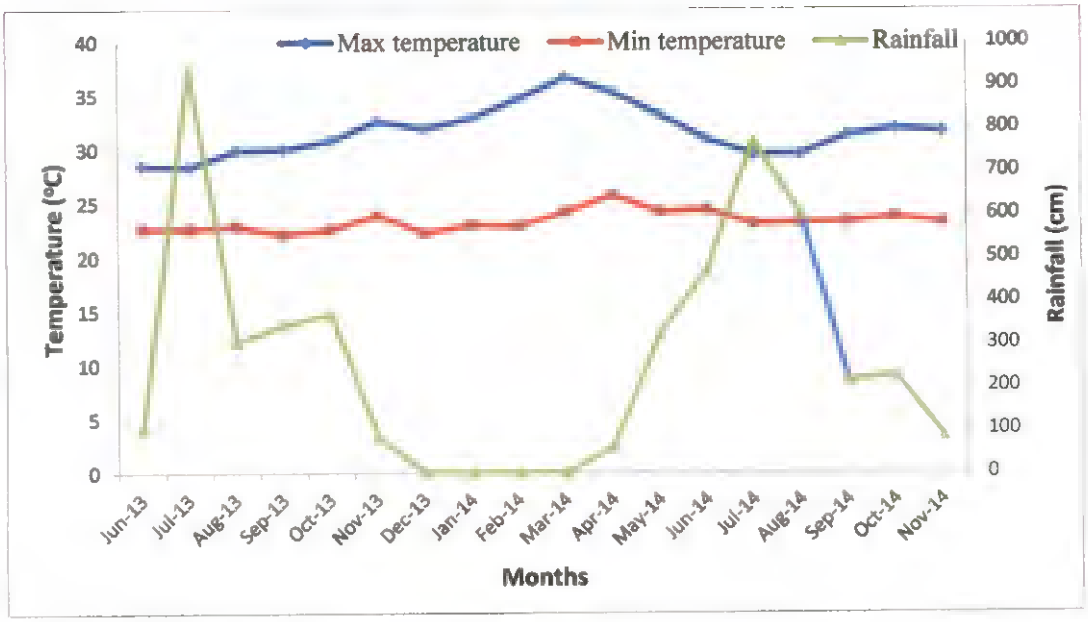


Fig: 1 Climate data during the study period (June 2013-November 2014) at Thiruvazhamkunnu, Kerala

3.3 FINE ROOT STUDY

Two prominent methods viz. sequential coring and ingrowth methods were employed for studying the fine root dynamics. Sequential coring is the traditional method of taking soil cores at specific soil depths and sampling the fine root count (Vogt *et al.*, 1998). Ingrowth method involves filling root free soil in the tree root zone by using specially designed ingrowth cores. Perforated circular aluminium mesh bags (diameter 15 cm, length 30 cm, mesh size 4 mm) were filled with root-free soil dug out from distinct sampling locations around the selected trees in each of planting density cum pruning treatment plots and installed in the same dugout location. Sequential coring involved taking soil core of the same size as the ingrowth cores (diameter 15 cm, length 30 cm) from specified locations around the selected trees (Plate 2 and 3).

2.a. Taking soil pits around the selected tree

2.b . Three pits were taken at equidistance from tree

2.c. Sieving the soil taken from the pits to remove the roots

2.d. Empty ingrowth mesh bag

2.e. Filling the mesh bag with root free soil

2.f. Ingrowth mesh bag installed in the field

Plate 2. Installation of Ingrowth cores in 12 year old *Acacia mangium* at varying stand density at Thiruvizhamkunnu, Kerala

3.a. Retrieval of ingrowth mesh bags

3.b. Sequential soil cores taken at 30 cm from ingrowth mesh bags

3.c. Soil samples of ingrowth and sequential cores

3.d. Soil samples sieved and the roots are separated

3.e. Fine roots separated from the soil samples

Plate 3.Retrieval of ingrowth mesh bag, digging of soil cores for sequential core method and processing of the fine roots in 12 year old *Acacia mangium* at varying stand density at Thiruvizhamkunnu, Kerala

3.3.1 Installation of ingrowth cores and sequential soil coring

Representative trees belonging to different spacing and pruning treatments were identified for installation of ingrowth cores and sequential coring based in random selection. One tree corresponding to each treatment plot was selected while care was taken to avoid border trees. The soil cores were taken corresponding to three seasons viz. summer season (February- April), rainy season (June- August) and winter season (October- December). Corresponding to each season three sampling points were selected around the selected tree for ingrowth and sequential coring separately. Three sampling points were taken at equidistance of one meter from the base of the tree such that two points occupy in N-S directions from the base of the tree. The third sampling point was randomly selected from the base of the tree at 90^0 either towards the E or W direction. The sampling was followed for each of the selected tree in the 24 experimental treatment plots. Hence, total number of sampling points for installation of ingrowth aluminium mesh bags was 72 (4 treatments x 2 pruning x 3 replication x 3 cores) for one season. A new set of 72 mesh bags was installed during December 2013, April 2014 and August 2014.

Sequential coring was made 30 cm adjacent to each of the installed ingrowth cores such that there were 72 sampling points (4 treatments x 2 pruning x 3 replication x 3 cores) for sequential coring also.

3.3.2 Root sampling and processing

During each season, 24 aluminium mesh bags were removed after 2 month of root re-colonization, one corresponding to each treatment plot from among the installed 72 bags. Another set of 24 mesh bags was removed after 3 months, and the last 24 mesh bags after 4 months of installation. Simultaneously as part of sequential coring, 24 soil cores were taken 30 cm adjacent to the ingrowth cores during each of the sampling dates.

All fine root samples (diameter <2 mm) were washed free of soil and separated carefully into living roots and dead roots. Living roots were sorted according to various criteria such as lack of flotation, living stele, bright colour and resilient aspect (Vogt and Persson, 1991). The samples of each component were dried at 65°C to constant weight. After carefully removing the last adherent soil particles by hand, samples were weighed on a scale accurate to 10^{-4} g.

3.3.3 Calculations

3.3.3.1 Sequential coring method

Fine root production was estimated from sequential soil coring data by "compartmental flow method" or "decision matrix method" (McClaugherty *et al.*, 1982; Fairley and Alexander, 1985; Santantonio and Grace, 1987). The decision matrix (Table 1) was adapted from Fairley and Alexander (1985). It estimated fine root production between two sampling dates from changes in living and dead root biomass and losses of root necromass due to decomposition:

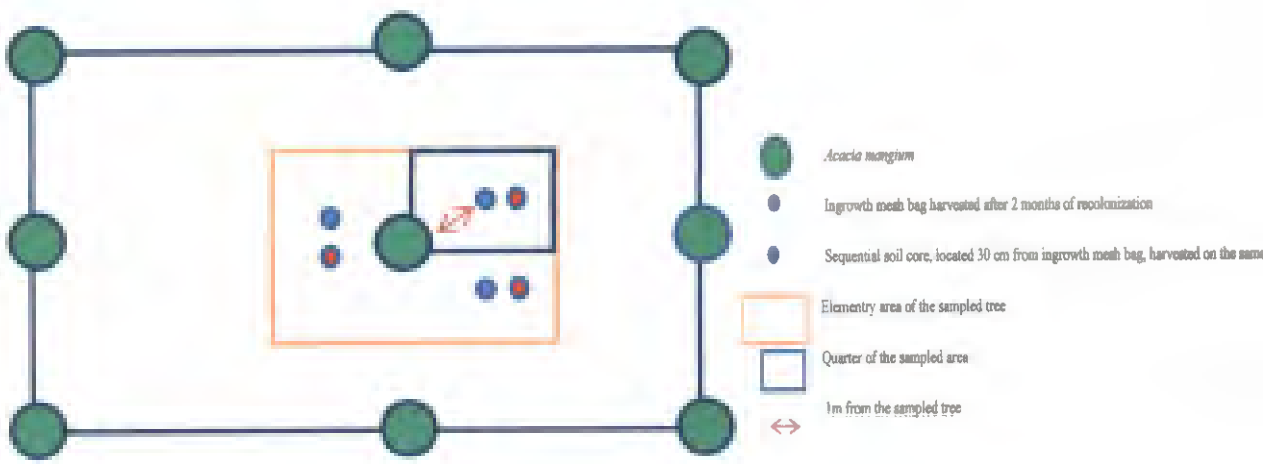


Fig. 2. Diagrammatic representation of one of the sampled plots for sequential core and ingrowth core method. Each soil core located in the centre of elementry area of sampled tree (1 m distance), in the diagonal between the sampled tree and the furthest sampled tree.

Table 1: Estimation of fine root adapted from Fairley and Alexander (1985) decision matrix

		B		
		Increase	Decrease	
			$\Delta B<\Delta N$	$\Delta B>\Delta N$
N	Increase	P= $\Delta B+\Delta N+D$	P= $\Delta B+\Delta N+D$	P=0
	Decrease	P= ΔB	P=0	P=0

P is fine root production, B is fine root biomass, N is fine root necromass, D is fine root decomposition rate from month i–1 to 1, Δ=(value of B, N collected in month i)-(value of B, N collected in month i–1).

$$P_a = \Delta B_{i,i+1} + \Delta N_{i,i+1} + D_{i,i+1}$$

where P_a was annual fine root production, $\Delta B_{i,i+1} + \Delta N_{i,i+1} + D_{i,i+1}$ were the variations in fine root biomass and necromass, respectively, from month i to month i +1, $D_{i,i+1}$ was the amount of necromass found in month i (N_i) decomposed between month i and month $i + 1$.

3.3.3.2 Fine root decomposition study

Conventional litter bag technique was employed for studying the fine root decomposition. Fine roots were excavated from the tree surface horizon (0-30 cm) and then carefully separated from the soil and the adhering soil particles using magnifying glasses and tweezers. The fine roots were kept for air drying for one week. Air dried fine roots of 10 g weight were transferred to nylon mesh bags of size 20 × 20 cm. Prior to installation of the bags in the soil, triplicate samples of fine roots of 10 g were subjected to oven drying and dry weights computed. Fine root mesh bags were installed in the treatment plots corresponding to the first replication of density cum pruning trial plots (8 plots; 4 spacing x 2 pruning). In each plot 36 bags were placed in the top soil (a thin layer of soil covered the bags) in the space in between the interior tree rows in the order of 12 bags in three rows. The total number of bags installed was 288 (36 bags x 8 plots). At monthly

intervals 3 bags were retrieved from each plot i.e., 72 bags for residual weight assessment. The fine root detritus were carefully washed and made free from all extraneous materials and oven dried at 70°C till constant weights. The oven dry weights were recorded. Representative bi-monthly samples (triplicate) were kept aside for phytochemical analysis.

3.3.3.3 Ingrowth core method

Fine root production was estimated as the increase in root biomass and necromass from the installation of mesh bags with up to 2–4 months of root re-colonization. Data obtained after 2 month of root re-colonization were excluded from the analysis as the fine root development could likely be influenced by mesh bag installation (Godbold *et al.*, 2003), because of the delay in regrowth after root severing (root scarring and reiteration) or, conversely, to avoid an excessive number of roots (cohorts) emitted after severing.

Annual fine root production (P_a) was estimated by the ''positive increments'' approach (Neill, 1992)

$$P_a = \frac{365}{N}\{\sum_{i=2}^{4}\sum_{j=1}^{3}(P_{i,j} - P_{i\_1,j})\}$$

where P_a was annual fine root production over the whole sampling year (three seasonal samplings periods j), P_{ij} was fine root production after i months of regrowth (where i = 3, 4) during season j, N was the number of days throughout the study period between 2 and 4 months after mesh bag installation (N = 270 days in our study).

The average annual fine root production obtained from the sequential coring method and ingrowth core methods corresponding to the core soil volume (15cm diameter and 30 cm deep) in grams were converted to Mg ha^{-1} by appropriate mathematical computations. Mean tree fine root production was computed by

dividing the per hectare production with the effective number of trees in each density regime.

3.3.4 Fine root turnover

For both soil coring methods, fine root turnover (year^{-1}) was calculated as the ratio of annual fine root production (Mg ha^{-1} year^{-1}) to mean standing fine root biomass at any given time (Mg ha^{-1}) obtained from the sequential coring data. We used the mean standing biomass (Aber *et al.*, 1985; Hertel and Leuschner, 2002; Ostonen *et al.*, 2005) instead of maximum (Gill and Jackson, 2000; Godbold *et al.*, 2003) or minimum (Hendrick and Pregitzer, 1993) standing biomass to take into account large seasonal fluctuations over the year.

3.3.5 Carbon and nutrient estimation in the annual fine root production

Elemental carbon concentration in the fresh fine roots were analyzed using elemental carbon analyzer (CHNS analyzer, Elementar, USA). For this triplicate samples of fine roots were collected separately from all the treatment plots. The average fine root carbon concentration (%) corresponding to various density regimes were multiplied by corresponding annual fine root production to get the carbon accumulation in the annual fine root production.

Similarly representative samples of fine roots from all the treatment plots were used for N, P and K analysis. Fine root nitrogen was analyzed using continuous flow analyzer method, phosphorus by vanado-molybdo phosphoric yellow colour method and potassium following flame photometry (Jackson, 1958). The average fine root N, P and K concentrations (%) corresponding to various density regimes were multiplied by corresponding annual fine root production to get the N, P, K accumulation in the annual fine root production.

3.3.6 Carbon, nutrient release in the decomposing fine roots

Triplicate samples of bi-monthly detritus corresponding to each density cum pruning treatments were analysed for elemental carbon (CNHS analyser). Also detritus nitrogen (Skalar method), phosphorus (vanado-molybdo phosphoric yellow colour method) and potassium (Flame photometry, Jackson, 1958) were assessed. The fine root carbon content (Mg ha^{-1}) corresponding to each density regime was multiplied by the annual rate of fine root decomposition to get annual carbon release to the soil. Similarly the N, P and K accumulation in the annual fine roots production were multiplied by the annual rate of fine root decomposition to get annual N, P and K release to the soil.

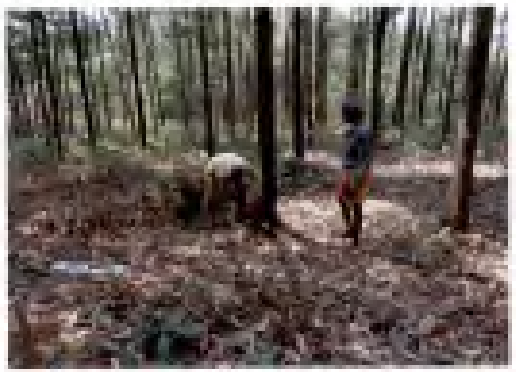
3.3.7 Statistical analysis

Treatment effects on fine root production, carbon content, N, P and K content, fine root decomposition rate, C and nutrient release in the fine roots in response to various density and pruning regimes were analyzed following software SPSS (version 20) using a two-way ANOVA. Treatment means were compared following Post hoc analysis using DMRT.

3.4 BIOMASS ESTIMATION

3.4.1 Aboveground biomass estimation

In order to study the functional relation between the aboveground biomass production and planting density, the 12-year-old *A. mangium* trees were subjected to destructive sampling (Plate 4). Two trees were randomly selected from each of the 24 planting density cum pruning experimental plots such that a total of 48 trees were selected for destructive sampling. The selected trees were marked using red paint. After recording the total height and diameter at breast 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



4.a. Felling of selected tree

4.b. Stump of the felled tree

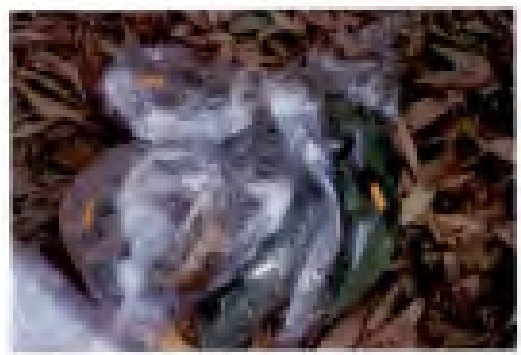
4.c. Cross cutting of felled tree

4.d. Branchwood assessment in progress

4.e. Stemwood assessment in progress

4.f. Leaf fresh weight assessment

4.g. Twig weight assessment in progress



4.h. Component samples for moisture content determination

Plate 4.Various stages of aboveground biomass study in 12 year old *Acacia mangium* at varying stand density at Thiruvizhamkunnu, Kerala

wood, branch wood, twigs and foliage. Fresh weights of the aboveground components were recorded immediately after felling using appropriate spring scales (nearest to 0.1kg or 10 mg). Triplicate samples (250 g each) of stemwood, branchwood, 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. The fresh weights of the component parts were multiplied by the corresponding moisture content and their dry weights computed on per tree basis. All the component dry weights were added to get the mean tree aboveground biomass. The mean tree dry biomass corresponding to each of the components were multiplied by the number of trees per ha and computed the component biomass per ha. Biomass per ha corresponding to each of the components were summed up to calculate the total aboveground biomass per ha.

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

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

3.4.2 Belowground biomass estimation

From among the two trees earmarked for aboveground biomass per plot, one tree was randomly selected for belowground biomass study (Plate 5). Hence a total of 24 trees were excavated for biomass study using powered earth mover (Tata Hitachi). The fresh weights were taken. 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 as discussed above for aboveground biomass determination.

5.a. Digging soil for root excavation

5.b. Separation of root system after soil removal

5.c. Root weight estimation and sample collection

Plate 5. Various stages of belowground biomass study in 12 year old *Acacia mangium* at varying stand density at Thiruvizhamkunnu. Kerala

3.5 BIOMASS C- SEQUESTRATION

Organic carbon content in the plant samples were determined by dry ash method using muffle furnace. Ten gram of the sample was weighed in a crucible. The crucibles were then placed inside the muffle furnace and heated at 506°C 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.

3.6 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 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.

3.6.1 Estimation of Nitrogen

Total nitrogen content in plant samples was determined by continuous flow analyzer 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 660 nm. 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 Selinium powder mixture – 3.5 g Se powder was weighed. One 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 ^{o}C. The black colour of the solution slowly changed to deep blue colour and then light yellow. The solution was then cooled.

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

Procedure: Plant sample (leaves, stem wood, branches and twigs) of 0.2 g was weighed in the digestion tube. Digestion mixture of 2.5 ml 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^{o}C 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^{o}C 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 continuous flow analyser.

3.6.2 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 continuous flow analyser 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.

3.6.3 Estimation of Potassium

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

3.7 VOLUME ESTIMATION OF FELLED TREES

Prior to biomass estimation all the 48 trees were assessed for volume. The trees were divided into 2 m sections up to the tip of the tree and mid girth of each section was recorded. The volume of each section was estimated following

Huber's formula, $(g^2/4\pi)$ x 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.

3.8 LITTER DYNAMICS

The primary objective of this trial was to evaluate the changes in litter production, decomposition and the associated nutrient flux as a function of stand density and pruning in a 12-year-old*A. mangium* stand.

Specially designed circular traps (Hughes *et al.*, 1987) were used for litter collections. Each circular trap had a collection area of 0.24 m^2 with 20 liters capacity (Fig 3). For each trap, four 210 cm long galvanized (2-3 mm) iron wire were used. A tripod was made using the three galvanized wires. The remaining one was made into a hoop of diameter 55.2 cm by overlapping the ends of wire. This hoop was tied horizontally over the tripod. Gunny bags were placed inside the wire hoop with the tapering end downwards. It was then fixed in the soil with the galvanized wire piercing the soil 5 cm deep.

Five litter traps were randomly placed in each of the 24 experimental plots (4 spacing x 2 pruning x 3 replications) giving a total of 120 traps. The traps were placed at a uniform height of 0.75 m from the ground. Care was taken to avoid placing the traps on plot edges to minimize the border effect. Litter collections (composite litter consisting of leaf, twigs and floral parts) were made at monthly intervals for one year period (July 2013 to June 2014). The monthly litter samples so collected were taken to the laboratory and oven dried at 70°C for 48 hours until constant weights and the mean monthly litterfall on unit area basis (g m^{-2}) was recorded. The monthly litter collection in g m^{-2} was converted to kg ha^{-1} basis. All the monthly collections were added to compute the total litter production per ha on yearly basis.

3.8.1 Litter decomposition

The rate of litter decomposition for *A. mangium* was studied following the standard litterbag technique (Bocock and Gilbert, 1957; Anderson and Ingram, 1989). Freshly fallen/senescent foliage of *A. mangium* were collected from the experimental area during June 2013 and were air-dried under shade for 48 hours. Three sub-samples were kept aside for analyzing initial nutrients concentration (N, P, K) and initial lignin content. Hundred grams of fresh litter was placed in the nylon mesh bags with dimensions 30 x 30 cm and mesh size 4 mm. Triplicate samples of the fresh litter were also collected for estimating moisture content, based on which the oven-dry weight of the samples were estimated.

Forty eight litter bags were placed in each plot which were arranged in such a way that there were 12 successive rows with four bags in each row (Total 960 bags for 24 plots). Bags were placed on the surface soil layer with a thin soil covering on it. The bags were tied to bamboo pegs and tagged using aluminium foil for easy detection during retrieval. From among the 12 rows of litterbags placed per plot, one row constituting four litterbags were randomly selected and retrieved from each treatment plot at monthly intervals starting from July 2013 to June 2014. The bags were gently rinsed with running water to remove soil and other extraneous materials. The residual litter mass removed from the bags were oven-dried at 70°C and weighed after excluding the fine roots and macro arthropods penetrating the mesh.

3.8.2 Phyto-chemical analysis of litter

In order to characterise the seasonal variations in litter nutrient concentrations and annual nutrient return through litterfall monthly litter collections were pooled over the plots and triplicate samples were analysed for total N, P (continuous flow analyser) and K (flame photometry) following Jackson (1958). The nutrient

addition through litterfall was computed by multiplying the monthly litterfall values with the corresponding monthly nutrient concentrations.

The detritus remaining in the litter bags were also analyzed for nutrient content. For this triplicate samples for residual biomass were pooled plot-wise and were analysed for N, P and K at monthly intervals till the 9th month. Thereafter, the residual litter mass recovered in the litter bags for all treatments were insufficient for chemical analysis.

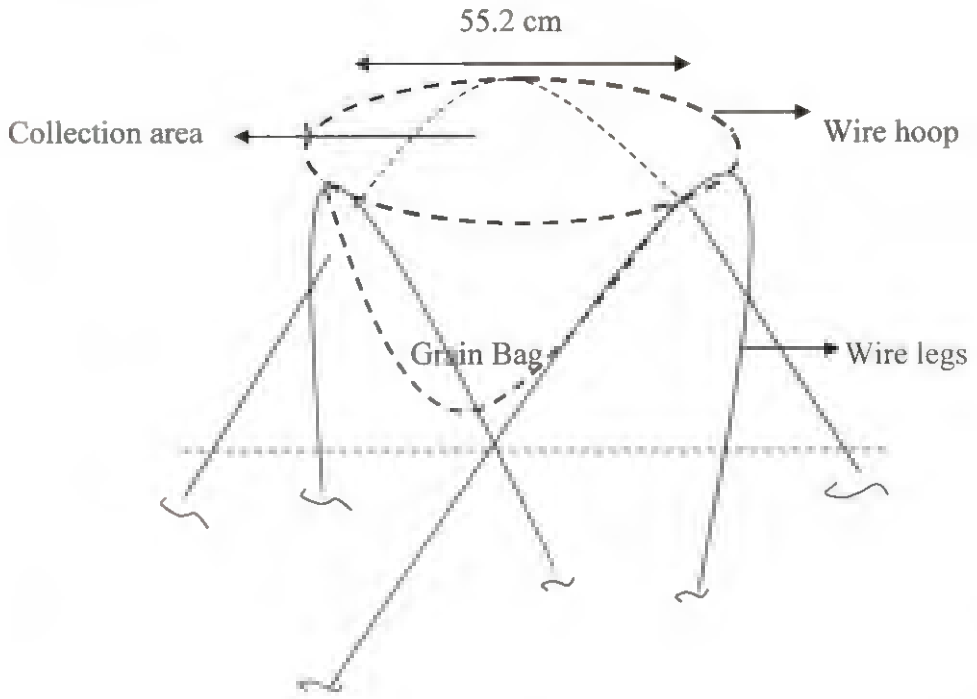


Fig. 3 Diagramatic representation of litter trap used for litter collection for *A. mangium* (Hughes *et al.*, 1987).

3.8.3 Statistical analysis and calculations

The data on litterfall and mineral nutrient concentrations for varying thinning intensity over time were subjected to ANOVA (using SPSS statistical package).

Residual litter mass in the litter bags and their nutrient concentrations were statistically tested following split plot ANOVA with months as main plot and thinning treatments as sub plots. For predicting the constant potential weight loss, model developed by Olson (1963) was used:

$$\frac{x}{x^0} = e^{-kt}$$

where 'x' is the weight remaining at time 't', 'x^0' is the original mass, e is the base of natural logarithm and 'k' is the decay rate coefficient. Replication-wise calculated k values for all the thinning treatments were tested for significance using ANOVA. Half life of the decomposing litter was estimated from the k-values using the equation (Bockheim *et al.*, 1991):

$$t_{0.5} = \frac{\ln(0.5)}{-k} = \frac{0.693}{-k}$$

3.9 SOIL ANALYSIS

3.9.1 Soil sampling

Soil samples were collected from the interspaces between the rows of trees avoiding locations adjacent to the plot borders. Four profile pits of one meter depth were taken from eight experimental plots each corresponding to a density regime and pruning level. 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 contiguous treeless area as control. Soil bulk density was separately assessed for each of the five soil depths in the profile using specially designed steel cylinder (Jackson, 1958). Bulk density was estimated by taking out a core of undistributed soil by using steel cylinder of known dimensions. The core was taken out without pressing the cylinder too hard on soil so that the natural bulk density of soil is not disturbed. The soil samples were oven dried and weight was determined. The volume of soil was calculated by measuring the volume of cylinder ($\pi r^2 h$). The bulk density was calculated by dividing the oven dry weight

of soil samples (g) by volume of 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 conducted for soil in the treeless control plot.

3.9.2 Soil C- sequestration

Representative soil samples were collected from each of the soil pits from the various density plots for estimating the soil C stock under 12-year-old *A. mangium* stands. Triplicate soil samples (c.a 200 g) were collected separately from five soil depths and were stored in sealed polythene covers and brought to laboratory as soon as possible. Samples were air-dried in a drying room and sieved to pass through a 2 mm sieve and stored for further analysis. The soil organic carbon was determined by Wakley and Black method using continuous flow analyzer (San ++, Skalar, Netherlands). 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.

The automated procedure using continues flow analyzer 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 620 nm.

3.9.3 Soil nutrient analysis

The composite soil samples collected depth-wise from each of the profile pits corresponding to the four densities were subjected to nutrient analysis (total N, P and K). The soil samples so collected 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 using continuous flow analyser (San ++, Skalar, Netherlands) and flame photometry for potassium (Jackson, 1958). Also, representative triplicate soil samples were collected from contiguous treeless plots as control analyzed for the above nutrients.

3.10 ALLOMETRIC EQUATIONS

The fine root production, total tree biomass, litter production, biomass C sequestration and volume data obtained from all the sampled trees of 12-year-old *A. mangium* were used to develop the allometric prediction equations. Simple measurable growth variables such as tree diameter at breast height, tree total height, tree basal area etc. were used as the independent variables for predicting the mean tree biomass, carbon stocks, volume. Attempts were also made to predict the fine root production by linking with basal area, aboveground litter production etc. Linear, quadratic, logarithmic, log linear, cubical and power functions were tried to develop the best prediction equations for various dependent variables such as fine root production, total aboveground biomass, total aboveground biomass C sequestration, total mean tree volume and bole volume.

3.11 STATISTICAL TREATMENT OF DATA

Data generated on various components such as fine root production, biomass production, photochemical analysis data and soil data (means of triplicate samples) for various density and pruning regimes were subjected to ANOVA (SPSS version 20). Treatment means were compared at appropriate levels of significance using LSD and DMRT for mean biomass yield, nutrient concentration, nutrient content of tree parts and whole trees and the soil parameters.

Results

RESULTS

Experimental evidences on the changes in the fine root productivity, turn over and the associated C and nutrient flux as influenced by stand density and pruning in twelve-year-old *A. mangium* stand are explained here. Also, results on the effect of stand density on litter production and nutrient turnover and associated changes in soil properties are summarized. Concurrently, the *A. mangium* stand was subjected to biomass production and nutrient accumulation study at varying densities and pruning levels. Influence of variable planting density on overall growth and form were also evaluated in 12-year-old *A. mangium* stand and are presented hereunder.

4.1 TREE GROWTH AND STAND DENSITY

Table 2 provides the changes in growth parameters such as tree height, diameter, basal area for 12-year-old *A. mangium* as a function of stand density. All the growth parameters showed significant difference with planting density while, tree pruning treatment had no significant effect on growth. Tree height ranges from 15.96 to 19.90 m. Trees in the low density stands (625 and 1250 tree ha^{-1}) were taller compared to high density stands. Pruning effect on height growth was insignificant.

The average tree diameter at breast height (DBH) ranged from 12.40 to 19.90 cm. Unlike the height growth a clear inverse trend in diameter variation has been observed across planting densities for *A. mangium*. Closely spaced stands showed lower DBH, which consistently increased with decreasing planting density. Despite a marginal advantage for the unpruned stands, in general the effect of pruning on diameter growth was not appreciable for *A. mangium*. Similar trends were also observed in the case of crown width which ranged from 2.66 to 4.05 m.

Mean tree basal area ranged from 0.013 m^2 to 0.031 m^2, which also followed a similar trend as that of diameter growth with an increase for decreasing stand density. For instance, almost 2.3 fold increase in mean basal area has been observed at lowest stand density (0.031 m^2; 625 trees ha^{-1}) as compared to stands at highest density (0.013 m^2; 5000 trees ha^{-1}). Again, the influence of tree pruning on mean tree basal area was not appreciable. Basal area at stand level (*i*.e. on hectare basis), however showed a different pattern with high values attached to high density stands and a consistent decline with decreasing stand density. Stand basal area value ranged from 67.96 m^2 ha^{-1} (5000 tree ha^{-1}) to 20.72 m^2 ha^{-1} (625 trees ha^{-1}). The high density stand accrued almost 3.2 fold higher stand basal area as compared to low density stand. Despite the marginal advantage of higher stand basal area in the unpruned stands the differences were not statistically significant.

4.1.1 Tree volume

The mean tree total volume and bole volume production of *A. mangium* of 12-year-age are shown in Table 3. Plant densities showed considerable difference on bole volume and total volume production. As observed for other growth variables, volume mean tree volume also followed an inverse relation with stand density. Maximum mean tree bole volume was recorded for stand at 4x4 m spacing 625 trees ha^{-1}; 0.51 m^3) followed by 2x4m spacing (1250 trees ha^{-1}; 0.38 m^3) and minimum was recorded in 2x1m (5000 trees ha^{-1}; 0.12 m^3). The same trend was followed for total mean tree volume as well with widely spaced stands (4x4m; 625 trees ha^{-1}) recording the maximum (0.61 m^3) which was followed by stands at 2x4 m (0.48 m^3) and 2x2 m (0.26 m^3) while, minimum was for 2x1m (5000 trees ha^{-1}) spacing (0.132m^3). Effect of tree pruning both on mean tree bole volume and total volume was not significant.

Table 2. Growth parameters of 12-year-old *A. mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

	Height (m)	DBH (cm)	Crown width (m)	Mean tree Basal area (m^2)	Stand Basal area (m^2 ha^{-1})
Stand density (trees ha^{-1})					
5000	15.96^{b} (±0.74)	12.4^{d} (±1.01)	2.66^{d} (±0.48)	0.013^{d} (±0.01)	67.96^{a} (±6.01)
2500	17.50^{ab} (±0.90)	14.1^{c} (±1.64)	3.04^{c} (±0.36)	0.017^{c} (±0.01)	42.11^{b} (±5.01)
1250	19.90^{a} (±0.73)	17.3^{b} (±1.00)	3.45^{b} (±0.27)	0.024^{b} (±0.01)	30.79^{c} (±5.01)
625	19.53^{a} (±0.90)	19.9^{a} (±1.92)	4.05^{a} (±0.55)	0.031^{a} (±0.01)	20.72^{d} (±4.01)
F-test	4.55	4.93	2.3	4.03	3.5
p- value	0.01	0.00	0.00	0.00	0.00
Pruning					
No pruning	18.72 (±1.01)	14.8 (±1.32)	3.34 (±0.82)	0.018 (±0.01)	48.46 (±5.01)
50% pruning	17.86 (±1.25)	14.0 (±1.04)	3.27 (±0.99)	0.02 (±0.01)	47.77 (±4.01)
F-test	1.02	5.1	0.43	0.34	2.45
p- value	0.32	0.02	0.51	0.007	0.12
Spacing x pruning					
F test	0.11	0.49	2.04	1.04	1.32
p- value	0.95	0.68	0.10	0.37	0.26

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly within column)

4.1.2 Stand volume and mean annual increment (MAI)

Volume at stand level ranged from 381.04 m^3 ha^{-1} to 797.75 m^3 ha^{-1} across the stand densities (Table 4). The stand volume showed a corresponding increase with increasing stand density. For instance, maximum stand volume production was observed for 5000 trees ha^{-1} stand (797.746 m^3 ha^{-1}) which consistently declined to

381.041 m^3 ha^{-1} corresponding to sand at 625 trees ha^{-1}. MAI in stand volume also showed a wide range among the various stand densities (27.21 to 56.98 m^3 ha^{-1} yr^{-1}). MAI changes are also in tune with the stand volume production trends. MAI value of 56.98 m^3 ha^{-1} yr^{-1} was recorded by 5000 trees ha^{-1} stand followed by 2500 and 1250 trees ha^{-1} stand (46.19 and 43.26 m^3 ha^{-1} yr^{-1} respectively). The minimum value was however recorded for 625 trees ha^{-1} stand (27.21 m^3 ha^{-1} yr^{-1}). Again the impact of tree pruning was marginal both on stand volume and MAI in stand volume.

4.1.3 Stem taper

Stem taper at different tree heights and for various stand densities are presented in Table 5. Significant variation in stem taper was noticed across the standing densities. Results suggest that higher taper ratio was associated with trees managed at higher densities. For instance, mean tree taper ratio corresponding to basal girth and girth at bole heights was highest 0.57 (5000 trees ha^{-1}) while the corresponding value for trees at wider spacing (625 trees ha^{-1}) was 0.35. Pruning could not inflict much effect on stem taper.

4.2 FINE ROOT PRODUCTION AND TURNOVER

4.2.1 Ingrowth method

Ingrowth method involves the assessment of fine root production in specially designed ingrowth cores. Annual fine root production at stand level as per this method ranged from 3.38 to 5.78 Mg ha^{-1} yr^{-1} across the stand densities for 12-year-old *A. mangium* (Table 6). They varied significantly among stand densities. Annual fine root production was 5.78, 5.38, 3.74, and 3.38 Mg ha^{-1} for 5000, 2500, 1250, 625 trees ha^{-1} respectively. A consistent reduction in fine root production with decreasing

Table 3. Mean tree total volume and bole volume for 12-year-old *A.mangium* at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Bole volume (m^3)	Total volume (m^3)
Stand density (trees ha^{-1})		
5000	0.12^d (±0.01)	0.16^d (0.01)
2500	0.20^c (±0.02)	0.26^c (±0.02)
1250	0.38^b (±0.02)	0.48^b (±0.02)
625	0.51^a (±0.03)	0.61^a (±0.03)
F- test	0.34	0.39
p Value	0.00	0.00
Pruning		
No pruning	0.33 (±0.03)	0.42 (±0.04)
50% pruning	0.28 (±0.03)	0.36 (±0.02)
F- test	0.53	0.33
p Value	0.06	0.07
Spacing x Pruning		
F- test	0.60	0.56
p Value	0.61	0.64

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

Table 4. Stand volume and MAI for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala.

	Stand volume (m^3 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})
Stand density (trees ha^{-1})		
5000	797.74^a (±50.32)	56.98^a (±4.55)
2500	646.79^b (±46.34)	46.19^b (±5.21)
1250	605.68^b (±61.42)	43.26^b (±3.57)
625	381.04^c (±32.42)	27.21^c (±4.67)
F-test	15.80	15.80
P Value	0.00	0.00
Pruning		
No pruning	640.28 (±46.78)	46.10 (±5.58)
50% pruning	570.16 (±51.57)	40.72 (±4.11)
F-test	30.02	3.02
P Value	0.09	0.09
Spacing x pruning		
F-test	0.60	0.60
P Value	0.61	0.61

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

Table 5. Taper ratio for 12-year -old *A. mangium* stands as influence by stand density and pruning at Thiruvazhamkunnu, Kerala

	Taper ratios			
	G_2/G_1	G_3/G_1	G_4/G_1	G_5/G_1
Stand density (trees ha^{-1})				
5000	0.89^{a} (±0.10)	0.86 (±0.12)	0.79 (±0.10)	0.57^{a} (±0.12)
2500	0.84^{c} (±0.10)	0.81 (±0.11)	0.73 (±0.09)	0.51^{a} (±0.09)
1250	0.88^{a} (±0.11)	0.86 (±0.09)	0.75 (±0.08)	0.42^{b} (±0.07)
625	0.87^{ab} (±0.21)	0.75 (±0.08)	0.75 (±0.09)	0.35^{c} (±0.08)
F- test	0.49	0.66	0.27	0.31
P Value	0.01	0.19	0.29	0.00
Pruning				
No pruning	0.87 (±0.12)	0.79 (±0.08)	0.75 (±0.12)	0.44 (±0.09)
50% pruning	0.87 (±0.09)	0.85 (±0.11)	0.77 (±0.09)	0.48 (±0.12)
F-test	0.19	1.58	0.86	0.33
P Value	0.66	0.21	0.36	0.13
Spacing x pruning				
F-test	1.71	1.94	0.57	0.99
P Value	0.17	0.13	0.63	0.40

G_1, G_2, G_3, G_4, G_5 represent girth at 0.15 m, 1.37 m, 2.0 m, 4.0 m and bole height of trees

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

planting density is discernible in the study. However, no significant difference in fine root production was observed with tree pruning treatment. As much as 72% increase in fine root production was observed in the higher density stand (5000 trees ha^{-1}) compared to lowest density stand (625 trees ha^{-1}).

Table 6 also shows the mean tree fine root production for 12-year-old *A. mangium*. The values showed a wide range of 1.16 to 5.42 kg $tree^{-1}$ among the stand densities. Contrary to the stand level, fine root production at mean tree production showed an increasing trend with decreasing planting density. Stands at lowest density registered the highest mean tree fine root production (5.42 kg $tree^{-1}$; 625 tree ha^{-1}) while high density stands showed a characteristically lower fine root yield (1.16 kg $tree^{-1}$; 5000 trees ha^{-1}). Tree pruning however could not inflict appreciable change in mean tree fine root production.

Fine root turnover values (number of rounds of decomposition per year) for 12-year-old *A. mangium* computed following ingrowth varied from method 2.81 to 3.16 (Table 6). However appreciable trends in fine root turnover were not discernible across stand densities. Fine root turnover showed marginal differences among the density regimes. Fine root turnover was apparently insensitive to tree pruning.

Annual standing fine root necromass (dead root dry weight) is given in the Table 7. Root necromass showed significant difference among the various stand densities with a distinct reduction with decrease in stand density. Necromass observed ranged from 0.19 to 0.09 Mg ha^{-1}. However stronger functionality between fine root necromass and tree pruning could not be observed in this study.

4.2.2 Sequential coring method

Annual fine root production was also estimated following the sequential coring method. The values were however, less as compared to ingrowth method. For instance, the annual fine root production on stand basis varied from

Table 6. Annual fine root production in *A. mangium* stands at varying stand densities and pruning by ingrowth coring method at Thiruvazhamkunnu, Kerala

Treatments	Fine root production (p_a) at stand level (Mg ha^{-1} yr^{-1})	Mean tree fine root production (p_a) (kg ha^{-1} yr^{-1})	Fine root turnover per year
Stand density (trees ha^{-1})			
5000	5.78^{a} (±0.82)	1.16^{c} (±0.41)	3.16 (±0.26)
2500	5.39^{ab} (±0.97)	2.16^{b} (±0.31)	3.06 (±0.77)
1250	3.74^{bc} (±0.81)	2.99^{b} (±0.21)	3.07 (±0.66)
625	3.38^{c} (±0.72)	5.42^{a} (±0.52)	2.81 (±0.69)
F-test	4.57	3.32	0.73
P value	0.02	0.00	0.55
Pruning			
No pruning	4.21 (±0.62)	2.86 (±0.34)	3.75 (±0.76)
50% pruning	4.94 (±0.98)	2.99 (±0.41)	4.41 (±0.50)
F-test	1.74	0.18	1.99
P Value	0.20	0.69	0.18
Spacing x pruning			
F-test	1.35	1.22	0.62
P value	0.29	0.34	0.61

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

Table 7. Annual standing fine root necromass in *A. mangium* stands at varying stand densities and pruning by ingrowth core method at Thiruvazhamkunnu, Kerala

Treatments	Necromass (dry wt) (Mg ha^{-1})
Stand density (trees ha^{-1})	
5000	0.19^{a} (±0.01)
2500	0.13^{b} (±0.01)
1250	0.12^{b} (±0.01)
625	0.09^{c} (±0.01)
F-test	0.18
P Value	0.00
Pruning	
No pruning	0.14 (±0.01)
50% pruning	0.13 (±0.02)
F-test	0.98
P Value	0.33
Spacing x pruning	
F-test	0.46
P Value	0.71

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

1.39 to 2.41 Mg ha^{-1} yr^{-1}. The prominent influence of stand density on fine root production was visible in this case also. A consistent reduction in fine root production was observed with decrease in planting density. The mean dry fine root production at stand level estimated by the sequential coring method amounted to 2.41, 1.98, 1.71 and 1.39 Mg ha^{-1} in the 5000, 2500, 1250, 625 trees ha^{-1} respectively (Table 8). The

increase in fine root production in the high density stand (5000 trees ha^{-1}) was approximately 72% of the production in the lowest density stand (625 trees ha^{-1}). Pruning effects on fine root production was not significant. However, apparently the pruned stands had marginally higher fine root production.

Table 8 also present the average mean tree fine root production which also was fairly lower as compared to the production estimated through ingrowth method. For example, the mean tree monthly production ranged from 0.48 to 2.24 kg $tree^{-1}yr^{-1}$. As against stand level fine root production, the mean tree production followed an inverse relation to stand density with a consistent increase with decreasing stand density. The insensitivity of tree pruning on fine root production was noticeable in sequential coring method also.

Mean standing dry biomass production for fine roots estimated in different density regimes ranged from 0.77 to 1.53 Mg ha^{-1} which also showed consistent decline with decreasing standing density (Table 8). The corresponding values were 1.53, 1.15, 0.98 and 0.77 Mg ha^{-1} for planting densities 5000, 2500, 1250, 625 trees ha^{-1} respectively. Significant difference was observed in the standing dry mass of fine root in different spacing. As observed for annual fine root production, tree pruning did not influence the standing biomass production also.

Fine root turnover values (number of rounds of decomposition per year) for 12-year-old *A. mangium* computed following sequential core method varied from method 1.58 to 1.81 (Table 8). However appreciable trends in fine root turnover were not discernible across stand densities Fine root turnover showed marginal differences among the density regimes. Tree pruning was apparently insensitive to fine root turnover.

4.2.3 Seasonality in fine root production

Plotted over a complete year, fine root production measured by both methods exhibited large seasonal variations. In both methods, the highest fine root production occurred during the rainy season (June - August), while the summer period (February – April) represented the lowest fine root production (Fig 4). Average fine root production observed by sequential core method during the rainy season was 1.62 Mg ha^{-1} while the summer season represented a production of 0.35 Mg ha^{-1}. Whereas, in ingrowth cores the observations were 2.47 Mg ha^{-1} and 0.24 Mg ha^{-1} respectively for both seasons.

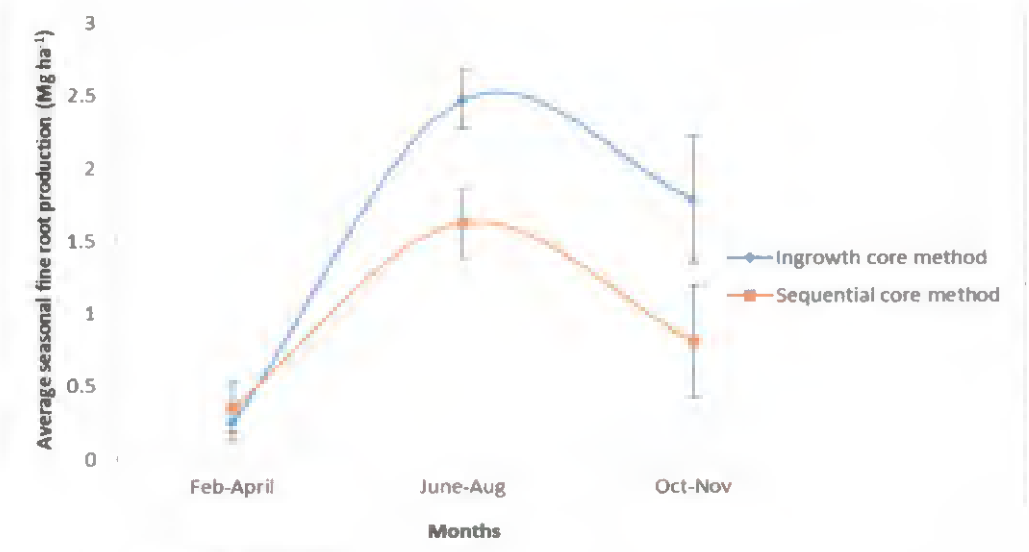


Fig. 4. Average fine root production in sequential core and ingrowth cores methods within the 0–30 cm soil layer after 2–4 months of fine root regrowth periods in *A. mangium* stands plotted over different seasons.

Table 8. Annual fine root production in 12-year-old *A. mangium* stands at varying stand densities and pruning by sequential coring method

Treatments	Fine root production (p_a) at stand level (Mg $ha^{-1}yr^{-1}$)	Mean tree fine root production (kg $tree^{-1}yr^{-1}$)	Standing fine root biomass (Mg ha^{-1})	Fine root turnover per year
Stand density (trees ha^{-1})				
5000	2.41^{a} (±0.59)	0.48^{c} (±0.06)	1.53^{a} (±0.41)	1.58 (±0.32)
2500	1.98^{ab} (±0.66)	0.79^{c} (±0.07)	1.15^{b} (±0.42)	1.72 (±0.41)
1250	1.71^{bc} (±0.42)	1.37^{b} (±0.21)	0.98^{c} (±0.32)	1.74 (±0.33)
625	1.39^{c} (±0.45)	2.24^{a} (±0.42)	0.77^{d} (±0.34)	1.81 (±0.31)
F-test	1.48	2.12	0.49	0.67
P Value	0.00	0.00	0.00	0.32
Pruning				
No pruning	1.98 (±0.30)	1.30 (±0.42)	1.10 (±0.43)	1.56 (±0.33)
50% pruning	1.76 (±0.26)	1.15 (±0.33)	1.11 (±0.32)	1.76 (±0.44)
F-test	1.72	1.07	0.02	1.52
P Value	0.21	0.13	0.87	0.24
Spacing x pruning				
F-test	0.10	0.28	1.670	4.46
P Value	0.96	0.84	0.213	0.52

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

4.2.4 Fine root decomposition

Empirical data on fine root decomposition for the *A. mangium* for a period of one year from January 2013 to December 2014 are presented in Table 9. Mass remaining in the fine root litter bags at monthly intervals followed an exponential decline with time. From the initial value of 4 g per bag, the average mass remaining after 6 months

(June) of incubation was 1.60 g while the corresponding value at the end of study period (12 months) was 0.39 g. Stand density had a significant effect on the fine root decomposition with higher decomposition rate attached to low density stands. For instance, percentage mass loss during the first month was 13.63, 19.14, 23.63 and 22.34% for stands with 5000, 2500, 1250, 625 trees ha^{-1} stocking levels, respectively (Table 10).

The inverse relation between rate of fine root decomposition and stand density was visible throughout the study period of one year. For instance, the residual fine root mass remaining after 6 months (June) was 48.86, 39.72, 37.23 and 34.39% for 5000, 2500, 1250 and 625 trees ha^{-1} respectively (Table 10). More than 50% of the initial mass was decomposed within six months (June) of soil incubation for all density regimes. An average of 51% of decomposition was observed for high density stand (5000 trees ha^{-1}) while about 64% decomposition recorded in low density stand (625 trees ha^{-1}) after six months. At 12 months after exposure to decomposition, there was roughly 24% of residual root mass remaining in the high density stand (5000 trees ha^{-1}) which however showed a marked decline with reduction in stand density. The corresponding mass remaining in the other stands after 12 months were 9.85, 4.12 and 1.20% for stands at 2500, 1250 and 625 trees ha^{-1} respectively (Table 10).

A biphasic pattern in root litter mass loss was observed with an initial faster decay phase, which extended over six months followed by a slow phase for the remaining months. On the whole, the average decay (irrespective of stand density) reached an asymptotic phase with 10% of the initial mass remaining at the end of the one year decay period.

Table 11 shows the decay rate coefficients and half-life periods for decomposing *A. mangium* fine roots. Decay coefficient (k) ranged from 1.44 to 4.42 for different stand densities with a consistent increase from high to low density stands. Decay

coefficient corresponding to high density stand was significantly lower from the rest. Estimated half-life periods i.e., time taken for 50% of initial mass loss, ranged from 0.16 to 0.48 months with lowest value associated with stand density of 625 tree ha^{-1}.

4.2.5 Carbon and nutrient content in the fine roots

Table 12 shows the carbon and nutrient content in the annual fine root yield. Carbon content in the fine roots ranged from 1.36 to 2.39 Mg ha^{-1}among the stand densities. The general trend of decrease in production with decreasing stand density was observed for Carbon storage also. About 57% increase in carbon content was observed in the high density stand compared to the low density stand.

Nitrogen content in the fine roots varied from 34.56 kg ha^{-1} (625 trees ha^{-1}) to 102.92 kg ha^{-1} (5000 trees ha^{-1}). It also was found to decrease with decreasing planting density. Phosphorus content in the fine roots was in the range of 1.64 to 3.31 kg ha^{-1} with a gradual decline with decreasing stand density. Potassium content in the fine roots also changed with a decline corresponding to the declining stand biomass. The K production of the fine roots ranged from 16.94 to 33.60 kg ha^{-1}.

Carbon and nutrient release to the soil through fine root decomposition is depicted in Table 13. Out of the total fine root production carbon released to the soil ranged from 1.35 to 2.00 Mgha^{-1} which however showed marginal difference among the stand densities. Corresponding ranges in values for nitrogen, phosphorus and potassium were 34 to 84, 1.06 to 2.77 and 16.74 to 28.90 kg ha^{-1} respectively. Except for nitrogen other nutrients did not show significant variation across the stand densities. However, a general declining trend with standing density is apparent.

Table 9. Residual fine root mass at monthly intervals for *A. mangium* stands at varying densities and pruning at Thiruvazhamkunnu, Kerala.

Months	Residual fine root mass in bags (g)				F-test	P value
	Stand density (trees ha^{-1})					
	5000	2500	1250	625		
Jan	3.45^{a} (±0.21)	3.23^{b} (±0.32)	3.05^{c} (±0.45)	3.11^{c} (±0.51)	33.03	0.00
Feb	3.21^{a} (±0.21)	2.98^{b} (±0.27)	2.79^{c} (±0.31)	2.77^{c} (±0.41)	28.37	0.00
Mar	3.03^{a} (±0.31)	2.98^{a} (±0.17)	2.74^{b} (±0.21)	2.69^{b} (±0.31)	11.83	0.003
April	2.79^{a} (±0.26)	2.80^{a} (±0.21)	2.48^{b} (±0.18)	2.51^{b} (±0.23)	4.60	0.03
May	2.49^{a} (±0.38)	1.96^{b} (±0.13)	1.54^{c} (±0.13)	1.40^{c} (±0.21)	49.03	0.00
June	1.95^{a} (±0.21)	1.96^{b} (±0.23)	1.49^{c} (±0.19)	1.38^{c} (±0.17)	29.93	0.00
July	1.30^{a} (±0.20)	1.26^{a} (±0.16)	1.18^{a} (±0.22)	1.04^{b} (±0.21)	8.78	0.007
Aug	1.26^{a} (±0.11)	1.0^{bc} (±0.19)	1.14^{ab} (±0.11)	0.89^{c} (±0.23)	9.57	0.005
Sept	1.13^{a} (±0.13)	0.97^{b} (±0.22)	0.90^{b} (±0.17)	0.78^{c} (±0.19)	29.99	0.00
Oct	1.07^{a} (±0.21)	0.91^{b} (±0.11)	0.79^{c} (±0.25)	0.59^{d} (±0.17)	55.17	0.00
Nov	1.05^{a} (±0.17)	0.89^{b} (±0.19)	0.76^{c} (±0.17)	0.5^{d} (±0.23)	66.36	0.00
Dec	0.95^{a} (±0.20)	0.39^{b} (±0.21)	0.16^{c} (±0.19)	0.05^{c} (±0.18)	102.19	0.00

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

Table 10. Percentage mass remaining in the bags at monthly intervals for decomposing *A. mangium* fine root litter.

Months	Residual fine root mass (%) in the bags as influenced by planting densities				Monthly average
	Stand density (trees ha^{-1})				
	5000	2500	1250	625	
Initial	100.00	100.00	100.00	100.00	100.00
January	86.37	80.86	76.37	77.66	80.31^{a}
February	80.29	74.58	69.83	69.33	73.50^{b}
March	75.79	74.46	68.61	67.29	71.54^{b}
April	69.15	70.04	62.04	62.66	65.97^{c}
May	62.37	49.10	38.72	35.02	46.30^{d}
June	48.86	39.72	37.23	34.39	40.05^{e}
July	32.97	31.57	29.58	26.02	30.04^{f}
August	31.89	25.38	28.62	22.36	27.06^{g}
September	27.82	24.27	22.53	19.58	23.55^{h}
October	26.76	22.73	19.85	14.74	21.02^{i}
November	26.38	22.28	18.97	12.92	20.14^{i}
December	23.79	9.85	4.12	1.20	9.74^{j}
Total mean	49.37^{a}	43.74^{b}	39.70^{c}	36.93^{d}	
SEM= ±1.523					
F=4.53					

(Monthly average values (presented in a column) as well as total mean values (presented in a row) with the same superscripts do not differ significantly)

Table 11. Decay rate coefficient and half-life periods corresponding to *A. mangium* fine roots at Thiruvazhamkunnu, Kerala.

Stand density	k-value	$t_{(0.5)}$ (Half life in months)
5000 trees ha^{-1}	1.44^{d}	0.48
2500 trees ha^{-1}	2.33^{c}	0.29
1250 trees ha^{-1}	3.28^{b}	0.22
625 trees ha^{-1}	4.42^{a}	0.16

(*Values within a column with the same superscripts do not differ significantly*)

Table 12. Carbon and nutrient content in the fine roots for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala

	C (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Stand density (trees ha^{-1})				
5000	2.39^{a} (±0.43)	102.92^{a} (±10.61)	3.32^{a} (±0.52)	33.60^{a} (±4.45)
2500	2.22^{ab} (±0.32)	92.94^{a} (±8.71)	3.07^{a} (±0.51)	31.97^{ab} (±3.50)
1250	1.59^{bc} (±0.21)	66.63^{ab} (±7.67)	1.46^{b} (±0.41)	19.29^{bc} (±2.35)
625	1.36^{c} (±0.31)	34.56^{b} (±5.56)	1.64^{b} (±0.22)	16.94^{c} (±3.31)
F-test	1.30	6.60	2.88	3.77
P value	0.02	0.004	0.001	0.03
Pruning				
No Pruning	1.73 (±0.31)	72.69 (±10.34)	2.21 (±0.32)	24.59 (±2.61)
50% Pruning	2.05 (±0.22)	75.83 (±7.34)	2.23 (±0.41)	26.30 (±3.54)
F-test	1.90	5.07	0.94	4.15
P value	0.19	0.80	0.35	0.70
Stand density x pruning				
F-test	0.63	0.81	0.96	0.75
P value	0.60	0.51	0.43	0.54

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

4.2.6 Correlation of fine root production with other growth variables

Attempts were also made to relate fine root production with various growth variables (Table 14). Interestingly significant positive correlation exists for most of the independent variables such as DBH, basal area, biomass, volume, crown width and coarse root production. Correlation coefficient was more than 0.80 for growth parameters such as DBH, basal area per tree, volume per tree, aboveground biomass per tree, and leaf area per tree. In general, most of the variables gave good correlation with fine root production when considered on per tree basis.

Table 15 gives the various regression equations developed linking mean tree fine root production with various growth variables for *A. mangium*. Average tree DBH as independent variable gave fairly good prediction of mean tree fine root production. Among the various model tried quadratic model gave the best fit with R^2 value of 0.74 for DBH. Mean tree fine root production prediction with mean tree basal area as independent variable suggested that quadratic equation giving good predictability with an R^2 value of 0.74.

Attempts to correlate mean tree volume with fine root production however yielded lower fit with R^2 values ranging from 0.64 to 0.68. However, the relationship was statistically significant ($p<0.001$). Interesting fine root production and mean tree leaf area showed fairly good relationship with good R^2 value for both linear model and quadratic model ($R^2=0.72$). Functional relation between crown width and fine root production was fairly good with reasonably good model fit. Among the growth variable probably mean aboveground biomass as independent variable showed very good prediction of fine root production with high R^2 value 0.80 ($p<0.001$).

Table 13. Carbon and nutrient release to the soil through fine root decomposition for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala

	C (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Stand density (Trees ha^{-1})				
5000	2.00 (±0.22)	84.00[a] (±5.54)	2.77 (±0.21)	28.90 (±1.67)
2500	1.83 (±0.31)	78.00[a] (±3.23)	2.54 (±0.24)	25.50 (±3.61)
1250	1.53 (±0.21)	64.00[ab] (±4.25)	1.41 (±0.16)	18.54 (±2.45)
625	1.35 (±0.18)	34.00[b] (±3.67)	1.62 (±0.18)	16.74 (±2.36)
F-Test	1.86	4.54	1.06	2.26
P Value	1.78	0.017	0.39	0.12
Pruning				
No pruning	1.50 (±0.21)	62.00 (±4.54)	1.92 (±0.13)	21.00 (±3.23)
50% Pruning	1.85 (±0.22)	68.00 (±6.44)	2.24 (±0.22)	24.00 (±3.12)
F-Test	2.51	5.36	1.66	5.50
p Value	0.13	0.55	2.16	0.48
Stand density x pruning				
F-Test	0.71	0.76	0.95	0.71
P Value	0.55	0.53	0.43	0.55

(Values in parenthesis are standard error of means)
(Values within a column with the same superscripts do not differ significantly)

Table 14. Correlation of fine root production with various growth variables for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala.

Dependent variable	Independent variable	Correlation coefficient
Fine root production per tree	DBH	0.85**
Fine root production per tree	Basal area per tree	0.85**
Fine root production per ha	Basal area per hectare	0.60**
Fine root production per tree	Volume per tree	0.82**
Fine root production per ha	Volume per ha	0.53**
Fine root production per tree	Aboveground biomass per tree	0.89**
Fine root production per ha	Aboveground biomass per ha	0.55**
Fine root production per tree	Crown width	0.78**
Fine root production per tree	Leaf area per tree	0.84**
Fine root production per ha	Leaf area per ha	0.44*
Fine root production per tree	Coarse root per tree	0.66**
Fine root production per ha	Coarse root per ha	-0.42*

4.3 BIOMASS ACCUMULATION

Observations on the biomass production in 12-year-old *A. mangium* stand are shown in Table 16. Significant variation in aboveground biomass (AGBM), belowground biomass (BGBM) and total biomass production is explicit for various stand density regimes.

Total mean tree total biomass production ranged from 67.58 kg tree^{-1} (5000 trees ha^{-1}) to 253.02 kg tree^{-1} (625 trees ha^{-1}). The total mean tree biomass production showed consistent increase with decreasing planting density. This increase at lowest density is as much as 3.7 fold of the biomass at highest density. The total biomass production in high density (5000 trees ha^{-1}) was characteristically lower (67.58 kg tree^{-1}) compared with other density regimes. Influence of pruning on total biomass production was however found to be minimal. Total mean tree aboveground biomass production ranged from 46.68 to 193.47 kg tree^{-1}. Similar to total biomass production, the aboveground biomass production also followed the same trend with stand at higher density stand (5000 trees ha^{-1}) showing significantly lower biomass (46.68 kg tree^{-1}) compared with other density regimes. The maximum aboveground biomass production was registered by 625 trees ha^{-1} stand with a value of 193.471 kg tree ha^{-1}. Here also the increase in biomass production with decreasing tree density is evident. Proportionate allocation of biomass to the aboveground ranged from 69.07% to 76.46% of the total biomass. Percentage allocation to the aboveground biomass was found to be higher in the stands at lower density regimes.

Belowground biomass production also showed similar trend as that of aboveground biomass yield. However, the low density stands appear to have accumulated more biomass to the belowground (59.58 and 47.65 kg tree^{-1} for 625 and 1250 trees ha^{-1} stand respectively). The mean tree belowground biomass

Table 15. Allometric equations developed linking oven dry mean tree fine root production with various growth variables for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala.

Dependent variable	Independent variable	Allometric equation	R^2	SE of estimate	F test
Fine root production (FRP) (kg tree^{-1})	DBH (D)(cm)	FRP = 0.38D -3.70	0.72	0.96	57.21
		FRP = 6.34 ln(D) –15.06	0.70	1.00	51.10
		FRP = 3.16-0.44(DBH)+0.02(D)^2	0.74	0.94	30.59
	Basal area(B) (m^2 tree^{-1})	FRP = 136.35(B) -0.54	0.73	0.95	58.32
		FRP = 14.72+3.12 ln(B)	0.69	1.02	48.34
		FRP = 0.66+26.98(B)+2074.99(B)^2	0.74	0.95	29.42
	Volume (V) (m^3 tree^{-1})	FRP = 0.06+7.6(V)	0.67	1.04	45.52
		FRP = 5.74+2.53 ln(V)	0.64	1.09	39.27
		FRP = 0.45+5.10(V)+3.11(V)^2	0.68	1.06	21.95
	Leaf area (L) (m^2 tree^{-1})	FRP = 1.17(L) -0.40	0.72	1.03	42.96
		FRP = 0.03+3.09(L)	0.65	1.14	31.87
		FRP = 1.30(L)–1.30(L)^2-0.58	0.72	1.06	20.26
	Crown width (C) (m)	FRP = 2.80(C) - 6.37	0.61	1.17	30.93
		FRP = 8.65ln(C) - 7.37	0.57	1.22	26.83
		FRP = 13.88–10.00(C)+1.97(C)^2	0.68	1.08	19.96
	Aboveground biomass (A) (kg tree^{-1})	FRP = 0.03(A) -0.24	0.80	0.83	80.21
		FRP = 2.79 ln(A) -9.64	0.72	0.97	52.83
		FRP = 0.27+0.02(A)+4.77-005	0.80	0.84	39.25

All relationships significant at 1% level of significance

Table 16. Mean tree biomass accumulation for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Total aboveground biomass (kg tree^{-1})	Total belowground biomass (kg tree^{-1})	Total biomass (kg tree^{-1})	Percentage aboveground biomass (%)	Percentage belowground biomass (%)
Stand density (trees ha^{-1})					
5000	46.68^{c} (±4.08)	20.91^{c} (±5.75)	67.58^{c} (±8.16)	69.07	30.94
2500	73.19^{c} (±4.89)	33.94^{bc} (±4.28)	107.15^{c} (±7.35)	68.31	31.68
1250	122.04^{b} (±7.34)	47.65^{ab} (±4.20)	169.69^{b} (±9.79)	71.92	28.08
625	193.47^{a} (±20.41)	59.58^{a} (±8.81)	253.02^{a} (±23.12)	76.46	23.55
F-test	26.40	40.71	26.6	1.20	1.20
P value	0.00	0.002	0.00	0.34	0.34
Pruning					
No pruning	108.91 (±23.43)	44.74 (±9.81)	153.66 (±14.43)	70.88	29.12
50% pruning	108.77 (±20.45)	36.30 (±5.77)	145.08 (±18.51)	74.97	25.02
F-test	0.00	2.29	5.34	1.43	1.43
P value	0.99	0.14	0.56	0.24	0.24
Spacing x pruning					
F-test	0.238	1.53	0.35	0.97	0.97
P value	0.869	0.25	0.79	0.43	0.43

(Values in parenthesis are standard error of means)
(Values within same column with the same superscripts do not differ significantly)

production among higher density regimes were 33.94 kg tree^{-1} (2500 trees ha^{-1} stand) and 20.91 kg tree^{-1} (5000 trees ha^{-1} stand) respectively. There was approximately 2.8 fold increase in mean tree belowground biomass for stands at 625 trees ha^{-1} as compared to high density stands. Proportionate allocation of biomass to the belowground ranged from 23.55 to 30.94% of the total biomass. Contrary

to the aboveground biomass partitioning trends, the belowground biomass portioning was found to be higher in the stands at higher density regimes.

4.3.1 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 17. Clearly, the largest component of biomass yield in all density treatment was stemwood which varies from 39.46 kg tree^{-1} (60.90%) to 168 kg tree^{-1} (67.12 %). Coarse 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. mangium* at 625 trees ha^{-1} stand density with a value of 168 kg tree^{-1} followed by 1250 trees ha^{-1} stand with 107.31 kg tree^{-1} and 2500 trees ha^{-1} stand having a value of 64.39 kg tree^{-1}. Stand at 5000 trees ha^{-1} registered the minimum value for stemwood biomass production (39.46 kg tree^{-1}).

Coarse root biomass contributed the second largest share to the total biomass production. The allocation of mean tree biomass to the coarse roots followed the order 54.16 kg tree^{-1} (625 trees ha^{-1}), 44.66 kg tree^{-1} (1250 trees ha^{-1}), 31.78 kg tree^{-1} (2500 tree ha^{-1}) and 19.76 kg tree^{-1} (5000 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 given by 5000 and 2500 trees ha^{-1} stand (27.74 and 29.76% respectively) followed by 1250 trees ha^{-1} stand (26.61%) and lowest of 21.74 % by 625 trees ha^{-1} density regimes.

Branchwood, production varied from 1.6 to 5.3 kg tree^{-1} among the density regimes. Maximum percentage allocation was observed in 625 trees ha^{-1} density (4.4%) and minimum for 5000 trees ha^{-1} (2.5%). The percentage contribution of leaf and twig was generally very low. Leaf biomass contribution ranged from 3.73% to 5.85% of total biomass. Twig invariably recorded the least biomass yield for all the density regimes (1.13% -2.56%).

Mean tree fine root biomass allocation ranged from 1.15 to 5.42 kg tree^{-1} and the high density stand showed the minimum mean tree fine root production and the highest value observed in the low density stand. Its percentage contribution to the total biomass ranged from 1.70 to 2.14%.

4.3.2 Biomass production on stand basis

Biomass production at stand level (on ha basis) showed considerable variation with stand density (Table 18). In general, the total stand biomass production decreased with decreasing stand density. For instance, stand at highest density (5000 trees ha^{-1}) recorded higher value to the tune of 332.97 Mg ha^{-1} followed by 2500 trees ha^{-1} stand having a value of 267.88 Mg ha^{-1}. The lowest stand biomass production was shown by 625 trees ha^{-1} stand (158.14 Mg ha^{-1}) while stand at 1250 trees ha^{-1} showed intermediate value (212.12 Mg ha^{-1}). In general, biomass productions by higher density regimes were significantly higher than the lower densities (two fold increase from lowest to highest stand density).

With respect to the allocation of total biomass among the various tissue fractions, stemwood registered the highest proportion for all the density regimes which ranged from 105.00 Mg ha^{-1} to 192.34 Mg ha^{-1}. A consistent reduction in stemwood biomass has been observed with reduction in stand density (Table 18).

For example, highest stemwood biomass was registered by stand at 5000 trees ha^{-1}density (197.34 Mg ha^{-1}) followed by stand at 2500 trees ha^{-1} (160.98 Mg ha^{-1}), 1250 trees ha^{-1} (134.14 Mg ha^{-1}) and lowest for 625 tree ha^{-1} stand (105.00 Mg ha^{-1}).

Coarse root recorded the second highest portion which varied significantly among various stand densities. The value ranged from 33.85 Mg ha^{-1} in lower density stand (625 trees ha^{-1}) to 98.78 Mg ha^{-1} in higher density stand (5000 trees ha^{-1}). Despite the apparent variation, branch wood portion didn't show significant change with stand density. Twig portion ranges from 2.46 Mg ha^{-1} (1250 trees ha^{-1}) to 8.50 Mg ha^{-1} (5000 trees ha^{-1}). Leaf biomass proportion was predominantly high in highest density stand 19.52 Mg ha^{-1}; 5000 trees ha^{-1}) while the values for other densities were at par

Significant difference in fine root biomass was observed at stand level among different standing densities. Fine root biomass value ranges from 3.38 to 5.78 Mg ha^{-1}. Again, the highest production was attributed to high density stand with a consistent reduction with decreasing stand density.

Mean annual increment also closely changed with stand density with maximum value attached to highest density stand (23.84 Mg ha^{-1} yr^{-1}; 5000 trees ha^{-1}) while the lowest density stand gave lowest MAI (11.11 Mg ha^{-1} yr^{-1}; 625 trees ha^{-1}).

Table 19 shows the partitioning of total biomass production to the aboveground and belowground portion of 12-year-old *A. mangium* stand. Maximum aboveground biomass production was registered in 5000 trees ha^{-1} stand with a value of 233.40 Mg ha^{-1} and minimum registered at 625 trees ha^{-1} stand with 120.92 Mg ha^{-1}. The belowground biomass production was also higher in the high density stand (5000 trees ha^{-1}) having a value of 104.57 Mg ha^{-1} and lowest in low density stand (625

trees ha^{-1}) with a value of 37.24 Mg ha^{-1}. The percentage contributions of aboveground biomass to total biomass vary from 70.0% (5000 trees ha^{-1}) to 76.0% (625 trees ha^{-1}). Table 19 also gave the root: shoot ratio that ranged from 0.32 to 0.45. Higher ratio was found attached with trees in the stands at wider spacing. Tree pruning could not make appreciable influence on biomass production.

4.3.4 Biomass carbon sequestration

Carbon storage in the various tissue fractions for *A. mangium* has been presented in Table 20. Total carbon sequestration for all the aboveground components ranged from 50.08 to 107.65 Mg ha^{-1}. Here also a consistent reduction in carbon stocking with decrease in stand density is obvious among all density regimes for all biomass components. Stands at 5000 trees ha^{-1} registered the highest Carbon sequestration with a mean production of 107.65 Mg C ha^{-1} which incidentally was almost two fold higher as compared to the carbon production at lowest standing density (50.08 Mg ha^{-1}; 625 trees ha^{-1}). Among the tissue components stemwood accounted bulk of the carbon storage. For example, stemwood registered about 83% of the total aboveground biomass for stands at high stand density (5000 trees ha^{-1}).

Leaf production registered the second largest component in terms of carbon content. It ranged from 2.81 to 9.61 Mg ha^{-1} across stand densities with lowest value corresponding to low density stands. Carbon content in the branchwood and twigs were relatively lower among various stand densities. Invariably pruning effects on carbon storage were all the more insignificant.

Table 17. Partitioning of mean tree biomass for 12-year-old *A. mangium* stand managed at variable densities and pruning Thiruvazhamkunnu, Kerala

	Stem		Branch		Twig		Leaf		Coarse root		Fine root		Total
	kg	%	kg	%	kg	%	kg	%	kg	%	kg	%	kg
Stand density (trees ha^{-1})													
5000	39.46^{c} (±3.31)	60.90	1.60^{b} (±0.57)	2.45	1.70^{b} (±0.35)	2.56^{a}	3.90 (±0.88)	5.85	19.76^{c} (±5.71)	27.74	1.15^{c} (±0.22)	1.70	67.58^{b} (±8.16)
2500	64.39^{c} (±5.12)	61.44	3.63^{b} (±0.73)	3.48	1.15^{b} (±0.34)	1.13^{b}	4.02 (±0.53)	3.73	31.78^{ab} (±4.28)	29.76	2.16^{b} (±0.12)	2.01	107.15^{b} (±7.64)
1250	107.31^{b} (±7.93)	63.92	5.29^{b} (±0.63)	3.19	1.96^{b} (±0.35)	1.16^{b}	7.46 (±0.73)	4.62	44.66^{a} (±4.20)	26.61	2.99^{b} (±0.22)	1.76	169.69^{a} (±9.79)
625	168.00^{a} (±20.64)	67.12	10.17^{a} (±2.28)	4.38	4.76^{a} (±0.95)	1.90^{ab}	10.53 (±1.06)	4.35	54.16^{a} (±8.70)	21.74	5.42^{a} (±0.14)	2.14	253.02^{a} (±23.27)
F-test	20.10	3.712	7.18	0.83	8.30	0.12	5.60	1.27	7.04	1.21	2.98	0.51	28.60
P value	0.00	0.559	0.003	0.49	0.001	0.02	0.00	0.32	0.003	0.34	0.00	0.68	0.000
Pruning													
No pruning	95.39 (±6.50)	62.38	5.65 (±1.21)	3.39	1.86 (±0.48)	1.33	6.01 (±0.58)	4.10	41.88 (±6.46)	28.34	2.86 (±0.22)	1.86	153.66 (±8.37)
50% pruning	94.19 (±17.75)	64.31	4.69 (±0.54)	3.36	2.92 (±0.79)	2.04	6.95 (±0.96)	5.18	33.31 (±5.62)	24.59	2.99 (±0.13)	2.06	145.08 (±13.57)
F-test	7.90	3.33	0.49	1.00	3.56	4.50	1.14	1.86	2.29	1.47	0.17	2.43	6.35
P value	0.92	0.57	0.47	0.97	0.07	0.05	0.30	0.19	0.15	0.243	0.69	0.14	0.57
Spacing X pruning													
F-test	0.23	0.76	0.47	0.21	1.49	0.35	0.24	0.05	1.52	0.97	3.80	1.19	0.35
P value	0.87	0.53	0.70	0.88	0.25	0.78	0.86	0.98	0.25	0.43	0.03	0.34	0.79

**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 18. Stand biomass accumulation and MAI for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Stand biomass accumulation (Mg ha^{-1})							MAI (Mg ha^{-1})
	Stem	Branch	Twig	Leaf	Coarse Root	Fine root	Total	
Stand density (trees ha^{-1})								
5000	197.34^{c} (±16.57)	8.05 (±2.85)	8.50^{a} (±1.73)	19.52^{a} (±4.08)	98.78^{a} (±14.53)	5.78^{a} (±0.06)	332.97^{a} (±41.23)	23.78^{a} (±2.93)
2500	160.98^{bc} (±12.65)	9.08 (±1.89)	2.88^{b} (±0.85)	10.06^{b} (±1.38)	79.48^{a} (±10.61)	5.40^{ab} (±0.05)	267.88^{b} (±19.06)	19.13^{b} (±1.35)
1250	134.14^{b} (±9.79)	6.62 (±0.81)	2.46^{b} (±0.43)	9.33^{b} (±0.89)	55.83^{ab} (±4.85)	3.74^{bc} (±0.03)	212.12^{bc} (±12.25)	15.15^{bc} (±0.85)
625	105.00^{a} (±12.66)	6.36 (±1.43)	2.97^{b} (±0.65)	6.58^{b} (±0.65)	33.85^{b} (±5.31)	3.38^{c} (±0.02)	158.14^{c} (±14.29)	11.30^{c} (±1.02)
F-test	10.70	0.36	7.00	4.53	3.80	4.57	14.06	14.06
P-value	0.000	0.78	0.003	0.018	0.03	0.017	0.000	0.00
Pruning								
No pruning	155.29 (±7.22)	7.80 (±2.41)	3.86 (±0.61)	10.89 (±1.43)	77.63 (±10.3)	4.21 (±0.06)	259.68 (±20.78)	18.55 (±1.47)
50% pruning	143.44 (±14.23)	7.25 (±2.45)	4.55 (±1.24)	11.86 (±1.71)	56.34 (±7.36)	4.91 (±0.03)	228.38 (±21.46)	16.31 (±1.54)
F-test	0.97	0.07	0.41	0.13	2.16	1.74	20.49	2.49
P value	0.34	0.79	0.53	0.72	0.16	0.21	0.13	0.13
Spacing x pruning								
F-test	2.47	0.13	0.73	0.09	1.92	1.36	3.68	3.68
P value	0.09	0.94	0.55	0.97	0.17	0.29	0.03	0.34

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Carbon stocking in the belowground tree parts are presented in Table 21. Total belowground C content ranged from 16.49 to 44.51 Mg ha^{-1}. Here also consistent reduction in carbon sequestration was discernible with decreasing planting density for *A. mangium*. Coarse roots accounted the highest proportion of the belowground carbon sequestration. For instance, the coarse root carbon content in the stands at 5000 trees ha^{-1} was 42.12 Mg ha^{-1} as against 2.39 Mg ha^{-1} for the fine root carbon content. Similar was the case with the remaining density regimes. The lowest carbon contents were recorded for coarse roots and fine roots in the lowest stand density (625 trees ha^{-1}), which were 15.13 and 1.36 Mg ha^{-1} respectively. Pruning effects on belowground carbon stocks were negligible.

Table 22 shows the total carbon sequestration by *A. mangium* which ranged from 66.58 (5000 trees ha^{-1}) to 152.16 Mg ha^{-1} (625 trees ha^{-1}). Corresponding values for the intermediate densities were 122.03 and 88.29 Mg ha^{-1} for 2500 trees ha^{-1} and 1250 trees ha^{-1} respectively. Among the components total aboveground carbon content was significantly higher as compared to belowground carbon. For instance, the aboveground carbon content in the stand at highest density.

4.3.5 Biomass nutrient accumulation

Accumulations of N, P and K in various tree components of 12- year-old *A. mangium* stand are depicted in tables 23, 24 and 25. The relative proportion of nutrients tied up in various tissue fractions, showed significant variation among density regimes. Total nitrogen accumulation within the biomass ranged from 2.78 to 12.04 Mg ha^{-1} (Table 23).

Table 19. Biomass accumulations at stand level in 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala.

	Total above ground biomass (Mg ha^{-1})	Total belowground stand biomass (Mg ha^{-1})	Total stand biomass (Mg ha^{-1})	Root:shoot ratio
Stand density (tree ha^{-1})				
5000	233.40^{a} (±21.64)	104.57^{a} (±28.57)	332.97^{a} (±41.23)	0.45
2500	180.97^{b} (±14.29)	84.87^{a} (±10.61)	267.88^{b} (±19.06)	0.47
1250	152.55^{bc} (±8.98)	59.57^{ab} (±4.89)	212.12^{bc} (±12.25)	0.39
625	120.92^{c} (±13.06)	37.24^{b} (±5.47)	158.14^{c} (±14.29)	0.32
F-test	11.45	4.12	14.06	0.89
P value	0.000	0.012	0.00	0.46
Pruning				
No pruning	177.84 (±7.65)	81.84 (±7.56)	259.68 (±20.78)	0.45
50% pruning	167.09 (±9.56)	61.23 (±8.34)	228.38 (±21.46)	0.37
F-test	10.57	2.02	20.36	0.31
P value	0.45	0.17	0.14	0.27
Stand density x pruning				
F-test	1.97	1.94	3.68	0.85
P value	0.15	0.16	0.03	0.48

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 20. Aboveground C stocks for various components for 12-year-old *A. mangium* at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Carbon stock in biomass (Mg C ha^{-1})				
	Stem wood	Branch wood	Twig	Leaf	Total
Stand density (Trees ha^{-1})					
5000	89.79[a] (±6.34)	4.19 (±0.16)	4.05[a] (±0.09)	9.61[a] (±0.23)	107.65[a] (±15.24)
2500	76.43[a] (±5.89)	3.65 (±0.24)	1.08[b] (±0.02)	4.82[b] (±0.13)	85.98[b] (±5.12)
1250	55.28[b] (±4.65)	2.87 (±0.14)	1.02[b] (±0.07)	4.09[b] (±0.14)	63.26[c] (±6.33)
625	42.67[b] (±4.93)	3.26 (±0.19)	1.27[b] (±0.03)	2.88[b] (±0.05)	50.08[c] (±5.45)
F-test	16.18	0.29	0.79	5.20	15.83
P value	0.00	0.82	0.001	0.01	0.00
Pruning					
No pruning	68.64 (±5.34)	3.62 (±0.19)	1.73 (±0.02)	5.13 (±0.11)	79.13 (±7.56)
50% pruning	63.44 (±4.65)	3.38 (±0.23)	1.97 (±0.05)	5.56 (±0.15)	74.35 (±8.45)
F-test	5.98	0.95	0.24	1.11	8.56
P value	0.33	0.81	0.63	0.74	0.46
Stand density X pruning					
F-test	2.72	0.14	0.69	0.08	2.03
P value	0.07	0.93	0.56	0.96	0.15

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 21. Belowground C stocks for various components for 12-year-old *A. mangium* at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Coarse root C content (Mg ha^{-1})	Fine root C content (Mg ha^{-1})	Total below ground C content (Mg ha^{-1})
Stand density (trees ha^{-1})			
5000	42.12^{a} (±4.45)	2.39^{a} (±0.35)	44.51^{a} (±3.45)
2500	33.84^{ab} (±5.34)	2.22^{ab} (±0.27)	36.05^{a} (±4.23)
1250	23.44^{ab} (±3.54)	1.59^{bc} (±0.19)	25.03^{ab} (±2.44)
625	15.13^{b} (±2.55)	1.36^{c} (±0.18)	16.49^{b} (±2.91)
F-test	3.56	4.30	3.91
P value	0.04	0.02	0.03
Pruning			
No pruning	33.24 (±3.11)	1.73 (±0.20)	34.97 (±2.43)
50 % pruning	24.02 (±3.01)	2.05 (±0.26)	26.07 (±2.11)
F-test	2.17	1.90	2.049
P value	0.16	0.19	0.17
Stand density x pruning			
F- test	2.14	0.63	2.18
P value	0.13	0.61	0.13

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 22. Total stand level C stocks for 12-year-old *A. mangium* at variable densities and pruning at Thiruvazhamkunnu, Kerala

	Total aboveground C stocks (Mg ha^{-1})	Total belowground C stocks (Mg ha^{-1})	Total vegetation C stock (Mg ha^{-1})
Stand density (trees ha^{-1})			
5000	107.65[a] (±15.24)	44.51[a] (±3.45)	152.16[a] (±18.43)
2500	85.98[b] (±5.12)	36.05[a] (±4.23)	122.03[b] (±10.43)
1250	63.26[c] (±6.33)	25.03[ab] (±2.44)	88.29[c] (±7.93)
625	50.08[c] (±5.45)	16.49[b] (±2.91)	66.58[c] (±8.22)
F test	15.83	3.91	18.91
P value	0.00	0.03	0.00
Pruning			
No pruning	79.13 (±7.56)	34.97 (±2.43)	114.10 (±10.45)
50% pruning	74.35 (±8.45)	26.07 (±2.11)	100.43 (±11.34)
F test	5.56	2.04	2.50
P value	0.46	0.17	0.13
Stand density X pruning			
F-test	2.03	2.18	4.23
P value	0.15	0.13	0.02

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Interestingly coarse roots accounted for major share of the nitrogen accumulation in the tree biomass with a range of 894.17 to 4992.41 kg ha^{-1}. Nitrogen accumulation varied in the order coarse root>Stemwood>leaf>branchwood>twig>Fine root. The corresponding percentage contribution among the components for the high density stand was coarse root (41.18%), stemwood (27.4%), branchwood (1.93%), twigs (4.51%), leaf (23.44%), and fine root (0.85%). Stemwood accounted the second highest proportion of nitrogen among the tissue components followed by leaf,

branchwood, twigs and fine roots (Table 23). Stemwood nitrogen content in general ranged from 666.59 to 3322.51 kg ha^{-1} while for the leaf biomass nitrogen content was in the premise of 875.4 to 2842.11 kg ha^{-1}. As observed earlier stand density showed profound influence on tissue nitrogen content which declined with decreasing planting density. Pruning effect on nitrogen accumulation also was however marginal.

Total phosphorus accumulation in the biomass ranged from 202.71to 423.11kg ha^{-1} across the sand densities (Table 24). Except for the branchwood and coarse roots stemwood, the variations in P content across stand densities were significant. As against nitrogen accumulation, Phosphorus accumulation was highest for the stemwood fraction which ranged from 132 to 260 kg ha^{-1} which was about 61% to 64% of the total phosphorus accumulation in the biomass. This was followed by coarse roots with a P accumulation range of 40 to 91 kg ha^{-1}. Leaf fraction represented the next highest source of phosphorus (40.04 to 12.84 kg ha^{-1}). Fine root fraction registered the lowest P content for all density regimes.

Potassium content in the biomass fraction are presented in Table 25. Total K accumulation in the tree biomass ranged from 3.61 to 8.31 Mg ha^{-1}. As expected, the stemwood fraction represented the highest proportion of potassium in the biomass. Stemwood potassium content in the high density stand was 2462.79 kg ha^{-1} which showed a decline with stand density to the tune of 1808.59 kg ha^{-1} in the stand at lowest density (625 trees ha^{-1}). Leaf component represented the second largest share of potassium in the biomass with a range of 1312.39 to 4061.25 kg ha^{-1} across stand densities. Coarse root proportion was higher in the high density stand (871.68 kg ha^{-1}; 5000 trees ha^{-1}). Among the components probably fine root accounted the lowest proportion of potassium that ranged from 16.94 to 33.60 kg ha^{-1}.

4.3.6 Allometric equation

Allometric were fitted linking DBH and height of trees various growth attributes such as biomass, volume and carbon sequestration (Table 26). High coefficient of determination and high levels of significance was observed for all the growth attributes tested. Regression equations with DBH as independent variable gave reasonably good fit for all dependent variable. For mean tree volume linear and quadratic models with DBH as independent variable gave good fit with R^2 values (>9.0). Quadratic models with DBH and mean tree aboveground biomass showed fairly high strength (R^2=0.86). Total tree biomass prediction with quadratic models gave high R^2 value (0.89). Total carbon sequestration at stand level was regressed with DBH and height. However the relations were comparatively weak with low R^2 values. Similar was the case with belowground biomass predictions also.

4.4 LITTER DYNAMICS IN *A. MANGIUM* STANDS AT VARYING STAND DENSITIES

4.4.1 Litter production

The total litter production in 12-year-old *A. mangium* varied from 9.99 to 11.69 Mg ha^{-1}among the stand densities (Table 27). Stand density exerted profound influence on the litter production with higher litter fall attached to high density stand (11.69 Mg ha^{-1}; 5000 tree ha^{-1}). Low density stand registered a lower litter yield of 9.99 Mg ha^{-1}. Other two density regimes showed intermediate values for litter production.

Table 23. Nitrogen accumulations in different components for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala.

	Nitrogen accumulation (kg ha^{-1})						
	Stem	Branch	Twig	Leaf	Coarse root	Fine root	Total (Mg ha^{-1})
Stand density (trees ha^{-1})							
5000	3322.51^{a} (±400.00)	234.75 (±36.24)	547.06^{a} (±41.35)	2842.11^{a} (±102.63)	4992.41^{a} (±408.35)	102.92^{a} (±10.61)	12.04 (±2.46)
2500	3507.56^{a} (±420.00)	190.54 (±41.75)	183.62^{a} (±36.24)	1497.86^{b} (±190.35)	2410.48^{b} (±285.68)	92.94^{a} (±8.71)	7.88 (±1.75)
1250	1089.21^{b} (±260.08)	161.00 (±28.32)	159.13^{b} (±28.45)	1263.75^{b} (±166.36)	1674.38^{b} (±300.78)	66.63^{ab} (±7.67)	4.41 (±1.01)
625	666.59^{b} (±139.35)	159.43 (±30.12)	152.43^{b} (±27.15)	875.40^{b} (±72.46)	894.17^{b} (±201.69)	34.56^{b} (±5.56)	2.78 (±1.52)
F-test	30.61	0.41	9.22	5.36	5.84	6.60	
P value	0.000	0.74	0.001	0.01	0.007	0.004	
Pruning							
No pruning	2511.09 (±300.41)	215.00 (±23.34)	236.58 (±33.12)	1578.39 (±147.68)	3335.54 (±425.77)	72.69 (±10.34)	7.94 (±2.01)
50% pruning	1781.85 (±252.13)	157.85 (±19.46)	284.82 (±26.56)	1661.18 (±185.35	1650.18 (±384.12)	75.83 (±7.34)	5.61 (±1.34)
F-test	70.46	10.07	10.58	69.05	50.25	5.07	
p value	0.01	0.31	0.45	0.82	0.03	0.80	
Spacing x pruning							
F-test	5.52	0.246	0.608	0.305	3.165	0.76	
p value	0. 009	0.863	0.620	0.821	0.053	0.53	

(Values in parenthesis are standard error of means)

(Values with the same superscripts do not differ significantly)

Table 24. Phosphorus accumulations in different biomass components for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala.

	Phosphorus accumulation (kg ha^{-1})						
	Stem	Branch	Twig	Leaf	Coarse root	Fine root	Total (kg ha^{-1})
Stand density (trees ha^{-1})							
5000	260.67^{a} (±12.35)	8.55 (±1.35)	18.84 (±6.32)	40.04 (±4.46)	91.69 (±10.57)	3.32^{a} (±0.52)	423.11 (±20.57)
2500	207.64^{ab} (±14.59)	11.49 (±3.32)	5.17 (±0.93)	19.37 (±1.67)	70.16 (±8.47)	3.07^{a} (±0.51)	316.90 (±16.33)
1250	170.58^{bc} (±13.24)	8.48 (±1.72)	6.45 (±1.35)	18.70 (±2.24)	63.26 (±9.47)	1.46^{b} (±0.41)	268.93 (±15.79)
625	132.45^{c} (±11.78)	7.58 (±2.33)	7.54 (±1.01)	12.84 (±1.98)	40.66 (±7.35)	1.64^{b} (±0.22)	202.71 (±15.65)
F-test	7.64	0.45	6.16	5.608	1.20	0.88	12.46
p value	0.002	0.72	0.005	0.008	0.34	0.001	0.005
Pruning							
No pruning	208.47 (±14.33)	8.49 (±2.19)	8.11 (±0.93)	21.62 (±4.57)	76.29 (±9.46)	1.92 (±0.13)	324.90 (±19.61)
50% pruning	177.20 (±14.32)	9.56 (±2.54)	10.89 (±1.42)	23.86 (±5.13)	56.60 (±7.46)	2.24 (±0.22)	280.08 (±20.43)
F-test	6.42	0.52	1.19	2.20	1.05	1.66	15.35
P value	0.31	0.62	0.29	0.66	0.32	2.16	0.35
Spacing x pruning							
F-test	1.51	0.21	0.74	0.19	0.71	0.95	
P value	0.24	0.88	0.54	0.89	0.55	0.43	

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 25. Potassium accumulations in different components for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala.

Treatments	Potassium accumulation (kg ha^{-1})						Total (Mg ha^{-1})
	Stem	Branch	Twig	Leaf	Coarse root	Fine root	
Stand density (trees ha^{-1})							
5000	2462.79^{ab} (±100.23)	218.85 (±36.56)	664.03^{a} (±68.89)	4061.25^{a} (±254.64)	871.68^{a} (±56.64)	33.60^{a} (±4.45)	8.31 (±1.46)
2500	2912.68^{a} (±154.44)	277.78 (±26.64)	217.40^{b} (±37.67)	2097.02^{ab} (±200.54)	463.88^{b} (±43.78)	31.97^{ab} (±3.50)	6.00 (±1.09)
1250	2368.67^{ab} (±178.367)	124.64 (±14.56)	188.18^{b} (±23.35)	2283.93^{ab} (±189.68)	233.90^{b} (±35.65)	19.29^{bc} (±2.35)	5.21 (±0.96)
625	1808.59^{b} (±134.56)	119.20 (±11.46)	214.22^{b} (±14.54)	1312.39^{b} (±146.55)	138.54^{b} (±24.65)	16.94^{c} (±3.31)	3.61 (±0.86)
F-test	20.10	10.29	60.51	29.56	23.98	3.77	
P value	0.14	0.31	0.004	0.091	0.006	0.03	
Pruning							
No pruning	2638.86 (±235.65)	188.11 (±22.54)	273.85 (±22.24)	2318.56 (±345.66)	568.15 (±46.73)	24.59 (±2.61)	6.01 (±1.67)
50% pruning	2137.51 (±179.67)	182.13 (±19.56)	368.06 (±2.44)	2558.73 (±256.66)	285.85 (±33.68)	26.30 (±3.54)	5.56 (±1.09)
F-test	20.56	10.08	10.10	65.11	14.47	1.50	
P value	0.12	0.93	0.31	0.74	0.05	0.48	
Spacing x pruning							
F-test	4.38	5.26	2.28	5.15	3.21	0.71	
P value	0.76	0.85	0.83	0.92	0.05	0.55	

(Values in parenthesis are standard error of means)

(Values with the same superscripts do not differ significantly)

Table 26. Allometric equation linking tree DBH and height with important growth attributes for 12-year-old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Palakad, Kerala

Dependent variable	Independent variable	Allometric equation	R^2 value	F test	SE of estimate
Volume per tree (VPT) (m^3)	DBH (cm) Ht (m)	VPT = 0.04(DBH)+0.018Ht-0.66	0.979	480.03	0.029
	DBH (cm)	VPT = 0.047(DBH) -0.448	0.95	420.47	0.04
		VPT = 0.794 ln(DBH)–1.876	0.93	300.17	0.05
		VPT = 0.003(DBH)+0.001$(DBH)^2$-0.076	0.96	227.14	0.04
Aboveground biomass per tree (AGBPT) (kg)	DBH(cm) Ht (m)	AGBPT = 12.69(DBH)+3.95(HT) –1.86.55	0.830	51.09	27.12
	DBH (cm)	AGBPT = 14.22(DBH) –140.61	0.82	98.37	27.44
		AGBPT = 237.38 ln(DBH) -565.09	0.79	80.10	29.79
		AGBPT = 185.79-24.92(DBH)+1.115$(DBH)^2$	0.86	63.18	24.79
Total tree biomass (TTB) (kg)	DBH (cm) Ht (m)	TTB = 16.46(DBH)+3.81(Ht) -211.07	0.86	67.01	9.71
	DBH (cm)	TTB = 17.89(DBH) –166.83	0.86	131.82	29.83
		TTB = 299.4 ln(DBH) -703.18	0.83	104.98	32.83
		TTB = 202.07-26.34(DBH)+1.26$(DBH)^2$	0.89	85.51	26.65
Total belowground biomass (TBGB) (kg)	DBH(cm) Ht(m)	TBGB = 3.73(DBH)-0.145(Ht) -24.53	0.57	13.93	13.33
	DBH (cm)	TBGB = 3.68(DBH) -26.21	0.57	29.18	13.03
		TBGB = 62.11 ln(DBH) –138.06	0.56	28.06	13.17
		TBGB = 16.27–1.42(DBH)+0.145$(DBH)^2$	0.58	14.34	13.22
Total stand C content (TSC) (Mg ha^{-1})	DBH(cm) Ht (m)	TSC = 193.03-8.78(DBH)+3.72(Ht)	0.57	13.93	13.33
	DBH (cm)	TSC = 236.22-7.35(DBH)	0.50	22.02	29.98
		TSC = 457.79–123.46 ln(DBH)	0.47	20.81	30.40
		TSC = 177.90-0.36(DBH)-0.19$(DBH)^2$	0.50	10.63	30.59

All significant at 1% level.

Pruning has an appreciable effect on litter production, with highest production observed in the stands without pruning.

Monthly variation in litter production was also significant across the density regimes. Average monthly production across density regimes was in the range of 832.43 to 973.79 kg ha^{-1}. Variations in litter production in the high density stands were fairly less. Similar closer production was observed among the lower density stands. Average month production irrespective of planting density was the highest during January (1599.2 kg ha^{-1}) (Table 28) while the lowest production was observed during March (633.39 kg ha^{-1}).

Unimodal distribution of litter production was observed with a distinct peak during summer. Summer months Feb- April represented almost 40% of the total annual litterfall. Rainy months in general showed lower litter production.

Attempts were made to relate the litterfall production with mean basal area per ha. There was high correlation between these two growth variables (Table 29). Allometric models with basal area as independent variable suggest reasonably good fit especially for quadratic model (R^2=0.71). Interestingly very strong relation has been observed between litterfall and fine root production with high correlation coefficient (R=0.90) with high levels of significance ($p<0.001$). Both linear and quadratic equations gave good fit with high R^2 values (0.82).

4.4.2 Carbon and nutrient return through litterfall

Table 30 shows the carbon and nutrient content in the litterfall. Litter carbon varied from 1.45 to 2.53 Mg ha^{-1} across planting densities. Highest carbon content was observed in the litterfall at 5000 trees ha^{-1} (2.53 Mg ha^{-1}). Nitrogen contribution through litterfall ranged from 36.66 to 58.18 kg ha^{-1}. The corresponding values for phosphorus were 1.16 to 4.28 kg ha^{-1} and for potassium was 4.36 to 7.69 kg ha^{-1}.

Consistent reduction in content with decreasing stand density was observed for litter C, N, P and K content

Table 27. Monthly litter production for 12-year-old *A. mangium* stand at variable densities and pruning at Thiruvazhamkunnu, Kerala

Stand density (Trees ha^{-1})	Average monthly litterfall (kg ha^{-1})	Average annual litterfall (Mg ha^{-1})
5000	973.798^{a} (±39.53)	11.69^{a} (±0.23)
2500	942.772^{a} (±28.37)	11.31^{a} (±0.31)
1250	853.544^{b} (±35.38)	10.24^{b} (±0.17)
625	832.432^{b} (±20.36)	9.99^{b} (±0.22)
F test	45.014	5.76
P value	0.000	0.011
Pruning		
No Pruning	949.005^{a} (±40.31)	11.04^{a} (±0.38)
50% Pruning	833.142^{b} (±27.33)	10.13^{b} (±0.25)
F test	36.74	4.65
P value	0.000	0.013
Stand density x Pruning		
F test	13.54	3.45
P value	0.024	0.035

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 28. Monthly variation in litterfall across stand densities for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala

Months	Monthly litter production (kg ha^{-1}) Standing density (trees ha^{-1})				F test	P value	Average monthly production (kg ha^{-1})
	5000	2500	1250	625			
July	785.43^{a} (±22.86)	787.17^{a} (±24.54)	677.74^{ab} (±31.02)	661.11^{b} (±34.57)	3.891	0.037	727.86^{ef} (±20.46)
Aug	855.41^{a} (±10.39)	781.83^{b} (±33.88)	669.30^{b} (±46.35)	743.06^{c} (±29.24)	13.343	0.000	762.40^{de} (±24.46)
Sep	1014.41^{a} (±46.57)	941.83^{b} (±42.57)	961.56 (±53.35)	831.82^{c} (±19.46)	25.214	0.000	937.40^{c} (±29.57)
Oct	751.13 (±12.34)	757.58 (±71.46)	698.84 (±42.24)	678.9 (±47.51)	1.313	0.316	721.45^{ef} (±79.67)
Nov	970.92 (±37.35)	986.7 (±64.71)	885.60 (±29.35	922.01 (±44.51)	0.680	0.581	941.20^{c} (±30.78)
Dec	870.43^{a} (±62.41)	831.76^{ab} (±13.57)	762.33^{ab} (±33.88)	686.90^{b} (±27.58)	3.125	0.066	787.86d^{e} (±28.33)
Jan	1733.10 (±15.57)	1682.80 (±70.61)	1489.95 (±40.00)	1491.27 (±44.09)	3.591	0.046	1599.20^{a} (±34.12)
Feb	1375.39 (±72.22)	1337.64 (±19.57)	1395.21 (±45.72)	1206.69 (±36.55)	0.511	0.682	1328.73^{b} (±24.77)
Mar	760.33^{a} (±51.57)	666.89^{ab} (±53.57)	563.96^{c} (±16.68)	662.38^{ab} (±58.64)	2.590	0.101	633.39^{g} (±15.64)
April	757.94^{ab} (±62.74)	810.68^{a} (±45.46)	661.79^{bc} (±45.35)	639.52^{c} (±40.07)	5.488	0.013	717.48^{ef} (±34.48)
May	908.77^{a} (±37.57)	860.81^{a} (±32.53)	698.57 (±56.35)	683.69 (±26.55)	4.677	0.022	787.96^{de} (±27.52)
June	902.25 (±66.33)	868.29 (±27.44)	777.67 (±37.24)	782.38 (±22.72)	1.216	0.346	832.64^{d} (±31.42)
Total (Mg ha^{-1})	11.69	11.31	10.24	9.99			10.77

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 29. Prediction models linking litterfall with basal area and fine root production for *A. mangium* at variable planting densities.

Dependent variable	Independent variable	Prediction model	R^2	SE	F test	R
Litterfall (LF) (Mg ha^{-1})	Basal area (B) (m^2 ha^{-1})	LF= 11.39(B) -70.05	0.70	7.89	21.20	0.84**
		LF= 123.51 ln(B) - 240.40	0.71	7.80	21.94	0.84
		LF= 39.66(B)–1.30$(B)^2$- 222.47	0.71	8.20	10.00	0.85
Fine root (FR) (Mg ha^{-1})	Litterfall (LF) (Mg ha^{-1})	FR = 1.43(LF) –10.81	0.83	0.64	66.06	0.91**
		FR = 5.40 ln(LF) - 31.98	0.82	0.66	63.17	0.91
		FR = 0.068$(LF)^2$ - 2.74-0.064(LF)	0.83	0.67	31.12	0.91

All significant at 1% level.

4.4.3 Litter decomposition

Patterns of litter decomposition for *A. mangium* are presented in Table 31 and average annual mass decomoposed in the litter bag is given in Table 32. Interestingly there was a sharp decline in litter decay during the first month of decomposition. There after the decay rates followed a gradual decline with time. At the end of 12 months (June) period the residual mass remaining in the litter bags were 5.26, 3.74, 2.82, 2.58 and 1.28g respectively for 5000, 2500, 1250, 625 trees ha^{-1} and control (open). In general, the higher rates of litter decomposition were associated with lower density stands.

Table 30. Litter C and nutrient content in the litterfall for 12-year-old *A. mangium* stand at variable densities and pruning at Thiruvazhamkunnu, Kerala

Stand density (Trees ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
5000	2.53^{a}	58.18	2.16	7.69^{a}
2500	2.29^{a}	52.72	1.97	4.43^{b}
1250	1.50^{b}	38.63	4.28	2.85^{b}
625	1.45^{b}	36.66	1.16	4.36^{b}
F value	0.97	2.41	0.99	1.78
P test	0.01	0.11	0.42	0.00
Pruning				
No pruning	1.93	42.77	1.56	4.46
50% pruning	1.96	50.32	3.23	5.21
F test	0.71	1.24	1.57	1.72
P value	0.90	0.28	0.23	0.21
Stand density X pruning				
F test	1.19	1.32	0.94	4.92
P value	0.35	0.30	0.45	0.01

(Values with the same superscripts do not differ significantly)

Mass remaining in the litter bags on percentage basis is given in Table 33. At the end of 6 months (December) the percentage mass remaining was 19.39, 18.83, 16.24, 14.26 and 12.75% for stands at 5000, 2500, 1250, 625 trees ha^{-1} and control (open). At the end of the study (ie after 12 months) the percentage mass remaining were 5.26, 3.74, 2.82, 2.58, 1.28 for stands at 5000, 2500, 1250, 625 trees ha^{-1} and control (open). Invariably the litter decay in the open area was showed the highest rate (Table 34). Except for the rapid mass loss in the initial month the reduction in residual mass followed a gradual trend in an asymptotic fashion.

4.4.4 Carbon and nutrient release through litter decomposition

The net carbon and nutrient return to the soil through litter decomposition is presented in Table 35. Litter contributes nearly 1.43 to 1.93 Mg C ha^{-1} through decomposition. Nitrogen return to the soil was in the range of 36 to 44 kg ha^{-1} across stand densities. Contribution of P was relatively low (1-4 kg ha^{-1}) while the corresponding values for potassium was 3-6 kg ha^{-1}. Except for potassium, significant variation in carbon and nutrient return through litter was not observed across stand densities.

4.5 SOIL CARBON AND NUTRIENT STOCKS

Total soil carbon stock up to 1m soil depth for *A. mangium* trees of 12-year stand age at Thiruvazhamkunnu are presented hereunder. The *A. mangium* stand registered significantly higher soil carbon stock compared to the treeless control plot. The soil organic carbon was significantly different across different density regimes.

4.5.1 Soil organic carbon concentration

Table 36 provide the depth-wise representation of mean soil organic carbon (SOC) concentration. The mean SOC concentration ranged from 0.31% (treeless control) to 1.03% (5000 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 1.41% (0-20 cm) to 0.27% (80–100 cm) in 5000 trees ha^{-1} stand. Similar is the case with almost all the density regimes. Invariably the SOC concentration was lower in treeless plot compared with *A. mangium* at different density regimes. However, soil carbon concentration was not influenced by tree pruning treatments.

4.5.2 Soil Bulk Density

Soil bulk density changes for various soil depths for *A. mangium* also showed considerable variation both across the density regimes, pruning levels and soil depths (Table 36). Soil bulk density varied from 1.15 to 1.54 between stand densities. Bulk density in the treeless control was higher compared to various stand densities except for stand at lowest density. Consistent reduction in bulk density was also observed across the soil depths for all stand densities. Bulk density also varied with tree pruning. For instance in the high density stand the average bulk density varied from 1.17 to1.32 from 0-20 cm to 80–100 cm in the unpruned stand while the corresponding value for pruned stand in the same density was 1.11 to 1.26.

4.5.3 Soil carbon sequestration

Total soil carbon sequestration across various planting densities and pruning levels showed considerable variation. In general the total soil content showed a decline with decreasing planting density while an increase was observed in pruned stands. For instance the total carbon sequestration in the high density stand (5000 trees ha–1) was 114.61 and 118.60 Mg ha–1for unpruned and pruned stands respectively. The corresponding value for the low density stand (625 trees ha–1) was 91.52 and 75.18 Mg ha–1 for unpruned and pruned stands respectively. In variably the tree less control soil showed considerably lower value compared to soil in all the density and pruning combinations. The tree less control soil showed the lowest soil carbon sequestration compared to all the densities (42.41 Mg ha^{-1}).

Table 31. Mass remaining in litter bags as influenced by planting density for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala.

Months	Monthly mass remaining in litter bags (g)					F test	P value
	Standing density (trees ha^{-1})				Control		
	5000	2500	1250	625			
Initial	66.81	66.81	66.81	66.81	66.81		
July	34.00^{a} (±0.33)	33.00^{a} (±0.32)	31.95^{a} (±0.20)	29.80^{a} (±0.06)	29.66^{b} (±0.09)	5.340	0.007
Aug	31.00^{a} (±0.31)	30.00^{a} (±0.34)	28.35^{b} (±0.08)	27.61^{b} (±0.13)	22.36^{c} (±0.12)	50.92	0.000
Sep	28.76^{a} (±0.31)	27.48^{b} (±0.27)	26.31^{c} (±0.31)	24.99^{d} (±0.12)	19.49^{e} (±0.15)	95.69	0.000
Oct	25.66^{a} (±0.27)	24.99^{a} (±0.12)	24.23^{a} (±0.41)	20.69^{b} (±-.08)	18.42^{c} (±0.07)	28.85	0.000
Nov	24.29^{a} (±0.34)	22.93^{a} (±0.31)	20.36^{b} (±0.34)	18.31^{c} (±0.12)	16.48^{d} (±0.13)	36.87	0.000
Dec	19.39^{a} (±0.12)	18.83^{a} (±0.21)	16.24^{b} (±0.21)	14.26^{bc} (±0.06)	12.75^{c} (±0.16)	15.96	0.000
Jan	17.52^{a} (±0.16)	14.93^{b} (±0.05)	12.49^{c} (±0.15)	11.37^{cd} (±0.28)	10.45^{d} (±0.25)	19.91	0.000
Feb	14.66^{a} (±0.31)	11.51^{b} (±0.07)	10.19^{bc} (±0.29)	8.68^{cd} (±0.30)	6.97^{d} (±0.17)	20.51	0.000
Mar	10.39^{a} (±0.12)	8.96^{b} (±0.13)	7.60^{bc} (±0.03)	6.44^{c} (±0.12)	4.72^{d} (±0.06)	25.77	0.000
April	8.88^{a} (±0.04)	7.91^{ab} (±0.07)	7.26^{b} (±0.16)	5.54^{c} (±0.24)	4.22^{d} (±0.04)	24.30	0.000
May	7.54^{a} (±0.12)	5.57^{b} (±0.08)	4.16^{c} (±0.03)	3.63^{c} (±0.04)	3.03^{c} (±0.13)	23.22	0.000
June	5.26^{a} (±0.08)	3.74^{b} (±0.05)	2.82^{c} (±0.12)	2.58^{c} (±0.06)	1.28^{d} (±0.08)	23.87	0.000

(Values in parenthesis are standard error of means)
(Values with the same superscripts do not differ significantly)

Table 32. Average mass decomposed in litter bags as influenced by planting density and pruning for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala.

Stand density (trees ha^{-1})	Monthly mass remaining in litter bags (g)
5000	14.49[c]
2500	15.99[c]
1250	17.48[b]
625	18.94[a]
F test	5.23
P value	0.020
Pruning	
No pruning	18.13[a]
50% pruning	16.33[b]
F test	4.86
P value	0.014

(Values with the same superscripts do not differ significantly)

Average soil carbon stocks for various planting densities and pruning levels showed considerable variation across soil depths (Table 36 and Table 37). In general, there was steady decline in soil carbon stock with increasing soil depth for all density regimes. High density stands sequestered more carbon (23.32 and 22.94 Mg ha^{-1} for 5000 and 2500 trees ha^{-1} respectively) while the corresponding values were lower for low density stands (15.96 and 16.67 Mg ha^{-1} for 1250 and 625 trees ha^{-1} respectively). Tree pruning in general showed an increase in soil carbon content. Invariably the treeless control soil showed considerably lower value compared to soil in all the density and pruning combinations

Table 33. Percentage mass remaining in litter bags as influenced by planting density for 12-year-old *A. mangium* at Thiruvazhamkunnu, Kerala.

Months	Monthly mass remaining in litter bags (%)					F test	P value
	Standing density (trees ha^{-1})				Control		
	5000	2500	1250	625			
	100	100	100	100	100		
July	50.89^{a}	49.39^{b}	47.82^{b}	44.60^{c}	36.82^{d}	74.83	0.000
Aug	46.39^{a}	44.90^{a}	42.43^{b}	41.33^{b}	34.88^{c}	49.42	0.000
Sep	43.04^{a}	41.13^{b}	39.38^{c}	31.40^{d}	29.45^{c}	115.97	0.000
Oct	38.41^{a}	37.41^{a}	36.27^{a}	30.98^{b}	27.84^{c}	28.32	0.000
Nov	36.56^{a}	34.33^{a}	30.47^{b}	27.40^{c}	24.57^{d}	37.95	0.000
Dec	29.02^{a}	28.19^{a}	24.30^{b}	21.34^{c}	21.38^{c}	8.36	0.001
Jan	24.67^{a}	22.35^{a}	19.69^{b}	17.01^{bc}	15.90^{c}	18.45	0.000
Feb	21.94^{a}	17.23^{b}	15.26^{bc}	12.99^{c}	9.94^{d}	23.23	0.000
Mar	15.56^{a}	13.01^{b}	11.38^{bc}	9.63^{c}	7.44^{d}	24.88	0.000
April	13.29^{a}	11.85^{ab}	10.87^{b}	8.29^{c}	6.32^{d}	27.85	0.000
May	11.29^{a}	8.33^{b}	6.22^{c}	5.43^{c}	5.16^{c}	22.67	0.000
June	7.87^{a}	5.59^{b}	4.23^{c}	3.14^{cd}	2.41^{d}	28.59	0.000

(Values with the same superscripts do not differ significantly)

Table 34. Decay rate coefficient, decomposition rate and half-life periods corresponding to 12-year-old *A. mangium* litter influenced by planting density and pruning at Thiruvazhamkunnu, Kerala.

Stand density (trees ha^{-1})	k-value	Decomposition rate	$t_{(0.5)}$
5000	2.55^{d}	0.08^{a}	0.27^{a}
2500	2.89^{c}	0.06^{b}	0.24^{b}
1250	3.17^{bc}	0.04^{bc}	0.22^{bc}
625	3.29^{b}	0.03^{c}	0.21^{c}
Treeless control plot	3.98^{a}	0.02^{d}	0.18^{d}

(Values within same column with the same superscripts do not differ significantly)

Table 35. Carbon and nutrient release through the decomposing litter for 12-year-old *A. mangium* influenced by planting density and pruning at Thiruvazhamkunnu, Kerala.

	C ($Mg\ ha^{-1}$)	N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)	K ($kg\ ha^{-1}$)
Stand density (trees ha^{-1})				
5000	1.93	44.00	2.00	6.00^{a}
2500	2.08	48.00	2.00	4.00^{b}
1250	1.44	37.00	4.00	3.00^{b}
625	1.43	36.00	1.00	4.00^{ab}
F test	2.38	8.11	1.07	5.82
P value	0.11	0.51	0.39	0.001
Pruning				
No pruning	1.68	37.00	1.00	0.01
50% pruning	1.76	45.00	3.00	0.01
F test	0.63	1.68	1.66	2.32
P value	0.72	0.21	0.22	0.15
Stand density x pruning				
F test	1.43	1.37	0.95	5.05
P value	0.27	0.29	0.44	0.01

(Values with the same superscripts do not differ significantly)

4.5.4 Soil nutrients

Soil Nitrogen content at two pruning levels and at five depth intervals in *A. mangium* stand with adjacent treeless plot as control has been depicted in Table 38. The 5000 trees ha^{-1} stands registered higher soil nitrogen content with a value 2343.51 kg ha^{-1}. There was a consistent reduction in the soil nitrogen content in 1 meter depth in different densities. Stand density 625 trees ha^{-1} registered 948.23 kg ha^{-1} N content. There is a consistent reduction in N content from the top soil (20 m) to1 meter depth (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. Soil N content in the 50% pruned stand is lower when compared to the unpruned stand.

Soil phosphorus showed considerable variation among stand density and pruning regimes for *A. mangium* (Table 38). The average C stock (average of 5 soil depths) ranged from 13.12 to 21.92 kg ha^{-1} with a consistent increase with increasing stand density. Top soil (0-20cm) represented the highest of P (average 21.89 kg ha) while a sharp reduction in soil P was observed with increase in soil depth.

Soil potassium also varied with stand density, pruning levels and soil depth (Table 38). The average K content in the soil (average of all five soil depths) ranged from 179.37 to 313.54 kg ha^{-1}. Also the K content declined steadily with increase in soil depth. For e.g. the average K content in the top soil was 408.02 which reduced to 176.35 kg ha^{-1} for the deepest soil (80–100cm).

Table 36. Depthwise distribution of Mean Soil carbon (SOC) concentration, soil carbon sequestration, and soil bulk density for 12-year old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala

	SOC concentration %	Bulk density (g cm^{-3})	C sequestration (Mg ha^{-1})
Stand density (Trees ha^{-1})			
5000	1.03^{a}	1.16^{e}	23.32^{a}
2500	0.91^{b}	1.31^{d}	22.94^{a}
1250	0.60^{c}	1.41^{c}	15.96^{b}
625	0.59^{c}	1.55^{b}	16.67^{b}
Control	0.32^{d}	1.46^{a}	8.48^{c}
F test	0.03	0.97	1.05
P value	0.000	0.000	0.000
Pruning			
No pruning	0.68	1.36	16.99
50% pruning	0.79	1.38	20.33
F test	0.15	0.70	5.79
P value	0.290	0.000	0.020
Soil depth (cm)			
0-20	1.42^{a}	1.24^{c}	34.59^{a}
20-40	0.91^{b}	1.24^{c}	22.37^{b}
40-60	0.62^{c}	1.22^{c}	14.67^{c}
60-80	0.43^{d}	1.51^{b}	12.44^{d}
80–100	0.27^{e}	1.64^{a}	8.34^{e}
F test	0.44	0.74	3.97
P value	0.000	0.000	0.000

(Values with the same superscripts do not differ significantly)

Table 37. Variation in soil mean carbon sequestration across stand density, pruning and soil depth for 12-year old *A. mangium* stand managed at variable densities and pruning at Thiruvazhamkunnu, Kerala

Treatments	Soil carbon sequestration (Mg ha^{-1})								
	Planting density (trees ha^{-1})								
	5000		2500		1250		625		Control
	Pruning levels								
Soil depth (cm)	No pruning	50% pruning	No pruning	50% pruning	No pruning	50% pruning	No pruning	50% pruning	
0-20	39.21	39.04	30.21	32.14	34.15	40.10	47.83	31.50	17.07
20-40	25.01	30.04	23.77	27.63	24.14	20.88	22.36	17.13	10.31
40-60	21.19	21.12	19.69	20.83	17.70	9.81	10.05	14.59	6.92
60-80	18.66	16.22	16.55	26.18	13.99	10.55	8.66	5.37	5.71
80–100	10.54	12.18	12.00	20.36	13.98	4.34	2.62	6.59	2.40
Total	114.61	118.60	103.22	127.14	103.96	85.68	91.52	75.18	42.41

Table 38. Depth wise distribution ns of mean soil N, P and K content in 12-year-old *A. mangium* stands at variable densities and pruning levels in different soil depths at Thiruvazhmkunnu, Kerala.

Treatments	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Stand density (trees ha^{-1})			
5000	2343.51^{a}	21.92^{a}	313.55^{a}
2500	1970.96^{b}	15.98^{b}	328.54^{ab}
1250	1660.56^{c}	14.74^{c}	302.65^{b}
625	948.23^{d}	13.13^{d}	261.25^{c}
Treeless Control plot	215.16^{e}	9.33^{e}	179.37^{d}
F test	29.64	10.16	84.13
P value	0.00	0.00	0.00
Pruning			
No pruning	1511.56	16.121	291.52
50% pruning	1343.79	13.923	262.62
F test	14.21	7.18	24.35
P value	0.00	0.00	0.00
Depth (cm)			
0-20	1995.61^{a}	21.89^{a}	408.03^{a}
20-40	1809.45^{b}	17.57^{b}	341.65^{b}
40-60	1391.82^{c}	14.34^{c}	255.50^{c}
60-80	1108.10^{d}	11.92^{d}	203.83^{d}
80–100	833.45^{e}	9.39^{e}	176.35^{e}
F test	93.39	11.23	21.44
P value	0.00	0.00	0.00
Spacing x pruning x depth			
F test	4.28	1.59	1.02
P value	0.00	0.09	0.44
Spacing x pruning			
F test	2.07	5.70	1.68
P value	0.09	0.00	0.16
Spacing x depth			
F test	4.69	5.15	3.32
P value	0.00	0.00	0.00
Pruning x depth			
F test	0.46	0.79	4.28
P value	0.76	0.54	0.003

(Values with the same superscripts do not differ significantly)

4.6. TOTAL SYSTEM CARBON SEQUESTRATION FOR 12-YEAR-OLD *A. MANGIUM*

Total carbon sequestration in a 12-year-old *A. mangium* stand contributed by the aboveground, belowground and soil at varying stand density are depicted in Table 39. The aboveground biomass carbon stocks varied from 49.09 to 102.67 Mg ha^{-1} across the stand densities. Clearly, the declining trend in carbon sequestration with decreasing planting density is visible in the study.

Table 39. Total system carbon sequestration in 12-year-old *A. mangium* stands at variable densities in different soil depths at Thiruvazhmkunnu, Kerala

Stand density (Trees ha^{-1})	Carbon stocks in the aboveground biomass (Mg C ha^{-1})	Carbon stocks in the belowground biomass (Mg C ha^{-1})	Soil organic C (Mg ha^{-1})	Total system C (Mg ha^{-1})
5000	102.67^{a}	44.51^{a}	116.61^{a}	263.79^{a}
2500	82.66^{b}	36.05^{ab}	115.18^{a}	233.89^{b}
1250	64.59^{c}	25.03^{ab}	95.82^{b}	155.44^{c}
625	49.09^{d}	16.49^{b}	83.35^{b}	148.93^{c}
F test	22.73	3.02	17.95	21.49
p- value	0.000	0.094	0.001	0.000

(Values with the same superscripts do not differ significantly)

Similarly, the carbon stocks in the belowground biomass also showed wide variation across density regimes with the same trend as that of aboveground biomass. For instance the stand at highest density sequestered almost 2.7 times as compared the same for lowest density stand. Interestingly the soil carbon stocks also varied with stand density with almost 1.4 times higher production in the high density stands (5000 trees ha^{-1}). Overall, the system carbon stocks varied with pronounced variation across stand densities ie., from 148.93 (625 trees ha^{-1}) to 263.79 Mg ha^{-1} (5000 trees ha^{-1}).

Discussion

DISCUSSION

Results presented in the preceding section deal with the effect of stand density management and pruning on tree growth, fine root production, turn over and associated carbon and nutrient fluxes, aboveground litter dynamics, aboveground and belowground biomass production and nutrient accumulation in twelve-year-old *A. mangium* stand. Implications of the salient findings are discussed hereunder.

5.1. TREE GROWTH AND STAND DENSITY

Tree density management for enhanced productivity has been a well-accepted practice in the plantation forestry (Sjolte-Jorgensen, 1967; Evert, 1984). Suitable planting distances ensure the required space for tree growth and this optimizes the biomass production per unit area (Harris, 2007). In the present study, most of the tree growth parameters had profound influence on stand density for 12 year old *A. mangium*. The average height growth ranged from 15.96 m (5000 trees ha^{-1}) to 19.90 m (1250 trees ha^{-1}) (Fig. 5) which is comparable with other fast growing tree species studied from the same location (*Acacia auriculiformis*; 17.84 m, *Casuarina equisetifolia* 12.13 m at 8.8 year; Kumar *et al.,* 1998). However, a report from S-E Asia (Malaysia) suggests higher height growth of 22-26 m for 12-year-old *A. mangium* (Naota, 2011). Interesting trends were observed in the height growth responses to stand density. In general, the medium density stand (1250 trees ha^{-1}) gave better height compared to high density stand. The trends were reverse in the same stand at younger ages of 6.5 year, where increase in height growth with increasing stand density was observed (Kunhamu *et al.,* 2011). It can be seen that, as the stand become mature, the facilitatory influence of density on height growth was found to be diminishing. Lanner (1985) and Henskens et al. (2001) also suggested that as stand mature, stand density has little effect on height growth, except where the stand is extremely dense

or so open that the trees are distinctly isolated. Probably, the crown competition and associated higher vertical competition for light and space cause trees in the denser stand to grow more in height at its younger grand growth phase (Long and Smith, 1984). However, in the present study, the lower height growth rate observed in the high density stand at mature age could be attributed to severe competition for resources which might have negatively influenced the overall growth of the trees, surpassing the competitive advantage expected in vertical growth. Koch *et al.* (2004) and Domec *et al.* (2008) made similar observation among trees of even-aged stands, where height growth rates declined with increasing stature after peaking at young age. The apparent height increase in widely spaced stands could be simply the result of better sharing of resources (water and nutrient) by lesser number of trees (Aref *et al.*, 1999).

In general, the radial growth in diameter was moderate for *A. mangium* in the present study which varied from 12.4 cm (5000 trees ha^{-1}) to 19.9 cm (625 trees ha^{-1}) (Fig. 6). For instance, studies from Malaysia reported higher average diameter growth of 26.7 cm for *A. mangium* stands at the same age (Naoto, 2011). However our values are comparable with other fast growers such as *Acacia auriculiformis* (13.63 cm), *Paraserianthes falcataria* (13.29 cm) reported from the same location (Kumar *et al.*, 1998). Probably the better adaptability to prevailing climatic and biophysical conditions could be the reasons for their better performance in the S-E Asian regions.

Contrary to the height growth, closely spaced stand showed distinctly lower growth rate in diameter, basal area, crown width and volume compared to widely spaced stands. Tree diameter growth usually increases with reduction in planting density (Harper, 1977). Trees often show variable plastic responses of morphological adaptations as a strategy to optimize resource acquisition in local competitive environment (Sultan, 2000; Ågren *et al.*, 2012; Poorter *et al.*, 2012). Eventually, they become more rational in the allocation of the resources among the biomass

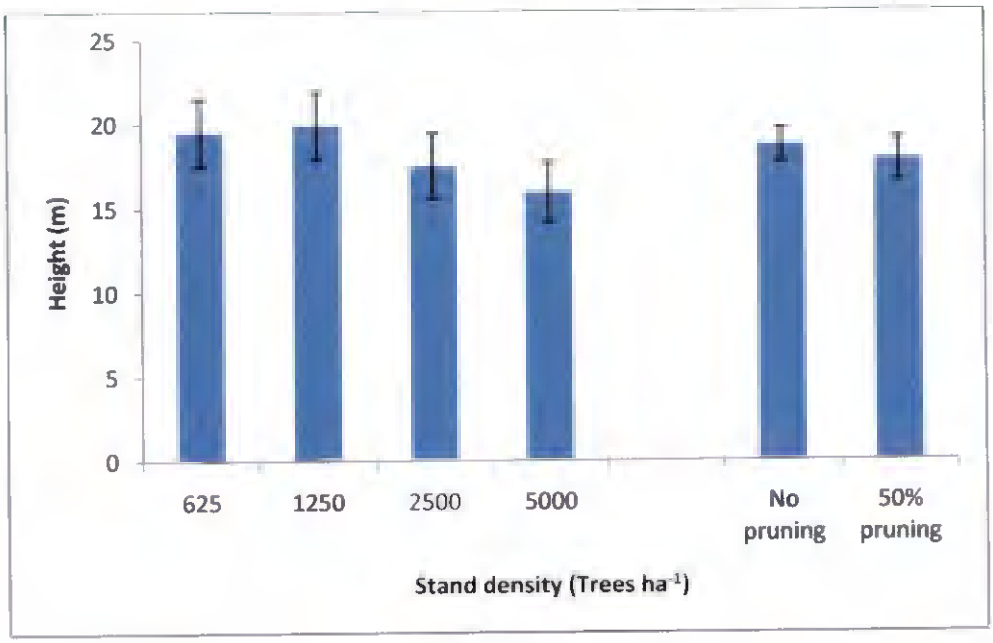


Fig. 5.Heightof 12-yr-old *Acacia mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

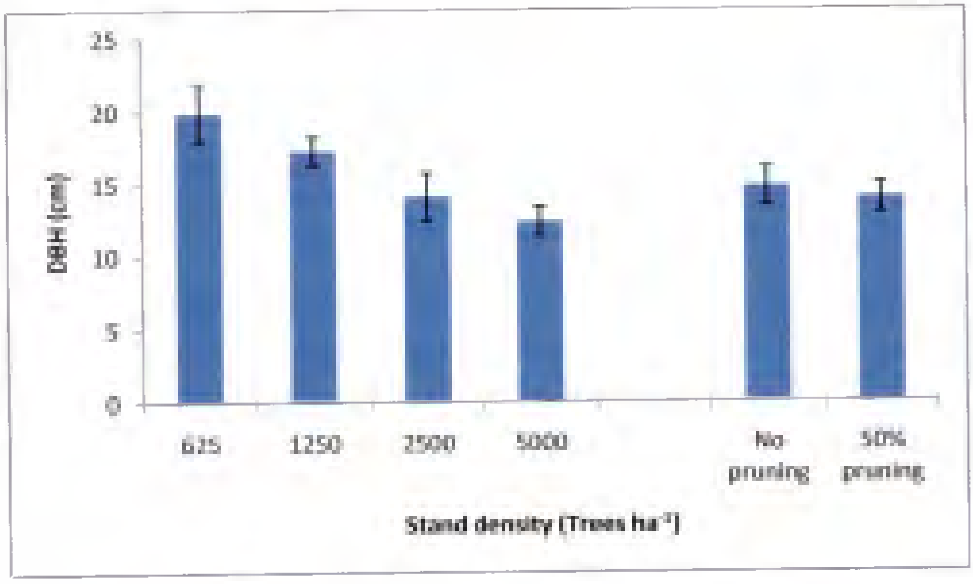


Fig. 6.Diameter at breast height of 12-yr-old *Acacia mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

components, such that they attain competitive advantage in the acquisition of scarce resources. The wide spacing may induce rapid crown expansion, which accelerates the diameter growth at the expense of height growth (Jonestone, 1985; Jiang *et al.,* 2007). The direct proportionality between tree diameter and crown spread has already been established (Macdonald and Hubert, 2002; Naji and Sahri, 2012). The widely spaced trees tend to effectively capture sufficient sunlight, moisture and nutrients for its growth. As tree planting density increases, greater competition is created among the plants, resulting in an increase in the number of trees with reduced diameter (Clutter *et al.,* 1983; Leite *et al.,* 2006; Kruschewsky *et al.,* 2007). In brief, the present study has shown that density management in intensively managed fast growing plantations such as *A. mangium* can bring desirable changes in improving the growth features and overall productivity.

In the present study, the average tree volume for 12-year-old *A. mangium* showed considerable variation across stand densities, which ranged from 0.16 m^3 (5000 trees ha^{-1}) to 0.61 m^3 (625 trees ha^{-1}) (Fig. 7). Tree volume, being a variable that is a cumulative manifestation of the radial growth and height of trees, the changes in these parameters with stand density may also affect the volume. The dominant role of density on trees growth was evident in the present study. For instance, the mean tree volume production strongly and inversely related to the stand density. As observed earlier, the better competitive advantage for resource acquisition at wide density promoted trees to acquire water and minerals at faster rates leading to higher volume production. Such trends have already been reported for many tropical tree species (Gerrand *et al.,* 1997; Medhurst *et al.,* 2001; Sukanya, 2014).

In the present study, the stand volume production for 12-yr-old *A. mangium* ranged from 381.04 m^3 ha^{-1} (625 trees ha^{-1}) to 797.74 m^3 ha^{-1} (5000 trees ha^{-1}) (Fig. 8). These values are even much higher than the stand level volume production for similar

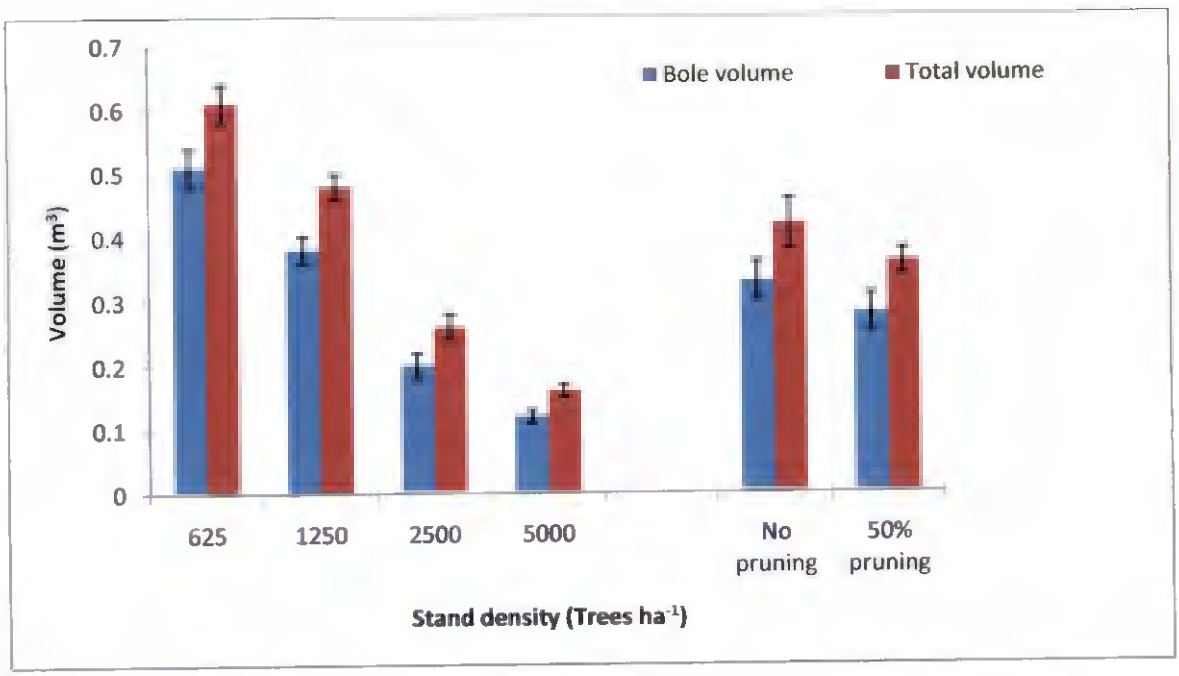


Fig. 7.Bole volume and Total Volumeof 12-yr-old *Acacia mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

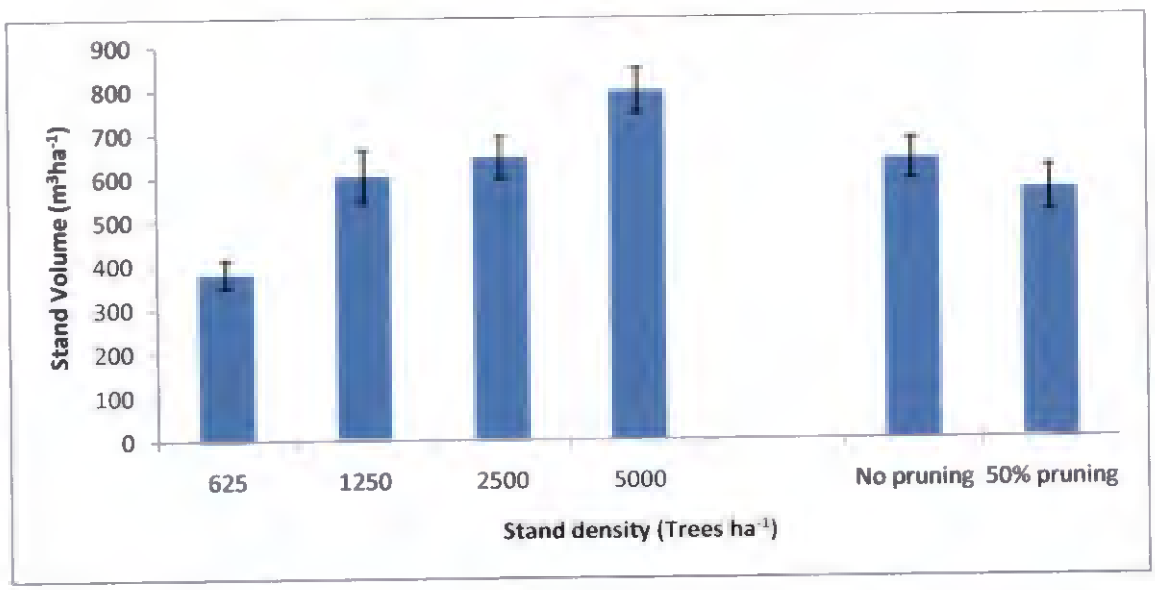


Fig. 8.Stand volumeof 12-yr-old *Acacia mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

aged *A. mangium* reported from Malayasia (234 m^3 ha^{-1}; Naoto, 2011). As compared to mean tree volume, the stand level volume showed variable trend across stand densities with a distinct decrease in stand volume per hectare with reduction in planting density. For instance, the volume at the lowest density stand was only half of that at highest density. Such vast changes in volume with tree density have been observed from several studies (Bernardo *et al.,* 1998; Leles *et al.,* 2001; Kruschewsky *et al.,* 2007; Magalha˜es *et al.,* 2007; Oliveira *et al.,* 2009). Probably, the influence of increase in individual tree volume at low stand densities was masked by the cumulative effect of large number of trees at high standing density.

Significant variation in stem taper was noticed across the standing densities (Table 5). Results suggest higher taper ratio associated with trees managed at higher densities. In general, trees allocate resources uniformly along the trunk in crowded stands as compared to widely spaced stands. Spacing and planting layout influence tree growth and form (Schönau and Coetzee, 1989; Gerrand *et al.,* 1997; Deans and Milne, 1999).

In the present study, pruning showed only marginal effect on the growth of 12 year old *A. mangium*. According to Mead and Speechly (1991), pruning is necessary in early stage of stand development of *A. mangium*, if the aim is to maintain full growth potential and produce good-quality timber. Kunhamu *et al.* (2011), in the same stand at 6.5 years of age observed that tree pruning did not significantly ($p < 0.05$) alter most of the growth parameters. Similar insensitivity to pruning has been reported for *A. mangium* in South Sumatra, (Beadle, 2007). In general, pruning had an inhibitory effect on most of the growth parameters for *A. mangium*.

5.2 FINE ROOT STUDY IN 12 YEAR OLD *A. MANGIUM* AT VARYING STAND DENSITY

5.2.1 Fine root production and turnover

Fine root production and turnover estimated through two different methods of ingrowth core and sequential core gives variable values with similar trends for 12-year-old *A. mangium* (Fig. 9). The fine root production estimated in the ingrowth method (3.38 to 5.78 Mg ha^{-1}) is higher compared to the sequential method (1.39 to 2.41Mg ha^{-1}). Turnover rate also estimated to be higher in ingrowth method. However, most of the reports suggest lower fine root estimates from ingrowth method compared to other methods (Vogt *et al.,* 1998; Hendricks *et al.,* 2006). For instance, Addo-Danso *et al.,* (2016) reviewed various methods of fine root production and turnover for different species and observed mean fine root production (FRP) lower in the ingrowth-core method (2.06 ± 0.23 Mg $ha^{-1}year^{-1}$, n=73) compared to estimates provided by sequential-coring method (3.84 ± 0.93 Mg $ha^{-1}year^{-1}$, n=59), though the differences were not significant (F = 2.851, p = 0.061). Likewise, Finér *et al.* (2011) reported higher FRP estimate for sequential-coring methods than the ingrowth-core method, although there were no significant differences in FRP estimates among these methods at the stand level. Earlier reviewers also reported lower FRP estimates from ingrowth-core than from other method (e.g. Moser *et al.,* 2010; Finér *et al.,* 2011).

Report from boreal mixed forest in Ontario, Canada reveals significant positive correlation between FRP between sequential-coring and ingrowth-core methods (Yuan and Chen, 2012) while, others reported contrasting relationships between these methods (e.g. Steele *et al.,* 1997; Hendricks *et al.,* 2006; Moser *et al.,* 2010). The methods explained less than 50% of the variation in FRP, indicating influences of other factors such as species, site conditions, sampling depth, fine-root size classification, resource availability, stand and environmental conditions on FRP (Addo-Danso *et al.,* 2016; Rytter, 1999; Makkonen and Helmisaari, 2001; Ostonen *et*

al., 2005; Hendricks *et al.,* 2006; Finér *et al.,* 2011; Mei *et al.,* 2010; Yuan and Chen, 2010, 2012; Smith *et al.,* 2013). Despite such limitations, ingrowth cores are very effective in studying ecosystems with rapid fine root growth and extremely suitable for humid locations, where moisture stresses are not intense (Neill, 1992; Vogt *et al.,* 1998; Oliveira *et al.,* 2000; Godbold *et al.,* 2003). Hence ingrowth method provides better conservative estimates of root-biomass and hence followed widely in the tropics.

The fine root production in the present study ranges from 1.39 to 5.78 Mg $ha^{-1}yr^{-1}$. This is fairly higher than values reported for similar such fast growing tree species. For instance, variable estimates of fine root production have been reported for many fast growing tropical tree species. Fine root production in the ranges 2.4–2.8 Mg $ha^{-1}year^{-1}$ has been reported for *Eucalyptus* species (Jourdan *et al.,* 2008) while Acacia monoculture stands in northern Kenya reported lower values (0.95 Mg ha^{-1} $year^{-1}$) (Lehmann and Zech, 1998). Tropical dry forests of India also observed moderate values (2.1 Mg $ha^{-1}year^{-1}$) (Singh and Singh, 1981). Fine root production obtained in the present study is higher than that reported in agroforestry systems of Acacia (2.1 Mg ha^{-1} $year^{-1}$) intercropped with Sorghum in Kenya (Lehmann and Zech, 1998). In contrast sugar maple trees from North America reported high FRP values to the tune of 6.5–8.1 Mg ha^{-1} $year^{-1}$) (Aber *et al.,* 1985). Similarly, higher fine root production has been reported for oak trees (9.9 t ha^{-1} $year^{-1}$; McClaugherty *et al.,* 1982). Table 40 provides a comprehensive account of fine root production, biomass, and turnover rates for various tropical tree species using different methods. It is interesting to observe that our values are similar or higher than that reported for most of the tree species.

5.2.2 Fine root production with stand density

Fine root production and turn over significantly varied with stand densities for both the methods (Fig. 9). In general, the production on unit area basis (per ha) showed an increasing trend with increasing stand density for both the methods. The prominent effect of stand density on the fine root production has been reported from available limited studies in this line. In a similar study, involving hybrid poplars of pastureland in New Zealand trees at 770 stems per ha had 3–12 times more roots than at densities of <237 stems per ha (Douglas *et al.,* 2010).

Mean tree fine root production showed an inverse trend, with trees at higher density giving lower production compared to trees grown at wider spacing. The difference was such that the mean tree fine root production at low density stand was as much as 4.6 times as compared to high density stands implied the enormous effect of tree density on fine root production. Trees, in general respond to stand density in a similar fashion with an overall increase in biomass production and partitioning to various tissue components. However, this assumes considerable importance when it comes to fine root production, as they are the primary tree component involved in water and mineral nutrient absorption. Evidently, such changes could significantly influence the resource accumulation efficiency in stands managed at variable stand densities. Resource allocation to different plant parts as a function of spacing shows that *A. mangium*, when planted at wider spacing levels, will respond by allocating more proportional growth to root systems, thereby reducing the amount of material allocated to large woody structures, in particular to the bole. Furthermore, the spatial advantage in widely spaced stands could promote the extended growth of fine roots in the trees. Also, less competition for resources in widely spaced stands endorses higher water and mineral uptake leading to higher biomass accumulation. Conversely, the denser stands are exposed to high degree of space limitation and may experience resource limitation in fine root production.

Table 40. Fine root production, biomass, and turnover rates for various tropical tree species using different methods

Tree species	Fine root production (Mg ha^{-1} yr^{-1})	Fine root biomass (Mg ha^{-1})	Fine root turn over (yr^{-1})	Method	Authors
Leucaena leucocephala	0.79	0.97	0.81	Sequential core (SC)	Jha and Mahopatra, 2010
Acacia nilotica	1.06	1.89	0.56	"	"
Azadirachta indica	1.69	1.75	0.97	"	"
Prosospis juliflora	1.71	2.35	0.73	"	"
Teak	1.63 1.72	1.38 -	1.17 -	Soil block method SC and IG (Ingrowth method)	Srivastava *et al.*, 1986 Sundarapandyan and Swamy, 1998
Acacia	1.55	-	-	SC and IG	Sundarapandyan and Swamy, 1998
Albizzia	1.46	-	-	"	"
Rubber	1.60	-	-	"	"
Banana	1.37	-	-	"	"
Pepper	1.50	-	-	"	"
Cassava	1.22	-	-	"	"
Arecanut	1.72	-	-	-	"

Our findings are in conformity with reports from other similar studies. For instance, Puri *et al.*, 1994), reported from desert region of India an increase of fine roots biomass from 30-75% when the spacing of *Populous deltoids* trees increased from a

2x2 m to 6x6 m respectively. Furthermore, they reported that trees growing under wider spacing allocated more total carbon to their roots compared to those with the narrow spacing. Similarly, Bernardo (1998) observed in *E. urophylla*, two times material allocated to roots (<2 mm), when the spacing level was increased from 3x1.5 m to 4x3 m. They also observed the same trend in other two species *E. camaldulensis* and *E. pellita*. Similar results also reported by Barton *et al.* (2006).

5.2.3 Fine root turn over

Fine root turnover rates in our study ranged from 1.58 to 3.16 yr^{-1}, implying that the cycle of entire fine root produced at a time dies and grows back varies from one to three times a year. This is higher than those reported for other tropical forests (average 0.8 $year^{-1}$; Gill and Jackson, 2000). Our values are also fairly higher than that reported for most of tropical broadleaved tree species including teak (Table 40). However, our study seems similar to six tropical species from Costa Rica, which ranged from 1.6 to 3 yr^{-1} (Valverde-Barrantes, 2007). Rapid fine root turnover is expected in tropical forests primarily on account of the prevailing congenial biophysical conditions (Lauenroth and Gill, 2003). The increase in the FRT rate may be related to the increase in maintenance of respiration, carbon addition, nutrient mineralization, especially that of nitrogen (Eissenstat and Yanai, 1997; Gill and Jackson, 2000; Nadelhoffer, 2000). Furthermore, fine root longevity varies between vegetation and is affected by soil conditions like temperature, moisture and nutrient availability (Pregitzer *et al.,* 1993; Gaul *et al.,* 2008; Graefe *et al.,* 2008). Gill and Jackson (2000) in a meta-analysis comprising 59 studies found that, the estimated fine root turnover ranged from 5 months to 2 years. Hickler *et al.* (2008), suggested a universal fine-root turnover rate of 0.7 yr^{-1} to all forest tree species based on the findings of Vogt *et al.* (1996) and Li *et al.* (2003). Li *et al.* (2003) found a linear relationship between fine root production and fine root biomass, with the turnover

rate 0.64 yr^{-1} which was lower than the original estimate of 0.73 yr^{-1} from a previous analysis (Kurz *et al.,* 1996).

5.2.4 Carbon and nutrient content in the fine roots

It was observed that, substantial amount of carbon and nutrients accumulated in the fine roots. For instance, the average carbon accumulation in the fine roots ranged from 1.36 to 2.39 Mg ha^{-1} (Table 12). Similarly fine roots accounted higher amounts of nitrogen (34.56 to 102.92 kg ha^{-1}), phosphorus (1.64 to 3.31 kg ha^{-1}) and potassium (16.94 to 33.60 kg ha^{-1}). Other reports also suggest similar content of nitrogen in *A. mangium* fine roots (yields 31–128 kg $ha^{-1}year^{-1}$; Bouillet *et al.,* 2008; Mercado *et al.,* 2011). In the present study, nutrient content of fine roots also showed considerable variation across stand densities. The dominant role of density management on overall growth of trees has been demonstrated before. However, such information on the fractional contribution of carbon and various nutrients in annual fine root production, especially in diverse stand density regimes are rather limited. The information converges to the realization that fine roots bestow great potential for enriching the soil carbon and nutrient pools. Several recent studies have implicated that fine roots are the main contributors to soil carbon (Rasse *et al.,* 2005; Clemmensen *et al.,* 2013). According to some workers (eg., Steele *et al.,* 1997; Brown, 2002; Ruess *et al.,* 2003; Howard *et al.,* 2004), rapid turnover and decomposition rate of fine roots contribute ~30 to 80% of the total organic carbon into soil. They are increasingly recognized as a key parameter for the accurate assessment of ecosystem carbon budgets (Guo *et al.,* 2008).

5.2.5 Fine root decomposition and nutrient release

Fine root decomposition is an important pathway contributing to the carbon and nutrient pools in the soil. Production, senescence and concomitant decomposition of

fine roots significantly contribute to enrich soil health. This unique ecological contribution ensures efficient replenishment of nutrient and carbon resource base in the soil in woody ecosystems (Person, 1978; Fogel and Hunt, 1979; Aerts *et al.,* 1992). The rates at which fine roots are decomposed and converted to labile nutrient forms is primarily depended on the tree species, the fine root quality and the biophysical condition of the soil.

Moderate decay rates have been exhibited by the fine roots in the present study with annual decay ranging from 76 to 90% (Fig. 10). In general, the rate of fine root decomposition increased with decreasing tree density. For instance, fine root decay rate constant of the *A. mangium* as per our study ranged from 1.44 (5000 trees ha^{-1}) to 4.42 (625 trees ha^{-1}) with highest decay rate constant (4.92) in the treeless control plot (included as a check to see the decay rate in open condition). Reports of fine root decay rates elsewhere suggest lower or comparable results. A similar study from lowland Costa Rica suggest fine roots from tree plantations such as *Virola koschnyi* decayed very slowly (k=0.29+-0.15 $year^{-1}$) while *Vochysia guatemalensis* decayed seven times faster (k=2.00+-0.13 $year^{-1}$) (Raich *et al.,* 2009). Decay rates of *Hieronyma alchorneides* and *Pentaclethra macroloba*, were 1.36 and 1.28 $year^{-1}$ respectively. The fine root decay rates from southern china indicate lower values in the range of 0.27 to 0.83 for evergreen broad leaved species, while 0.52 to 0.87 for coniferous species (Lin *et al.,* 2011).

Decay rates for many tropical tree species suggest similar ranges, though variations abound with species and site management conditions. Our study clearly demonstrates stand density also influence root decay rates in addition to fine root production as discussed before. Higher decay rates attached to the widely spaced stands suggests better edapho-climatic conditions available for hastening decomposition. More importantly the relatively higher soil exposure in the widely spaced stands offers soil micro-climate conducive for soil faunal activities and concomitant enhancement in

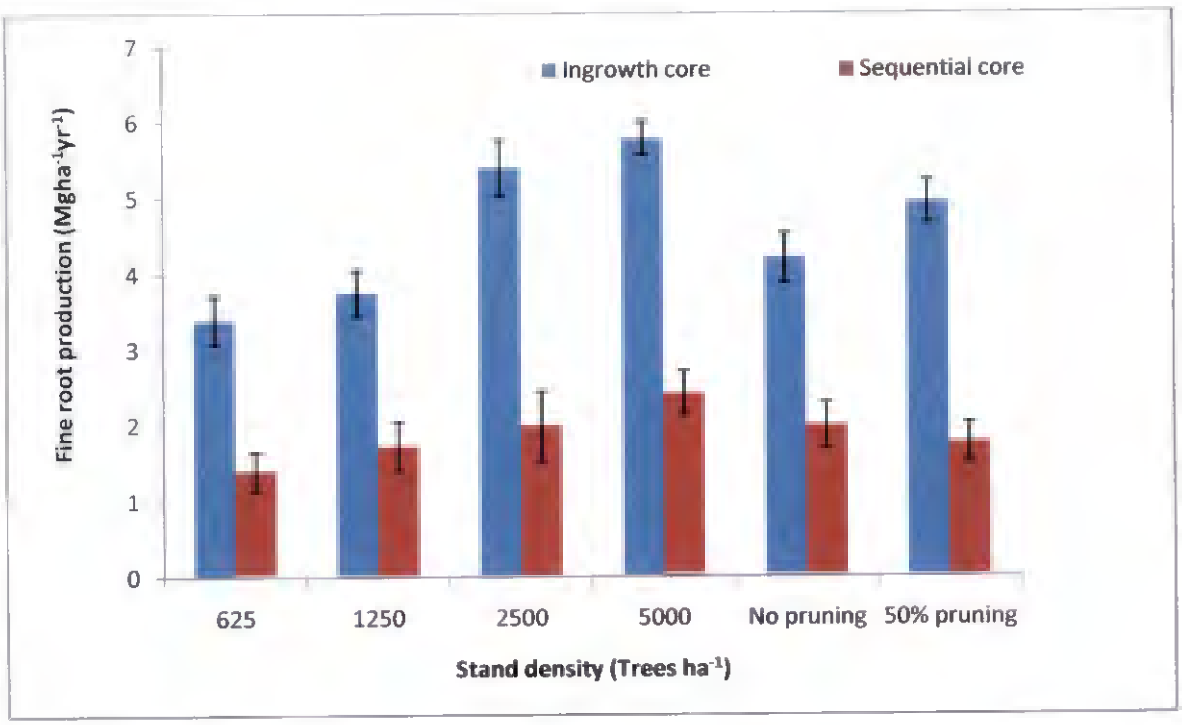


Fig.9.Annual fine root productionin 12-year old *Acacia mangium* stands at varying stand densities by ingrowth core and sequential coring methodat Thiruvazhamkunnu, Kerala

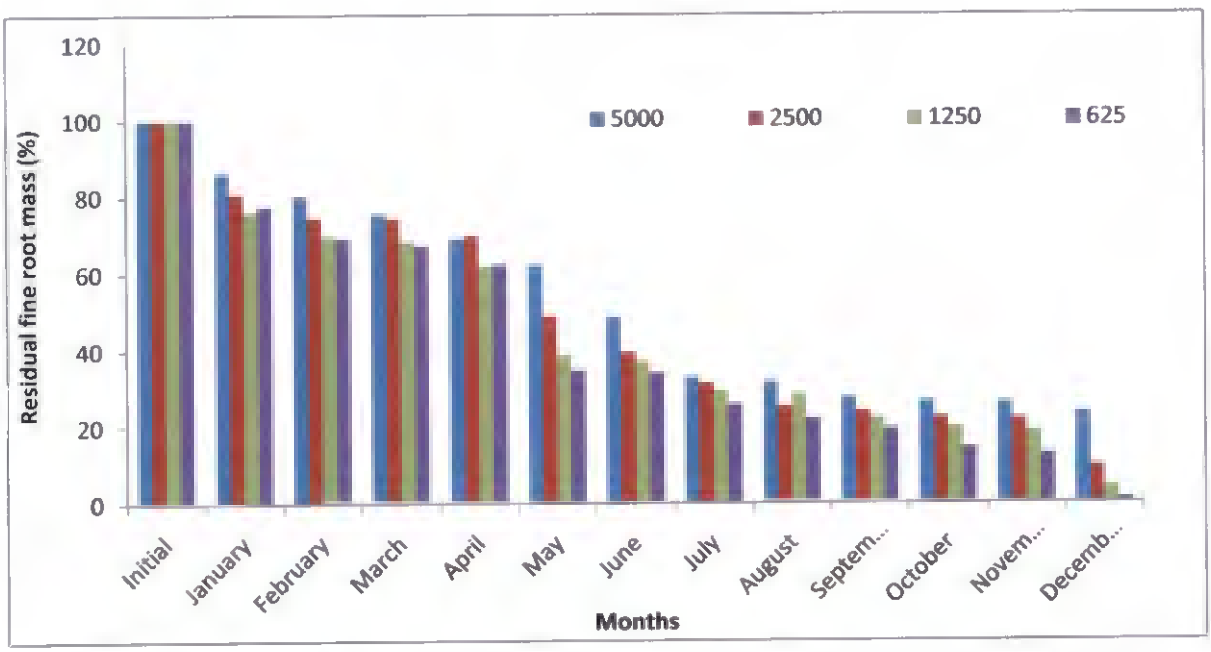


Fig. 10.Percentage residual fine root mass of12-yr-old *Acacia mangium* as influenced by standing density and pruning at Thiruvazhamkunnu, Kerala

decay rates. A study in same location, on the effect of tree density on leaf litter decomposition in *A. mangium,* demonstrated faster decay rates in stands at wider spacing (Kunhamu *et al.,* 2005).

Root C:N ratios also played an important role in predicting patterns in root decay. The initial C:N ratio of fine roots in the present study ranged from 43.63 (2500 trees ha^{-1}) to 40.27 (625 trees ha^{-1}). Valverde-Barrantes *et al.* (2007) reported a range of 22.8 to 32.6 C: N ratio in live roots of 16 year old six tropical lowland Costa Rica species. As the stand density influences the edaphic conditions, C:N ratio also varied widely in different stand densities. Interestingly, there was inverse relation between C:N ratio and fine root decay rates. For example, the stand at lowest density had the lowest C:N ratio which incidentally showed the highest fine root decay rates. The labile components degrade first, whereas the recalcitrant components remain much longer (Dornbush *et al.,* 2002; Fan and Guo, 2010; Lei *et al.,* 2010; Lin *et al.,* 2011). As the former disappear and the latter accumulate, the decomposition rate decreases, presumably in a continuous manner. The importance of substrate C:N ratios in governing the rate of organic matter decomposition was recognized as early in 1916 (Jensen, 1929). Soil moisture, soil temperature and C:N ratios of soils together explained 24% of the variance of the fine root mass loss in forests (Solly *et al.,* 2014).

Annual decomposition rate for *A. mangium* fine roots are fairly faster (76-90%) and major portion of the nutrients were mineralized to the soil. Similarly, substantial proportion of the carbon in the fine roots was found released to the soil (76.57 - 99.26%). The status of the carbon and nutrients (N, P, K) present in decomposing root litter demonstrates this observation (Table 13). For instance, approximately 34 kg ha^{-1} (625 trees ha^{-1}) to 78 kg ha^{-1} (5000 trees ha^{-1}) of nitrogen was released from the decomposing fine roots which constituted almost 75.79 to 98.37% of the initial N in the fresh fine roots. In a similar study however, lower amounts of nitrogen was returned through fine roots that ranged from 15–34 kg ha^{-1} y^{-1} under different

broadleaved tree species (Jha and Mahapatra, 2010). Our nitrogen release values are higher or within range as compared to many reported values. For eg. Zewdie *et al.* (2008) reported fluxes of 64–65 kg N ha^{-1} y^{-1} through fine root turnover for *Enseteven tricosum*. Vogt *et al.* (1996) estimated this as high as 100 kg N ha^{-1} $y^{-1}$for a mature *Abies amabillis* stand while only 20 kg N $ha^{-1}y^{-1}$ for undisturbed mature Douglas fir forests (Gill and Jackson, 2000). In the present study phosphorus and potassium also showed similar high release to the soil to the tune of 76.51 to 98.78% and 75.89 to 98.82% respectively. Overall, the fine root nutrient flux for *A. mangium* in the present study indicate high levels of dynamism suggesting the pivotal role of fine roots in improving the carbon and nutrient content in the soils and thereby maintaining the long term fertility.

5.2.6 Fine root allometry

Considering the overwhelming importance of fine roots in the nutrient and carbon cycling and on the overall productivity of the woody ecosystems, it is imperative that, realistic estimates of fine root production are indispensible. The arduous nature of fine root quantification puts considerable limitations in its realistic estimates. However, we have made good attempt to correlate fine root production with other easily measurable growth variables such as DBH, basal area, volume, biomass, crown width, leaf area, coarse root etc. Interestingly, good positive correlations were evolved between DBH and fine root production ($R^2 = 0.85$ at $p < 0.001$). Similarly good relationships were established with basal area (R^2=0.85), volume (R^2=0.82) and aboveground biomass (R^2=0.89) (Table 14).

Allometric equations linking biomass production and easily measurable growth variable such as DBH and height have been worked out for large number of tropical forestry species (Kumar *et al.*, 1998; Kunhamu *et al.*, 2005; Anitha *et al.*, 2015). However this functionality with fine root has not been tested so far especially for *A.*

mangium. Based on the best fitting correlations, we also made allometric equations for predicting fine root production for 12-yr-old *A. mangium*. Despite the lower coefficient of determination (r^2= 0.72) for fine root prediction equations based on DBH and basal area compared to biomass and volume as independent variables (r^2=0.8), it would be desirable to stick to DBH based allometric equations on account of the simplicity in DBH measurements. Yet another observation is that prediction equations for fine root production on unit area basis (ha) could not yield strong relations as against mean tree production estimates. Probably the stand density changes are primarily influencing the mean tree growth attributes and hence fine root prediction equations based on individual trees gives realistic estimates. This trend was also visible for aboveground allometric relations for *A. mangium* in the same experiment.

5.3 BIOMASS STUDY IN 12 YEAR OLD *A. MANGIUM* AT VARYING STAND DENSITY

5.3.1 Biomass production

A. mangium at 12th year showed high biomass production potential with average mean tree aboveground production ranging from 46.68 to 193.47 kg ha^{-1} (Table 16; Fig. 11). These values are comparable with value reported for fast growing trees of similar growth habit such as and reported for *Acacia auriculiformis* (130.57 kg tree^{-1}) and *Paraserianthes falcataria* (73.39 kg tree^{-1}) at 8.8 years of age at the same study site (Kumar *et al.*, 1998). A mean tree aboveground biomass production of 42 Mg ha^{-1} was reported for the same *A. mangium* stand at younger age of 6.5 years (Kunhamu *et al.*, 2011).

As observed for the fine root production trends, stand density exerted profound influence on the biomass production for 12-yr-old *A. mangium*. Clearly, stands maintained at high density had low mean tree biomass while stands at lowest densities

showed manifold increase in mean tree biomass. This is a very common trend observed for most of the tree species (Lanner, 1985). Availability of wider rhizosphere provides competitive advantage of resource acquisition for widely spaced trees. While the trees at extreme density might experience intense competition for the resource, eventually it results in their suboptimal performance.

Stand biomass production potential for *A. mangium* (per ha) also showed considerable variation among density regimes (Fig. 12). Present study followed a consistent decline in stand biomass production with maximum value in high density stand (332.97 Mg ha^{-1}; 5000 trees ha^{-1}) and minimum in low density stand (158.14 Mg ha^{-1}; 625 trees ha^{-1}). Similar trend was followed in plantations of *Ailanthus triphysa* at different densities (8.8 year; Shujauddin and Kumar, 2003 and 22 year; Sukanya, 2014) and in 6.5-year-old *A. mangium* stand in Kerala (Kunhamu *et al.*, 2011). 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 unit area basis, it would be desirable to follow closer spacing such as 5000 or 2500 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.

MAI is a strong indicator of the productive potential of the trees, which is often helpful in the intra-specific and inter-specific growth comparisons of different stands. The average total biomass production on per hectare basis irrespective of density regimes was 242.77 Mg ha^{-1} and corresponding MAI was 20 Mg ha^{-1} yr^{-1}. Similar trend of total biomass production (223.61 Mg ha^{-1}) but with lower MAI (10.16 Mg$ha^{-1}yr^{-1}$) was observed in 22 year old *Ailanthus triphysa* stand (Shujauddin and Kumar, 2003). Inter-specific variation in biomass production has been reported for variable management regimes for different ages. For eg. Kumar *et al.* (1998) reported biomass increment of 37.09, 4.61, 9.32, 10.86 Mg ha^{-1} for *A. auriculiformis*, *A.*

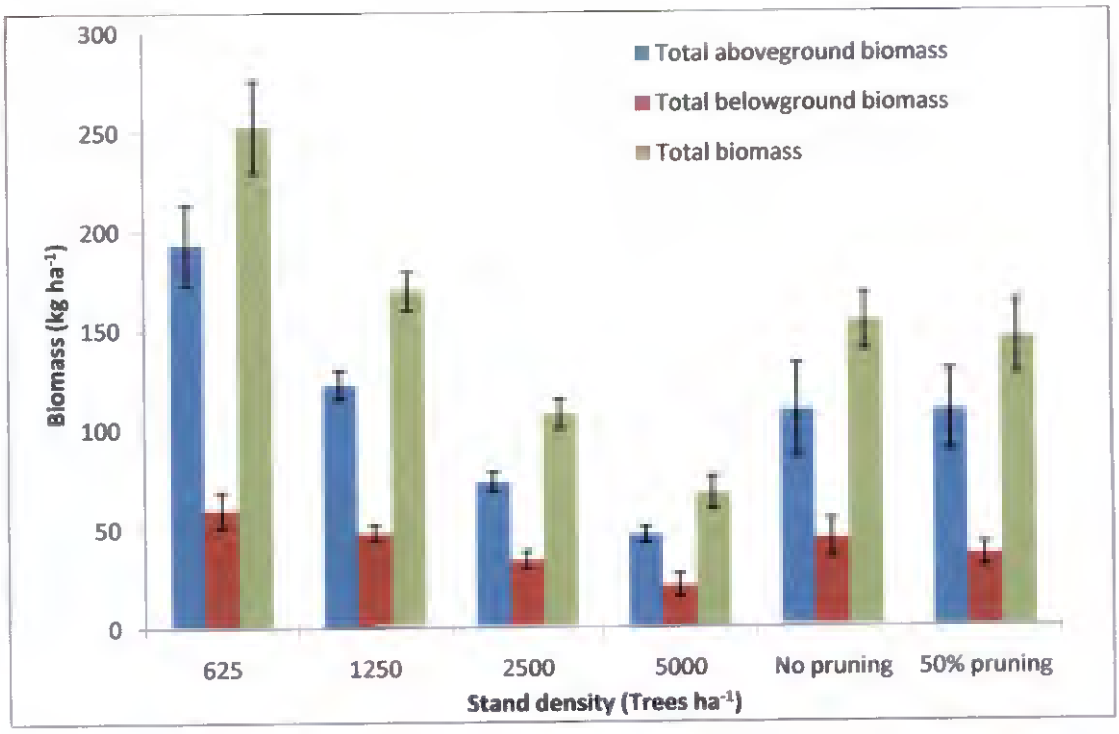


Fig.11.Meantreebiomassaccumulationfor12-year-old *A.mangium*standmanagedat variable densities at Thiruvazhamkunnu, Kerala

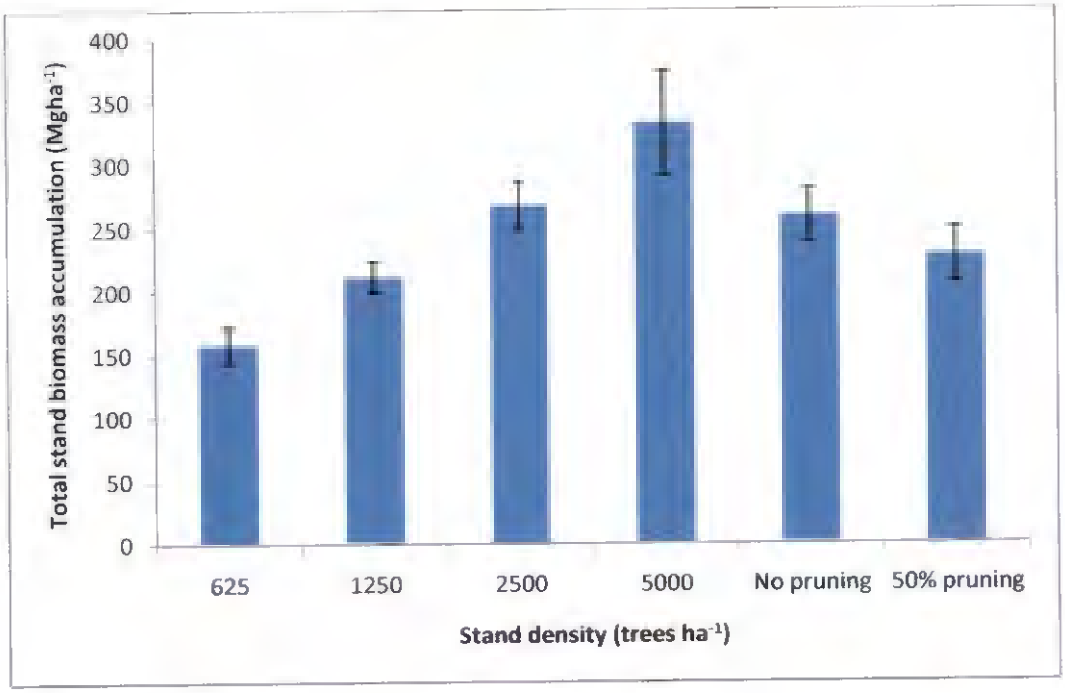


Fig.12. Stand biomass accumulation of12-year-old*A.mangium*stand managed at variable densities and pruning at Thiruvizhamkunnu, Kerala

triphysa, *A. heterophyllus*, and *C. equisetifolia* respectively under monoculture conditions in a study conducted at an adjacent site (8.8 years of age; 2x2 m spacing).

The mean aboveground stand biomass production in this study was 171.96 Mg ha^{-1} (MAI: 14.33 Mg ha^{-1} yr^{-1}). This was lower compared to stands of other fast growing species of older age. For instance, the mean aboveground stand biomass production was 192.41 Mg ha^{-1} (MAI: 8.74 Mg ha^{-1} yr^{-1}) for 22 year old *Ailanthus triphysa* stand. Similarly 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. Interestingly, the corresponding annual increment values were, however, less compared to the values for *A. mangium* in the present study. Implicit is that fast growing trees usually exhibit higher MAI in biomass production during younger age. For instance, Kunhamu *et al.* (2005) observed MAI to the tune of 30.03 Mg ha^{-1} yr^{-1} for seven years old *A. mangium* stand. High MAI in aboveground biomass (24.55 Mg ha^{-1} yr^{-1}) reported 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.

Density management also significantly influenced the biomass allocation patterns. Convincingly aboveground biomass represented the largest share of the total biomass. The overall trend in biomass allocation followed in the decreasing order stemwood > coarse roots > leaves > branch wood > fine roots/twigs (Table 17). Biomass allocation patterns for tropical tree species generally follow the order bole > branch > roots > leaves> twigs (Kunhamu *et al.,* 2005; Kueh *et al.,* 2013). However, there was wide variability in branch wood production and coarse root production especially in the high density stands. Coarse root production was many fold higher than branch wood. Probably, *A. mangium* with it high self pruning nature especially in the higher density stands may have sacrificed branches at maturity. In addition, tree age, site and stand

management also may influence biomass allocation patterns (Henry *et al.,* 2010; Kueh *et al.,* 2014). The proportional contribution of aboveground biomass to total biomass varied from 70% (5000 trees ha^{-1}) to 76.0% (625 trees ha^{-1}). The belowground biomass production was also higher in the high density stand (104.57 Mg ha^{-1}; 5000 trees ha^{-1}) while the lowest was recorded in stands at lowest density (37.24 Mg ha^{-1}; 625 trees ha^{-1}) (Fig. 13).

Root: shoot ratio increased with increasing stand density implying that belowground biomass production is more in the denser stands as compared to stands at lower density. Probably the belowground systems may be more effective in functioning so as to meet the water and nutrient requirements of large number of trees. Such density regulation in intensively managed plantations has made good improvement in growth features, biomass and wood properties of different tree species, as demonstrated by Lei *et al.* (1997), Debell *et al.* (2002), and Naji *et al.* (2) on red alder (*Alnusrubra*), poplar (*Populus* spp.), and rubberwood (*Hevea brasiliensis*), respectively.

5.3.2 Biomass C sequestration

Tree based systems assume considerable ecological importance while recognizing their potential to sequester atmospheric C (Nowak and Dwyer, 2007). By virtue of the deep rooted nature, trees effectively dispense carbon in the deeper soil layers through the turnover and decay of large quantity of roots. Furthermore, the aboveground litter (leaf + twig) add high amount of carbon and nutrients into the soil. In the present study the total carbon stock in the vegetation (aboveground + belowground) ranged from 88.29 to 152.16 Mg ha^{-1} across various stand densities (Fig. 14). This range is comparable to many other tree species of similar growth habit. The same stand at 6.5 years of stand age showed carbon storage of 110 Mg ha^{-1} (Kunhamu *et al.,* 2011). In yet another study Aneesh (2014) reported comparable values of total carbon stocks for *Casuarina equisetifolia* (151.50 Mg ha^{-1}),

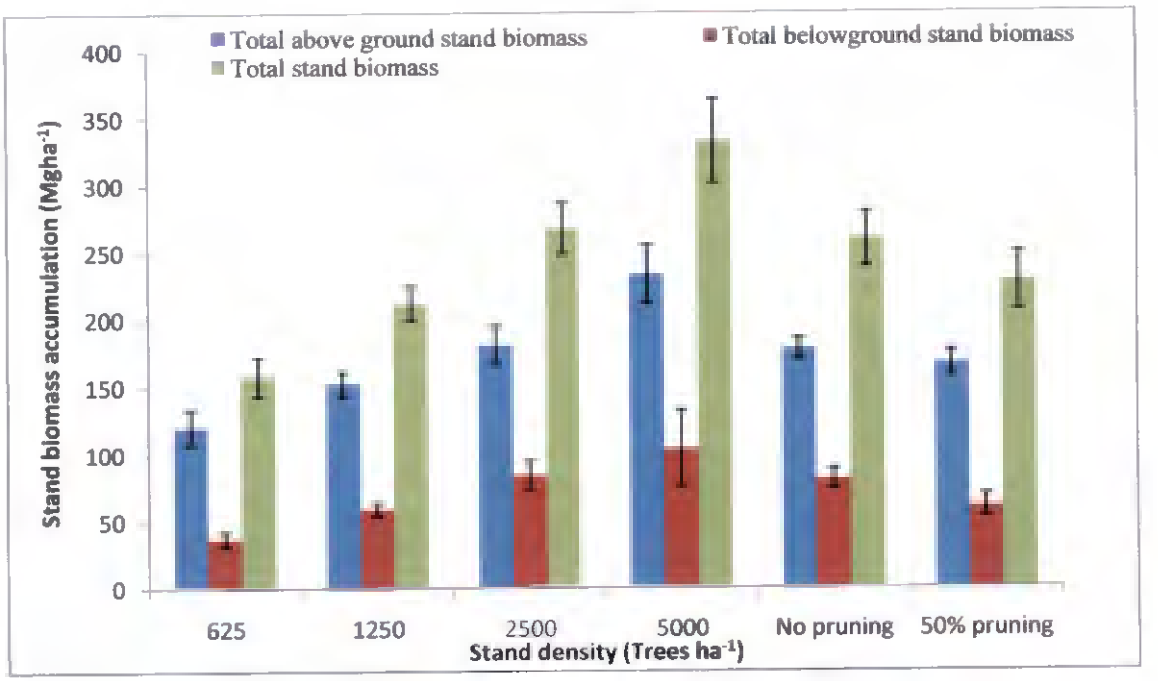


Fig.13.Total biomass accumulations at stand level in 12-year-old*A. mangium* stand managed at variable densities at Thiruvazhamkunnu, palakkad, Kerala

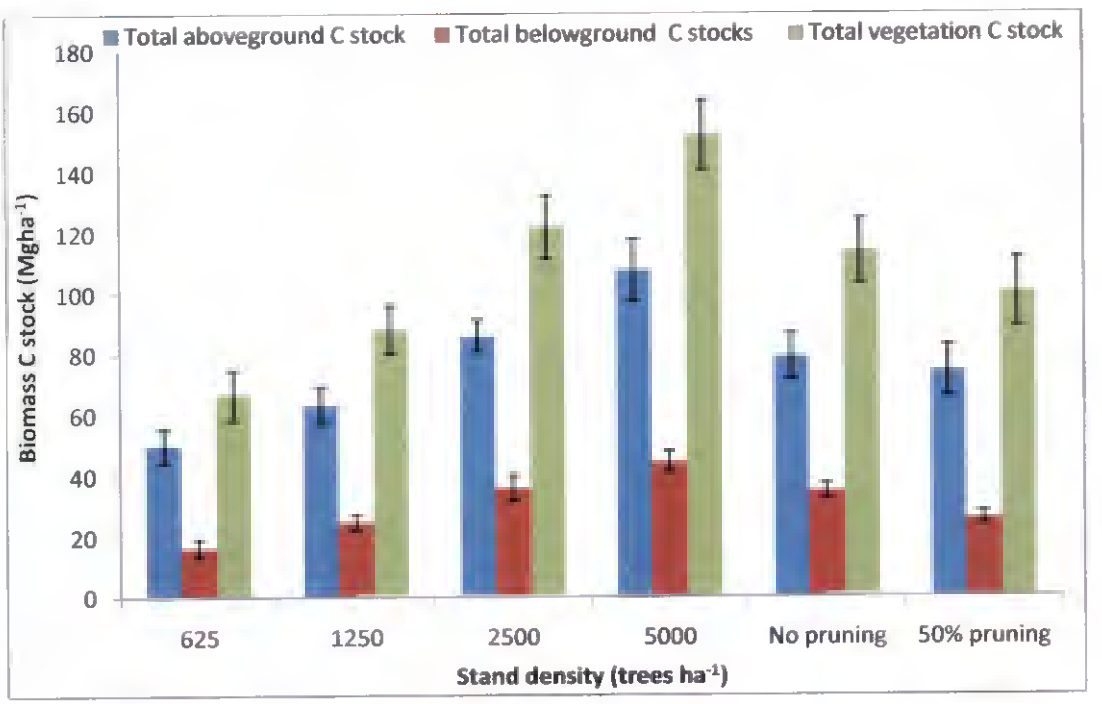


Fig. 14. Total stand level C stocks for 12-yr-old *Acacia mangium*stand managed at variable densities at Thiruvazhamkunnu, Kerala

Macaranga peltata (82.45 Mg ha^{-1}), *Ailanthus triphysa* (70.33 Mg ha^{-1}), *Artocarpus heterophyllus* (134.08 Mg ha^{-1}), *Acacia auriculiformis* (154.67 Mg ha^{-1}) and *Grevillea robusta* (169.24 Mgha^{-1}) in a multi-purpose tree based black pepper production system from Kerala, India.

The average aboveground carbon sequestration was in the range of 50.08 (625 trees ha^{-1}) to 107.65 Mg ha^{-1} (5000 trees ha^{-1}) (Fig. 14). Belowground biomass also contributed substantial carbon to the extent of 16.49 to 44.51 Mg ha^{-1} which also showed profound variability across stand densities. These values are fairly high compared to many other fast growing tree species of similar growth habit. For instance, reports from tropical MPTs suggest average belowground carbon sequestration values in the range of *Casuarina equisetifolia* (16.83 Mg ha^{-1}), *Macaranga peltata* (20.10 Mg ha^{-1}), *Ailanthus triphysa* (11.35 Mg ha^{-1}), *Artocarpus heterophyllus* (26.07 Mg ha^{-1}), *Acacia auriculiformis* (30.13 Mg ha^{-1}) and *Grevillea robusta* (29.64 Mg ha^{-1}). Our values for *A. mangium* especially at high density stands were considerably higher compared to the above values reported for other tree species. Hence species and management regimes can inflict large scale changes in the carbon sequestration in tree based systems. Just as biomass, carbon storage is also intricately linked with choice of species, site quality, nature of land use, silvicultural and other crop management practices adopted (Swamy *et al.*, 2003; Kueh *et al.*, 2014).

Carbon stocks of different tissue fractions decreased in the order: stem> coarse root > leaves > branch > fine root/twig which is consistent with the observations of Swamy *et al.* (2003) and Kaur *et al.* (2002). Obviously stem wood accounted bulk of the (60-70%) carbon sequestered in the carbon biomass. From the ecological point it would be desirable for the tree to allocate more elemental carbon towards the stemwood, as it assures prolonged retention of sequestered carbon in the biomass. Carbon

sequestration through other dynamic components such as leaves, twigs, fine root etc. might result in recycling and partial loss through respiration.

The potential ability of trees to trap atmosphere carbon varies with species and management conditions. In the modern production forestry this aspect has bagged considerable importance while choosing species for various end uses such as establishment of wood lots, agroforests, carbon forests etc. Hence, the information gathered in this study will serve as bench mark for further screening tree species for various end uses.

5.3.3 Biomass nutrient content

Nutrient accumulation in the biomass is primarily a function of the tissue elemental concentration and the biomass production. Our observations indicated that biomass consisted of sizeable proportion of nutrients in addition to elemental carbon. For instance, the nitrogen accumulation in the biomass ranged from 2.82 to 12.12 Mg ha^{-1} from lower to higher densities (Table 23). Such higher rates of N accumulation in the biomass has been reported by Kumar *et al.* (1998) for fast growing trees species such as *Acacia auriculiformis* (958.3 kg ha^{-1}) and *Paraserianthes falcataria* (622.8 kg ha^{-1}) from humid tropical Kerala, India. The proportionate allocation of nutrients in the biomass showed variable trends. Interestingly coarse roots accounted for major share of the nitrogen accumulation in the tree biomass with a range of 894.17 to 4992.41 kg ha^{-1} and trend in nitrogen accumulation was in the order coarse root > Stemwood > leaf > branchwood > twig > Fine root. Such high levels of nitrogen accumulation in the roots has been reported for *Acacia polyacantha* and *Senna siamea* which represented 52 and 47% respectively of the total accumulated nitrogen in the biomass (Harmand *et al.,* 2004). However, this observation is contrary to many earlier findings where bulk of the tissue nitrogen was shared by stemwood (Halenda, 1993; Kumar *et al.* 1998; Aneesh, 2014). Presence of higher nitrogen in the root

fraction as compared to aboveground components offer the scope for possible conservation of nitrogen in the soil as compared to aboveground components that are liable for removal from the system through harvest. Yet another finding is the fairly high proportion of nitrogen in the leaf fraction (875.40 to 2842.11 kg ha^{-1}; Table 23) that indicate the possibility of substantial N transfer to the soil through nutrient cycling. However, for P the stemwood proportion was considerably higher as compared to other components indicating possible loss of P through harvest (Table 24). Potassium accumulation in the biomass followed a different pattern with stemwood and leaves contributing major share of the total biomass potassium (approximately 77% in the high density stand). Interestingly the leaf K proportion was higher than that in the stemwood in the highest density stand which in turn reiterate the possible higher amounts of K available for nutrient cycling in 12-year-old *A. mangium* stand (Table 25). Such large scale retention of nutrients in the biomass has been reported for many fast growing tree species (Sukanya, 2014; Aneesh, 2014). In the present study high density stands in general accumulated higher nutrients in all the tissue fractions which consistently declined with declining density. The stronger influence of stand density on biomass nutrient partitioning is evident in the studies that highlight the role of density management in nutrient partitioning in woody ecosystems.

Nutrient accumulation and export from the site have become important considerations in short-rotation plantations (Hopman *et al.,* 1993). In high density stand stemwood, branchwood, twigs and leaves accounted almost 58% of the total biomass nitrogen which could be partially or wholly removed from the system through harvest. Such continuous rotations eventually lead to heavy depletion in soil nitrogen content. Interestingly leaf portion retain substantial amount of nitrogen (2842 kg ha^{-1}) which could be returned to the soil through judicious interventions. Similarly all such non-economic biomass components need to be returned to the soil for efficient nutrient cycling and compensate the harvest related losses (Somasiri *et al.,* 2003).

5.4 LITTER STUDY IN 12 YEAR OLD *A. MANGIUM* AT VARYING STAND DENSITY

5.4.1 Litter production

A. mangium showed substantial litter build up that varied across stand densities. The average annual litter production ranged from 9.99 to 11.69 Mg ha^{-1} (Fig. 15). These figures are very much comparable with the values obtained for *A. mangium* at 9 years of stand age (11.18 Mg ha^{-1}) managed at stand density of 1600 trees ha^{-1} in a nearly location (Kunhamu *et al.,* 2010). Other fast growing tree species also yielded comparable litter yield such as *Acacia auriculiformis* (12.69 Mg ha^{-1}) and *Paraserianthes falcataria* (9.17 Mg ha^{-1}) at 7 years of stand age (Jamaludheen *et al.,* 1999). However higher annual litter production rates have been reported for moist deciduous forests of tropical India (12.18 to 14.43 Mg ha^{-1}; Kumar and Deepu, 1992). Large variation in litter production with changing stand density has been observed in the study. Higher production was associated with stands with higher densities (11.69 Mg ha^{-1}; 5000 trees ha^{-1}) both on monthly and annual basis, with convincingly higher production from high density stands. Such variable patterns of litter production with density manipulation for *A. mangium* have been reported earlier. For eg. in a study on the effect of thinning on litter production in a 9-year-old *A. mangium* it was observed that litter production under various thinning regimes ranged from 5.73 Mg ha^{-1} (density 533 tree ha^{-1}) to 11.18 Mg ha^{-1} (density 1600 trees ha^{-1}). In general, individual trees produce higher litter at widely spaced stands primarily owing to larger crown area due to space advantage. At closer densities space limitations restrict the crown expansion and consequently limit the litter yield. However, this trend was not discernable in the present study. Probable reason for the higher litter production from the high density stands could be cumulative effect of the litter production by large number of individuals which outweighed the lower mean tree production in this density. Furthermore, the high density stand may contribute higher litter on account of the larger proportion of non functional crown attached to them as compared to widely

spaced stands. Such observations have also been reported for *A. mangium* in a stand in the similar location by Kunhamu *et al.* (2010). There is enough reason to conclude that litter production and its subsequent returns are largely decided by the density management practices.

In general, the average monthly litterfall peaked during the winter months (January – February) (Fig.16). The seasonal pattern is basically monomodal. Seasonal variation in litter production also was influenced by the standing densities. Distinct seasonal variation in monthly litter production across the density regimes was visible in the present study. Average monthly production across density regimes was in the range of 832.43 (625 trees ha^{-1}) to 973.79 kg ha^{-1} (5000 trees ha^{-1}). Winter months (January-February) accounted higher litter production for all density regimes (27% of average total annual production). Invariably the dry months (March-April) were the lean periods in respect of litterfall. Higher litter production during winter months for tropical fast growers has been reported before (*Acacia auriculiformis*, Kunhamu *et al.*, 1994; *Leucaena leucocephala*, George and Kumar, 1998). Most studies in the tropics indicate peak litter fall during dry months (Jamaludheen *et al.*, 1999). However, evergreen phyllodes of *A. mangium* shed more litter during the winter months. A similar pattern of seasonality in litter fall has been reported for *Acacia auriculiformis*, a close relative of *A. mangium* (Kunhamu *et al.*, 1994; Jamaludheen *et al.*, 1999).

Attempts to correlate litter production with mean stand basal area showed fairly good relations (Table 29). The proportionality between annual litter production and stand basal area was evident. That is, higher the stand basal area, higher the litter production. Such functional relationship between litter production and basal area has been reported earlier for 9-year-old *A. mangium* while studying the effect of stand thinning on litter production (Kunhamu *et al.*, 2005). This relationship is reasonable as both litter production and basal area are direct functions of productivity and both

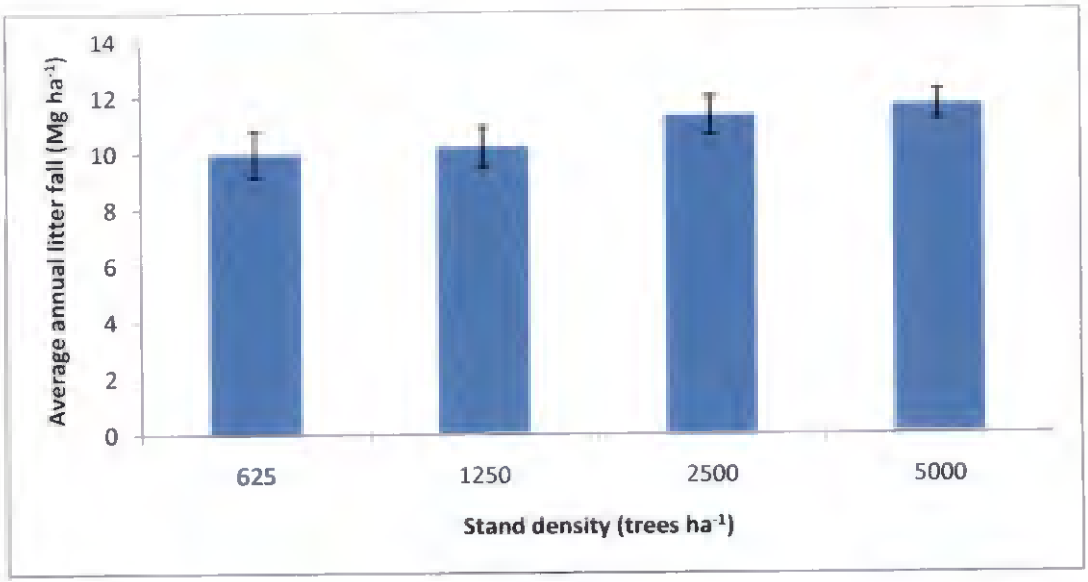


Fig. 15.Average annual litterfall for 12-yr-old *Acacia mangium*stand managed at variable densities at Thiruvazhamkunnu, Kerala

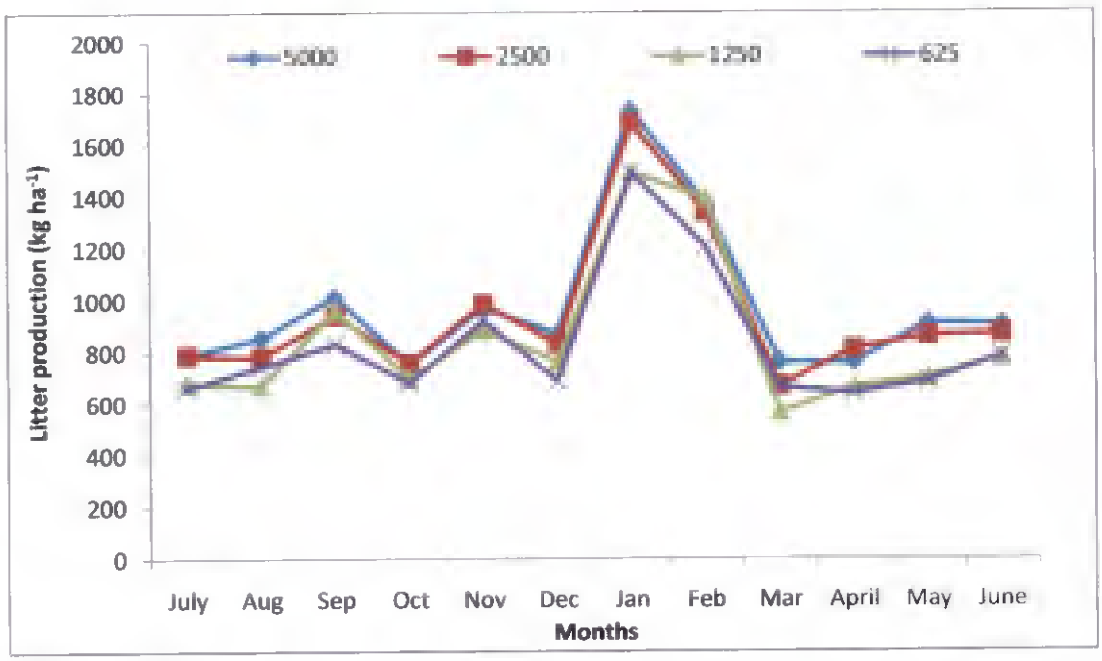


Fig. 16.Monthly variation in litterfall across stand densities for 12-yr-old *Acacia mangium* standat variable densities and pruning at Thiruvizhamkunnu, Kerala

are controlled by similar biophysical elements such as moisture, temperature and nutrient availability.

5.4.2 Leaf litter and fine roots

One major land mark in the present study is the strong functional relationship established between aboveground litter and belowground fine root productions for *A. mangium* (Table 29). Attempts to correlate these variables yielded good correlation coefficients (R^2=0.9). Regression equations also showed higher coefficient of determination (r^2=0.83; $p<0.01$). Simple linear equation relating fine root prediction with litterfall as independent variable was found to give reasonably good fit. Hence our study converge to the generalization that, there exists sound functionality between aboveground litter production and belowground litter production. This will help in the prediction of fine root production with reasonable accuracy, which otherwise is difficult through other methods. However, one limitation of our study is that the live standing fine root production was used for relating with litterfall instead of dead fine roots (fine root litter). The practical difficulty in getting a fair account of the fine root necromass was a major limitation of our study.

5.4.3 Carbon and nutrient content in the litter

In the present study there was substantial production of elemental carbon in the litterfall which range from 1.45 to 2.53 Mg ha^{-1} (Table 30). Carbon content in the litter is basically a function of carbon concentration and litter production. Our observation suggests that, there was not much difference in elemental carbon concentration across the litter corresponding to various stand density. Hence, the probable reason for the variation in carbon content across densities could be on account of variation in litter production. This is validated by the higher carbon content observed in higher density stands (2.53 Mg ha^{-1}; 5000 trees ha^{-1} and 2.29 Mg ha^{-1};

2500 trees ha^{-1}). It was observed that approximately 21.64% of litterfall carbon was produced solely from litter production in stands at 5000 trees ha^{-1}. Carbon and nitrogen content in the litter is often cited as the index of the litter quality. Higher litter carbon content implies higher possible transfer of elemental carbon to the soil through litter decomposition. Present study also observed substantial quantity of nutrients in the litterfall. For instance, nitrogen content in the litter varied from 36-58 kg ha^{-1}. Phosphorus and potassium content in the litter also were good. In general the nutrient content in the litter did not influence the stand density except for potassium. Many investigations of tropical tree litter showed such enormous accumulation of carbon and nutrients which could be transferred to the soil through litter route (Kumar and Deepu, 1992; Jamaludheen *et al.,* 1999; Kunhamu *et al., 2005*).

5.4.4 Litter decomposition

Litter decomposition of *A .mangium* was studied over a period of one year and the result suggests considerable reduction in the litter after 12 months decomposition (Fig.17). In general, the litter decomposition followed a biphasic pattern with a heavy loss during the first months and graduall decline during the subsequent months. Density regulation excreted profound influence on the litter decay rates especially during the early phase of decomposition . Results indicate that decomposition rate was faster in the low density regimes while stands at higher densities showed lower decay rates. At the end of 12 months, the average detritus remaining in the litter bags were 3.14%, 4.23%, 5.59% and 7.87% for 625, 1250, 2500, 5000 trees ha^{-1} respectively. Interestingly, a heavy mass loss has been observed during the initial month of decomposition in the present study, which could probably be the result of intense rainfall during this period and the associated loss of soluble carbon compounds from the litter bags. The higher amounts of labile carbon present in the *A. mangium* litter may explain the faster mass loss especially during the initial decay phase. While

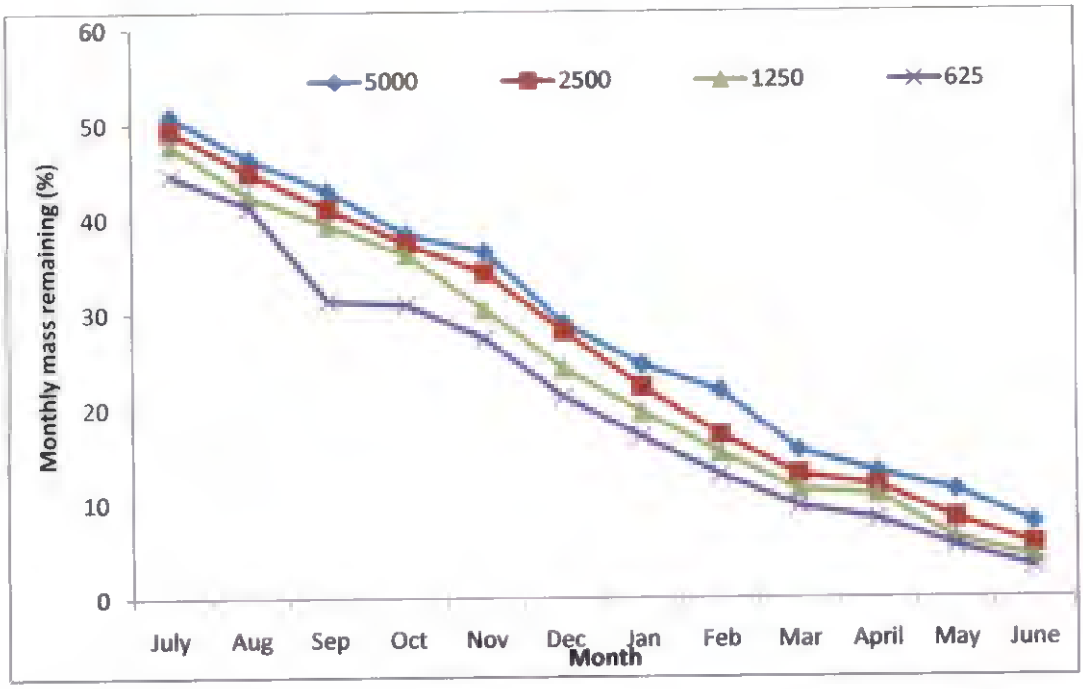


Fig.17. Mass remaining in litter bags as influenced by planting density for 12-year-old *Acacia mangium* at Thiruvazhamkunnu, Kerala.

analyzing the substrate quality on litter decay rates, Fujii and Takeda (2010) observed heavy loss (>50%) of soluble carbohydrate and polyphenols during the initial moths of decomposition that support our observations.

The decay rate coefficient also showed significant variation among stand densities which ranged from 1.69 (5000 trees ha^{-1}) to 1.73 (625 tree ha^{-1}) (Table 34). These values are in general higher as compared to values reported earlier for *A. mangium*. In a thinning trial on 9-year-old *A. mangium* a lower decay constant of 0.30 to 0.35 has been reported with distinct increase with decreasing stand density (Kunhamu *et al.*, 2005). Higher litter decay rate in the low density stands may be related to the favorable biophysical conditions that promote faster decomposition. Probably the better light availability in the understory might promote higher microbial activity in the low density stands. Furthermore the heavy mass loss during the initial months might have partly contributed to the high decay constant observed in the present study. However, higher decay constants similar to our findings has been reported for tropical tree species such as *Dyera costulata* (1.3), *Macaranga kinjii* (1.75), *Artocarpus elasticus* (1.24) and *Artocarpus anisophyllus* (1.02) from lowland tropical rain forest in Sarawak, Malaysia (Hirobe *et al.*, 2004). Litter decomposition is controlled primarily by factors such as climate, litter quality and the nature and abundance of the decomposing organisms.

5.4.5 Carbon and nutrient release

Our results indicate faster release of carbon through litter decomposition, which ranged from 1.43–1.93 Mg C ha^{-1} (Table 35). For instance, almost 76% of the carbon content the litter released to soil through litter decomposition in 5000 trees ha^{-1} stands. However no apparent trend in carbon release has been observed across the stand densities. Faster release of carbon from the litter is a desirable characteristic in tree based ecosystem, where the enrichment of the soil carbon pool through litter

addition is the most important pathway. Many studies indicate the role of soil carbon pool enrichment through litter decomposition (Melillo *et al.,* 1989; Loranger *et al.,* 2002). However, efficiency of carbon addition to the soil depend on facts such as turnover times of the C stores, changes in quality of these C stores such as nutrient ratios, carbon-based secondary compound concentrations, and the effects of such C-flux into the soil will have on the native C and N stores (Cotrufo *et al.,* 2005). During the initial phase of litter decomposition labile carbon fractions used to decompose very fast and loss along with water during rainy season. This is very much clear in the present study also. However with advancement in decay more recalcitrant forms of carbon such as lignin, hemicellulose etc. decomposes at very slower rate (Fujii and Takeda, 2010).

Nutrient release patterns also showed such higher nutrient transfer to soil through the litter decomposition which was more prominent in the case of nitrogen. For instance, the elemental nitrogen content in the fresh litter ranged from 36-58 kg ha^{-1} of which 36-44 kg ha^{-1} released to soil i.e., approximately 75–100% release. The release patterns of phosphorus also showed higher returns to the soil through decomposition (92%) despite the non significant response to stand density. Despite the maximum potassium release observed in the decomposing litter corresponding to 5000 trees ha^{-1} stand (78%), no characteristic trend in release pattern was discernible across stand densities. The higher mobility of potassium due to its characteristic weak structural binding explains the unstable responses. Similar high levels of nutrient release have been reported for other species. For e.g. reports from tropical rain forests of Cameroon suggests that *Vitex grandiflora* released 90%, 78% and 99% of N, P and K within about 23 weeks after incubation while species such as *Entandrophragma utile* immobilized considerable amounts of N and P in the decomposing litter (Ibrahima *et al.,* 2011). The one year-long study on the litter production and decomposition rates for 12-year old *A. mangium* converges to fair clarity on the role played by litter in

cycling of nutrients in woody ecosystems explaining their immense self nourishment potential.

5.5 SOIL STUDY IN 12- YEAR- OLD *A. MANGIUM* AT VARYING STAND DENSITY AND PRUNING REGIMES

5.5.1 Soil carbon and nutrient stocks

Changes in soil properties such as soil bulk density, organic carbon concentration, carbon sequestration and nutrient contents were evaluated and compared with treeless control soils for 12-year old *A. mangium*. All these properties showed consistent changes with soil depth and stand densities. Overwhelming significance of woody ecosystems on improvement in soil properties is evident from the study.

Soil organic carbon content showed remarkable improvement in *A. mangium* stands as compared to open soil (Table 36, Fig. 18.a,b,c). It changed from 8.48 Mg ha^{-1} in the open soil to 23.32 Mg ha^{-1} in the high density stand (5000 trees ha^{-1}). The role of woody ecosystems in improving the soil organic carbon content has been well known fact and has been reported earlier (Lal and Kimble, 2000). Similar higher soil carbon content attached to eucalyptus and poplar plantations compared to adjacent barren lands has been reported from Uttarakand and Haryana regions of India (Gupta and Pandey, 2008). The primary source of soil organic carbon in woody ecosystem is through the transfer of plant fixed carbon in the leaves and other plant parts (Oelbermann *et al.,* 2006; Gupta and Pandey, 2008). The present study has shown that *A. mangium* produced large quantity of annual litter which returned substantial amounts of carbon through litter route to the soil.

Furthermore, the present study observed fairly high carbon and nutrient transfer to the soil through fine roots. Soil organic carbon content also showed consistent reduction

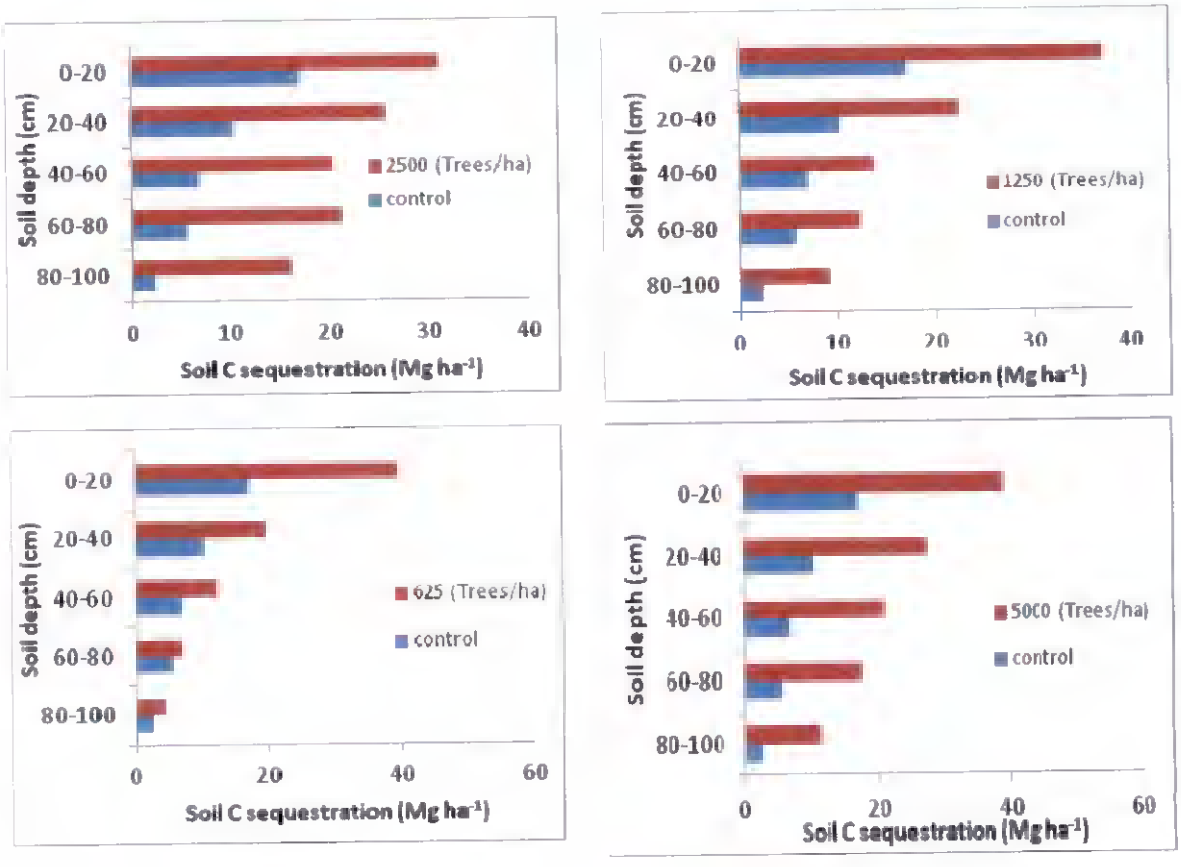


Fig.18a,b,c,d. Variation in soil mean carbon sequestration across stand densityand soil depth for 12-year old *A. mangium* stand managed at variable densities at Thiruvazhamkunnu, Kerala

with decreasing planting density. Interestingly, the litter and fine root production and associated carbon transfer to the soil was more prominent in the high density stand that has reflected in overall increase in soil carbon content in such stands. Soil carbon concentration also showed significant variation in their vertical distribution as well with consistent decline with increasing soil depth (1.41% to 0.27 across one meter soil depth). The organic matter addition and carbon immobilization by microbes are more intense at shallow depths that explain the sharp decline with soil depth (Thakur, 2015; Du et al., 2015).

5.5.2 Soil carbon sequestration

Soil carbon sequestration assessed over one meter soil depth also showed remarkably high values in the *A. mangium* as compared to contiguous open soil. The soil carbon content at one meter soil depth was 114.61 and 118.60 Mg ha^{-1} in unpruned and pruned stands respectively at highest planting density while the corresponding value in the open soil was just 42.41 Mg ha^{-1} (Table 36). Our values on soil carbon stocks for *A. mangium* are predominantly higher than many fast growing tree based systems (Gupta and Pandey, 2008). They observed mean soil carbon sequestration to the tune of 21.33, 30.55, 27.98 and 38.97 Mg ha^{-1} for Poplar, Eucalyptus, Shisham and Teak respectively at 0-30 cm soil depth in Uttarakhand, India. Similarly *Grevillea robusta* plantations from humid tropical Kerala, India reported lower soil carbon stocks of 77.56 Mg ha^{-1} and 66.04 Mg ha^{-1} for contiguous treeless plots (Thakur *et al.,* 2015). Yet another observation is that, there was substantial buildup in soil carbon stocks as compared to the values of the same *A. mangium* stand at 6.5 years of stand age (Kunhamu *et al.,* 2011). They reported soil carbon sequestration values of (top soil; 0–15 cm soil depth) 31.79, 34.64, 27.02 and 30.01 Mg ha^{-1} for stands at 5000, 2500, 1250 and 625 trees ha^{-1} respectively as against 24.70 Mg ha^{-1} in the treeless open. Interestingly increase in the top soil carbon stocks over subsequent 5.5 years was modest implying that top soil carbon storage for *A. mangium* stands leveled within a

period of 6.5 years. However, many plantation systems show higher buildup in soil carbon sequestration with advancement in time and rotation. For e.g. fair increase in soil carbon sequestration after first rotation has been observed for Eucalyptus, Poplar and Teak that increased respectively from 75, 67 and 52 Mg C ha^{-1} to 85, 102 and 73 Mg C ha^{-1} by the end of the first rotation (Kaul *et al.,* 2010).

As observed with soil organic carbon concentration, the prominent role of litter in soil carbon sequestration is evident in the study. In addition to aboveground litter, our study has established that fine roots also contribute substantially in enriching the soil carbon pools. Trees allocate considerable biomass in the belowground for production of roots and mycorrhizae (Giardina and Ryan, 2002; Fujii and Takeda, 2014; Thakur *et al.,* 2015). Interestingly stand density and pruning impacted the soil carbon stocks with higher values attached to pruned high density stands (Table 37). The higher production of litter, coarse and fine roots in the belowground at high densities observed in the present study explain this high soil carbon stocks. Further, the addition of annually pruned materials into the soil contributed additional carbon to the soil carbon pool. Out of the total carbon assimilated by the plants, more than 50% is usually transferred to the belowground through root growth and turnover (Kumar, 2008).

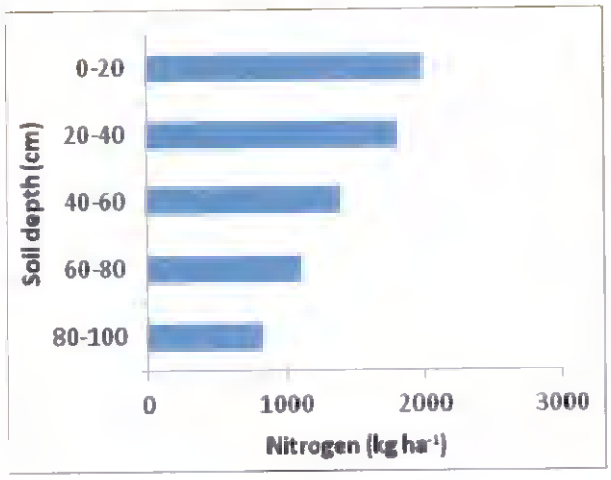
Depth-wise variation in carbon sequestration is evident in the present study. For instance, the upper soil depth of 0-40 cm accounted almost 56% of the total soil carbon storage in one meter soil depth in the unpruned stands at high density (5000 trees ha^{-1}). The profound role of trees in nourishing the soil is evident in the study. Yet another observation is that fairly high amounts of carbon were found in the soil even at deeper soil depths compared to the open treeless soil. The prominent role of deep root systems in fertilizing the soil at deeper soil depth thereby enriching large volumes of soil is a strategic advantage in tree based production systems (Thakur *et al.,* 2015).

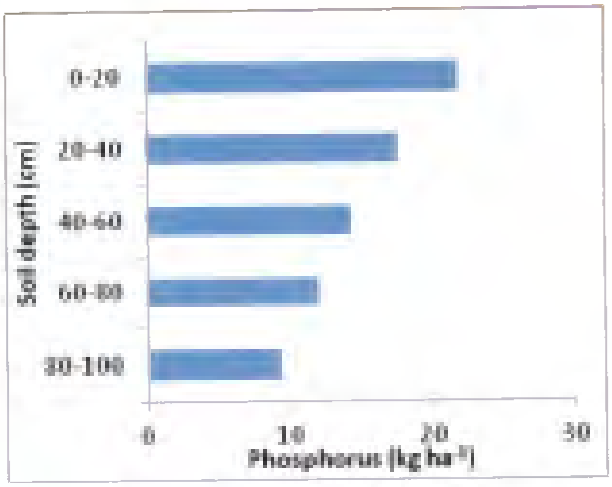
5.5.3 Soil nutrient content

Following the trends in soil carbon contents, 12-year-old *A. mangium* also stored higher amounts of nutrients (N, P, K) in the soil as compared to treeless open soils (Table 38). For instance, the soil nitrogen content in the high density stand was almost eight fold higher as that in the contiguous open soil. Other stand densities also showed higher values compared to open soil. As discussed before, tree litter and belowground root dynamics play a predominant role in enriching the soil nutrient pools (Kumar, 2008; Thakur *et al.,* 2015). The trends were same for soil P and K contents as well. The soil nutrients contents were also influenced by stand density with heavy decline with decreasing stand density (N, P, K; $P<0.001$) (Fig. 19.a,b,c). The variable production and release patterns of litter and belowground plant parts with stand density explains this large variation in their soil nutrient contents. As in the case of soil carbon, a general decline in soil nutrient stocks has been observed with increase in soil depth. For instance soil N stock of 1995 kg ha^{-1} recorded in the top 0-20 cm soil layer got reduced to 833 kg ha^{-1} in the 80–100 cm soil layer. Despite such changes it is appreciable that fair amounts of nutrients were distributed throughout the one meter soil depth which further reiterate the deep fertilization potential of woody systems through efficient cycling involving leaf and root litter (McClaugherty *et al.,* 1982; Vogt *et al.,* 1996).

5.6 PRACTICAL IMPLICATIONS OF THE STUDY

Two year long field study on *A. mangium* provided vital information on the biomass production and their allocation as a function of planting density with particular focus on the fine root and litter production. The prominent role of fine roots and litter as the major players in soil nourishment in *A. mangium* and their regulation through density management has been clearly demonstrated in the study. Litter and fine roots contributed substantial amount of organic carbon and nutrients even at deeper soil





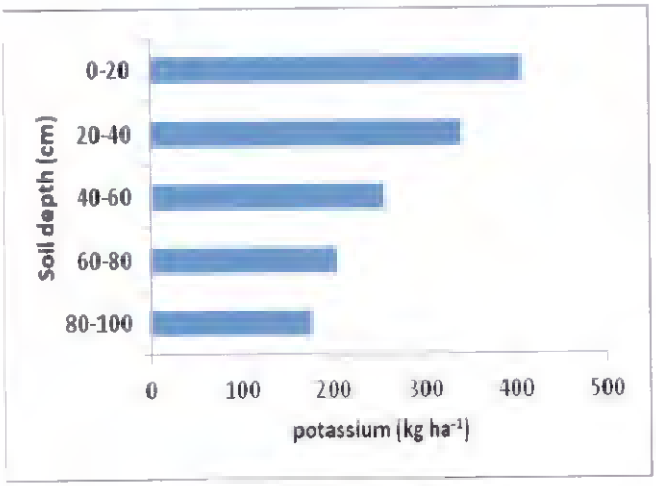


Fig. 19a,b,c. Depth wise distributions of mean soil N, P and K content in 12- year-old *A. mangium* stands at variable densitiesin different soil depths at Thiruvazhmkunnu, Palakad, Kerala.

layers implying the potential of *A. mangium* to nourish soil to deeper depths. This self nourishment may be advantageous for integrating suitable intercrops especially in widely spaced stands. The study reiterates the carbon sequestration potential of *A. mangium* through its heavy carbon returns to the soil though fine roots and litter. Hence, fast growing tree species like *A. mangium* may be a suitable candidate tree in the carbon inventory sector.

Prevailing methodologies for fine roots quantification especially excavation methods are complex and laborious. However, our study demonstrated that a combination of ingrowth method and sequential coring method can give a fairly reasonable account of the fine root production. Another outcome of the study was the development of allometric models for fine root estimation with easily measurable growth variables such as DBH, basal area and leaf area. These relationships are helpful in assessment of fine root production with sound precision without sacrificing the trees.

Yet another management implication of the study is that substantial quantity of nutrients could be removed from the system through repeated harvests; leaf and twig contributes a prominent share to this loss. Also, the belowground coarse roots and fine roots contributed significantly to the soil carbon and nutrient pools. Such roots after harvest may be allowed to decompose in the course of time such that they add to the soil carbon and nutrient reserves. Hence, retention of tops and lops including leaves and roots in the site during tree harvest may be a conservative strategy for maintaining the soil resource base.

Summary

SUMMARY

Acacia mangium Willd., a fast growing evergreen Australian tree introduced to India in the 1980s, has gained acceptance as a plantation species and as a component of the multistrata agroforestry systems. Despite the widespread use of *A. mangium* in the humid tropics, species-specific information on the aboveground and belowground biomass production, their carbon and nutrient dynamics are lacking. Inventory of the various biomass components such as stemwood, branchwood, leaves, twigs, coarse roots and fine roots and assessment of their contribution to the soil carbon and nutrient pools and their functional relation to stand density management practices, will provide valuable information on strategies to be evolved for optimization of productivity in *A. mangium* plantations. In this context a comprehensive field study was carried to investigate the biomass production potential, biomass allocation patterns, carbon and nutrient accumulation in the biomass, litter production and its turnover and fine root dynamics and changes in the soil carbon and nutrient pools as influenced by stand density regulation in 12 year old *A. mangium*.

Salient findings of the study are summarized below

6.1 *Fine root production, turnover, decomposition, C and nutrient release as function of planting density in a 12-year-old A. mangium stand.*

1. Profound influence of stand density on fine root production has been observed in the present study. In general, the production on unit area basis (per ha) showed increasing trend with increasing stand density for both the methods. Fine root production and turn over for both ingrowth core and sequential core methods ranged from 1.39 to 5.78 Mg ha^{-1}. However,

mean tree fine root production showed an inverse trend with trees at higher density giving lower production compared to trees grown at wider spacing.

2. The fine root turnover rates in this study ranged from 1.58 to 3.16 yr^{-1}. This implies that, the cycle of entire fine root produced at a time dies and grows back varies from one to three times a year.
3. The average carbon accumulation in the fine roots ranged from 1.36 to 2.39 Mg ha^{-1} across stand densities. Similarly fine roots contained good amount of nitrogen (34.56 to 102.92 kg ha^{-1}), phosphorus (1.64 to 3.31 kg ha^{-1}) and potassium (16.94 to 33.60 kg ha^{-1}) which also showed considerable variation across stand densities.
4. Fine root decay rates across stand densities showed variable trends with 76.21 to 98.8% biomass decomposed within one year. Decay constant of *A. mangium* ranged from 1.44 (5000 trees ha^{-1}) to 4.42 (625 trees ha^{-1}). Substantial proportion of the carbon in the fine roots was found released to the soil within one year (76.57 to 99.26%) that ranged from 1.35 to 2.0 Mg ha^{-1}. Similarly 34 kg ha^{-1} (625 trees ha^{-1}) to 78 kg ha^{-1} (5000 trees ha^{-1}) of nitrogen was released from the decomposing fine roots within one year which constituted almost 75.79 to 98.37% of the initial N in the fresh fine roots. In the present study phosphorus and potassium also showed similar high release to the soil to the tune of 76.51 to 98.78% and 75.89 to 98.82% respectively.
5. Good positive correlations were evolved between DBH and fine root biomass (R^2 = 0.85; $p<0.001$). Similarly good relationships were established with basal area (R^2=0.85), volume (R^2=0.82) and aboveground biomass (R^2=0.89). Based on the best fitting correlations, allometric equations for predicting fine root production for 12-yr-old *A. mangium* was made using DBH, basal area, crown width and leaf area as independent variable.

6.2 *Growth characteristics of as function of planting density in a 12-year-old A. mangium stand*

1. Mean tree aboveground biomass production ranged from 46.68 to 193.47 kg tree^{-1}. Stands maintained at high density had low mean tree biomass while stands at lowest densities showed manifold increase in mean tree biomass. However, present study followed a consistent decline in stand biomass production with maximum value in denser stand (332.97 Mg ha^{-1}; 5000 trees ha^{-1}) and minimum in low density stand (158.14 Mg ha^{-1}; 625 trees ha^{-1}). The belowground biomass production also followed the same trend in present study.
2. The average total biomass production (aboveground + belowground) on per hectare basis irrespective of density regimes was 242.77 Mg ha^{-1} and corresponding MAI was 20 Mg ha^{-1}yr^{-1}. The mean aboveground stand biomass production in this study was 171.96 Mg ha^{-1} (MAI: 14.33 Mg ha^{-1}yr^{-1}).
3. Density management also significantly influenced the biomass allocation patterns and the overall trend followed in the decreasing order stemwood > coarse roots > leaves>branch wood>fine roots/twigs. The proportional contribution of aboveground biomass to total biomass varied from 70% (5000 trees ha^{-1}) to 76.0% (625 trees ha^{-1}). The belowground biomass production was also higher in the high density stand (104.57 Mg ha^{-1}; 5000 trees ha^{-1}) while the lowest was recorded in low density stand (37.24 Mg ha^{-1}; 625 trees ha^{-1}). Overall, the regulatory effect of stand density on biomass production for *A. mangium* is explicit in the study.
4. In the present study the total carbon stock in the vegetation (aboveground + belowground) ranged from 88.29 to 152.16 Mg ha^{-1} across various stand densities. The average aboveground carbon sequestration was in the range of 50.08 (625 trees ha^{-1}) to 107.65 Mg ha^{-1} (5000 trees ha^{-1}).

Belowground biomass also contributed substantial carbon to the extent of 16.49 to 44.51 Mg ha^{-1} which also showed profound variability across stand densities.

5. Biomass consisted of sizeable proportion of nutrients in addition to elemental carbon. For instance the nitrogen accumulation in the biomass ranged from 2.82 to 12.12 Mg ha^{-1} from lower to higher densities. The proportionate allocation of nutrients in the biomass showed variable trends. Interestingly, coarse roots accounted major share of the nitrogen accumulation in the tree biomass that ranged from 894.17 to 4992.41 kg ha^{-1}. Trend in nitrogen accumulation was in the order coarse root > stemwood > leaf > branchwood > twig > fine root. Yet another finding is the fairly high proportion of nitrogen in the leaf fraction (875.40 to 2842.11 kg ha^{-1}) that indicates the possibility of substantial N transfer to the soil through nutrient cycling. However, for P the stemwood proportion was considerably higher as compared to other components indicating possible loss of P through harvest. Potassium accumulation in the biomass followed a different pattern with stemwood and leaves contributing the major share of the total biomass potassium.

6.3 *Above ground litter production, turnover, decomposition, C and nutrient release as function of planting density in a 12-year-old A. mangium stand.*

1. *A. mangium* showed substantial litter build up in the aboveground that varied across stand densities. The average annual litter production ranged from 9.99 to 11.69 Mg ha^{-1}. Higher production was associated with stands at higher densities, both on monthly and annual basis.
2. Distinct seasonal variation in monthly litter production across the density regimes was visible in the present study. Average monthly production across density regimes was in the range of 832.43 (625 trees ha^{-1}) to

973.79 kg ha^{-1} (5000 trees ha^{-1}). Winter months (January- February) accounted higher litter production for all density regimes while the dry months (March-April) were the lean periods in respect of litterfall.

3. Attempts to correlate litter production with mean stand basal area showed fairly good relations. There existed strong proportionality between annual litter production and stand basal area.
4. A major land mark in the present study is the strong functional relationship established between aboveground litter and belowground fine root productions for *A. mangium*. Attempts to correlate these variables yielded good correlation coefficients (R=0.9). Regression equations also showed higher coefficient of determination (R^2=0.83; $p<0.01$). Simple linear equation relating fine root prediction with litterfall as independent variable was found to give reasonably good fit.
5. There is substantial buildup of elemental carbon in the litterfall which range from 1.45 to 2.53 Mg ha^{-1}. Present study also observed substantial quantity of nutrients in the litterfall. For instance, nitrogen content in the litter varied 36-58 kg ha^{-1}. Phosphorus and potassium content in the litter also were fairly good. In general, the nutrient content in the litter did not influence the stand density except for potassium.
6. At the end of 12 months of decomposition study, the average detritus remaining in the litter bags were 3.14%, 4.23%, 5.59% and 7.87% for 625, 1250, 2500, 5000 trees ha^{-1} respectively. The decay rate coefficient also showed significant variation among stand densities which ranged from 1.69 (5000 trees ha^{-1}) to 1.73 (625 tree ha^{-1}).
7. There is a faster release of carbon through litter decomposition which ranged from 1.43–1.93 Mg C ha^{-1}. Almost 76% of the carbon content the litter released to soil through litter decomposition in 5000 trees ha^{-1} stands. However, no apparent trend in carbon release has been observed across the stand densities.

8. Elemental nitrogen content in the fresh litter ranged from 36-58 kg ha^{-1} of which 36-44 kg ha^{-1} released to soil i.e., approximately 75–100% release. The release patterns of phosphorus also showed higher returns to the soil through decomposition (annual release-92%) despite the non-significant response to stand density. Despite the maximum potassium release observed in the decomposing litter corresponding to 5000 trees ha^{-1} stand (annual release-78%), no characteristic trend in release pattern was discernible across stand densities.

6.4 Soil characteristics as function of planting density in a 12-year-old A. mangium stand.

1. Soil properties such as bulk density, organic carbon content, carbon sequestration and nutrient contents consistent changes with soil depth and stand densities. Overwhelming significance of woody ecosystems on improvement in soil properties is evident from the study. The soil carbon content at one meter soil depth was 114.61 and 118.60 Mg ha^{-1} in the unpruned and pruned stands respectively at highest planting density (5000 trees ha^{-1}) while the corresponding value in the open soil was just 42.41 Mg ha^{-1}. Soil organic carbon content also showed consistent reduction with decreasing planting density. Soil carbon concentration also showed significant variation in their vertical distribution with consistent decline with increasing soil depth (1.41% to 0.27 across one meter soil depth). The upper soil depth of 0-40 cm accounted almost 56% of the total soil carbon storage in one meter soil depth in the unpruned stands at high density (5000 trees ha^{-1}).

2. *A. mangium* also stored higher amounts of nutrients (N, P, K) in the soil as compared to treeless open soils. For instance, the soil nitrogen content in

the high density stand was almost eight fold higher as that in the contiguous open soil. Other stand densities also showed higher values compared to open soil. The trends were same for soil P and K contents as well. The soil nutrients contents were also influenced by stand density with heavy decline with decreasing stand density (N, P, K; $P<0.001$).

3. The field study on 12-year-old *A. mangium* converges to the conclusion that stand density has profound influence on vital ecosystem processes such as fine root and litter dynamics and may regulate the overall system productivity.

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FINE ROOT DYNAMICS AND ASSOCIATED CARBON AND NUTRIENT FLUX IN 12 YEAR OLD *ACACIA MANGIUM* AT VARYING STAND DENSITIES

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ABSTRACT OF THE THESIS

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ABSTRACT

Fine root production has been estimated to account for up to 33% of global annual Net Primary Production, NPP (Gill and Jackson, 2000). Thus, fine root turnover has important implications for individual plant growth, plant interactions, and belowground carbon and nutrient cycling. Direct and indirect methods for measuring fine root production and turnover in 12-year-old *Acacia mangium* Willd. at varying stand densities were studied. Fine root production estimated ranged from 3.8-5.75 Mg ha^{-1} with a turnover of 4 yr^{-1}. It was estimated that through fine root decomposition about 1.36-2.39 Mg C ha^{-1}, 34.56-102.52 kg N ha^{-1}, 1.46-3.3 kg P ha^{-1} and 19.94-33.60 kg K ha^{-1} is released to soil. Even though fine root constitutes only 1.7-2.14% of the total tree biomass its contribution to the system productivity is very high. Attempts were also made to relate fine root production with various growth variables and in general most of the variables (DBH, basal area per tree, volume per tree, aboveground biomass per tree and leaf area per tree) gave good correlation (R>0.8**) with fine root production when considered on per tree basis. Average annual litter production was estimated to a range of 9.99–11.69 Mg ha^{-1}. Interestingly, annual litter production had a high correlation (R=0.9**) with fine root production. Through litter decomposition, 1.4-2.07 Mg C ha^{-1}, 36-48 kg N ha^{-1}, 1-4 kg P ha^{-1} and 3-6 kg K ha^{-1} is released to the soil. Total soil carbon stock up to 1 m soil depth was estimated and it was significantly different across different density regimes. Invariably the SOC concentration was relatively lower in treeless plot compared with *A. mangium* at different density regimes. Soil C sequestration was 15.96 - 34.58 Mg C ha^{-1} and the nutrient content of soil estimated as 2343.811-948 kg N ha^{-1}, 13.12-21.92 kg P ha^{-1}, 313.52-261.25 kg K ha^{-1}. Total system C content estimates in the ranges from 148.93 -263.79 Mg ha^{-1}. So Density manipulation plays a significant role on productivity in 12 year old

A. mangium. Hence, management objectives should be based on assessment of their impact on various productivity attributes