LONG TERM EFFECT OF THINNING ON PRODUCTIVITY AND WOOD PROPERTIES FOR 20-YEAR-OLD *Acacia mangium* Willd. STANDS

by

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(2015 - 17 - 011)

THESIS

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2017

DECLARATION

I, hereby declare that this thesis entitled **"LONG TERM EFFECT OF THINNING ON PRODUCTIVITY AND WOOD PROPERTIES FOR 20-YEAR-OLD *Acacia mangium* Willd. STANDS"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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Certified that this thesis entitled **"LONG TERM EFFECT OF THINNING ON PRODUCTIVITY AND WOOD PROPERTIES FOR 20-YEAR-OLD *Acacia mangium* Willd. STANDS"** is a record of research work done independently by Mr. S. Suresh Ramanan 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 him.

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Assistance given by those who never received our aid,
Is debt by gift of heaven and earth but poorly paid.
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Introduction

I. INTRODUCTION

The demand for timber and wood products are on the increase in India which has exacerbated since the ban on green felling in natural forests. The projected demand for wood has peaked from 2.75 billion m^3 per year in 1990 to around 4.0 billion m^3 per year in 2020 (FAO, 2015). The present demand is mainly met from forest plantations, homesteads, community and linear plantations in addition to the import from the other countries. Green India Mission of the Government of India focuses on increasing the green cover through the restoration of degraded forest as well as through planting of trees outside the conventional forest (TOF). In this context, a large number of fast growing exotic trees had already been introduced to India to meet various wood based needs. *Acacia mangium* is one such species that was widely cultivated for various end uses. Ever since its first introduction by His Grace Benedict Mar Gregorius, the Archbishop of Thiruvananthapuram during 1980's, there was a rapid establishment of *Acacia mangium* plantations in Kerala (Dhamodaran and Chacko, 1999; Newaz *et al.*, 2005; Shanvas and Kumar, 2003). Fast growth, ability to withstand adverse conditions and amenability to integrate with other crops are the potential advantages that endear this species (Kunhamu *et al.*, 2009; Hedge *et al.*, 2013).

Effective stand management practices are indispensable for deriving optimal productivity of plantation, especially for a quality sawlog production. However, such stand management practices for fast growing species like *Acacia mangium* has not been understood completely. Among the stand management practices, thinning is a vital silvicultural tool which is defined as *felling carried out in an immature stand for the purpose of improving the general growth and form of remaining trees, without permanently breaking the canopy.* Generally for fast growing species, the initial spacing will be closer and prefer high thinning intensity with a short thinning interval. This leads to faster allocation of resources to remaining trees thus ultimately increasing the yield from the plantation. For instance, better economic returns were realised from *A. mangium* plantations established with closer spacing of around 2.5 m x 2.5 m

(Srivasata, 1993). Furthermore, such stand management reduces forking of the leader stem as well as reducing inherent fungal infection (heart rot). Effects of thinning on productivity in such fast growing species have been studied only for shorter periods (Kunhamu *et al.*, 2011) but long term consequences of thinning on growth and biomass production are not extensively studied in humid tropics. This may provide a way for optimal utilisation of the site potential and also provide an opportunity for enhancing the utilisation potential of *A. mangium*.

Stand thinning may also bring qualitative improvement in the wood properties of the remnant stems. It is well-established fact that thinning produces larger diameter trees but its effect on wood properties has not been studied extensively especially among fast growing tree species. The commercial preference of fast growing species with better wood quality is on the increase and any improvement in the wood quality through silvicultural management practices such as thinning would provide considerable economic leverage. The utility of *A. mangium* is mainly for pulpwood production (Peh *et al.*, 1982; Peh and Khoo; 1984; Griffin *et al.*, 2011) and a small percentage is used for the production of particle boards, medium density fibre boards, plywood and for fuel wood and charcoal production due to its high calorific value (4800 to 4900 kcal kg^{-1}) (Tomimura *et al.*, 1987; Dhamodaran and Chacko, 1999; Sein and Mitlohner, 2011).

Acacia mangium as a source for sawn log has not been appreciated hitherto due to the need for longer rotation which is usually avoided as it has better prospective in a shorter rotation. Yet, the wood has comparatively better density value (450 - 690 kg m^{-3}) that can be seasoned without much defects and also is amenable to preservative treatment for enhanced utilisation (Awang and Taylor, 1993; Shanavas and Kumar 2003; Krisnawati *et al.*, 2011; Hedge *et al.*, 2013). The demand of this species for structural and saw log is on the increase in the local market which could enhance its economic prospects. With land becoming very scarce and demographic pressure also increasing, it may not be economically and culturally feasible to have a large chunk of land for timber production. In this context, the fast growing potential and multi-utility nature can be explored efficiently in conjunction with better stand management practices such as thinning. Thinning also may have a multifarious influence on carbon sequestration potential, soil nutrient utilisation, photosynthetically active radiation (PAR) and also wood properties. However, the long term effect of thinning on these parameters is not explored so far in the Indian context.

Carbon sequestration potential of fast growing species does vary with stand management practices such as thinning apart from other factors (Nair *et al*., 2010). Hence the present study also focused on long term impact of thinning on the carbon storage potential in *A. mangium* stands. Stand density regulation apart from facilitating growth and yield of the existing trees may also improve the understorey productivity. This is primarily through improvement in understorey light regimes and reduced belowground competition among the trees. Hence attempts were also made to assess the changes in the understorey productivity as a function of stand thinning through monitoring the understorey light availability. Studies relating the impacts of thinning on the aboveground parameters are in plenty while such information on the belowground characteristics like biomass and root distribution is few. This is particularly important in agroforestry context where the spatial distribution of tree roots decides the competitive interaction in polyculture systems. However, studies focusing the long term impact of thinning on root distribution are rare. Hence, a nondestructive methodology was deployed to characterise the root distribution pattern consequent to thinning for *A. mangium*. In this background elaborate field study was designed to investigate the long-term implications of thinning in a 20-year-old *A. mangium* stand with the following specific objectives:

i) To assess the long term effect of thinning on growth, biomass production, carbon storage potential and soil properties in 20-year-old *Acacia mangium*.

ii) The study also attempts to understand the effect of stand thinning on wood properties of 20-year-old *Acacia mangium*.

Review of Literature

II. REVIEW OF LITERATURE

Literature pertaining to the impact of stand management practices like thinning on biomass production and allocation, carbon sequestration potential and soil nutrient dynamics was collected with particular focus on *Acacia mangium*. An attempt was also made to compile literature pertaining to the influence of thinning on wood properties, root distribution and underground PAR (Photosynthetically Active Radiation) for this species. Pertinent reviews are summarised below:

2.1. Stand density management

Stand density regulation is an effective silvicultural management strategy for enhanced productivity and quality sawlog production in plantation forestry (Wood *et al.*, 2009; Newton, 2012). Many earlier classical studies have clearly demonstrated the prominent role of density management for the realisation of stand management objectives (West, 2006; Nyland *et al.*, 2016). However, the effect of density management is influenced by factors such as species, planting density, the age of the crop, the intensity of regulation, rotation age, site conditions, etc. Most of such studies are centred in temperate forestry (Drew and Flewelling, 1979; Ameztegui *et al.*, 2017). Reports suggest that timely regulation of density could make 25% gain in diameter of sawlog (Medhurst *et al.*, 2011).

Primarily, stand density management aims at the production of quality saw logs by judiciously regulating the biomass allocation pattern within the stand. Tropical hardwood by virtue of their faster resource utilisation potential is more sensitive to such density management practices as compared to temperate plantations (Piotto *et al.*, 2003; Brown *et al.*, 2004). Initial planting space regulation and thinning are the common density management strategies. Standardisation of initial spacing depends primarily on the growth habit of the species and management objective (West, 2006). Such studies on standardisation of optimum planting density for *A. mangium* were attempted in humid tropics. It was observed that the early growth was significantly influenced by plant density (Kunhamu, 2006). However, the response of initial planting density to growth and biomass production was found to stabilise over advancing age. At about 6.5 year age, the volume production was 40.42 $m^3 ha^{-1}$ for planting density at 2x1 m while the production was considerably lower at 4x4 m spacing (3.63 $m^3 ha^{-1}$). Therefore thinning becomes mandatory to enhance production of trees in a site that has been already occupied.

2.2. Thinning and its significance

To achieve desirable products from plantations, apart from suitable site conditions and good planting materials, good silvicultural management technique is also needed. Silviculturist plays a critical role especially when the goal is to produce large diameter trees for saw log production that too in shortest time. This can be accomplished by appropriate stand management practices (Gerrand *et al.*, 1997; Medhurst *et al.*, 2001; West, 2006). In short rotation forestry, one of management practices is to have high density in the initial stages when the focus is sawlog production; so that land resources are fully utilised (Forrester *et al.*, 2010). It is a fact that the high-density plantations accrue the resource at a faster rate during early growth phases leading to vertical competition for light and space. This competitive advantage offers a large number of individuals to acquire maximum attainable height which is inferred as site index (West, 2006). As the competition for resources become intense in the later stages it results in the stagnation of growth. Any further increment in size at this stage is possible only at the cost of the released resources through the sacrifice of some existing trees (Schönau and Coetzee, 1989; Neilsen and Gerrand, 1999). In such cases, thinning treatments are necessary. Thinning is *felling made in an immature stand for the purpose of improving growth and form of trees that remains, without permanently breaking the canopy* which can improve the quality of the residual stand and also produce larger, better quality retained trees by removing damaged, unhealthy and slow-growing trees (Kariuki, 2008; Youngblood, 2011). Henceforth, the high initially stocking density (range of 1110-1600 trees) is generally thinned to 200-400 stems/ha on high-quality sites for fast growing species (Schönau and Coetzee, 1989; Gerrand *et al.*, 1997; Montagu *et al.*, 2003). Ultimately, thinning is a form of density control that may have to be considered if the optimum use of the site potential is to be realised.

2.2.1. Thinning regime

Thinning regimes will vary according to species, site conditions, stand status and intended products (Smith and Brennan, 2006a). Therefore, it is necessary to design an optimum thinning regime for any particular edaphoclimatic condition (West, 2006). Issues such as when to thin, how to thin and how many trees to remove should also be considered in terms of factors including stand conditions, target products and market demands (Smith and Brennan, 2006a; West, 2006). Development of thinning regime is classically based on density management diagrams (DMD) (West, 2006). After the first stand density management diagram was brought out by Drew and Flewelling (1979), the concept was extended to many species including tropical species like teak (Kumar *et al.*, 1995; Tewari and Álvarez-González, 2014). However, DMD's are not the ready reckoner for developing thinning regime. Management objectives, the timing of thinning, thinning intensity, initial planting density, tree rotation age, biophysical condition and site quality should also be considered while developing thinning regimes.

2.2.2. Thinning and management objectives

For *A. mangium* normally thinning is not carried out when the end usage is pulp production even though it has been proved to be beneficial. However, thinning is called for when the goal is to produce quality saw log (Sein and Mitlöhner, 2011). The thinning regime is also complicated as thinning can be done in two manners – single early stand thinning or multiple light thinning (Awang and Taylor, 1993). The latter is a progressive thinning regime, where the stand is reduced to its final number of harvest trees in a number of steps (Medhurst *et al.*, 2001). This sort of thinning has been recommended for a few eucalyptus plantations in New Zealand (Mckenzie and Hawke, 1999), Chile (Muñoz *et al.*, 2008) and South Africa (Schönau and Coetzee, 1989). The former case constitutes a heavy early thinning whereby the stocking was reduced to its final crop density in a single step at a relatively young age with no commercial value attributed to the thinned stems. This type of thinning regime could be preferred as the multistage thinning regimes are costly to conduct. However, a single later-age commercial thinning regime for sawlog eucalyptus plantations in Tasmania has been found to offer the best financial returns on good quality sites (Gerrand *et al.*, 1993; Candy and Gerrand, 1997). In Vietnam, the initial density of 900 trees per ha in *A. mangium* is reduced to 200-300 trees per ha in two or three thinning cycles. The first cycle was carried out when the trees were around nine metres tall and the rotation was planned for about 15 to 20 years (Sein and Mitlohner, 2011). Similarly, a three-phase thinning schedule for 20-year rotation *A. mangium* in the Peninsular Malaysia (i.e., first thinning at two years after planting, second thinning at 4-5 years and the final thinning after 8-9 years) was suggested when the objective is sawlog production (Awang and Taylor, 1993). Further, in many cases thinning is carried out in a similar phase like in Vietnam where thinning is recommended at three, five and seven years after planting (Sein and Mitlohner, 2011).

2.2.3. Timing of thinning

To attain the maximum growth for final trees, thinning is supposed to be undertaken as early as possible to achieve the benefits from early rapid growth rates (Smith and Brennan, 2006a). However, thinning too early may lead to the development of large branches in the lower part of the crown (Medhurst and Beadle, 2001) and also leads to increase in the size and number of knots in timber. This may ultimately result in the degradation of wood quality (West, 2006). Although pruning is commonly recommended after thinning to minimise the knots especially in *A. mangium* as it forms multiple shoots profusely, it is not practised (Smith *et al.*, 2006b; Eldoma *et al.*, 2015). Delaying thinning until the lower branches die off or are shed may be an alternative regime to minimise the potential for development of large branches in these species

(Smith *et al.*, 2006b). However, the delaying of thinning may cause the slower growth of the final crop trees due to competition, and consequently, the target trees will take more time to achieve the desired log size. The timing of thinning becomes a compromise between increasing growth and degrading wood quality (Ye, 2011). If both growth rate of the stem and its wood quality are optimised, the maximum recovery value will be obtained (Smith and Brennan, 2006a).

2.2.4. Thinning intensity

Thinning intensity decides the growth and condition to which the remaining trees are exposed. High thinning intensity may expose the remaining trees to wind damage especially the taller and thinner a tree (Moore and Maguire, 2005). As they have the greater the risk of a tree snapping off or being uprooted (West, 2006). Therefore, some scientists use the ratio of tree height to the diameter at breast height (1.3m) in a plantation to assess the susceptibility to wind damage for some softwood species (Moore and Quine, 2000; Wilson and Oliver, 2000; Wonn and Hara, 2001). However, there is little information on using this ratio to reliably assess the wind damage.

In India condition, thinning schedule for fast growing species like *A. mangium* has not been much attempted (Kunhamu, 2006). However, the timing and intensity of thinning are highly subjected to scientific debate. In Malaysia, sequential thinning at third, fifth and seventh year along with stand pruning is practised (Awang and Taylor, 1993). This may involve huge cost, especially in Kerala scenario. Hence, a single stage thinning at seven-year-old *A. mangium* was carried out at varying intensity to understand the thinning impact as well as standardise thinning regime. It was found that heavy thinning (retaining 533 trees ha^{-1}) in 1600 trees ha^{-1} plantation had better growth increment and biomass accumulation after two years (Kunhamu, 2006). This sort of thinning intensity may be suited for pulpwood production with the rotation of eight to ten years maximum. This practice tends to reduce the cost incurred in harvesting and other operations (Awang and Taylor, 1993).

The biophysical condition of the site has sway on the thinning regime. In paper birch, the growth of a stand that was thinned recently was less than the unthinned stand. This was attributed to the good site condition and the copious rainfall in the site (Wang *et al.*, 1995). Similarly, heavy thinning intensity may end up in a scenario where the remaining trees density are less compared to the actual production potential of the site (Medhurst *et al.*, 2001). Further, the thinning may lead to vigorous weed invasion that strives with the retained trees for resources from the site (West and Osler 1995; Ares *et al.*, 2010).

Hence, aspects such as species concerned, site productivity, management objectives of the plantation enterprise and economical gain from thinning will interact in complex ways in determining thinning regime for particular plantation. Apparently, it is a multifaceted mission to ponder all these factors together and their interactions, to select the most appropriate thinning regime. Equally, there is little information available for understanding the effect of thinning on *A. mangium* when the objective is sawlog production. Furthermore, the long term effect of thinning on trees in tropical condition has not also been attempted earlier.

2.3. Growth responses to thinning

Thinning influence on tree growth parameters varies considerably with species and time. Major growth variables such as diameter, height, stem taper and crown characteristics tend to show divergent responses to thinning.

2.3.1. Diameter

Stand age is the cardinal factor that influences radial growth response to thinning. On the good sites of Malaysia, 9-year-old *A. mangium* trees attain an average diameter increment of 2-3 cm year^{-1}. However, growth declines rapidly after seven or eight years except under ideal conditions over long periods (above 20 years). The tree probably does not grow beyond 35 cm in dbh. Growth studies further revealed an average girth at breast height (GBH) will be of 112 cm for 10-year-old *A. mangium* (Awang and Taylor, 1993).

Thinning intervention showed a significant increase in the radial growth of trees between thinned and unthinned stand. This sort of positive increment on radial growth due to thinning is common (Krisnawati *et al.*, 2011). However, the increment in the girth tends to decrease with increase in age as the space available due to thinning may get utilised. This was also clearly comprehended in the same work where the current annual increment of girth in the first year after thinning was 6.84 cm in the heavily thinned stand but in the second year the girth increment declined down to 4.94 cm (Kunhamu, 2006). Therefore, it is clear that radial growth varies with site, species and the release period (Orwig and Abrams, 1997).

2.3.2. Height

The height response of trees to stand thinning often depends on age and tree stocking. The mean height of A. *mangium* varied from 4 to 9 m in one-year-old to 26.2 m in the 10-year-old tree. Further, a 9-year-old *A. mangium* in Malaysia attained an average height of 23 m (Awang and Taylor, 1993). The corresponding MAI in height was in the range of 1.8-6.1 m (Awang and Taylor, 1993). Height growth in *A. mangium* was insensitive to thinning (Kunhamu *et al.*, 2011). Reports suggest that the stand density management has little effect on height growth, except where the stand is extremely dense or so open where the trees are distinctly isolated (Lanner, 1985). The height response to thinning is species dependent. For instance, the response of tree height to thinning in eucalyptus plantations was inconsistent, with either no response (Gerrand *et al.*, 1997; Medhurst *et al.*, 2001, Nogueira *et al.*, 2015) or increased height growth (Forrester *et al.*, 2010). In a naturally regenerated stand, the thinning effect on dominant trees shows little change in height growth rates whilst intermediate trees are more likely to show increased height growth (Forrester *et al.*, 2010). However, in the even-aged plantation, the impact of thinning on the height growth is not noteworthy.

Still, the variation in the radial growth due to thinning will ultimately reflect in other parameters such as volume and biomass (Nyland, 2016).

A study in *Eucalyptus nitens* has shown that the increment of the cumulative basal area was decreasing with increase thinning density (Medhurst *et al.*, 2001). Overall, the principal reason for thinning is to accelerate the production of larger, more valuable logs to be used for sawn wood production (West, 2006), maximising the size and value of the potential remaining trees are more vital than maximising the total stand volume production (Forrester *et al.*, 2010). The stand basal area is relatively less important when the objective of management is for sawlog production. Moreover, several studies reported that thinning redistributes the increment from smaller trees to larger ones such that wood quality and value of the remaining trees are improved (Skovsgaard and Vanclay, 2008; Aldea *et al.*, 2017).

2.3.3. Tree taper

Stand thinning moderately increased tree taper as evidenced by a good stem form in unthinned plots compared to that of thinned plots. Medhurst *et al.* (2003) also made similar observations in a stand thinning trial on *Acacia melanoxylon.* The higher tree taper at heavy thinning intensity could be due to the differential photosynthate allocation where growth advantage on account of thinning may be distributed unevenly, more towards the lower portion of the tree (Plauborg, 2004). Similar sort of finding has been reported by Perez and Kannien (2005).

2.3.4. Crown characteristics

Many reports are available on the effects of thinning pertaining to changes in tree crowns (Medhurst and Beadle, 2001; Muñoz *et al.*, 2008). The retained trees have more space and thereby receive more solar radiation after thinning. In a thinning study for *E. nitens*, although the basic elements of crown structure (including branch angle, branching density and orientation) were unaffected by thinning, the crown was found to be deeper along the tree height and wider towards the crown base due to larger branches in the lower crown of retained trees (Medhurst and Beadle, 2001). Such heavy thinning leads to an increase in crown asymmetry (Medhurst *et al.*, 2011). Changes in crown size and structure due to thinning will directly affect tree growth (Evans and Turnbull, 2004). The effect of thinning on crown width increment was highest in the heavily thinned stand and lowest in the unthinned stand in the first year after thinning (Kunhamu, 2006). Generally, the response to thinning in fast growing species is often quick and tree crowns expand to occupy the released space. The rate of crown expansion may however, slow down with time (Pretzsch and Schutze, 2005).

2.4. Thinning and biomass production

The effect of thinning on biomass production are discussed under two major sections namely aboveground biomass and belowground biomass production.

2.4.1. Aboveground biomass

Often the tree biomass production gives better understanding of the production potential of the site. Especially in pulpwood plantations and agroforestry systems, estimation of biomass is more meaningful in comparing the impact of managerial intervention than it comparing in volume basis. However, biomass estimation is very laborious and tiresome process. Hence in most cases, the allometric equations are often resorted. Nevertheless, the direct method of biomass estimation studies is being carried to have well elucidations. This is true when the purpose of the study is to understand the impact of stand management practices like pruning, thinning, and fertilisation.

Many biomass estimation studies have been carried out in *A. mangium* under different site conditions and age (Krisnawati *et al.*, 2011). Biomass production potential varies with regard to species and within species, the production potential may vary due to age, location and biophysical factors. For instance biomass production at 3-year-old *A. mangium* in Riau, Indonesia was significantly higher than plantation in West Java. Krisnawati *et al.* (2011) have tabulated the biomass studies of *A. mangium* globally at different sites, age and spacing. In humid tropical condition, biomass estimation in *A. mangium* has been carried out by Kunhamu (2006), Mereena (2014), Jajo (2015) and Rocha (2017) at different age and spacing which is comprehended in Table 1.

Table 1. Biomass production in *Acacia mangium* in Kerala at different age and spacing

Age	Spacing (m)	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Total biomass (Mg ha^{-1})	MAI (Mg ha^{-1} yr^{-1})	Root-shoot ratio	Reference
7	2.5x2.5	210.24	-	-	-	-	Kunhamu, 2006
12	2x1	233.40	104.57	332.97	23.78	0.45	Rocha, 2017
	2x2	180.97	84.87	267.88	19.13	0.47	
	2x4	152.55	59.57	212.12	15.15	0.39	
	4x4	120.92	37.24	158.14	11.30	0.32	
14	4x4	108.00	-	-	-	-	Gopikumar, 2009
18	3x3	298.43	69.33	367.76	20.43	0.23	Mereena, 2014

Biomass allocation patterns for tropical tree species generally follows the order of bole > roots > branch > leaves> twigs (Kumar *et al.*, 1998; Kumar *et al.*, 2001a; Kumar *et al.*, 2001b; Kunhamu *et al.*, 2008; 2016). The partitioning of aboveground biomass across different biomass component in *A. mangium* tends to be about 55-80% stemwood, 10-22% branchwood and 2-9% leaves (Krisnawati, 2011). The pattern of biomass allocation does also get affected by the silvicultural intervention. For example, a study in same site condition by Rocha (2017) to that of the present study reported that the spacing did influence the biomass accumulation in different components. The biomass allocation pattern in various espacement followed a different trend i.e. stemwood > coarse roots > leaves > branchwood > fine roots > twigs. The variability in biomass allocation pattern of high density stand is due to higher production coarse root than branch wood which may be due to the self-pruning nature of the lower branches. Nonetheless, the proportional contribution of aboveground biomass to total biomass was around 70.0% (5000 trees ha^{-1}) to 76.0% (625 trees ha^{-1}).

A distinctive trend of higher belowground biomass production in the high-density stand (104.57 Mg ha^{-1}; 5000 trees ha^{-1}) compared to that of the low-density stand (37.24 Mg ha^{-1}; 625 trees ha^{-1}) was also reported in the study (Rocha, 2017). As similar to spacing, thinning also influence the biomass allocation pattern. The biomass allocation pattern in the biomass study carried out in the same experimental plot by Kunhamu (2006) concluded that stem wood accounted for greater part of the aboveground biomass (65-75%) trailed by branchwood (12.5-25.2%), foliage (5.0-6.5%) and twigs (4.1-6.5%). The study also concluded that there is a steady increase in stemwood biomass with an increase in tree size. However, the proportional increase was more for branchwood at higher girth classes.

2.4.2. Belowground biomass

Mostly thinning experiments are concerned with the aboveground biomass (AGB) and least importance is provided for the belowground biomass. Root systems are a vital part of the tree. Root systems directly influence stand growth and development. They also influence wind firmness of the tree. Root system's structure, amount, depth and extension, all factors do affect tree stability. Any change in one of these aspects will influence stand stability. Poor wind firmness is the main factor that limits many thinning applications in dense, middle-aged or older stands (Achim *et al.*, 2005). Response to thinning in the belowground biomass might be similar to that of aboveground biomass. However, there is no literature assessing this relationship in the tropical scenario.

2.5. Long term effect of thinning

For decades, research reckoning the increase in forest productivity associated with stand density management like thinning, pruning has been a carried out in both temperate and tropical trees species. Most of this investigation reported growth and yield outcomes for few years following the silvicultural intervention. To understand the benefits of stand density management on forest productivity, studies should contain a holistic measurement over a significant portion of a stand's rotation which could lead to meaningful conclusion on the growth and yield response associated with silvicultural interventions. The practice of conventional thinning has not resulted in significant increase or reduction of the volume increment per unit area in many studies. For example, the thinning studies in the Norway spruce stands have recorded such findings (Eriksson, 1987). Understanding the significance of the versatile information that can be obtained from long-term experiments, new thinning experiments called HARKAS series has been established and studies were carried out in Finland (Mäkinen and Isomäki, 2004a; 2004b). The study concluded that effect of thinning on long term resulted in higher number of larger-sized stem at the expense of poorer stem form in heavy thinning plots. On the other hand, the average stem diameter of the standing trees at stand level remained lower on the heavily thinned plots. This sort of information plays a vital role in reframing the thinning regimes. Similar to long term thinning experiment in Norway spruce, thinning trail in yellow poplar (*Liriodendron tulipifera* L.) at the USA concluded that the escalation in growth is short-lived when thinning intensity is low and moderate whereas the long lasting response of trees was observed in heavy thinning intensity (Keyser and Brown, 2014).

The above two studies have a contradictory finding which is mainly because of the species involved in the study are different. This strongly implies that there is need to understand the thinning regime in long term with specific to species. Furthermore, the studies on long term effect of thinning focusing on understory vegetation (He and Barclay, 2000), microclimate condition (Trentini *et al.*, 2017), soil nutrient status and water availability (Albaugh *et al.*, 2004); thinning and fertilizer regime (Albaugh *et al.*, 2017); physiological response of trees to thinning in long term (Sohn *et al.*, 2013) and many more areas are carried out in temperate regions. Unfortunately, such studies are not carried out in tropical conditions. The present study may be first of its kind in the Indian context.

2.6. Carbon sequestration

About 25 % of carbon emission can be attributed to anthropogenic activities like deforestation, landuse and land cover changes (Houghton *et al*., 2012). Trees can be the potential carbon sink by reducing atmospheric levels of CO_2 in the long term (Silver *et al*., 2004 and House *et al*., 2003). This has led to the increase in tree plantations in tropics and subtropics towards carbon sequestration, management of degraded lands and for other environmental concerns (Lamb *et al*., 2005). Studies on carbon sequestration potential in tropical and subtropical tree species are not to the level as compared to that of temperate species (Paul *et al*., 2002; Silver *et al*., 2004). Carbon sequestered in the tree is a function of biomass production. Hence, any silvicultural intervention that aims to increase the biomass production does ultimately have an impact on the carbon sequestration (Nair *et al*., 2010). For instance, pruning influence tree growth and productivity, which in turn does influence the potential of tree stands to store carbon in the vegetation and soil. Kunhamu *et al*. (2011) observed significant reduction in vegetation carbon pool of 6.5-year-old *A. mangium* stands planted at four different spacing in response to pruning. Correspondingly, pruning in high-density stand had better carbon sequestration capacity than low density. Such studies pertaining to the effect of the silvicultural intervention on carbon sequestration potential is yet to be attempted.

2.6.1. Aboveground carbon sequestration

Trees possess enormous potential to sequester elemental carbon in their biomass. However, the potential to accure carbon in biomass varies considerably with species. A study on nine native and exotic taxa in the humid tropics of peninsular India concluded that the aboveground carbon stock ranged from 9.9 to 172 Mg C ha^{-1} with the highest for exotic species such as *Acacia auriculiformis*, followed by *Paraserianthes falcataria* (Kumar *et al*., 1998). Similarly, a study on aboveground carbon sequestration potential of six MPTs (Multipurpose Trees) in pepper based production system showed considerable variation with *G. robusta* showing maximum carbon sequestration with 139.60 kg C tree^{-1} and lowest recorded is by *Ailanthus triphysa* 58.99 kg C tree^{-1} (Kunhamu *et al.*, 2016). Further, a comparative study on the carbon sequestration between leguminous trees (*Cassia siamia* and *Dalbergia sissoo*) and non-leguminous tree (*Tectona grandis*) in the red lateritic soil of Chhattisgarh revealed that carbon sequestration by leguminous trees was higher than the non-leguminous trees (Dhruw *et al.*, 2009).

Generally, large percentage carbon storage does occur in the stemwood. However, carbon sequestered in the different biomass factions does vary. In 25-year-old *G. robusta*, the higher concentration of carbon was in the boles (49.50%) and branches (48.46%) followed by leaves (45.57%) and roots [coarse roots (42.18%) and fine roots (43.52%)] (Jangra *et al.*, 2010). However, this gets altered with an increase in age, as the share of carbon accumulated in the branches increases in older stands. Carbon concentration was found to be increasing from 47 percent (young stand) to 49.30 percent (middle aged stand) and then decreasing in the old stand (49.19 percent) in the case of the silver birch stem. Similarly, carbon content in stem bark was found to be 51.06 percent in the young stand, 54.03 percent in the middle-aged stand and 51.88 percent in the old aged stand. Old branches were also reported to have 48.30, 50.78 and 50.73 percent carbon concentration in young, middle and old stands respectively (Uri *et al.*, 2012). Similar trend can also be observed in *A. mangium* too. For instance, the carbon sequestered in the aboveground biomass in seven, five and three-year-old *A. mangium* plantation in East Kalimantan, Indonesia was 88.54, 68.92 and 47.12 Mg ha^{-1} in mined site (Ilyas, 2013).

2.6.2. Belowground carbon sequestration

Intensive research involving roots began in the 1990s (Atkinson, 2000; van Noordwijk *et al.*, 2015). The high biomass (Albaugh *et al.*, 2004; Samuelson *et al.*, 2004) and slow decay rates (Ludovici *et al.*, 2002) make roots probably much more important in contributing to belowground carbon sequestration. The amount of carbon sequestered in the tree root is substantial but unknown for many species. The net carbon sequestration in the belowground is function of elemental carbon concentration in the roots and their dry biomass production which also vary considerably with species. Roots of various MPTs have been reported to have varying carbon concentrations such as 40.26 (*Anogeissus pendula*), 41.49 (*A. nilotica*), 41.80 (*Dalbergia sissoo*), 41.86 (*Azadirachta indica*), 42.38 (*Emblica officinalis*), 42.90 (*Butea monosperma*), 44.43 (*Eucalyptus tereticornis*) and 44.96 percent (*Albizzia procera*) respectively (Prasad *et al.*, 2010).

In 20-year-old teak plantation at Panama an average 13.1% of the carbon was stored in their roots (Kraenzel *et al.*, 2003). There always exists considerable variation in the belowground carbon sequestration with tree species. A study in 25-year-old *G. robusta* plantation has reported an appreciable carbon in belowground tree components of 23.41 Mg C ha^{-1}. Thakur *et al.* (2015) reported stand level carbon sequestered in belowground biomass of 20-year-old *G. robusta* plantation was 8.04 Mg ha^{-1}. A similar study conducted in a pepper based system revealed that the belowground carbon production varies considerably among different MPTs with *A. auriculiformis* (30.13 Mg C ha^{-1}) showed maximum belowground carbon production followed by *G. robusta* (29.64 Mg C ha^{-1}) and lowest was recorded for *Ailanthus triphysa* (11.13 Mg C ha^{-1}) (Kunhamu *et al.*, 2016). Another study in a 6.5-year-old *A. mangium* plantation showed that belowground carbon stocks vary with planting density and the value ranges from 5.42 Mg C ha^{-1} in the widely spacing stand to 15.39 Mg C ha^{-1} in the closely spacing stand (Kunhamu *et al.*, 2011).

2.6.3. Soil carbon stock

The soil carbon stock in woody ecosystems is usually location specific and often influenced by factors such as climate, soil type, vegetation and management practices (Saha *et al.*, 2010). This pool of carbon in the soil is the largest storage site in the global carbon cycle (Schlesinger, 1990). Thus increased allocation to belowground through root production, turnover and exudation are important for sequestering carbon under conditions of increasing atmospheric CO$_2$ concentration (Curtis *et al.*, 1995; van

Veen *et al.*, 1991). In this context, tree based system owe a considerable advantage in improving the soil carbon stock. For instance a comparison of soil carbon stock under different land use system in Kerala by Saha *et al.* (2010) reported higher soil carbon stocks under tree based system like forest (177 Mg ha^{-1}), homegarden (119 Mg ha^{-1}), rubber plantation (119 Mg ha^{-1}), and coconut (91 Mg ha^{-1}) compared to rice paddy (54 Mg ha^{-1}).

Considerable variation in soil carbon storage with tree species has been observed in woody ecosystems. Changes in the carbon concentration and turnover rates in the dynamic components such as leaf litter and fine roots primarily contribute to this variation (Post and Kwon, 2000). The soil carbon stock estimated in the rhizosphere of five black pepper support trees viz. *Ailanthus triphysa, Erythrina variegata, Gliricidia sepium* and *Garuga pinnata* in the humid tropics of Kerala reported that greater levels of soil organic carbon in the rhizosphere of *G. sepium* (26.5 g kg^{-1}), and the lowest level was registered under *Ailanthus triphysa* (21.6 g kg^{-1}) (Dinesh *et al.*, 2010). Soil carbon stock estimated in three MPTs interplanted coconut plot reported that highest soil carbon levels under *Leucaena* interplanted coconut followed by *Casuarina* and *Ailanthus* interplanted plots (Srinivasan *et al.*, 2010). Moreover, surface soil showed highest organic carbon percentage as compared to soil from deeper layers. Roots help in accumulation of carbon by their decomposition (Brady and Weil, 1999) and supply carbon to the soil through the process known as rhizodeposition. Roots are the sources of soil carbon in deeper soil depth, where they are better protected. The deeper root development accumulates carbon at lower depths and the soil at lower depths is better protected from the disturbances leading to longer residence time (Fontaine *et al.*, 2007).

Tree management practices like thinning, pruning and removing litter residue also influence the extent of soil carbon storage in agroforestry systems. The importance of organic matter input from pruning and litterfall, to help maintain or increase the soil carbon pool, has been demonstrated by several studies in tropical and temperate agroforestry systems. Stand density regulation also influences the soil carbon stocks. For example, 6.5-year-old *A. mangium* stands at variable planting densities in Kerala showed higher soil organic carbon content in the range of 27.02 to 34.64 Mg C ha^{-1} at 0-15 soil depth (Kunhamu *et al*., 2011). Soil organic carbon was more in the high density stands (31.79 Mg ha^{-1}; 5000 trees ha^{-1}) while the lowest soil organic carbon was for stands at lowest planting density (24.70 Mg ha^{-1}; 625 trees ha^{-1}). However, for 6-year-old Poplar (*Populus deltoides*) based agroforestry systems in Punjab reported a lower value of 13.3 Mg ha^{-1} (0 to 15 cm layer) (Gupta *et al*., 2009). Similar lower soil carbon stock (18.2 Mg C ha^{-1}) has been reported for cacao (*Theobroma cacao* L.) based agroforestry system for 0-20 cm soil layer in West Africa (Isaac *et al*., 2005). For instance, Jangra *et al*., (2010) conducted an experiment on carbon sequestration in the *G. robusta* plantation on a reclaimed sodic soil in northern India and they found that about 0.96 percent 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 percent of the total organic carbon pool up to one meter 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. The higher soil organic carbon in the upper layers of soil may be ascribed to the higher litterfall and litter decomposition which subsequently declines with soil depth.

Soil organic carbon study conducted in a 21-year-old *G. robusta* plantation found to be 77.45 Mg C ha^{-1} within 1 m depth (Thakur *et al*., 2015). Similar study conducted in a pepper based production system involving six MPTs (1111 trees ha^{-1}) revealed that soil organic carbon stock decreases with depth and the highest value recorded for

A. auriculiformis 71.39 Mg ha^{-1}, *Ailanthus triphysa* recorded a value of 65.56 Mg ha^{-1} and lowest recorded for *G. robusta* 61.26 Mg ha^{-1} (Kunhamu *et al.*, 2016).

2.6.4. Effect of thinning on carbon sequestration

The overwhelming effect of stand thinning on biomass production and allocation has been studied in detail for many species. Carbon sequestration being a function of biomass production, thinning may influence this also. Young forests have a large carbon sink capacity but mature forests have a high carbon density (Jandl *et al.*, 2007). Thus, short rotation lengths maximise aboveground biomass production but not carbon storage. If management activities are aimed to increase the terrestrial carbon sink, prolonging rotations will generally contribute to carbon sequestration (Binkley *et al.*, 2004). Longer harvesting cycles may increase the forest carbon density (Canadell and Raupach, 2008). The increase in the rotation period of natural forests may allow a progressive accumulation of carbon (Liski *et al.*, 2001). Increased rotation lengths increase biomass and ecosystem carbon pools at the landscape level (Krankina and Harmon, 2006; Liski *et al.*, 2001; Hudiburg *et al.*, 2009). However, site-specific conditions may prohibit the prolongation of rotation periods as the risk of disturbances may also increase. Very long rotation lengths do not necessarily maximise the total carbon balance (Jandl *et al.*, 2007). The increased carbon balance is combined product of various factors acting on the stand.

Thinning is one of the most important silvicultural activities primarily aimed at improving the quality and quantity of growing stock. However, its implications on stand level carbon storage has not been much explored. (Solomon and Freer-Smith, 2007; Bravo *et al.*, 2008). Interestingly, thinning affects carbon sequestration by reducing the amount of tree biomass and soil organic matter by stimulating microbial decomposition facilitated by more solar radiation and throughfall precipitation. The forest floor carbon pools, however, decrease with increase in thinning intensity. However, the effects of thinning on the mineral soil organic pool are less known (Jandl *et al.*, 2007). Overall, thinned stands hold less than the maximum carbon density in vegetation, detritus and soil. Experimental evidence indicates that thinning causes a short-term decreases carbon sequestration but soon carbon sequestration reaches to the levels that were observed before the thinning occurred (Jarvis and Linder, 2007). This may result in higher landscape carbon sink (Smithwick *et al.*, 2007).

Thinning interventions increase the radial growth of the remaining trees at the expense of the total biomass and are not primarily aimed at maximising carbon sequestration (Sobachkin *et al.*, 2005). Thinning does also change the microclimate. Decomposition of the forest floor is temporarily stimulated because soils become warmer and possibly wetter due to reduced evapotranspiration and the soil carbon pool decreases. The stand microclimate returns to previous conditions unless the thinning intervals are short and intensities are low. Apart from the changed microclimate, litterfall is temporarily lowered in heavily thinned stands (Kunhamu *et al.*, 2009). This reduces forest floor accumulation and contributes to lower soil carbon stocks. The input of thinning residues into the soil may compensate for losses (Paul *et al.*, 2002; Finkral and Evans, 2008). Forest floor carbon stocks decreased with increasing thinning intensity in field studies in New Zealand, Denmark and the USA (Jandl *et al.*, 2007). In the Danish study, forest floor carbon stocks were inversely related to the basal area, but the change in the forest floor carbon pool was smaller than its variation between experimental sites with different soil types (Vesterdal *et al.*, 1995). There is very less experimental evidence is available for the effect of thinning on the soil carbon pool. The balance in forest soil carbon depends on the extent of the soil disturbance, the input of thinning residues into the soil and the rate of the litterfall. The long-term carbon sequestration depends on the extent of soil disturbance. Felling or harvesting influences soil carbon in two contrasting ways: harvest residues left on the soil surface increase the carbon stock of the forest floor and disturbance of the soil structure leads to soil carbon loss. In a comparative study, harvesting turned forests into a carbon source because soil respiration was stimulated, or reduced to a lesser extent, than photosynthesis (Kowalski *et al.*, 2004).

Management interventions such as thinning add value to the stand, but remove biomass. The net effect for carbon is a loss. Nevertheless, thinning increases the stand stability as well as alters the biophysical condition and therefore offers an important control mechanism for the maintenance of carbon storage in ecosystems.

2.7. Root studies

Literature pertaining to the methodology of root distribution studies elsewhere and especially on *A. mangium* are discussed below.

2.7.1. Methodology for root distribution studies

Roots are the vital organ for the stability of aerial parts and acquisition of resources for tree growth. Information on tree root distribution is essential for better understanding of belowground interaction plantations as well as in agroforestry systems. In the tropical scenario, the data and information pertaining root distribution are now available to a better extent. Root structure and distribution have been well documented in temperate regions. As the edaphic condition does differ between the tropical and temperate regions much of the review has been collected from the tropical condition. The methodology adopted is very important for comparing and contrasting results. It is very clear that methodology adopted generally depends upon two important criteria, technical soundness and economic considerations (Bohm, 1979, Vogt *et al.*, 1996; Smit *et al.*, 2000). Bohm (1979) suggests some classical methods, direct methods like root excavation, trenching, monolith, profile wall trenching and indirect methods like gravimetric method, neutron probe method, radioactive tracer methods. In conjunction, with the advancement of age and techniques many improvements in methodology have been accomplished globally and also new methods have been invented. A review by Maegth *et al.* (2013) has better detailing.

In India, there has been some commendable work on root distribution that include studies on MPTs (Dhvani *et al.*, 1990), root phytomass study of trees in eastern India (Das and Chaturvedi, 2008), root distribution and biomass studies (Puri *et al.*, 1994;

Swamy *et al.*, 2003; Verma *et al.*, 2014; Singh *et al.*, 2014), root interaction and completion studies (George *et al.*, 1996; Kumar *et al.*, 1999; Gowda and Kumar, 2008), radiotracer studies (Sankar *et al.*, 1988; Wahid *et al.*, 1989a; Wahid *et al.*, 1989b; Jamaludheen *et al.*, 1996), fine root studies on trees (Raizada *et al.*, 2013; Rocha, 2017) and many others. Methods for studying the root architecture and distribution are many, all have their own advantage and disadvantages. Root excavation or destructive sampling has been widely adopted a method which is capable of giving more reliable results but it is very tedious to carry out on a large scale. Of all the direct methods, tree excavation is now considered as a standard for coarse root biomass estimation and has been widely used (Snowdon *et al.*, 2002; Samritika, 2013; Rocha, 2017). Root excavation method helps in better understanding of the root system. However, main lacunae are the destructive sampling which is laborious and time-consuming nature. Further, it fails to determine the actual area to which fine roots and its activity are confined which is of much relevance in agroforestry context. Nevertheless, most of the root studies reported in the literature concerning plantation forestry and agroforestry systems are based on the excavation method.

In order to overcome the drawback of destructive sampling, a new innovative method of was proposed by Huget - known as logarithmic spiral trenching (Tomlinson, 1998). It was implemented by Fernandez *et al.* (1991) for understanding the effect of drip irrigation in olive trees followed by Tomlinson *et al.* (1998) in *Parkia biglobosa*. This method has been very innovative and it was adopted by other researchers with slight modification (Divakara *et al.*, 2001; Srinivasan *et al.*, 2004; Samritika, 2013, Kittur, 2014). Among the above works, modification done by Divakara *et al.* (2001) in the logarithmic spiral trench design is suitable for the species under the study was bamboo. However, the usage of same modification to dicot trees may not give a valid result (Srinivasan *et al.*, 2004 and Samritika, 2013). Hence, the original method was followed using the equation adopted by Tomlinson *et al.* (1998).

2.7.2. Root studies in *Acacia mangium*

A. mangium is a nodulating nitrogen-fixing tree and much of the work has been focused on the nodulating mechanism and behaviour. About 37 % of roots of *A. mangium* are concentrated in the 0-10 cm soil depth (Avani *et al.*, 2015). This makes them as one of the species suitable for slope stabilisation and erosion control measures (Voottipruex *et al.*, 2008; Ali, 2010).

Radioisotope (^{32}P) based study was carried out to understand the root activity of young trees that were subjected to stand management practice like spacing and pruning (Kunhamu *et al.*, 2010). It was reported that root activity at 0-30 cm layer of the soil was maximum compared to the lower depths. Further, the effect of stand management practices such as spacing and pruning have also been reported for *A. mangim* (Kunhamu, 2006). The crown pruning has improved the root activity and high density planting enhances the root activity in the deeper horizons closer to the stem. High density planting combined with pruning does promote root activity in the sub-surface horizon (31-60 cm). In the same site, fine root assessment was carried out and it was found that fine root production ranged from 1.39 to 5.78 Mg ha^{-1} yr^{-1} and the production on a unit area basis (per ha) showed an increasing trend with increasing stand density (Rocha, 2017). Peter and Lehmann (2000) reported reduction in root length at all depths and lateral positions of hedgerow plantings of *Acacia salicina* after tree pruning as a result of the lowering the supply of assimilates from the leaves and retranslocating sugars to aboveground components. Similarly, Fownes and Anderson (1991) reported a reduction of the root length following pruning in the case of *Sesbania sesban* and *Leucaena leucocephala*.

2.8. Soil properties of *Acacia mangium* plantation

The soil is the versatile medium that maintains the productivity of any plant ecosystem. Vegetation does influence the nature of the soil, especially of the woody ecosystem that has the greatest influence on physical properties of the soil (Yanai *et* *al.*, 2003). The high rainfall along with other factors makes the biophysical conditions and nutrient level in tropics suitable for higher productivity (Brouwer and Riezebos, 1998). Even in the predominant acidic soil of Kerala, *A. mangium* do perform well (Kunhamu *et al.*, 2009; Nurudin *et al.*, 2013).

2.8.1. Soil pH

In *A. mangium* plantations as age increases, there will be greater amount translocation of base cations from the soil to plant biomass leads to decrease in the concentration of base cations in the soil which leads to decreased pH (Yamashita *et al.*, 2008; Gonzales-Munoz *et al.*, 2012). This drain of base cation from the soil was also evident in a study by Matali and Metali (2015) who reported the low concentration of total and exchangeable Ca and P concentration. Another important reason for this acidic pH is due to release of protons during nitrification in exchange for nitrate uptake by N-fixing bacteria (Li *et al.*, 2001). Further, high amount of ammonia release from leaf litter is also a reason for decreased pH (Xiong *et al.*, 2008). Even the high amount of soil organic matter content also contributes for the former (Augusto *et al.*, 2002; Yousefi and Darvishi, 2013).

2.8.2. Soil organic carbon

Soil organic carbon content and nitrogen has a greater impact on the biomass production. Soil organic content showed a remarkable increase in *A. mangium* stands as compared to open soil. It changed from 0.31% (42.41 Mg ha^{-1}.) in the open soil to 1.03% (114.61 Mg ha^{-1}) in a density of 5000 trees ha^{-1} (Rocha, 2017).

2.8.3. Nitrogen

Among the primary soil macronutrient, nitrogen has very important role in the productivity of the soil. *A. mangium* can fix N_2 at the rate of 31 to 128 kg ha^{-1} yr^{-1} which very high compared to other nitrogen fixers (Osunkoya *et al.*, 2005; Bouillet *et al.*, 2008; Morris *et al.*, 2011). The other members of Acacia genus tend to have nitrogen fixing potential like *A. melanoxylon* which can increase the productivity when incorporated into agroforestry systems (Power *et al.*, 2003). Further, the foliage is rich in nitrogen which is a feature of tropical nitrogen fixers (Krisnawati *et al.*, 2011; Morris *et al.*, 2011). This contributes to higher nitrogen concentration in the soil (El Tahir *et al.*, 2009; Morris *et al.*, 2011; Jeddi and Chaieb, 2012). A high proportion of nitrogen in the foliage fraction (875.40 to 2842.11 kg ha^{-1}) was reported in spacing cum pruning trail in *A. mangium* which provides the possibility of substantial N transfer to the soil (soil N stock of 1995 kg ha^{-1} in 0-20 cm soil layer) through nutrient cycling (Rocha, 2017). *A. mangium* plantation established during 1998 had a higher concentration of nitrogen compared to the natural forest in Andulau Forest Reserve, Brunei (Matali and Metali, 2015).

2.8.4. Available phosphorus

Height growth is dependent upon the phosphorus content of the soil. It becomes a critical factor in acidic soils as it gets fixed in its immobilised form (Majid and Paudyal, 1999; Nykvist and Sim, 2009). Available phosphorus generally tend to lower in *A. mangium* plantation than its initial condition as well as with other vegetation. The mycorrhizal association in the roots of *A. mangium* facilitate greater uptake in tree biomass which might be the reason for decrease phosphorus concentration (Chauhan *et al.*, 2008). However, this trend was not reported in many studies as there will be variability in available phosphorus because leaching and fixation occur rapidly in tropic soils (Vijayanathan *et al.*, 2011). The low concentration of available P in the soil can be correlated to acidic pH. The available phosphorus in 3.8-year-old *A. mangium* (12.1 kg ha^{-1}) was lower compared to that of initial condition (18.6 kg ha^{-1}) at Malaysia. However, at the 10th year on the same site, the available phosphorus content increased to 20.4 kg ha^{-1} (Awang and Taylor, 1993).

2.8.5. Exchangeable potassium

Total and exchangeable potassium concentrations did not significantly different between soil of the *A. mangium* plantation and natural forest of Andulau Forest

Reserve, Brunei (Matali and Metali, 2015). Similarly, exchangeable potassium did not vary between secondary forest, imperata grassland and *A. mangium* plantation (Yamashita *et al.*, 2008). It can be attributed to the high mobility of potassium in the soil (Xiong *et al.*, 2008). In general, as the age increases, the soil nutrient did vary tremendously. The soil nutrient composition did vary significantly as the plantation was aged up, as in the case of *A. tortilis* (Singh *et al.*, 2002).

2.8.6. Soil properties in response to thinning

Thinning generally provides large biomass residue to the site and also the root portion when left undisturbed act as a source for soil carbon stock (Binkley *et al.*, 2004; Bolstad and Vose, 2005). Generally the carbon and nitrogen content in thinned plot tends to increase which can be attributed to ample space availability and sunlight penetration (Herdiyanti and Sulistyawati, 2009).

The impact of thinning of *A. mangium* on soil chemical properties was studied in a 9-year-old thinning trial in Thiruvazhamkunnu, Kerala (Kunhamu *et al.*, 2008). It was found that available nitrogen and organic carbon did vary significantly between thinning regimes and with the treeless plot. However, soil pH, exchangeable potassium and available phosphorus did not vary with thinning. Similar sort of study conducted in Peninsular Malaysia also concluded that the thinning increased soil carbon and nitrogen content significantly while the low phosphorus content was observed in 20-year-old thinned *A. mangium* compared to the natural forest (Vijayanathan *et al.*, 2011). Yet, another study in Malaysia reported declining trend in soil chemical attributes with an increase in age. This profound decrease in nutrients status necessitated the option of fertiliser application or thinning to sustain the productivity in long run (Lee *et al.*, 2015).

Among the soil physical property, the bulk density of the surface soil may increase with felling or thinning operation mainly because of the compaction (Greacen and Sands, 1980). In long run between subsequent operations tends to return back to normal bulk density (Markewitz *et al.*, 2002; Coleman *et al.*, 2004).

2.9. Thinning and PAR

Photosynthetically Active Radiation (PAR) plays a key role in maintaining the understorey productivity in agroforestry systems. Better understanding on PAR availability may help us to assist regeneration (Sevillano *et al.*, 2016) or to control weeds. Establishment of native vegetation in Vietnam was achieved by adjusting the canopy structure *Acacia* hybrid plantation thereby to facilitate the growth of *Hopea odorata* shade demanding species (Dong *et al.*, 2016). Photosynthetically active radiation (PAR) in the understorey can vary due to many factors such as the tree species, stand density, canopy structure, row orientation, leaf area index, site, latitude, season, spectral quality of incoming light (Kunhamu, 2006). Among all the factors that influence understorey PAR availability, stand density and canopy structure are the two factors that can be manipulated to increase the productivity. As canopy structure directly depends on stand density, by altering the stand density the desired understorey PAR availability can be achieved. However, the stand density manipulation can be achieved by two means either by adopting different spacing while planting which truly influence the productivity or by maintaining desired density through thinning (Kumar *et al.*, 2001). Among the above, thinning is the best option as it judiciously uses the site potential to increase the productivity as well as understorey productivity. A study by Kunhamu *et al.* (2009) on different thinning intensity trial to increase the productivity of ginger under 8-year-old *A. mangium* have concluded that productivity under open condition was better than heavily thinned plot. However, the system productivity was better in the heavily thinned plot compared to other thinning intensities. A similar canopy management had a positive impact on the intercrop production in a *Morus alba* based agrisilvicultural system (Thakur and Singh, 2002).

The increase in the productivity is mainly due to increase the availability of nutrients and space after thinning. Crown shape is significantly altered by thinning which in turn has a direct impact on the incident PAR flux density. However, the remaining trees may expand their crown due to increased growth thereby reducing the PAR availability. This trend is also reported in the tropical orchards where removal of trees boosts productivity in short duration (Tscharntke *et al*., 2011). In long run, the remaining trees tend to fill up space. Henceforth in orchards, pruning is recommended to increase the productivity than thinning (Avila *et al*., 2006). In long term forest management scenario, the increased availability of PAR due to thinning does get fade away which has been reported in temperate species. The effect of thinning after 27 years in 51-year-old *Pseudotsuga menziesii* (Mirb.) (Douglas-fir) in British Columbia has faded away and the understorey growth between unthinned and thinned plot was on par (He and Barclay, 2000). Thinning trial of *Fagus sylvatica* L. in long term does not have any statistically significant difference in the PAR transmittance (Chianucci *et al*., 2016). However, studies on the long term impact of thinning on the understorey PAR availability in tropical conditions are scarce which need utmost attention.

2.10. Wood property of *Acacia mangium*

The literature pertaining to wood physical properties of *A. mangium* and impact of thinning on wood properties are discussed in the upcoming subsections.

2.10.1. Physical properties

The basic density of 8-10-year-old *A. mangium* ranges from 425-575 kg m^{-3} (mean value 500 kg m^{-3}) (Dhamodaran and Chacko, 1999; Lim and Gan, 2000; Jusoh *et al*., 2013). In humid tropics of Kerala, the wood basic density of *A. mangium* (14-year-old) was reported to be 477 kg m^{-3} (Jajo, 2015) and 516 kg m^{-3} for wood samples from homegarden in Kerala (Shanavas and Kumar, 2003). Heartwood percentage of *A. mangium* was reported to be 72.35 % (Anoop *et al*., 2012) but certain cases the soft-core wood may be more than 50% which gets detached while drying (Dhamodaran and Chacko, 1999). The moisture content ranges between 49-52% for the nine-year-old tree which is very high compared to *A. auriculiformis* and other *Acacia* hybrids

(Yamamoto *et al.*, 2003; Shanavas and Kumar, 2003). Yet another work by Gan and Amin (2011) reported for the moisture content for 20-year and 16-year-old trees in the range of 6.3-20.2 % and 6.9-22.6% respectively. Similarly, the shrinkage value reported do vary from studies and across ages. The mean radial and tangential shrinkage value were 3.89 % and 7.62 % respectively and shrinkage tends to increase as age increases (Shanavas and Kumar, 2003). The radial and tangential shrinkage reported for a nine-year-old *A. mangium* were 2.3% (maximum of 9.6%) and 2.8 % (maximum of 21.5 %) respectively (Tenorio, 2012). The volumetric shrinkage for seven-year-old *A. mangium* was 15.89±3.53 % (Jusoh *et al.*, 2013). As age increases the density, moisture content, shrinkage (radial and tangential) does vary significantly. This has been confirmed in *A. mangium* by Chowdhury *et al.* (2005) in a study on 10, 15 and 20-year-old plantations in Bangladesh. Further, longitudinal, tangential and radial shrinkage did not vary with increasing height but vary with age except for longitudinal shrinkage. Some other works such as Sahri *et al.* (1998) and Jajo (2015) have proved that physical properties do vary across provenances.

2.10.2. Heartwood to sapwood ratio

The heartwood of *A. mangium* has a brownish colour which turns to dark brown when dried and is easily distinguishable from white colour sapwood. In the heartwood, it has a distinct, large and loose fibre corewood forming about 7 percent to 34 percent of the wood volume which gets detached from the rest of the wood while drying (Dhamodaran and Chacko, 1999). The percentage of the heartwood-sapwood ratio can be a factor for the determinant of the utility of the wood i.e. when the ratio is more; it can be widely used for structural timber, if not it can use for pulp production. This makes it mandate while determining the productivity. Further, estimating the ratio can help us to define the difference in the quality of wood due to management practices.

The sapwood and heartwood have distinct coloration. The sapwood is often white or yellowish-white and the heartwood is yellowish brown to golden brown when fresh, to dull brown upon long exposure. For 20 years old *A. mangium,* the average percentage of sapwood was highest at 2.5 m (18.6%) above base and decreased as it moves upward to 5 m height (17.72%) and towards the base (16.52%), but for 16 years old trees, in the same study, the percentage of sapwood was lowest at 2.5 m (9.4%) and increased in both the directions to 10.5 percent and 11.9 percent respectively (Lim and Gan, 2011). This indicated that sapwood-heartwood percentage follow no particular pattern but greatly vary within an individual tree.

High variations ranging from 0 percent to 77 percent in the percentage heartwood has been reported for 18-year-old *A. melanoxylon* (Bradbury *et al.*, 2011). While Knapic *et al.* (2006) found that large portion of the volume (61%) in the species are occupied by heartwood and the heartwood area in the stem cross-section decreased from the tree base upwards. The heartwood diameter positively correlated with the total diameter i.e. larger tree had higher heartwood. They found that on an average 69 percent of the stem cross-sectional area at the base of the tree in the species was occupied by heartwood and gradually reduced to 67 percent, 58 percent and 26 percent at a height of 15 percent, 50 percent and 75 percent of the total tree height respectively. The lower half portion of the tree heartwood represented 66 percent of the wood volume. The radial width of sapwood was found to be constant within the tree at on average of 31 mm up to 50 percent of total tree height but increased to 35 mm upwards till 75 percent height level.

2.10.3. Effect of thinning on wood properties

The wood of *A. mangium* has been so far focused as raw material for pulp and paper only (Arisman and Hardiyanto, 2006). However, there are several issues in the utilisation of *A. mangium* for structural purposes. Especially drying may give rise to some defect that can be avoided on careful processing after felling (Lim *et al.*, 2003; Basri and Wahyudi, 2007; Moya *et al.*, 2000; Anoop *et al.*, 2012). Many works have been done on wood properties of *A. mangium* yet only a few studies pertaining to the effect of silvicultural operation such as thinning on wood properties. Many reports emphasise that the wood quality can be improved by silvicultural operation and by breeding (Buijtnen, 2004; Zobel and Buijtnen, 2012). Thinning have major effects on the growth and wood properties as more space and nutrients are available to the remaining trees after thinning. There are certain conifers which have not responded to thinning, have been listed in the classic work of Zobel and Buijtnen (2012). In the case of hardwoods, the response of wood properties to thinning is still complex than softwoods. Thinning can also lead to the formation of epicormic branches in the hardwoods which has a greater influence on wood properties (Zobel and Buijtnen, 2012).

Generally, thinning results in opening up tree canopy which increases the rate of growth but reduces the wood density (Evans and Turnbull 2004; Wistara *et al.*, 2016). A study by Hegazy *et al.* (2014) on the effect of thinning on wood density in *A. salicina* on heavily thinned plots was reduced by 3.8 % compared to that of an unthinned plot. However, the effect is temporary and many studies have indicated that wood basic density is not significantly influenced by thinning. Wood density in *Eucalyptus nitens* did not vary at 22- year old which was thinned at a sixth year from planting (Medhurst *et al.*, 2012). In other work by Lin *et al.* (2012) concluded the row thinning in 24-years old *Cryptomeria japonica* did not significantly influence wood physical and mechanical properties. However, wood properties of *Cupressus lusitanica* in Tanzania was varied in regard to different thinning schedule (Malende and Ringo, 1987).

In India, thinning schedules in teak did not influence wood properties including heartwood percentage, specific gravity and density (Tewari, 1999). Perez and Kanninen (2005) concluded that impact of thinning on the wood properties such as heartwood percentage and density tends to be temporary and in the long run the effect gets nullified, based on his work on different thinning schedule in teak plantations of Costa Rica.

Additionally, a study aimed at understanding the effect of growth rate on wood specific gravity and mechanical properties in softwood, diffuse porous wood and porous wood by Zhang (1995). Revealed that the wood properties of diffuse porous species were very little influenced by an enhancement in growth rate while the porous species was least influenced. Similar sort of finding has also been reported in *Swietenia macrophylla, Khaya senegalensis* and *Paulownia fortunei* where increased growth rate did not influence wood properties (Perera *et al*., 2012).

Materials and Methods

III. MATERIALS AND METHODS

3.1. Location

The study involving the long-term effect of thinning on the growth and productivity of *A. mangium* was carried out at Livestock Research Station (LRS), Thiruvazhamkunnu, Palakkad district, Kerala, India during 2015-17 [11^0 21' 30" N, 76^0 21' 50" E]. The elevation of the study region is 60 m above mean sea level. The place encounters a warm humid tropical climate with mean annual rainfall ranging from 2600 to 3200 mm year^{-1}. Mean maximum temperature ranged from 27.3°C to 37.7°C and mean minimum temperature from 17.5°C to 24.3°C. Most of the rainfall is received during the southwest monsoon .i.e. June to August with an ancillary peak in September to October. The soil in the study site is Ultimo (very deep, clayey, mixed Ustic Palehumults) type, with pH and bulk density of 5.4 and 0.86 g cm^{-3} respectively (AICRPAF, 2005-2013; Jajo, 2015). The site has an undulating terrain with the general slope in North - South direction.

3.2. Experimental details

This study forms a part of thinning trial that was undertaken during 2002 in a pre-existing seven-year-old *Acacia mangium* stand. The stand was established during August 1995 in the area of 2 ha using polybag grown seedling from local seed source and at a spacing of 2.5 x 2.5 m. The thinning treatment involving four thinning intensities were executed in Randomised block design (RBD) with six replications with each plot of size 17.5 x 17.5 m (306 m^2). As part of the present study, four well-stocked replications were selected such that there was a total of 16 plots for the study (Plate 1).

Thinning treatments:

1. Treatment 1: Thinning of one-third growing stock by removing every third row (Retaining 1066 trees ha^{-1})
2. Treatment 2: Thinning of half growing stock by removing alternate diagonal row (Retaining 800 trees ha^{-1})

3. Treatment 3: Thinning of two-third growing stock by removing alternate tree in diagonal rows and alternate in each diagonal row (Retaining 533 trees ha^{-1})
4. Treatment 4: No thinning (Control) (Retaining 1600 trees ha^{-1})

3.2.1. Stand conditions after thinning

Regular biometric observations were made for two years after thinning in 2002 and the results were published (Kunhamu, 2006). Since then the trees were managed following routine stand management practices. The unthinned plot (control) having 1600 trees ha^{-1} has undergone moderate self-thinning. The overall stand condition was good and healthy.

3.3. Tree growth observations

In order to study the long-term effects of thinning, the stand was subjected to detailed growth observation. The total height and bole height of individual trees were made using hypsometer (Vertex laser, Haglof: Sweden). The diameter (dbh) of study trees was measured using tape. Border trees were excluded from the measurement in order to minimise the edge effect. The crown diameter was measured by projecting the crown surface to the ground. This was used for computation crown ratios as per Van Laar and Akça (2007).

3.3.1. Procedure for destructive sampling

For the detailed analysis of the growth and biomass production, two trees were randomly selected from each plot. Care was taken to avoid border trees. The trees selected for felling were marked; total height and dbh were recorded prior to felling. The trees were felled using chainsaw (Oleo-mac, Italy). Care was also taken to give minimum disturbance to the remaining trees while felling (Plate 2).

3.3.2. Volume estimation of felled trees

For estimating the volume of felled trees, the trees were divided into 2 m sections up to the tip of the tree and mid girth of each section was recorded. The volume of each section was estimated following Huber's formula, $(g^2/4\pi) \times L$ (where g is the mid girth of each section and L is the length of the section). The volume of each section was summed up to obtain the total volume and volume corresponding to the bole height.

Stand volume per ha was computed following two strategies. The mean tree volume was multiplied by the expected number of retained trees per ha to get the assumed volume per ha. Also, volume per ha was separately computed based on actually available trees in each plot and computed for actual volume per ha basis.

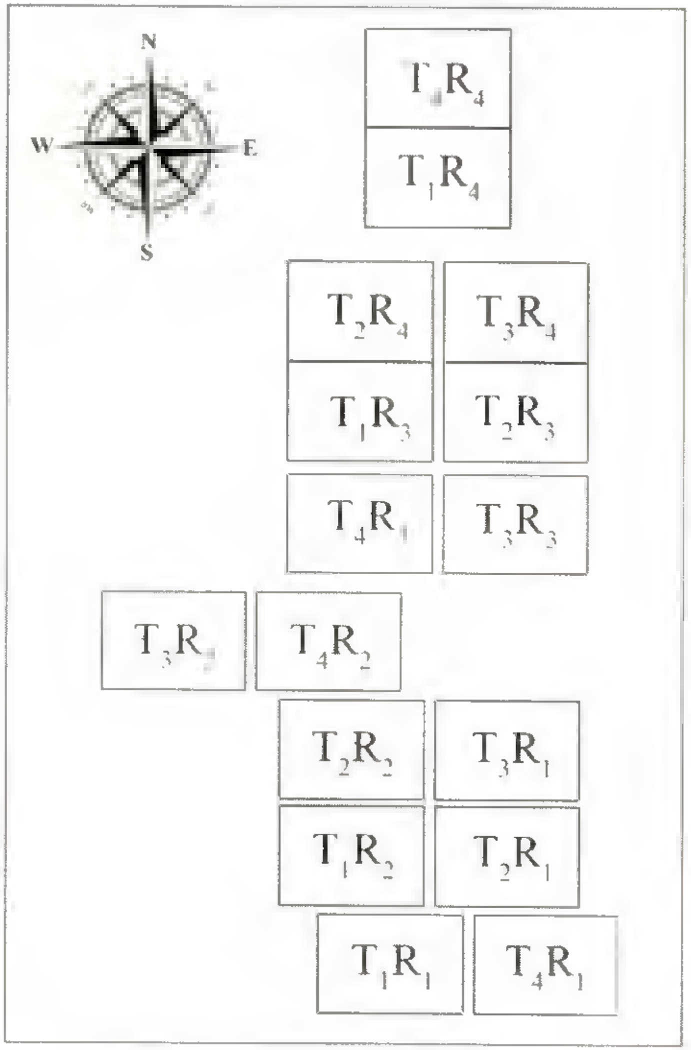
3.4. Biomass estimation

The methodology for aboveground biomass estimation and belowground estimation are discussed separately.

3.4.1. Aboveground biomass

The aboveground biomass of the felled trees was segregated into stem wood, branch wood (branch <7cm diameter), twigs and foliage. Initial fresh weights of various biomass components were estimated immediately after felling using appropriate spring scales (nearest to 0.1kg or 10 mg). Triplicate samples (250g each) of stem wood, branch wood, twigs and foliage were collected from all the felled trees and carried out to the laboratory. The samples were oven dried at 70°C for constant weights and dry weights recorded for moisture estimation. The dry weight of the biomass components was calculated from the respective fresh weights (stem, branch, twig and leaf) and moisture percent. Total tree biomass (dry weight basis) was obtained by summing up the biomass of the different tree component. Average biomass per individual tree (mean tree biomass) was extrapolated to biomass on hectare basis by multiplying it with number of trees per hectare as discussed earlier for volume estimation

Plate 1. Field layout of 20-year-old *Acacia mangium* subjected to stand thinning at Livestock Research Station, Thiruvazhamkunnu,Palakkad district, Kerala, India



T_1- One third thinning (1066 trees ha^{-1} remaining)
T_2- Half thinning (800 trees ha^{-1} remaining)
T_3- Two third thinning (533 trees ha^{-1} remaining)
T_4- Unthinned (1600 trees ha^{-1})

Replications: 4
Plot size: 17.5m x 17.5m (306.25 m^2)
Initial spacing: 2.5m x 2.5m

* *The experimental plots are delineated inside large plantation. Hence there are sufficent border trees between the treatment plots.*

Plate 2. Aboveground biomass estimation in 20-year-old *Acacia mangium* subjected to stand thinning at Thiruvazhamkunnu, Kerala, India

A. Conversion of felled tree into billets; B. Disc collection for wood properties assesment; C, D and E. Fresh weight measurement of stemwood, branchwood, twigs and foliage respectively

Plate 3. Belowground biomass estimation in 20-year-old *Acacia mangium* subjected to stand thinning at Thiruvazhamkunnu, Kerala, India

A. Measurement of lateral root spread; B. Cleaning of excavated root; C. Assessing fresh weight of root biomass; D. Assessing fresh weight of sample root biomass and E. Collection of soil samples in different soil depth for laboratory analysis.

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

$$Dry\ matter(kg) = \left\{\frac{Dry\ weight\ of\ the\ sample\ (g)}{Fresh\ weight\ of\ the\ sample\ (g)}\right\} \times Fresh\ weight\ of\ the\ part\ (kg)$$

3.4.2. Belowground biomass estimation

The belowground biomass (coarse roots) was estimated following root excavation technique. One tree per plot was selected randomly for belowground biomass study using powered earth mover (Tata Hitachi) followed by mechanical removal of coarse roots. The fresh weights were recorded after a thorough cleaning. Triplicate samples (250 g each, coarse roots) were sampled for moisture content determination. The dry weight of roots was derived from the fresh weights and their corresponding moisture contents (Plate 3). During the excavation of the root system the root morphometric parameters such as lateral root length, total root length (total length of the entire root system) and tap root length (the length of main leader root).

3.4.3. Allometric equations

The trees sampled for biomass estimation were also used to develop the allometric equations to predict the aboveground biomass per tree (AGBPT), belowground biomass per tree (BGBPT), total tree biomass (TTB), total volume per tree and bole volume per tree using tree height and GBH as predictor variables. A variety of equations were tried. The model with a maximum coefficient of determination and minimum Furnival index was selected to give the best fit (Kunhamu *et al.*, 2016). Furnival index is obtained by multiplying the square root of the MSE with the inverse of the geometric mean of the derivatives of the dependent variable. In the case of dependent variable as Y then derivative of Y is 1 and so

$$\text{Furnival index} = \sqrt{MSE}$$

When the dependent variable is ln Y then derivative of lnY is Y^{-1}. Then

$$\text{Furnival index} = \sqrt{MSE}\left(\frac{1}{\text{Geometric mean}\,(Y^{-1})}\right)$$

3.5. Biomass C- sequestration

Elemental carbon content in the various tree components was determined by using dry ash method in a muffle furnace (Varsha *et al*., 2017). Triplicate samples of each tissue types (stem, branch, twig, leaf and coarse root) were analysed for respective carbon concentration. Biomass C stock in the different tree component parts was calculated by multiplying their oven-dry biomass with the corresponding carbon concentration. Total whole tree carbon content was estimated by adding all the component carbon content. Stand level biomass C stock was estimated by multiplying the average C stock per tree with the number of trees per ha.

3.6. Soil analysis

3.6.1. Soil sampling

One profile pit was taken from each experimental plot (total 12 pits) and triplicate soil samples were collected from five depths viz. 0-20, 20-40, 40-60, 60-80 and 80-100 cm for soil carbon and soil nutrient analysis. Similarly, soil profile was also taken from a treeless control plot and from a contiguous natural forest for comparison. Soil bulk density measurement was done using specially designed steel cylinder (AOAC, 1995). Bulk density was estimated by taking out a core of undisturbed soil from each soil depth by using steel cylinder. The core was taken out without pressing the cylinder too hard on soil so that the natural bulk density of soil is disturbed. The soil samples were oven dried and weight was determined. The volume of soil was calculated by measuring the volume of a 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 passed through 2 mm sieve after air drying and stored in polyethene bags for further analysis.

3.6.2. Soil carbon stocks

The soil organic carbon was analysed using Walkley and Black method. Soil mass at each soil depth was estimated from the corresponding bulk density. Soil C-sequestration were computed for each soil depth by multiplying soil mass with the corresponding soil organic C-concentration (%). Soil carbon stocks in each soil depth were summed up to obtain the total carbon stock for one metre soil depth and expressed in per hectare basis.

3.6.3. Soil nutrient analysis

Triplicate samples from the composite samples for each soil depth were taken for analysing total nitrogen, available phosphorus and exchangeable potassium. Representative soil samples collected from treeless plots and from a contiguous natural forest were also subjected to nutrient analysis for comparison. Total nitrogen was determined by Auto N digestion and distillation method. Available phosphorus under each treatment at each depth of soil was determined by reduced molybdate blue colour method (Watanabe and Olsen method). Available K using neutral normal ammonium acetate method (AOAC, 1995).

3.7. Understorey photosynthetically active radiation (PAR)

Understorey measurement of PAR was undertaken in the treatment plots from 8 am to 4 pm by using line quantum sensor installed in between the inter-row space such that they are at the centre of the plot at a height of 0.7m from the ground level. PAR was monitored from all the intercropped plots. A battery powered data logger (LI 1400, LI COR Inc.) was used to integrate the mean photosynthetic photo flux density (moles per hour) at hourly intervals. From this, the mean daily PAR and mid-day understorey PAR were calculated (Plate 4).

3.8. Root distribution study

One random tree was selected from each of the treatment plots for root distribution study. Each tree from replication plots was subjected root distribution studies following logarithmic spiral trenching method (Tomlinson *et al.*, 1998). The crown radius of the selected trees was measured by projecting the crown edges to the ground.

Plate 4. Photosynthetically Active Radiation (PAR) measurement in 20-year-old *Acacia mangium* subjected to stand thinning at Thiruvazhamkunnu, Kerala, India

A. Line quantum sensor used for estimating understorey PAR and B. Estimation of PAR in field

Roots of the selected tree were partially excavated by trench whose dimension was determined using the following formulae:

$$x = 1.5\,(d)$$

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

$$z = xe^{y\theta}$$

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

The trajectory of the trench was laid down on the field using plastic ropes by calculating the distance 'x' on the north side from the tree which will be the origin and further extension is done in the spiral clockwise direction with θ taking values 0°, 22.5°, 45°, 67.5°, 90°, 112.5°, 135°, 157.5° and 180° (Plate 5). The trench was dug to a depth of 60 cm and a breadth of 60 cm and care was taken so that the sides remain intact. Severed roots (living) on the internal and external trench walls were counted by placing a 50 cm x 50 cm quadrat (subdivided into 10 cm depth intervals). Roots were classified into less than 2mm, 2 to 5mm, 5 mm to 2 cm and >2cm diameter classes at the time of counting by placing the quadrates at fixed distances from the trunk. Root counts were converted into rooting intensity (number of roots m^{-2}) (Bohm, 1979).

3.9. Wood physical properties

The wood samples from the felled tree corresponding to various thinning treatments were used for studying the wood properties. IS 1708: 1986 was followed for sample preparation (ISI, 1986).

3.9.1. Basic density (g cm^{-3})

The green volume of the wood sample was estimated by using the immersion method. These samples were also oven dried at 102^{0}C ± 1^{0}C (until constant weight) for the determination of oven dry weight using electronic weighing balance. The basic density (standard specific gravity) of sample was determined using the formula,

Basic density (g cm^{-3}) = (oven dry weight/ green volume)

3.9.2. Radial and tangential shrinkage (%)

Wood samples were collected from each of experimental plots for radial and tangential shrinkage observation. A test specimen for radial or tangential shrinkage shall be 2 x 2 x 5 cm in length. These blocks were marked at radial and tangential positions for assessing shrinkage. The samples were then measured at these positions for finding the radial and tangential length using a digital vernier calliper. Subsequent measurements were made at the same positions for assessing the radial and tangential shrinkage at air dry (12% moisture content) and oven dry conditions 102±1°C as per IS 1708 (part 4):1986 (ISI, 1986). Radial and tangential shrinkage was calculated using the formula:

$$Radial\ or\ Tangential\ shrinkage\ (\%) = \frac{L_g - L_a}{L_g} \times 100$$

where Lg – Length of the specimen along the radial or tangential plane at green condition (mm) and L_a – Length of the specimen along the radial or tangential plane at air-dry condition (mm).

3.9.3. Volumetric shrinkage (%)

The test specimen of 2 x 2 x 6 cm in length were collected from the wooden disc. The specimen was weighed initially (usually green) correct to 0.001 g and the volume was determined by immersion method correct to 0.01 cc. A suitable container that is half filled with water, was kept on the pan of a weighing balance and weighed correct to 0.001 g.

Plate 5. Logarithmic spiral trenching for root distribution assessment in 20-year-old *Acacia mangium* subjected to stand thinning at Thiruvazhamkunnu, Kerala, India

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

The specimen was completely dipped in water by means of a needle and weighed again. Care was taken that no air bubble sticks to the specimen and the specimen were not touching sides of the vessel. The difference between the two readings gives the volume of the specimen. The specimen was taken out from water wiped with a dry cloth and end-coated by immersion in hot paraffin and allowed to air-season under room conditions which were weighed periodically until the moisture content of about 12 percent. The volume was again determined by the above method. The specimen was kept in an oven at 103±2°C until an approximately constant weight was reached. After oven-drying, the specimen was again weighed and, while still warm, it was immersed in the hot paraffin wax bath, care was taken to remove it quickly to ensure only a thin coating. The volume of the paraffin-coated specimen was determined by immersion as before.

$$Volumetric\ shrinkage_{(initial\ condition\ to\ dry\ condition)} = \frac{V_1 - V_r}{V_1} \times 100$$

where V_1 = volume in cc at initial condition (usually green) and V_r = volume in cc at the initial required dry condition at r percent moisture content (usually 12 percent moisture content or oven dry condition).

3.9.4. Moisture content (%)

The moisture content of wood samples was estimated in accordance with ISO 3130. Test specimens were weighted to obtain the green weight (by soaking the specimen in the water to regain the moisture) and then air dried till the weight became constant and the samples showed no further decrease in the volume. The samples were then oven-dried at temperature 102±1°C to obtain the dry weight. The moisture percent of each specimen was calculated using the formula:

$$Moisture\ content\ (\%) = \frac{Wr - Wo}{Wo} \times 100$$

where W_0 = weight in g at initial condition (usually green) and W_r = weight in g at the initial required dry condition at r percent moisture content (usually 12 percent moisture content or oven dry condition).

3.9.5. Heartwood to sapwood ratio

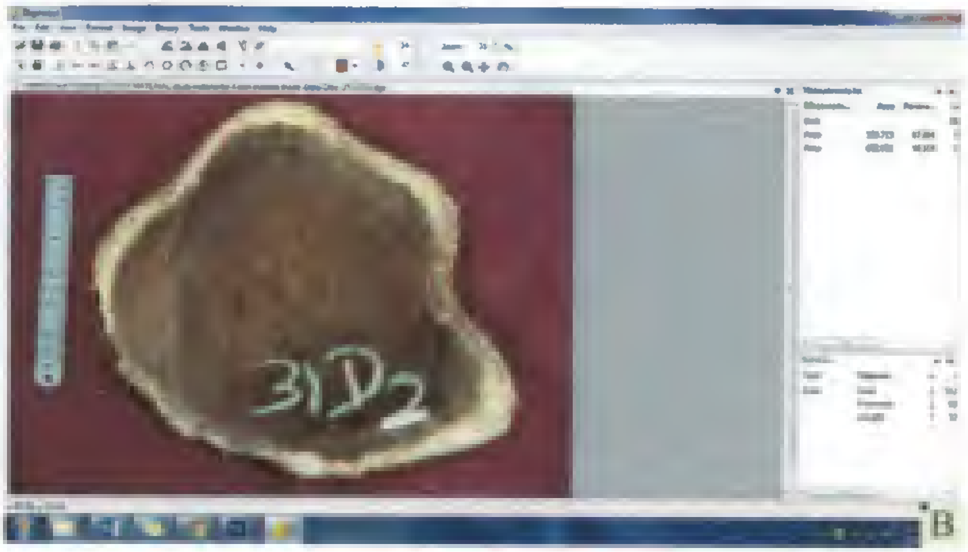
Since *A. mangium* shows a predominant distinction between heartwood and sapwood it was easy for demarcation between heartwood and sapwood. .Heartwood - Sapwood ratio of all 32 tree samples was estimated using the digimizer software (Version 4.6.1) (Plate 6). Stem cross-sectional samples (disks) were collected at 0.15m, breast height level (1.37 m from ground level) and at 50% commercial bole height and at bole height for all trees that were felled for biomass estimation.

3.10. Statistical analysis

The growth data, biomass, photochemical and soil data were analysed using statistical software SPSS V.22.0. Duncans Multiple Range Test was used to test the differences among treatment means. Wood physical properties were analysed in the same manner and heartwood percentage, sapwood percentage and heartwood to sapwood ratio along different axial position were subject to two-way ANOVA.

Plate 6. Heartwood to Sapwood ratio estimation from stem discs of 20-year-old *Acacia mangium* subjected to stand thinning at Thiruvazhamkunnu, Kerala, India

T_4-No thinning (Control) (Retaining 1600 trees ha^{-1}); T_1-Removal of one third growing stock by eliminating every third row (Retaining 1066 trees ha^{-1}); T_2-Removal of half growing stock by eliminating alternate diagonal row (Retaining 800 trees ha^{-1}); T_3-Removal of two-third growing stock by eliminating alternate diagonal row and alternate in each diagonal row (Retaining 533 trees ha^{-1})



A. Stem disc at DBH level across different thinning intensity and B. Screenshot of Diginizer 4.6.1

Results

IV. RESULTS

Field works associated with thinning experiment on 20-year-old *A. mangium* such as tree growth measurements, volume, biomass, soil properties, understorey PAR and wood properties were completed and the data are tabulated. The pertinent results are presented in this chapter.

4.1. Radial growth

The diameter measurement at various height levels is tabulated in table 2 and figure 1. There was significant variation in the diameter at breast height ($p < 0.002$) and at bole height ($p < 0.032$) among the different thinning treatments. The maximum radial growth was in two-third thinned plot of 30.68 cm. However, the diameter of trees in the heavily thinned plot (566 trees ha^{-1}) was on par with that of the medium thinned plot (800 trees ha^{-1}). This trend was repeated in the diameter at bole height too.

Table 2. Growth parameters of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Height (m)	Commercial bole height (m)	DBH (cm)	Diameter at bole height (m)
Unthinned	21.77 (2.18)	11.90 (0.79)	19.32^{c} (4.61)	15.40^{b} (2.42)
One-third thinning	22.19 (2.55)	13.75 (3.01)	24.45^{b} (1.60)	17.00^{ab} (1.30)
Half thinning	23.23 (3.20)	13.58 (3.79)	27.26^{ab} (1.41)	19.72^{a} (2.95)
Two-third thinning	22.07 (1.61)	11.69 (1.74)	30.68^{a} (1.80)	20.43^{a} (2.82)
p-value	ns	ns	0.002	0.032

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

4.2. Height growth

Total tree height ranged from 21.77 to 23.23 m and bole height ranged from 11.69 to 13.75 m. However, there was no perceptible difference in height measurements in response to various thinning treatments was observed (Table 2 and Figure 2).

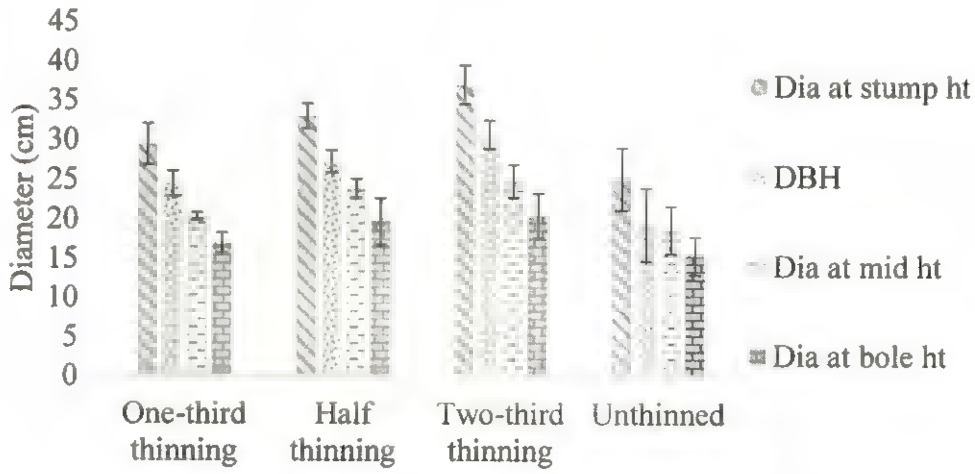


Figure 1. Diameter at different heights of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

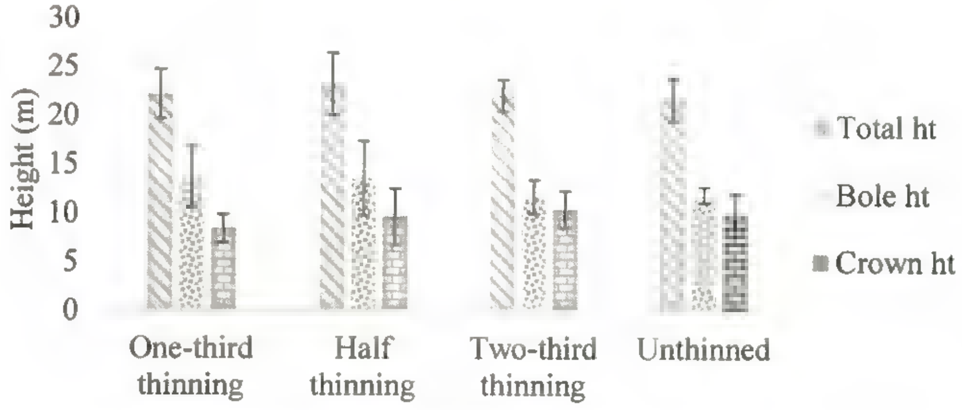


Figure 2. Height, bole height and crown height of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

4.3. Crown parameters

Table 3 shows the crown diameter and crown height responses after 13 years of stand thinning where the crown diameter ranged from 3.87 to 5.52 m. Despite the lack of significant trends, it appears that the crown diameter and crown height increased with increase thinning intensities. The other crown growth parameters like crown ratio, crown form index, crown thickness ratio and crown spread ratio did not show any statistically significant difference between the thinning treatments after 13 years thinning.

Table 3. Crown parameters of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Crown diameter (m)	Crown length (m)	Crown ratio	Crown form index	Crown thickness index	Crown spread ratio
Unthinned	3.87 (1.09)	9.88 (2.17)	0.384 (0.078)	2.16 (0.57)	0.489 (0.129)	0.181 (0.016)
One-third thinning	4.03 (0.72)	8.44 (1.41)	0.418 (0.124)	2.10 (0.57)	0.498 (0.110)	0.200 (0.035)
Half thinning	4.66 (1.19)	9.65 (2.88)	0.470 (0.078)	1.88 (0.31)	0.544 (0.102)	0.251 (0.027)
Two-third thinning	5.52 (0.33)	10.39 (1.92)	0.450 (0.063)	2.66 (0.81)	0.401 (0.113)	0.179 (0.053)
p-value	ns	ns	ns	ns	ns	ns

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

4.4. Basal area and stand basal area

The mean basal area per tree ranged from 0.031 to 0.075 m^2 with distinct variation between thinning treatments (Table 4). There was a clear increase in mean tree basal area with an increase in thinning intensity even after 13 years of stand thinning. For instance, the lowest mean tree basal area was observed for the unthinned stand (0.031m^2) while, the heavily thinned stands showed as much as 2.5 fold increase (0.075 m^2) as compared to unthinned stand. Stand basal area did not show significant change across the thinning treatments after 13 years of thinning. Nevertheless, a general declining trend in stand basal area has been observed with increasing intensity of thinning.

Table 4. Basal area and stand basal area of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Basal area (m^2)	Stand basal area ($m^2\ ha^{-1}$)
Unthinned	0.031^c (0.0130	30.10 (13.15)
One-third thinning	0.047^b (0.006)	37.40 (5.03)
Half thinning	0.059^b (0.006)	29.45 (2.92)
Two-third thinning	0.075^a (0.008)	26.86 (3.00)
p-value	0.001	ns

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

4.5. Stem taper

The thinning intensities at different levels did not show any significant influence on the taper ratio. The rate of stem taper showed significant response to stand thinning ($p < 0.007$) which increased with increase in thinning intensities (Table 5). The rate of taper was maximum for heavily thinned plots (2.38 cm m^{-1}) and minimum for the unthinned plots (1.20 cm m^{-1}).

4.6. Volume

The bole volume (m^3) and tree total volume (m^3) estimated for the trees in different thinning intensities are tabulated in table 6 and figure 3. The tree total volume ($p < 0.008$) as well as bole volume ($p < 0.038$) showed significant variation similar to the diameter at breast height (cm) across different thinning treatments. The maximum total tree volume (1.16 m^3) was in two-third thinned plot (533 trees ha^{-1}) while bole volume (0.60 m^3) was maximum in half thinned plot (800 trees ha^{-1}). Interestingly, the mean total tree volume in the heavily thinned plot showed 90.16% increase as compared to the unthinned plot after 13 years of thinning. Similar was the case with bole volume in the heavily thinned stand showed 78.12 % increase as compared to the unthinned plot.

Table 5. Taper ratio and rate of taper for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Taper ratios			Rate of taper (cm m^{-1})
	G_2/G_1	G_3/G_1	G_4/G_1	
Unthinned	0.82 (0.02)	0.73 (0.02)	0.62 (0.06)	1.20^{c} (0.27)
One-third thinning	0.83 (0.02)	0.72 (0.08)	0.58 (0.06)	1.77^{b} (0.27)
Half thinning	0.83 (0.01)	0.73 (0.04)	0.60 (0.09)	1.82^{b} (0.36)
Two-third thinning	0.83 (0.04)	0.67 (0.06)	0.55 (0.03)	2.38^{a} (0.34)
p- value	ns	ns	ns	0.007

(Values in parenthesis are standard deviation)
(Values with the same superscripts do not differ significantly within a column)
G1, G2, G3 and G4 represent girth at 0.15m, 1.37m, girth at midpoint and girth at bole height respectively

Table 6. Tree total volume and bole volume of 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Bole volume (m^3)	Tree total volume (m^3)
Unthinned	0.32^{b} (0.11)	0.61^{c} (0.26)
One-third thinning	0.46^{ab} (0.10)	0.74^{bc} (0.08)
Half thinning	0.60^{a} (0.14)	1.03^{ab} (0.14)
Two-third thinning	0.57^{a} (0.05)	1.16^{a} (0.20)
p-value	0.038	0.008

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

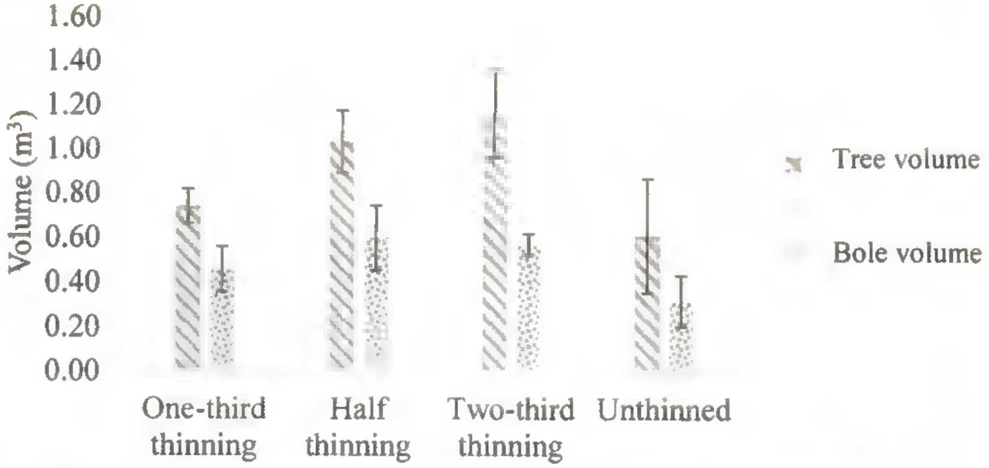


Figure 3. Mean tree total volume and bole volume of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

4.7. Stand volume

Contrary to the mean tree volume, the volume at stand level could not bring stronger trends in response to thinning (Table 7). However, both tree volume and bole volume at stand level showed marked variation across various thinning intensities. The stand tree volume ranged from 595.76 m^3 ha^{-1} (heavily thinned) to 731.92 m^3 ha^{-1} (unthinned). The corresponding value for stand bole volume was 389.30 m^3 ha^{-1} (unthinned) and 310.54 (heavily thinned) respectively. MAI in stand volume also followed a similar trend with insignificant difference among the various thinning intensities.

4.8. Biomass production

The long term effect of stand thinning on biomass production for 20-year-old *A. mangium* has been shown in table 8. Profound variation in aboveground biomass (AGB) ($p < 0.000$), belowground biomass (BGB) ($p < 0.000$) and total biomass production ($p < 0.000$) was observed between the thinning treatments after 13 years of stand thinning.

Table 7. Stand volume and MAI volume of 20-year-old *Acacia mangium* after 13 years after stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Stand bole volume (m^3 ha^{-1})	Stand volume (m^3 ha^{-1})	Stand volume MAI (m^3 $ha^{-1}yr^{-1}$)
Unthinned	389.30 (129.53)	731.92 (289.77)	36.60 (14.49)
One-third thinning	522.64 (164.38)	832.57 (178.19)	41.63 (8.91)
Half thinning	404.89 (144.02)	678.94 (121.60)	33.95 (6.08)
Two-third thinning	310.54 (37.79)	595.76 (41.76)	29.79 (2.09)
p-value	ns	ns	ns

(Values in parenthesis are standard deviation)

The maximum AGB and BGB was recorded in the two-third thinned (533 trees ha^{-1}) which showed a constant decrease with a reduction in the thinning intensities. The same pattern was reflected in the total tree biomass production per tree. In fact, the two-third thinned stands showed 1.4 fold increase in total aboveground biomass compared to unthinned stand. Probably the change in belowground biomass with thinning is considerably similar as compared to aboveground biomass. For example, the increase in belowground biomass in the heavily thinned plot was as much as 5.4 fold as compared to unthinned stand. Even the difference was enormous between the two-third and half thinned stand (132.62 % higher in two-third thinned compared to half thinned). On the contrary, the AGB percentage (percentage of total tree biomass) was minimum in the two-third thinned plot (74.04%) and other thinning intensities were on par among themselves as well as with the unthinned plot (1600 trees ha^{-1}). Interestingly the BGB percentage showed an inverse trend with maximum attached to two-third thinned plot (25.9%) and the unthinned plot had the lowest (11.21 %) (Figure 4). Root–shoot ratios varied considerably among the various thinning intensities. Highest ratio (0.35) was observed in the two-third thinning treatment. The root shoot ratio in other thinning treatments were on par with each other (Table 8).

Table 8. Mean tree biomass accumulation of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Total AGB (kg tree^{-1})	Total BGB (kg tree^{-1})	Total biomass (kg tree^{-1})	AGB (%)	BGB (%)	Root shoot ratio
Unthinned	266.54^{d} (38.83)	35.11^{c} (19.79)	298.76^{c} (66.78)	88.79^{a} (3.67)	11.21^{b} (3.67)	0.13^{b} (0.05)
One-third thinning	368.45^{c} (48.64)	72.71^{b} (17.38)	429.49^{c} (63.93)	83.11^{a} (2.56)	16.89^{b} (2.56)	0.20^{b} (0.04)
Half thinning	551.40^{b} (36.14)	96.81^{b} (20.08)	664.07^{b} (31.76)	85.47^{a} (2.61)	14.53^{b} (2.61)	0.17^{b} (0.04)
Two-third thinning	663.67^{a} (121.03)	225.20^{a} (20.62)	878.99^{a} (166.14)	74.07^{b} (2.47)	25.93^{a} (2.47)	0.35^{a} (0.04)
p-value	0.000	0.000	0.000	0.006	0.006	0.005

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

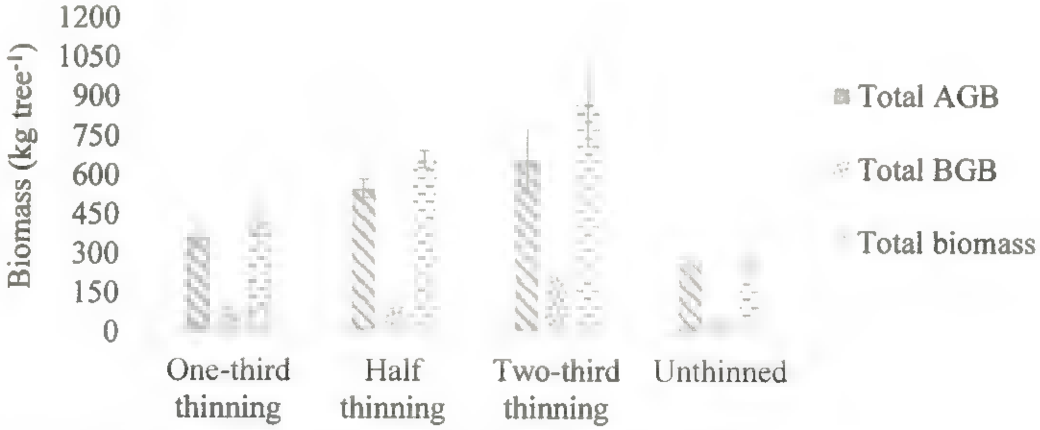


Figure 4. Mean tree total biomass accumulation of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

4.8.1. Biomass partitioning

The aboveground biomass estimation was done by partitioning the entire biomass into different components and values are tabulated in table 9. Biomass partitioning in terms of stemwood, branchwood, twigs and foliage for different thinning intensities showed tremendous variations.

For all treatments, the stemwood accounted for the bulk of the above ground biomass (80-85%) followed by branchwood (10-13%), foliage (1.5-3.5%) and twigs (1.5-3.5%). Only stemwood ($p < 0.000$) and twigs ($p < 0.015$) did express statistical significance between the treatments. In the case of stemwood, the highest production (541.58 kg tree^{-1}) was in the two-third thinned plot (533 trees ha^{-1}) but it was on par with that of (461.47 kg tree^{-1}) half thinned plot (800 trees ha^{-1}). For all treatments, the stemwood accounted for the bulk of the above ground biomass (80-85%) followed by branchwood (10-13%), foliage (1.5-3.5%) and twigs (1.5-3.5%).

A similar tendency was also seen in twigs where the highest was in the two-third thinned plot (533 trees ha^{-1}) with a deviation. The twigs biomass of half- thinned plot (800 trees ha^{-1}) was on par with that of one-third thinned plot (1066 trees ha^{-1}). Branchwood and foliage biomass did vary across treatments but the branchwood and foliage biomass in two-third thinned plots were 185.49% and 74.27% higher compared to unthinned plots.

4.8.2. Stand level biomass accumulation

The biomass production on stand level is a function of stand density. As a result, considerable variation in the stand biomass accumulation has been observed in the study (Table 10, Figure 5 and 6). Total stand biomass accumulation trend was completely different from that of the mean tree total biomass accumulation.

Table 9. Partitioning of biomass in 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Stem		Branch		Twig		Foliage		Root	
	kg tree^{-1}	%	kg tree^{-1}	%	kg tree^{-1}	%	kg tree^{-1}	%	kg tree^{-1}	%
Unthinned	218.16^{b} (49.92)	70.50 (8.58)	31.03 (16.09)	12.61 (7.35)	8.68^{b} (3.91)	2.94 (1.87)	8.67 (3.29)	2.75 (1.54)	35.11^{c} (19.79)	11.21 (3.67)
One-third thinning	310.31^{b} (35.53)	69.94 (3.01)	40.47 (11.08)	9.64 (1.92)	7.82^{b} (2.38)	1.59 (0.23)	9.84 (3.94)	1.94 (0.60)	72.71^{b} (17.38)	16.89 (2.56)
Half thinning	461.47^{a} (44.29)	72.38 (8.01)	69.56 (40.69)	10.13 (6.91)	10.27^{b} (1.64)	1.44 (0.15)	10.09 (3.93)	1.53 (0.64)	96.81^{b} (20.08)	14.53 (2.61)
Two-third thinning	541.58^{a} (91.06)	60.49 (5.44)	88.59 (49.48)	10.12 (5.12)	18.39^{a} (8.99)	2.04 (1.56)	15.11 (7.55)	1.42 (0.62)	225.20^{a} (20.62)	25.93 (2.47)
p-value	0.00	ns	ns	ns	0.01	ns	ns	ns	0.00	0.006

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

The maximum stand level AGB accumulation of 291.81 Mg ha^{-1} was in the one-third thinned stand and the minimum of 237.59 Mg ha^{-1} was in the heavily thinned stand. Statistically, there was no significance between the treatments in case of stand level AGB but in the case of stand level BGB, there was a statistically significant difference. The two-third thinned plot showed the maximum stand level BGB of 38.94 Mg ha^{-1} in actual stand density based calculation respectively. The stand level BGB (Mg ha^{-1}) had a similar trend to that of the tree level BGB (kg ha^{-1}). The stand level total biomass did not show any statistically significant difference between the thinning treatments. The stand MAI did not vary statistically across thinning intensities. However, the stand MAI ranged from 14.58 to 17.01 Mg ha^{-1}yr^{-1} with a distinct decreasing trend with an increase in thinning intensity.

Table 10. Total stand biomass accumulation and MAI in 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Aboveground biomass (Mg ha^{-1})	Belowground biomass (Mg ha^{-1})	Total biomass (Mg ha^{-1})	Stand MAI (Mg ha^{-1} yr^{-1})
Unthinned	260.14 (37.90)	16.55^{c} (9.33)	291.59 (65.18)	14.58 (3.26)
One-third thinning	291.81 (38.52)	27.82^{b} (6.65)	340.16 (50.63)	17.01 (2.53)
Half thinning	275.70 (18.07)	23.38^{c} (4.85)	332.03 (15.88)	16.60 (0.79)
Two-third thinning	237.59 (43.33)	38.94^{a} (3.56)	314.68 (59.48)	15.74 (2.97)
p- value	ns	0.004	ns	ns

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

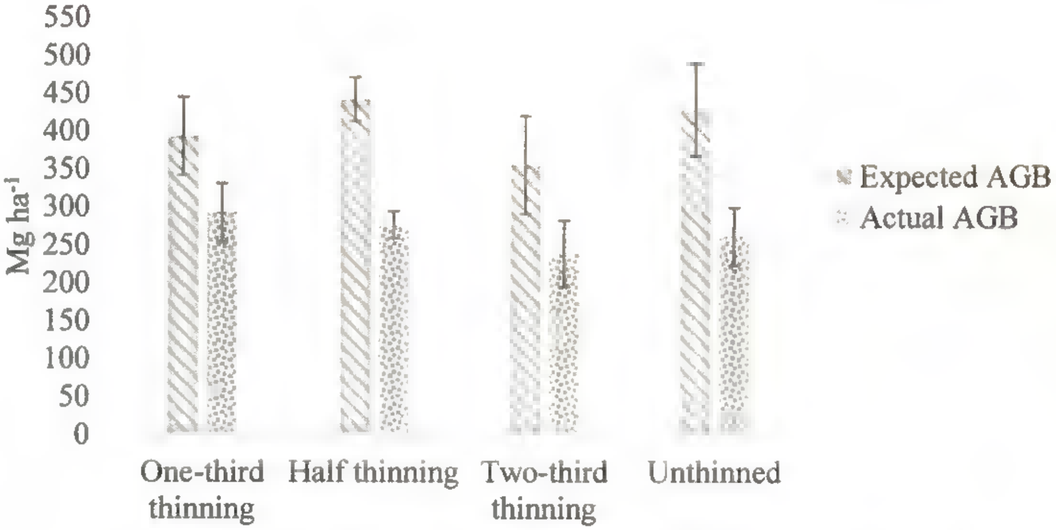


Figure 5. Aboveground Stand biomass accumulation of 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

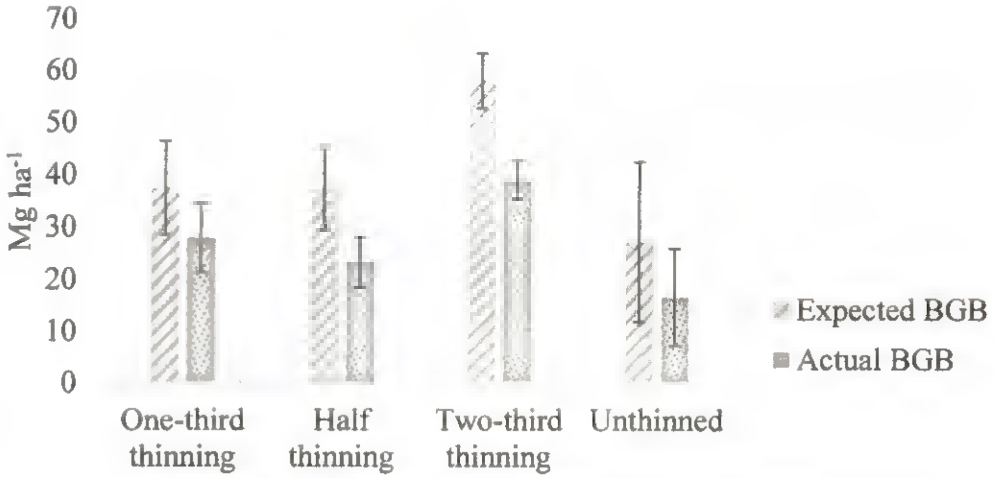


Figure 6. Belowground stand biomass accumulation of 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

4.9. Allometric equations

Allometric relationships were attempted in the present study linking aboveground tree biomass, total aboveground biomass carbon sequestration, total volume and bole volume with DBH and/or total height, bole height of the trees which gave reasonably good predictions (Table 11). Strong linear trends were observed for tree aboveground biomass and DBH. The introduction of the second variable (tree height) did not improve predictability of biomass equations considerably as evidenced by their relatively lower R^2 values compared to DBH alone as the independent variable. In the case of belowground biomass, diameter at stump height was giving better prediction than that of DBH. Further inclusion of crown width as a variable didn't increase the predictability of the equation. Interestingly, tree total volume and bole volume yielded poor prediction for DBH-alone as a predictor variable. However, the total volume and bole volume predictability was significantly improved for a quadratic model with the introduction of height as the second variable. Among the models tried, simple linear and quadratic equations showed better fit with reasonably high R^2 values and lower furnival index value.

4.10. Carbon (C) sequestration

4.10.1. Carbon concentration in different components

The carbon concentration in different tissue fractions of 20-year-old *A. mangium* is presented in table 12. The carbon concentration did not vary in different components. However, the root had the highest carbon concentration followed by foliage, stemwood, twigs and branchwood. The whole the average carbon content was 45.95%.

Table 12. The carbon concentration in different biomass fractions of 20-year-old *Acacia mangium* at Thiruvazhamkunnu, Kerala, India.

Biomass fraction	Stem	Branch	Twig	Foliage	Root
Carbon content (%)	46.133 (1.25)	43.433 (5.58)	44.000 (0.66)	47.900 (0.50)	49.267 (0.42)

Table 11. Allometric equations developed for 20-year-old *Acacia mangium* at Thiruvazhamkunnu, Kerala, India.

Dependent Variable	Allometric equations	Coefficients					R^2	MSE	FI
		a	b	c	d	e			
Aboveground biomass per tree (AGBPT) (kg)	$Y^{0.5} = a + b D$	1.46^{ns}	0.73^{**}				0.91	1.30	43.40
	$\text{Ln } Y = a + b \ln D$	-0.18^{ns}	1.91^{**}				0.92	0.01	41.01
	$Y^{0.5} = a + bD + cH$	3.203^{ns}	0.760^{**}	-0.108^{ns}			0.92	1.28	43.00
	$Y = a + bD$	-331.53^{**}	29.49^{**}				0.92	1880.80	43.37
	$Y = a + bD + cD^2$	-416.20^{ns}	36.22^{ns}	-0.13^{ns}			0.92	1960.65	44.28
	$Y = a + bD + cH$	-246.58^{**}	30.73^{**}	-5.24^{ns}			0.93	1762.81	41.99
Belowground biomass per tree (BGBPT) (kg)	$Y = a + bD + cC_W$	-200.42^{*}	9.07^{*}	18.32^{ns}			0.72	1988.90	44.60
	$Y = a + bD_S$	-256.64^{*}	11.85^{**}				0.79	1326.18	36.42
	$Y = a + bD + cD_S$	-270.38^{*}	16.39^{*}	-5.00^{ns}			0.81	1396.76	37.37
	$Y = a + bD + cC_W + dD_S$	-269.19^{**}	-4.42^{ns}	7.04^{ns}	14.88^{ns}		0.81	1526.27	39.07
Total tree biomass (TTB) (kg)	$Y = a + bGSH + cC_W + dH + eGBH$	-241.34^{ns}	-25.71^{*}	-16.77^{ns}	42.95^{ns}	31.67^{**}	0.97	5601.42	74.84
	$Y = a + bGSH + cH + dGBH$	-325.19^{ns}	-25.62^{*}	-12.30^{ns}	33.37^{**}	-	0.96	6448.23	80.30
	$Y = a + bGSH + dGBH$	-570.88^{**}	-22.80^{*}	30.74^{**}	-	-	0.95	6835.13	82.67
Total volume per tree (m^3)	$Y = a + bH + cD^2$	1.08^{**}	-0.05^{*}	-0.0015^{*}			0.89	0.001	0.03
Bole volume per tree (m^3)	$Y = a + bH + cD$	-1.93^{*}	0.10^{*}	0.03^{**}			0.98	0.004	0.06
	$Y = a + bD^2H + cH + dD^2$	2.25^{**}	0.00022^{ns}	-0.11^{*}	-0.004^{*}		0.80	0.46	0.68

ns = not significant at 0.05 level; * significant at 0.05 level; ** significant at 0.01 level

GSH = girth at stump height; GBH = girth at breast height D = diameter at breast height, D_S = diameter at stump height, C_W= crown height, H = tree height, MSE = mean squared error and FI = Furnival index

4.10.2 Mean tree carbon sequestration

Carbon sequestration on a per tree basis was computed (Table 13) and the highest total value was recorded for two-third thinned plot (405.62 kg C tree^{-1}) and the minimum was for the unthinned plot (137.87 kg C tree^{-1}). Carbon accretion trends for various tissue fraction followed a general pattern of increase with increasing thinning intensity. The changes were more appreciated for stem, twigs and roots. Invariably unthinned treatment showed the lowest C stock in all the tissue fractions. Incidentally, the stemwood carbon sequestration was 2.5 times higher in the two-third thinned plots as compared with unthinned plots. Despite the apparent increasing trend with thinning intensities, the changes were not significant for the branchwood and foliage.

4.10.3 Stand level biomass carbon sequestration

Biomass C sequestration of 20-year-old *A. mangium* at stand level which was subjected to thinning at different intensities is furnished in table 14. Similar to stand level biomass calculation, C sequestration at stand level among different components was calculated both at expected stand level and actual stand level which reveals the real-time C accumulation potential of the stand. The mean carbon sequestration potential BGB ranges from 27.13 to 57.98 Mg C ha^{-1}. There was a substantial difference in the belowground carbon sequestration due to thinning even after 13 years of stand thinning. Unfortunately, thinning did not produce any statistically significant difference when computed for aboveground C sequestration as well as the total stand level across treatments.

4.10.4. Soil carbon sequestration

Total soil carbon stock up to 1m soil depth for different thinning regimes along with a control and natural vegetation are presented in table 15. The maximum SOC was recorded in the half thinned plot (42.38 Mg ha^{-1}). The treeless plot was had the lowest SOC (21.85 Mg ha^{-1}) which was not on par within any of thinning treatment.

Table 13. Partitioning of biomass carbon stock in different fractions of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Biomass fractions (kg C tree^{-1})					
	Stem	Branch	Twig	Foliage	Root	Total(kg C tree^{-1})
Unthinned	100.64^{b} (23.03)	13.48 (6.99)	3.82^{b} (1.72)	4.15 (1.58)	12.97^{b} (11.75)	137.87^{c} (30.82)
One-third thinning	143.16^{b} (16.39)	17.58 (4.81)	3.44^{b} (1.05)	4.72 (1.89)	26.86^{b} (19.23)	198.20^{c} (29.50)
Half thinning	212.89^{a} (20.43)	30.21 (17.67)	4.52^{b} (0.72)	4.84 (1.88)	35.77^{b} (25.17)	306.45^{b} (14.65)
Two-third thinning	249.85^{a} (42.01)	38.47 (21.49)	8.09^{a} (3.95)	7.24 (3.62)	83.20^{a} (56.08)	405.62^{a} (76.67)
p- value	0.000	ns	0.015	ns	0.006	0.000

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

Table 14. Stand level biomass carbon stock in 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Stand level biomass C sequestration (Mg C ha^{-1})					
	Stemwood	Branchwood	Twig	Foliage	Root	Total biomass
Unthinned	98.23 (22.48)	13.15 (6.82)	3.73 (1.68)	4.05 (1.54)	16.55^{c} (9.33)	133.99 (29.95)
One-third thinning	113.38 (12.98)	13.92 (3.81)	2.72 (0.83)	3.73 (1.49)	27.82^{bc} (6.65)	156.30 (23.26)
Half thinning	106.45 (10.22)	15.11 (8.84)	2.26 (0.36)	2.42 (0.94)	23.38^{b} (4.85)	152.57 (7.30)
Two-third thinning	89.45 (15.04)	13.77 (7.69)	2.90 (1.42)	2.59 (1.30)	38.94^{a} (3.56)	144.59 (27.33)
p-value	ns	ns	ns	ns	0.004	ns

(Values in parenthesis are standard deviation)

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

Table 15. Total soil organic carbon (SOC) content in 1m soil column for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Total (Mg ha^{-1})
Treeless plot	21.85^{b} (0.86)
Natural vegetation	31.50^{ab} (0.58)
Unthinned	35.15^{ab} (4.82)
One-third thinning	31.12^{ab} (10.38)
Half thinning	42.38^{a} (11.28)
Two-third thinning	40.78^{a} (12.58)
p-value	0.042

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

Distinctly, the treeless control soils showed the lowest soil carbon stock (21.85 Mg ha^{-1}) while the corresponding value was considerably higher for all wooded treatments. Interestingly, the average soil carbon stock for *A. mangium* plots was higher than the continuous natural vegetation (except for one-third thinned stand which was on par). In general, the high thinned stands viz. half thinned and two-third thinned showed the highest soil carbon stock of 42.38 and 40.78 Mg ha^{-1} respectively.

4.11. Soil properties

4.11.1. Soil bulk density

The bulk density of the soil being physical parameter did not vary between the thinning treatments. The mean soil bulk density ranged from 1.060 to 1.275 g cm^{-3} (Table 16). The soil bulk density changes were marginal across soil depth and thinning intensities. The changes were not appreciable between the open soils and soils under *A. mangium* even after 20-years of stand establishment.

Table 16. Variation in soil bulk density as the effect of stand thinning for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Soil bulk density ($g\ cm^{-3}$)				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	1.169 (0.000)	1.225 (0.000)	1.272 (0.000)	1.157 (0.000)	1.214 (0.000)
Unthinned	1.125 (0.190)	1.177 (0.084)	1.174 (0.074)	1.191 (0.075)	1.225 (0.070)
One-third thinning	1.206 (0.055)	1.226 (0.029)	1.151 (0.085)	1.102 (0.137)	1.072 (0.213)
Half thinning	1.275 (0.066)	1.146 (0.213)	1.223 (0.018)	1.141 (0.042)	1.122 (0.102)
Two-third thinning	1.155 (0.101)	1.188 (0.098)	1.224 (0.162)	1.222 (0.061)	1.168 (0.038)
Natural vegetation	1.120 (0.000)	1.070 (0.000)	1.060 (0.000)	1.070 (0.000)	1.080 (0.000)
p - value	ns	ns	ns	ns	ns

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

4.11.2. Soil pH

The soil pH was varying across thinning treatments and was statistically significant too (Table 17). However, there appears no trend across treatments and across soil depth.

4.11.3. Soil carbon and nutrient status

Soil samples collected from the field was used to assess the influence of stand thinning on the soil organic carbon, total nitrogen, available phosphorus, and exchangeable potassium across one metre depth. The result of the soil nutrient assessments is given below.

Table 17. Variation in soil pH as the effect of stand thinning for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Soil pH				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	4.16^{b} (0.06)	4.76^{a} (0.04)	4.85^{b} (0.02)	4.75^{b} (0.05)	4.89^{a} (0.04)
Unthinned	4.15^{b} (0.12)	4.48^{bc} (0.04)	4.67^{c} (0.03)	5.12^{a} (0.23)	4.52^{b} (0.05)
One-third thinning	4.13^{b} (0.06)	4.36^{cd} (0.00)	4.48^{d} (0.12)	4.70^{bc} (0.17)	4.39^{b} (0.21)
Half thinning	4.28^{b} (0.16)	4.52^{b} (0.11)	4.66^{c} (0.08)	4.78^{b} (0.10)	4.40^{b} (0.27)
Two-third thinning	4.10^{b} (0.01)	4.25^{d} (0.12)	4.37^{d} (0.10)	4.47^{c} (0.06)	4.09^{c} (0.07)
Natural vegetation	4.47^{a} (0.02)	4.52^{b} (0.12)	5.22^{a} (0.03)	5.11^{a} (0.02)	4.41^{b} (0.12)
p - value	0.008	0.000	0.000	0.001	0.002

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

4.11.3.1. Soil organic carbon (mg g^{-1})

The soil organic carbon concentration showed significant changes for 0-20 cm and 20-40 cm depth (Table 18). However, all thinning intensities were having values more or less on par but varying distinct from the treeless plot. As expected the soil organic carbon decreased with increase in soil depth. Interestingly, the natural vegetation also had similar soil carbon content with that of 20- year-old *A. mangium* stand. Yet another observation is the drastic reduction in the carbon concentration in the treeless plot at deeper soil as compared to other treatment plots. Incidentally, the high thinned stands maintained better carbon concentration at deeper depths (80-100 cm).

Table 18. Depth wise distribution of organic carbon for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Organic carbon (mg g^{-1})				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	18.50^{b} (0.02)	12.63^{c} (0.030)	9.07 (0.037)	3.41 (0.047)	1.64 (0.043)
Unthinned	28.90^{a} (0.11)	23.50^{ab} (0.580)	10.91 (0.464)	7.87 (0.419)	4.25 (0.078)
One-third thinning	27.40^{a} (0.26)	17.43^{bc} (0.596)	11.70 (0.683)	5.34 (0.340)	3.29 (0.157)
Half thinning	28.50^{a} (0.22)	24.79^{a} (0.280)	15.88 (0.783)	10.90 (0.596)	7.83 (0.503)
Two-third thinning	28.60^{a} (0.18)	21.39^{ab} (0.699)	17.43 (0.824)	10.33 (0.246)	7.14 (0.339)
Natural vegetation	28.40^{a} (0.00)	22.23^{ab} (0.014)	13.02 (0.030)	4.73 (0.044)	3.94 (0.046)
p - value	0.000	0.016	ns	ns	ns

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

4.11.3.2. Total nitrogen (mg g^{-1})

The total soil nitrogen was significantly varying across thinning treatments in all depths except for the 40-60 cm (Table 19). As before, the highest nitrogen was in the surface soil (0-20cm) which was decreased with increase in the depth. The highest nitrogen concentration (0-20 cm) was 4.34 mg g^{-1} for the natural vegetation which was on par with the one-third thinned as well as half thinned plot. The treeless plot recorded the minimum nitrogen concentration of 2.73 mg g^{-1}.

4.11.3.3. Available phosphorus (mg g^{-1})

The available phosphorus content across different treatments in five depths is tabulated in table 20. The available phosphorus concentration showed significant variation only for 80-100 cm depth. Thought the soil phosphorus concentration in the *A. mangium* plots in all thinning intensities were on par. They were distinctly higher as compared to open soil and soil under continuous natural vegetation. This trend was visible in almost all soil depths despite their weak significance. On the whole, the available phosphorus content declined with increase in depth.

Table 19. Depth wise distribution of total nitrogen concentration for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Total nitrogen concentration (mg g^{-1})				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	2.73^{c} (0.07)	1.61^{bc} (0.07)	1.96 (0.00)	1.40^{ab} (0.00)	1.33^{a} (0.07)
Unthinned	3.45^{b} (0.41)	2.05^{b} (0.25)	1.82 (0.02)	1.42^{ab} (0.15)	1.05^{b} (0.07)
One-third thinning	4.06^{ab} (0.64)	3.13^{a} (0.32)	1.33 (0.20)	1.59^{a} (0.21)	1.17^{ab} (0.08)
Half thinning	3.66^{ab} (0.11)	2.17^{b} (0.36)	1.33 (0.02)	1.10^{bc} (0.25)	1.10^{b} (0.25)
Two-third thinning	3.48^{b} (0.33)	2.29^{b} (0.70)	1.77 (0.09)	0.37^{d} (0.16)	0.14^{c} (0.00)
Natural vegetation	4.34^{a} (0.14)	1.19^{c} (0.07)	1.91 (0.01)	1.05^{c} (0.07)	0.98^{b} (0.00)
p - value	0.006	0.002	ns	0.000	0.000

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

4.11.3.4. Exchangeable potassium (mg g^{-1})

The exchangeable potassium concentration also declined with soil depth similar to other nutrients (Table 21). Comparing various depths, the potassium content varied significantly only at 80-100 cm depth, with the range of 0.015 to 0.035 mg K g^{-1} soil. However, no discernable pattern was observed between various treatments.

Table 20. Depth wise distribution of available phosphorus concentration for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Available phosphorus (mg g^{-1})				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	0.027 (0.002)	0.014 (0.001)	0.012 (0.001)	0.009 (0.000)	0.007^{c} (0.000)
Unthinned	0.042 (0.014)	0.030 (0.004)	0.026 (0.166)	0.012 (0.017)	0.019^{ab} (0.013)
One-third thinning	0.034 (0.022)	0.044 (0.028)	0.032 (0.010)	0.032 (0.007)	0.029^{a} (0.005)
Half thinning	0.032 (0.024)	0.024 (0.014)	0.024 (0.010)	0.032 (0.025)	0.024^{a} (0.015)
Two-third thinning	0.055 (0.034)	0.023 (0.023)	0.014 (0.001)	0.022 (0.016)	0.027^{a} (0.004)
Natural vegetation	0.019 (0.000)	0.015 (0.000)	0.009 (0.000)	0.005 (0.001)	0.001^{b} (0.001)
p - value	ns	ns	ns	ns	0.013

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

Table 21. Depth wise distribution of exchangeable potassium concentration for 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Exchangeable potassium (mg g^{-1})				
	Soil depth (cm)				
	0-20	20-40	40-60	60-80	80-100
Treeless plot	0.052 (0.007)	0.052 (0.011)	0.022 (0.370)	0.033 (0.005)	0.035^{a} (0.002)
Unthinned	0.053 (0.007)	0.035 (0.031)	0.016 (0.046)	0.016 (0.003)	0.015^{b} (0.000)
One-third thinning	0.058 (0.020)	0.031 (0.007)	0.030 (0.054)	0.020 (0.005)	0.016^{b} (0.007)
Half thinning	0.044 (0.009)	0.026 (0.010)	0.025 (0.048)	0.021 (0.004)	0.023^{ab} (0.010)
Two-third thinning	0.053 (0.016)	0.028 (0.005)	0.026 (0.038)	0.025 (0.006)	0.021^{b} (0.002)
Natural vegetation	0.023 (0.040)	0.033 (0.011)	0.025 (0.800)	0.027 (0.008)	0.026^{ab} (0.010)
p - value	ns	ns	ns	ns	0.03

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

4.12. Root morphometry

Among the four thinning treatments, the maximum rooting depth of 2.25 m was recorded for two-third thinned plot which was at par with (1.93m) half thinned plot (Table 22). The unthinned plot had the lowest rooting depth 1.00 m. The same trend was followed for the tap root length also. The two-third thinned plot has maximum taproot length of 2.00 m and the minimum was in the unthinned plot of 0.857m. A similar trend for the root spread also which differed significantly between thinning treatments. The lowest root spread was for trees in the unthinned plot 0.9 m.

Table 22. Root morphometric parameters of 20-year-old *Acacia mangium* after 13 years after stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Mean root spread (cm)	Total root length (cm)	Tap root length (cm)
Unthinned	90.00^{c} (32.48)	100.33^{c} (9.87)	85.67^{c} (16.44)
One-third thinning	129.00^{c} (22.00)	152.00^{b} (25.24)	128.33^{b} (26.08)
Half thinning	208.08^{b} (51.68)	193.33^{a} (14.05)	171.33^{a} (13.50)
Two-third thinning	284.17^{a} (51.62)	225.00^{a} (10.00)	200.00^{a} (12.29)
p-value	0.000	0.000	0.001

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

4.13. Logarithmic spiral trenching

The logarithmic spiral trench was employed to understand the effect of thinning on the root distribution patterns in 20-year-old *A. mangium*. Information on the spatial spread of roots belonging to size classes viz. <2 mm, 2.0-5 mm, 5 mm – 2.0 cm and > 2.0 cm was collected. Mean rooting intensity in terms of a number of roots per m^2 at a different lateral distance is shown in Table 23, 24, 25, 26 and 27. Results clearly indicate a decrease in rooting intensity with increase in lateral distance from the tree base. However, in the case of unthinned trees and one-third thinned plot, the mean root intensity fluctuated with lateral distance. This pattern was seen in all root class but half thinned and two-third thinned plots did not show this variation.

Table 23. Rooting intensity (number m^{-2}, total roots) of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Distance from base of the tree (m)				
	0.6	1.1	1.6	2.1	2.6
	Root intensity (number m^{-2})				
One-third thinning	328.8	447	223.4	384	509.6
Half thinning	603.8	623.2	446.6	303.6	161.0
Two-third thinning	896.4	659.8	319.8	239.6	209.4
Unthinned	540.8	445.4	517.4	378	-

Table 24. Rooting intensity (number m^{-2}, <2 mm) of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India

Treatments	Distance from base of the tree (m)				
	0.6	1.1	1.6	2.1	2.6
	Root intensity (number m^{-2})				
One-third thinning	309.6	434.2	218.6	501	368.4
Half thinning	561.4	593.6	437.2	284.4	75.8
Two-third thinning	879	645.2	316.2	228.6	207.8
Unthinned	528	434.2	492.4	363.6	-

Table 25. Rooting intensity (number m^{-2}, 2-5 mm) of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Distance from base of the tree (m)				
	0.6	1.1	1.6	2.1	2.6
	Root intensity (number m^{-2})				
One-third thinning	18.6	9.2	4.4	6.2	11.2
Half thinning	30.4	17.6	18.4	8.2	9.4
Two-third thinning	9.4	9.2	5.0	2.0	1.2
Unthinned	7.6	9.2	11.4	4.8	-

Table 26. Rooting intensity (number m^{-2}, 5mm-2cm) of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Distance from base of the tree (m)				
	0.6	1.1	1.6	2.1	2.6
	Root intensity (number m^{-2})				
One-third thinning	0.6	0.8	0.4	1.5	1.8
Half thinning	8.6	11	1.2	0.8	-
Two-third thinning	6.6	4.8	1.6	0.6	0.4
Unthinned	4.0	0.8	6.2	5.6	-

Table 27. Rooting intensity (number m^{-2}, >2cm) after 13 years of stand thinning in 20-year-old *Acacia mangium* at Thiruvazhamkunnu, Kerala, India.

Treatments	Distance from base of the tree (m)				
	0.6	1.1	1.6	2.1	2.6
	Root intensity (number m^{-2})				
One-third thinning	1.0	1.2	-	-	-
Half thinning	3.4	1.0	-	-	-
Two-third thinning	1.4	0.6	-	1.0	-
Unthinned	1.2	1.2	3.0	1.0	-

The depthwise distribution of root intensity number (m^2) indicates that most of the root concentration is found in the surface layer and subsurface layer irrespective of the thinning intensities (Table 28).

There was a gradual decline in root intensity as the distance from the trees increase in all depths. Further, the maximum rooting intensity was found near the proximal end in all treatments. However, the maximum rooting intensity at the proximal end was observed in the two-third thinned treatment which was 18.24 % higher than the distal end. In regard to the lateral root spread in the unthinned, there was intense competition at the distal end (2.6 m) compared to thinned plots.

The total rooting intensity for various thinning regimes showed a considerable difference. For instance, the overall rooting intensity was 4706, 4736.5, 5345, and 6009 per m^2 across unthinned, one- third thinned, half thinned and two-third thinned stands, respectively. Obviously, the highest overall rooting intensity of 6009 per m^2 was observed at root spread regime of lateral distance (2.6 m) and soil depth (50 cm) in the two-third thinned stand compared to 4706 per m^2 in the unthinned stand. Stands at lower thinning intensities showed a decline in the overall root intensity.

Table 28. Rooting intensity (number m^{-2}, total roots) across soil depths of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Thinning intensities	Root intensity (m^2)					
	Soil depth (cm)	**Distance from base of the tree (m)**				
		0.6	**1.1**	**1.6**	**2.1**	**2.6**
One-third thinning	0-10	509.0	425.5	294.5	405.5	326.0
	10-20	214.0	344.0	155.0	350.0	278.5
	20-30	73.0	215.0	73.0	255.0	207.5
	30-40	13.0	90.0	23.5	163.5	94.5
	40-50	13.0	39.0	12.5	108.5	53.5
	Total	822	1113.5	558.5	1282.5	960
Half-thinning	0-10	473.5	562.0	372.5	276.0	169.5
	10-20	414.5	447.0	340.0	204.0	138.5
	20-30	293.5	298.0	251.5	139.0	51.0
	30-40	200.0	177.5	104.5	91.5	17.0
	40-50	128.0	73.5	48.0	48.0	26.5
	Total	1509.5	1558	1116.5	758.5	402.5
Two-third thinning	0-10	1145.0	639.0	292.5	253.5	209.5
	10-20	661.0	661.0	214.5	153.0	146.0
	20-30	222.0	307.0	177.5	101.0	88.5
	30-40	139.5	192.0	89.0	61.0	53.5
	40-50	73.5	47.0	26.0	30.5	26.0
	Total	2241	1846	799.5	599	523.5
Unthinned	0-10	403.5	425.5	482.0	341.0	-
	10-20	321.5	344.0	352.0	254.0	-
	20-30	451.5	215.0	214.0	166.0	-
	30-40	132.5	90.0	168.0	129.5	-
	40-50	43.0	39.0	79.5	54.5	-
	Total	1352	1113.5	1295.5	945	-

4.14. Understorey photosynthetically active radiation

Diurnal variations in understorey photosynthetically active radiation (PAR) from 8 am to 5 pm for different seasons are tabulated in Table 29. PAR values varied significantly across thinned plots, unthinned plot and treeless open plots were distinct (Figure 7). Understorey transmittance for the unthinned plot was minimum in August (7.73) and maximum in March (34.03). This trend continued in other thinned plots too.

Table 29. Understorey photosynthetically active radiation (PAR) variation for 20-year-old *Acacia mangium* after 13years of stand thinning at Thiruvazhamkunnu, Kerala, India.

Treatments	Aug		Nov		Mar	
	MMD-PAR	TR	MMD-PAR	TR	MMD-PAR	TR
Open	1688.00^{a}	100.00	1768.00^{a}	100.00	1683.00^{a}	100.00
Unthinned	130.50^{c} (18.15)	7.73	158.25^{b} (70.28)	9.38	504.63^{c} (88.28)	34.03
One-third thinning	148.00^{c} (34.60)	9.00	171.00^{b} (47.67)	10.13	573.13^{c} (123.8)	38.65
Half thinning	130.88^{c} (11.88)	7.75	173.63^{b} (86.30)	10.29	606.25^{b} (67.6)	40.80
Two-third thinning	248.37^{b} (36.24)	14.7	154.88^{b} (42.01)	10.18	952.50^{b} (211.78)	50.22

(Values in parenthesis are standard deviation)
(Values with the same superscripts do not differ significantly within a column)
MD-PAR=Mean daily PAR understorey (μ moles m^{-2} s^{-1});
MMD-PAR=Mean midday understorey PAR (μ moles m^{-2} s^{-1});
TR=PAR transmittance (%)

As expected greater the thinning intensity resulted in increased transmittance. The same pattern was followed for the mean midday PAR (12 –1 pm) too. The understorey mean mid-day PAR was statistically significant between the treatments. Mean midday understorey Photosynthetic Photon Flux Density (PPFD) levels were maximum in the open condition irrespective of the month. The minimum PPFD was recorded in the unthinned plot and the maximum was in two-third thinned plot.

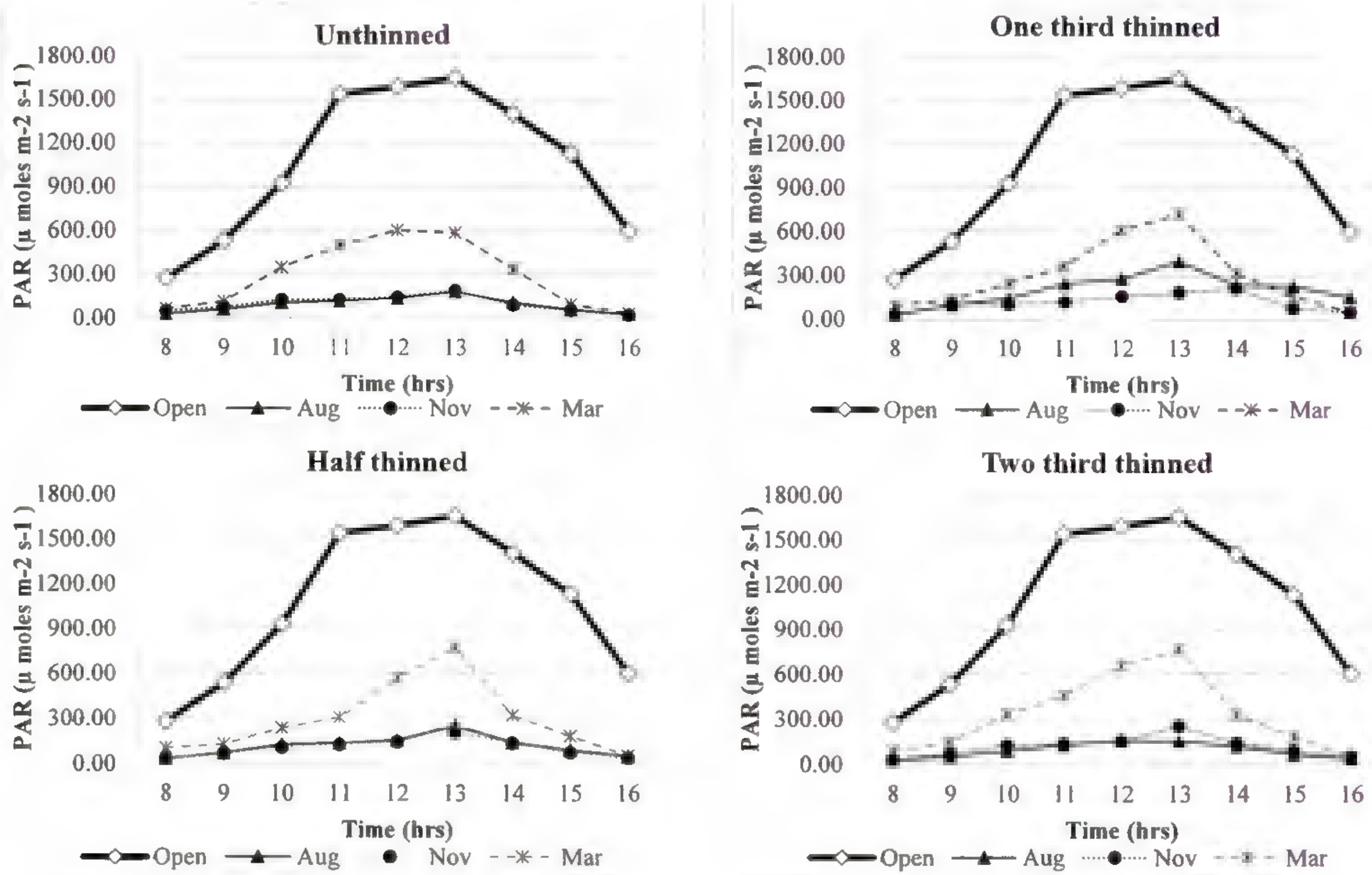


Figure 7. Seasonal variation in understorey PAR of 20-year-old *Acacia mangium* after 13 years of stand thinning at Thiruvazhamkunnu, Kerala, India.

As expected the understorey PAR transmittance increased with the increase in thinning intensity. For instance, the highest PAR transmittance during August was 14.7 % in two-third thinned stand while the corresponding transmittance in the unthinned plot was only half the transmittance in two-third thinned plot (7.73%). A similar pattern was discernible for other seasons. A sharp increase in understorey PAR (midday PAR) is observed during the peak summer month (March). For instance, the understorey PAR incident in the two-third thinned plot was much as 50% of the open PAR (midday).

4.15. Wood properties

An attempt also was made in the present study to investigate the possible influence of long term thinning on the wood properties. Few basic wood physical properties such as basic density, moisture content, and volumetric shrinkage, radial, tangential and longitudinal shrinkage were assessed and are tabulated in table 30.

4.15.1. Basic density

The basic density value ranged from 530 kg m^{-3} (Two-third thinned plot) to 600 kg m^{-3}(unthinned plot). Analysis of variance conducted revealed that there is no significant difference in basic density between thinning treatments. The mean basic density for 20-year-old *A. mangium* was 570.50 kg m^{-3}.

4.15.2. Moisture content

Analysis of variance for moisture content of wood across four thinning treatments does not show the significant difference even though the values ranged from 32.99 % (one-third thinned plot) to 40.05 % (two-third thinned plot) with a mean value of 37.51%.

4.15.3. Shrinkage

The volumetric shrinkage values ranged from 7.32 % (Unthinned plot) to 11.82 % (Half thinned plot). Analysis of variance conducted revealed that there is no significant difference in volumetric shrinkage (VS) between treatments. Other measurements of shrinkage such as tangential, radial and longitudinal shrinkage did not show statistically significant result too. The mean value of tangential, radial and longitudinal shrinkage for 20-year-old *A. mangium* was 6.75 %, 4.30 % and 1.15% respectively.

Table 30. Effect of stand thinning on wood physical properties of 20-year-old *Acacia mangium* trees at Thiruvazhamkunnu, Kerala, India.

Treatments	Basic density ($kg\ m^{-3}$)	VS (%)	LS (%)	RS (%)	TS (%)	MC (%)
Unthinned	602.00 (89.45)	7.32 (1.21)	1.44 (0.69)	3.89 (1.19)	6.48 (1.63)	40.05 (10.43)
One-third thinning	572.25 (53.13)	10.10 (2.71)	0.90 (0.44)	4.82 (1.35)	7.87 (1.96)	32.99 (7.23)
Half thinning	577.25 (34.86)	11.82 (3.43)	0.40 (0.34)	3.98 (0.88)	6.14 (1.53)	38.38 (4.04)
Two-third thinning	530.50 (47.06)	10.33 (1.11)	1.88 (2.28)	4.53 (1.05)	6.51 (2.89)	38.62 (7.79)
Mean	570.50 (25.67)	9.89 (1.63)	1.15 (0.56)	4.30 (0.44)	6.75 (0.66)	37.51 (3.10)
p-value	ns	ns	ns	ns	ns	ns

VS = Volumetric shrinkage; LS = Longitudinal shrinkage; RS = Radial shrinkage; TS = Tangential shrinkage and MC = Moisture content

(Values in parenthesis are standard deviation)

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

4.15.4. Heartwood and sapwood percentage

The heartwood proportion (cm^2) at DBH (1.37m) of 20-year-old *A. mangium* was found in the range of 229.95 to 961.44 cm^2 (mean of 488.31cm^2). The trend line representing the proportion of heartwood area does increase slightly with an increase in thinning intensity the same trend followed in the case of the sapwood too. Plotting the heartwood and sapwood area (cm^2) against DBH (cm), one can appreciate that increment in sapwood area with reference to DBH was not similar to that of heartwood area with reference to DBH (Figure 15). Even though, there was an increase in heartwood area across treatment, the analysis of variance (two-way ANOVA) did not show any statistically significant difference across treatments in both heartwood and sapwood percentage. However, with reference to axial position, the heartwood percentage increased from the bottom to the top and vice-versa in the case of sapwood percentage which was statistically significant too (Table 31).

4.15.5. Heartwood to sapwood ratio

The heartwood to sapwood ratio was estimated at the different axial position for the four different thinning intensity and it has been tabulated in table 32. Analysis of variance (two- way ANOVA) revealed that the across thinning treatment, there is no statistically significant variation. In the reference with the axial positions, there was the statistically substantial difference in all thinning treatments ($p < 0.000$).

Table 31. Effect of stand thinning on heartwood percentage of 20-year-old *Acacia mangium* trees at Thiruvazhamkunnu, Kerala, India.

Treatments	Heartwood percentage (%)					
Axial positions	One-third thinning	Half Thinning	Two-third thinning	Unthinned	Mean	p-value
At stump (0.15m)	82.42 (1.76)	83.37 (4.20)	81.11 (1.34)	81.90 (3.09)	82.20^{a} (2.67)	0.000
At DBH (1.37m)	79.84 (2.77)	81.37 (3.58)	82.27 (2.53)	80.18 (3.03)	80.92^{a} (2.87)	
At 50 % of Commercial bole height	78.32 (2.51)	79.73 (3.92)	77.73 (1.67)	74.25 (4.53)	77.51^{b} (3.65)	
At commercial bole height	70.90 (5.07)	74.35 (4.87)	72.67 (3.84)	70.25 (4.29)	72.04^{b} (4.39)	
p-value	0.111					

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

Table 32. Effect of stand thinning on heartwood to sapwood ratio of 20-year-old *Acacia mangium* trees at Thiruvazhamkunnu, Kerala. India.

Treatments	Heartwood to Sapwood ratio					
Axial positions	One-third thinning	Half thinning	Two-third thinning	Unthinned	Mean	p-value
At stump (0.15m)	4.735 (0.624)	5.300 (1.528)	4.315 (0.397)	4.750 (0.950)	4.75^{a} (0.95)	0.000
At DBH (1.37m)	4.038 (0.744)	4.513 (1.001)	4.730 (0.848)	4.355 (0.819)	4.36^{a} (0.82)	
At 50 % of Commercial bole height	3.665 (0.605)	4.068 (0.916)	3.513 (0.354)	3.553 (0.720)	3.55^{b} (0.72)	
At commercial bole height	2.530 (0.703)	3.018 (0.858)	2.713 (0.500)	2.668 (0.632)	2.67^{c} (0.63)	
p-value	0.120					

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

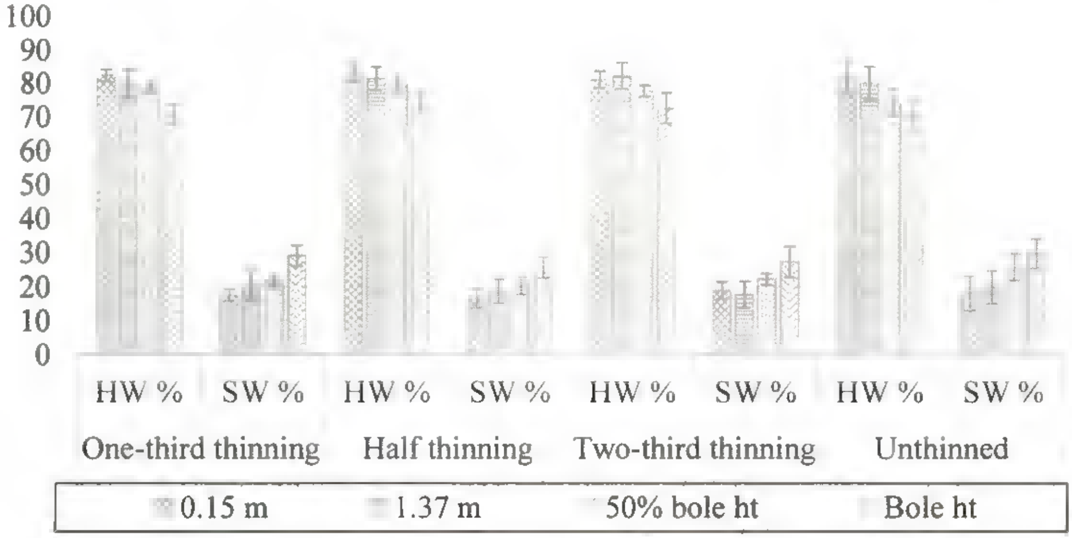


Figure 8. Heartwood and sapwood percentage at different axial positions across different thinning treatment of 20-year-old *Acacia mangium* trees at Thiruvazhamkunnu, Kerala, India.

The heartwood percentage generally decreased with increase in the height (Table 31 and Figure 8). The average heartwood percentage was about 78.17 % along the whole length of the tree. The mean heartwood to sapwood ratio at stump height (0.15m), at DBH (1.37m), at 50% of commercial bole height and commercial bole height was 4.75, 4.36, 3.55 and 2.67 respectively.

Discussion

V. DISCUSSION

The previous chapter portrayed the results pertaining to the long term effect of thinning on the growth, biomass production, carbon sequestration, understorey PAR, soil attributes and wood properties of 20-year-old *A. mangium*. Scientific and managerial implications of the results are discussed under. In addition, the salient findings of the present study in 20-year-old *A. mangium* are compared with short term effect of thinning for answering the objectives of the present study.

5.1. Radial growth

Diameter or girth of individual trees increases with increase in the thinning intensity. This has been reported for many of the temperate as well as tropical trees (Piotto *et al.*, 2003; Bebber *et al.*, 2004; Mäkinen and Isomäki, 2004a; Kim *et al.*, 2016). However, this increment trend depends upon species, initial tree size and thinning intensity (Plaugorg, 2004; Boncina *et al.*, 2007). However the long term effect, the trend may get changed or not; which has not been understood so far in tropical species. Generally, the effects of thinning are well manifested shortly after thinning which may decline with time. However, the response period normally varies with species, age and management levels. For instance, this early effects of thinning in the same stand during 2003-04 suggested that the mean tree CAI (Current annual increment) in girth was 6.84 cm during the first year after thinning while this was dropped to 4.94 cm yr^{-1} in the second year. Closer analysis of the MAI at thinning after 13 years indicates considerable changes. For instance, the MAI in girth after two years of thinning was 4.27, 4.52, 4.80 and 5.13 cm yr^{-1}for unthinned, one-third, half thinned and two-third thinned plots respectively (Kunhamu, 2006). While the corresponding MAI after 13 years of thinning were 3.22, 3.84, 4.28 and 4.82 cm yr^{-1} respectively. Implicit is that, despite the marginal overall improvement in radial growth after thinning, the impact of thinning on diameter growth are still prominent even after 13 years of thinning. Over the years this trend did have implications on the girth/ diameter. As there was a statistically substantial distinction between the two-third thinned plot (heavy thinning) and one-third thinned plot (light thinning) even after long term (Table 2 and Figure 9).

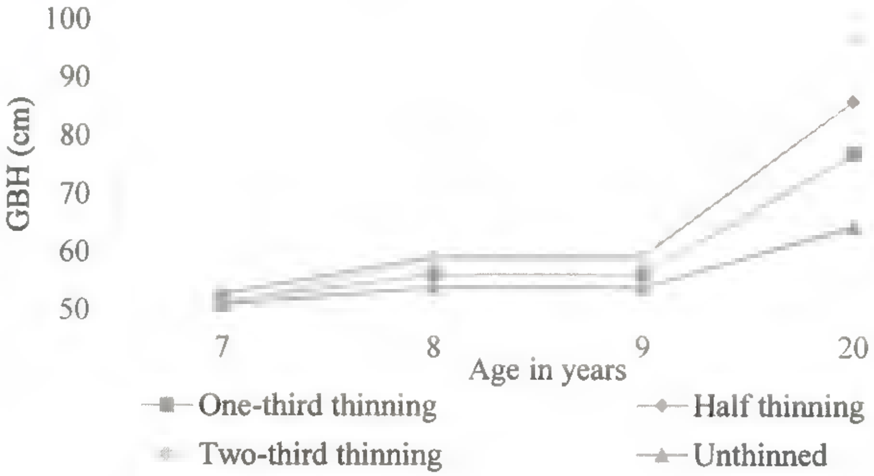


Figure 9. Changes in GBH across age for *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

5.2. Height growth

The insensitivity of height to different thinning intensities was exhibited during the early period after thinning (Kunhamu, 2006). The insensitivity of height to thinning has been reported before provided the stems are too close (Lanner, 1985). Maximum height attainable at a particular age is species and site specific. In the present study, it is reasonable to assure that neither the short term nor the long term effect of thinning on height was marginal. Probably, an early thinning at second and third year could have influenced more height response to thinning. Figure 10 portrays the total height and bole height before thinning and after thinning. The increment in height followed the same trend even after 13 years of thinning. Further, the height growth is expected to occur during the initial stages of the tree growth. Hence for the present stand, it can be concluded that height growth has already culminated. Further, the thinning had no significant effect on height growth.

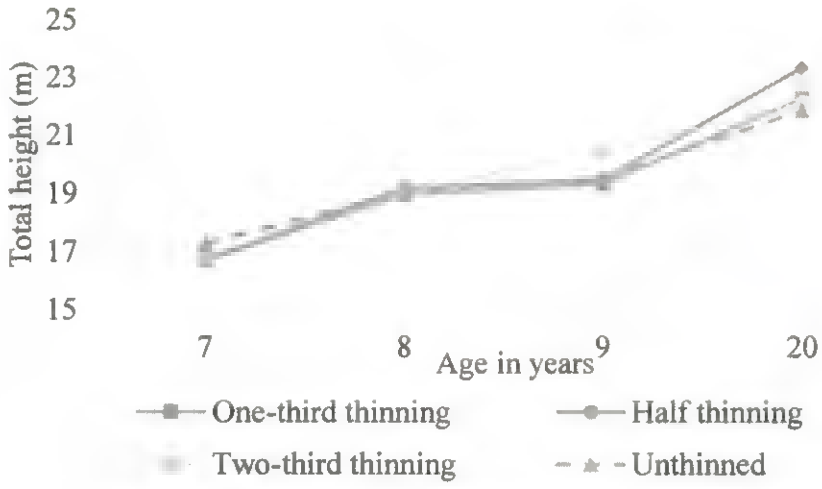


Figure 10. Changes in height across age for *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

5.3. Crown parameters

Crown growth parameters showed poor response to stand thinning after 13 years of thinning. Early reports on the same thinning trial (two years after thinning) also showed marginal changes in crown expansion due to thinning. Crown diameter usually shows a marked response to thinning especially during the early period of thinning (Medhurst *et al.*, 2011). However divergent response is reported for different species. For instance, Medhurst and Beadle (2001) reported a statically significant difference in the crown diameter alone and crown height did not respond for thinning. This trend did not continue in the long term duration (Table 3). Both crown diameter and crown height were found to be no significant among the thinning treatments. This may because of the lack of space for further expansion as stated Pretezsch and Schutze, (2005). The lack of studies in the broadleaved species is a major curtailment in interpreting our results.

Since the primary objective of thinning is to provide significant space which is directly related to radial growth. In the present study probably the faster site occupancy after stand thinning could be the reason for their poor response to stand thinning.

Obviously in fast growing species like *A. mangium* thinning at early ages might bring perceptible changes in the crown spread.

5.4. Basal area

The basal area being a strong index of stand level productivity, its response to thinning assume greater importance (Bailey and Ware, 1983). The tradeoff between the maximum total production and maximum individual production can decide based on basal area (Pinkard and Neilsen, 2003). As for *A. mangium* which is generally used for pulpwood does require the large biomass rather than the large dimension but there is a scope for utilisation of *A. mangium* of more than 15-year-old for the structural purpose (detailed in section 5.6.). Thinning carried out in the experimental is mainly focused on the production of sawlog. Hence there is need to determine the trade off from the figure 11. Optimally, it should be the half thinned plot but after taking mortality into account; one-third thinned plot appears to be more prospective.

Probably among the growth variables mean tree basal area showed a profound response to thinning even after 13 years of stand thinning. The positive growth response observed in the present study with a two-fold increase in mean basal area at two-third thinned plots testify the observation (Table 4). However, the response seemed confounded in the present study across various density at the stand level. The number of trees per ha being an important factor that decides the stand basal area. Hence probably the increase in mean tree basal area at two thinned plot may have confounded by the lower number of trees per ha. Such trends have been earlier reported for *A. mangium* at varying density regimes (Kunhamu, 2006; Kunhamu *et al*., 2009). The marginal increase in stand basal area in the unthinned plot and one-third thinned plot despite the low mean tree basal area is attributed to the higher density of available trees per ha.

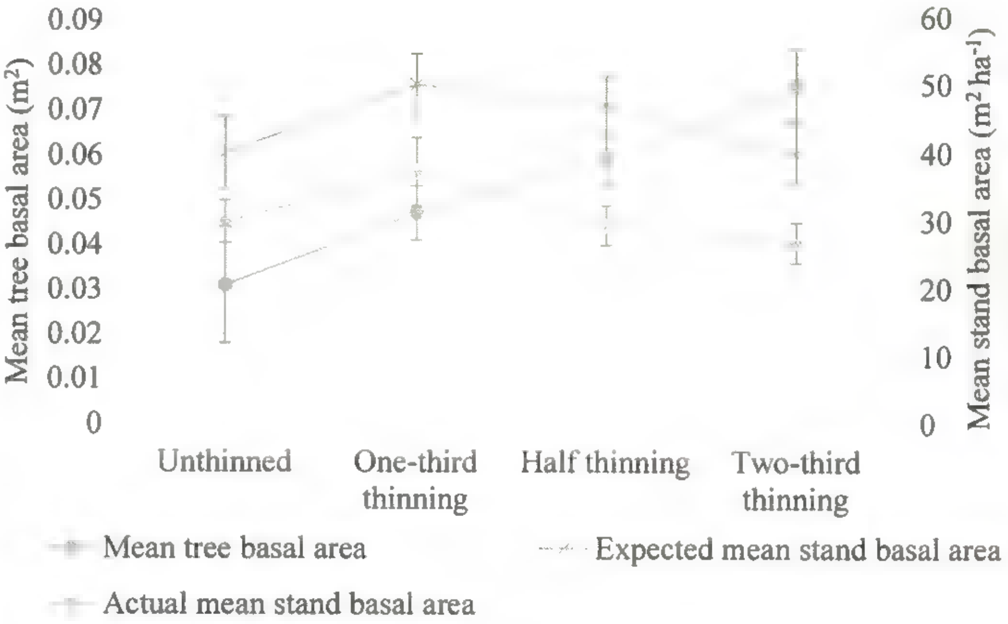


Figure 11. Basal area and stand basal area (expected as well as actual) of 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

5.5. Taper ratio

Heavy stand thinning will increases the tree taper which is clearly depicted in the present study with a better stem form in the unthinned plots compared to that of thinned plots. The results of the thinning carried out in the study site is also in agreement with results of Medhurst *et al.* (2003) also made observations in a stand thinning trial on *Acacia melanoxylon* as well as by Perez and Kannien (2005) in teak. The taper ratio did not change even after 13 years after thinning. The taper ratio reported in the same thinning trial (two-year after thinning) for all thinning treatments were was similar to the results from the present study. For instance, the taper ratio at breast height level in the unthinned plot was 0.85 (two-year after thinning). The taper ratio after 13 years of stand thinning in the unthinned plot at breast height level was 0.82. This leads to the conclusion that the thinning has not impact on the taper ratio. However, the rate of taper may get accelerated due to thinning (Table 5). This sort of trend is agreement with other works (Medhurst *et al.*, 2003; Mäkinen and Isomäki, 2004b).

5.6. Volume and stand volume

Even though height was insensitive to different thinning; the dominance of the basal area was reflected in the tree volume as well as bole volume (Table 6, 7 and Figure 3). The conspicuous increase in mean tree volume at heavily thinned stands compared to unthinned stand observed in the present study in agreement with the observation. However, the inverse trend in stand volume at later stages of stand thinning is attributed to the gross reduction in tree number per ha with the improvement of thinning treatments. One of the primary objectives of stand thinning is the production of trees with larger size especially when sawlog production is considered. Hence, despite the lower stand volume observed in the present study, the high intensity thinning justified by the production of larger volume trees though the number of the tree is lesser. The high value attached to such large trees may justify such reduction in heavily thinned plots. Such observation has been earlier reported for *A. mangium* from the same location (Kunhamu, 2006). The effect of stand thinning on short term on the individual tree was still seen in the long term. However, the stand volume production did not show any statistically significant difference between the treatments. The two third thinning has the maximum volume production, but the half thinned plot was having maximum the bole volume. This mainly because of the heavy thinning that has caused high branching and forking in the two-third thinned plot (Tsai, 1986; Zobel and Buijtnen, 2012). Further, the stand bole volume in the two-third thinned plot is relatively less compared to other thinning intensity. Hence the tradeoff between the bigger sized individual tree and maximum stand volume production has to be decided based on the net final product value (West, 2006).

5.7. Biomass

The present study revealed interesting observation on the short term and long term effects of thinning on biomass production. The increase in mean tree biomass with an increase in thinning intensity was discernible in both short and long term intervals (Table 8). The aboveground biomass ranged from kg 17.91 to 396.61 kg in the different girth class before thinning (Kunhamu, 2006). After thinning the mean tree biomass accumulation showed a steep increase in the average biomass ranging from 266.54 (unthinned) to 663.74 kg (two-third thinned plot.). The lack of data in the intermittent periods is one of the greatest drawbacks. With the available data, the above ground biomass production was relatively higher in terms with rotation age (Mereena, 2014).

The belowground biomass followed the same stance as that of AGB with respect to thinning intensity. The very close relationship between the AGB and BGB is generally employed in allometric equations (Cairns *et al.*, 1997; Ilyas, 2013). The result of the present study is also in line with this relationship. The tedious nature of BGB estimation had its implications on the availability of literature. Therefore, data on the impact of thinning BGB production in mature trees is a key base finding of the present study. The maximum belowground biomass production in the two-third thinned plot (225.20 kg tree^{-1}) was 7.3 times more than the unthinned stands (35.11 kg tree^{-1}). In a study in Kerala estimated that 18-year-old *A. mangium* AGB and BGB biomass production was around 270.78 (81.80) and 62.41 (18.85) at 3 x 3 m spacing. The finding of the present study is also agreeable with other studies (Table 1).

On stand level, the principle of equitable distributions of site resources to the standing is always maintained. So employing prudent thinning strategy will help in producing better size trees from the site. The stand level biomass even though marginally higher in the one - third thinned plots compared to other thinning treatments. This mainly attributed to the more number of trees per ha even though the mean tree biomass of one-third thinned plot was very low. There was a lack of statistically significant difference in the stand level total biomass between the treatments in the long term. This clearly is agreement with the principle of equitable distributions of site resources.

5.7.1. Biomass partitioning

The aboveground biomass contribution by different component before thinning is tabulated in table 33 (Kunhamu, 2006). · The patterns of biomass partitioning observed in the present study is in tune with the trends prior to stand thinning (Table 9). For instance, stemwood accounted for the bulk of the above ground biomass (65-75%) followed by branchwood (12.5-25.2%), foliage (5.0-6.5%) and twigs (4.1-6.5%).

Table 33. Partitioning of biomass in 7-year-old *Acacia mangium* before imposing stand thinning at Thiruvazhamkunnu, Kerala, India.

Girth class (cm)	Mean tree biomass dry weight (kg tree^{-1})								
	Stem wood		Branch wood		Twigs		Leaves		Total
	kg	%	kg	%	kg	%	kg	%	kg
<30	13.11 (1.71)	74.95	2.20 (0.48)	12.57	1.14 (0.18)	6.51	1.04 (0.11)	5.94	17.49
30.1-45	45.40 (3.84)	77.1	7.43 (1.16)	12.6	2.58 (0.28)	4.38	3.45 (0.34)	5.89	58.86
45.1-60	128.56 (4.74)	78.1	21.73 (1.90)	13.19	6.11 (0.48)	3.70	8.17 (0.66)	4.97	164.57
60.1-75	168.44 (5.75)	64.31	65.73 (8.84)	25.08	10.83 (0.82)	4.14	16.92 (2.03)	6.46	261.92
>75	256.16 (41.07)	64.63	99.9 (17.1)	25.15	17.36 (2.71)	4.31	23.19 (0.26)	5.89	396.61

(Values in the parenthesis are standard error of the mean)

The post thinning biomass partitioning also showed a similar pattern of biomass partitioning (stem>branch>foliage>twigs). However, the percentage contribution of the stem has profoundly increased compared to pre-thinning (81%). This may be due to the age. Similar high biomass in stemwood has been reported for 12-year-old *A. mangium* (Rocha, 2017). Both stemwood and branchwood showed a manifold increase in the intensity of thinning. Higher spatial variation for tree growth is implicit in the stands at high density. The study clearly demonstrates that the thinning effects on biomass production could not be masked over longer periods after thinning (Pinkard and Beadle, 1998).

Both thinning and fertiliser application can increase the proportion of aboveground biomass that was leaf relative to wood, as illustrated by an increased ratio of leaf to stem mass. (Forrester *et al.*, 2012). The ratio of foliage to stemwood biomass in the experimental site (figure 12) is in line with Forrester *et al.* (2012).

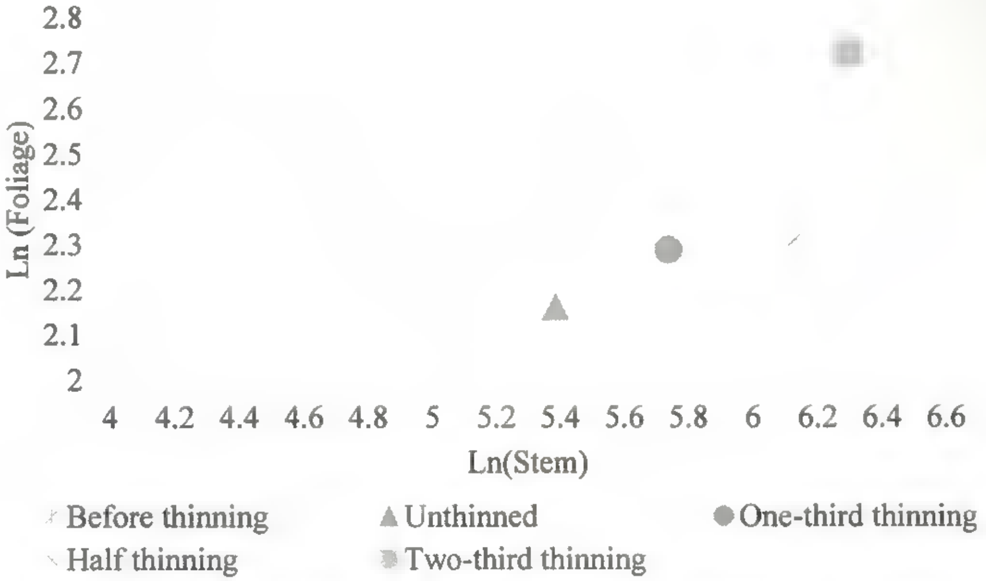


Figure 12. Foliage biomass to stemwod biomass for *Acacia mangium* stand before and after stand thinning at Thiruvazhamkunnu, Kerala, India.

5.8. Carbon sequestration

The carbon concentration in different components in the present study was similar to that of a study conducted in 18-year-old *A. mangium* (Meerana, 2014). In the present study, the total mean tree carbon stock (aboveground + belowground) ranged from 137.87 (unthinned) to 405.62 kg tree^{-1} (two-third thinned) (Table 13). This range is comparable to many other tree species like *Casuarina equisetifolia, Artocarpus heterophyllus, Acacia auriculiformis* and *Grevillea robusta* of similar growth habit (Aneesh, 2014; Rocha, 2017). Longer harvesting cycles will increase the forest C sequestration compared to the younger plantation (Liski *et al.*, 2001; Binkley *et al.*, 2004; Canadell and Raupach, 2008). Prior to concluding that mean tree carbon sequestration increase with thinning, the carbon sequestration per ha basis comparison is very much essential. Despite the higher belowground carbon stock in the two-third thinned plot, the total biomass carbon sequestration on hectare basis did not differ between the treatments (Table 14). The quite interesting finding of the present study is that the objective of large sized tree production could be achieved without any compromise in the stand level carbon sequestration. This could be attributed to the long term effect of thinning. Generally, after thinning there will be a decline in the total stand level carbon sequestration due to the loss of the trees. Another implication of thinning in the present study is the belowground carbon sequestration in two-third thinned stand which was relatively higher compared to the unthinned plots.

Soil carbon contributes to the greater percentage of the C sequestered in forest ecosystem. The same has to be taken into account when evaluating the C sequestration potential of fast growing exotic plantation too. The long-term carbon sequestration depends on the extent of soil disturbance. Despite the fact that soil carbon sequestration in the two-third plot (40.78 Mg ha^{-1}) was higher, the other treatment plots were on par with it. The treeless plot was having less value (21.85 Mg ha^{-1}) that vegetated plot (31.50 Mg ha^{-1}) and all treatment plot (Table 15). This gives us the indication that thinning effect on the long term did not influence the carbon sequestration both in terms of the biomass as well as soil carbon. Thinning causes only short-term decreases carbon sequestration but soon carbon sequestration reaches to the levels that were observed before the thinning occurred (Jarvis and Linder, 2007).

5.9. Allometric equations

The interest in tree biomass and carbon sequestration are rising after a long gap (Zianis and Mencuccini, 2004). This has led to the development of an array of allometric equations for many species. Most of the studies generally tend to utilise already available equations. Kumar *et al.* (1998) and Henry *et al.* (2011) suggests the significance of developing allometric equation based on destructive sampling that gives better predictions. Usually, linear models will have lower values of coefficient of determination compared to nonlinear equations but their iterative nature is a major drawback. Hence in the present study, linear, quadratic and simple logarithmic equations were given priority. Interestingly, good positive correlations were evolved between DBH and AGB ($R^2 = 0.92$ and FI= 43.37 at $p < 0.001$). (Table 11). Considering the time invested in obtaining height data in the field and the associated measurement error and the fact that the inclusion of height did not significantly improve the performance of the model, the inclusion of height data in aboveground biomass models is of little significance ($Y = a + bD + cH$). Tumwebaze *et al.* (2013) and Kunhmu *et al.* (2016) made similar observations in biomass models in MPT's (Multipurpose Tree Species).

Generally, the prediction of root biomass being tedious in nature, mostly allometric equations are used for estimating the BGB. Knowledge on the root to shoot ratio also help to compute root biomass. However the real time destructive sampling gives out better prediction equation for belowground biomass even though the R^2 values are low (Chave *et al.*, 2005; Ilyas, 2013). Hence, simple linear equation with dbh, diameter at stump height and crown width were developed (Table 11).

5.10. Soil properties

5.10.1. Soil bulk density

The soil bulk density was not significantly influenced by the thinning treatments. It is known that the bulk density tends to change very slowly during like felling or thinning (Greacen and Sands, 1980), but later in the long gap that change tends to get nullified (Markewitz *et al.*, 2002; Coleman *et al.*, 2004). This was vivid from our study where the control plot or unthinned plot's bulk density did not differ from the thinned plots. However, soil bulk density increased with increase in depth, mainly due to the compaction in the deeper layers.

5.10.2. Soil pH

The soil pH variability across depth did not follow a specific pattern (Table 17). This can be attributed to the undulating terrain in certain replications in the experiment site. However, all *A. mangium* plots had lower pH values when compared to that of the treeless plot and natural vegetation throughout the profile. This may be due to the extraction of base cation from the soil by *A. mangium* and the release of proton during the nitrogen fixation process, creating an acidic effect (Yamashita *et al.*, 2008; Gonzales-Munoz *et al.*, 2012). A similar sort of result has also been provided by Matali and Metali (2015). For analysing the long term impact of thinning on soil pH, the present pH values (20-year-old) were compared with the values collected 13 years back (7-year-old) from the same treatment plots. The results from the previous 7-year-old study (Table 34) indicates that soil pH showed no significant variation across *A. mangium* treatments as well as with control plot (Kunhamu, 2006). A similar trend was observed even after 13 years which indicates that thinning had no long term effect on soil pH across treatments. However, the soil pH declined by an average of 20% over the entire study area with more manifestation in *A. mangium* plots during this period.

Table 34. Soil properties (0-15 cm) in 7-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India (Kunhamu, 2011).

Treatments	Soil pH	Organic Carbon (mg g^{-1})	Available nitrogen (mg g^{-1})	Available phosphorus (mg g^{-1})	Exchangeable potassium (mg g^{-1})
Unthinned	5.1	14.83^{a}	0.148^{cd}	0.048	0.022
One-third thinning	5.2	12.70^{c}	0.230^{bc}	0.050	0.028
Half thinning	5.1	14.43^{ab}	0.412^{a}	0.041	0.024
Two-third thinning	5.4	13.36^{bc}	0.347^{ab}	0.049	0.029
Treeless plot	5.4	8.80^{d}	0.073^{d}	0.034	0.026
p-value	ns	<0.01	<0.01	ns	ns

5.10.3. Organic carbon

In general, organic carbon declined with depth in all the treatments. Comparing the carbon content in various layers, significant variation among treatments was observed only in surface layers (0-20 cm and 20-40 cm) (Table 18), wherein the mangium plots and natural vegetation had higher values than treeless control. This variation in the 0-20cm and 20-40cm can be primarily attributed to the litter fall as well as the intense fine root activity of trees (Kunhamu *et al.*, 2009 and Rocha, 2017). However, within the *A. mangium* stands, only marginal variation in carbon content was observed between the thinning intensities. Even though the carbon content showed no significant variation in deeper layers among treatments, all the *A. mangium* plots had slightly higher values compared to control plots.

Soil carbon values from 7-year-old *A. mangium* study (Table 34) also showed similar trends to that of present study after 13 years, which indicates that thinning regimes had no significant impact on the soil organic carbon content on the long term. However, OC content had doubled (13.85 mg g^{-1} to 28.35 mg g^{-1}) over the period of 13 years in *A. mangium* plots.

5.10.4. Total nitrogen

Similar to soil organic carbon, the total nitrogen value also decreased with increase in soil depth. The nitrogen fixing capacity of *A. mangium* is clearly visible from the table 19. The thinning did not create any appreciable variation in the total nitrogen value and did not follow any pattern with regard to thinning intensity. This can be endorsed by the reason that most of the nitrogen fixing trees are also the greatest uptaker of the nitrogen. In 40 – 60 cm depth there appears no variation between the treeless plot and that of the treatment plots and in the subsequent depths. The treeless plot was on par with treatment plots indicating that most of the nitrogen fixation occurs in the surface (0-20cm) and sub-surface layer (20-40cm) of the soil.

5.10.5. Available phosphorus

The available phosphorus content in the soil did not vary between treeless plot, treatment plots and natural vegetation plot in all depths except for the 80-100cm. Phosphorus that tends to get fixed in the acidic soils may reason for this pattern (Majid and Paudyal, 1999; Nykvist and Sim, 2009). The mycorrhizal association in the roots of *A. mangium* facilitate greater uptake in tree biomass which might decrease phosphorus concentration (Chauhan *et al.*, 2008). This was very clear on comparing the comparing the value of the present study with the values that were collected 13 years back (Table 20).

5.10.6. Exchangeable potassium

Following the same pattern as that of the phosphorus, the exchangeable potassium did not vary with treatments and treeless plots except for the 80 -100cm. This sort of results have been reported in a comparison study between *A. mangium* plantation and natural forest of Andulau Forest Reserve, Brunei (Matali and Metali, 2015) and in another study by comparing the secondary forest, imperata grassland and *A. mangium* plantation (Yamashita *et al.*, 2008). On the long term effect of thinning, the exchangeable potassium value was higher than the previous measurement in all the plots which might be due to the high mobility of potassium leading to inconsistent results (Table 21).

Based on the results of the study, available phosphorus and exchangeable potassium concentrations showed poor response to stand thinning in long term. Soil organic carbon concentration exhibited substantial variation among thinning regimes in the long term. Generally, the soil under tree cover tends to have higher organic carbon content this was evident in the present study too. Soil pH tends to be lower in the treatment plots due to the nitrogen fixing capacity as well as the translocation of base cations. Collectively, there was very less impact of stand thinning on the soil properties in the long term.

5.11. Root studies

The knowledge of the vertical root distribution is crucial for the optimisation of resource use (van Noordwijk *et al.,* 2015). Especially, changes in root distribution pattern of the tree with regard to silvicultural intervention such as thinning are greater significance for evaluating the feasibility of agroforestry. Density manipulation through thinning had a profound influence on aboveground biomass and its portioning. This may be true for the root distribution as well. All the thinned plots had well-developed tap root system compared to that of unthinned plots. This trend was continued in the spread of lateral roots (Table 23). This is a direct implication of the thinning which provided free space for the remaining tree.

The logarithmic spiral trenching was successfully employed in the field following the works of Fernandez *et al.* (1991) and Tomlinson *et al.* (1998). However, the lack of replication had become one of the major disadvantages of the study. Still, the study could provide some valuable results that were in line with already published works. About 37 % of roots of *A. mangium* tend to concentrated in the 0-10 cm soil depth (Avani *et al*., 2015). In the present study, irrespective of the lateral distance, the maximum root concentration was in the 1-10 cm and 10-20 cm (Table 28). This makes them as one of the species suitable for slope stabilisation and erosion control measures (Voottipruex *et al*., 2008; Ali, 2010). The decrease in the rooting intensity with increase in the distance from the tree base was clearly visible from the tree. However, the rooting intensity in the unthinned plot did not show the above trend. Confirming the high rooting intensity in the unthinned plot. The overall root spread across thinning regimes showed interesting results. The net root count for the given root distribution regime (lateral distance up to 2.6m and soil depth up to 50cm) was highest for the two-third thinned stand followed by half-thinned. Results imply that long term effect of thinning in stands subjected to heavy thinning regimes has substantially improved the vertical and horizontal root spread. The lower overall rooting intensity in the unthinned and moderately thinned stands converges to the conclusion that belowground competition has led to decline in the overall root growth.

5.12. Understorey photosynthetically active radiation (PAR)

Stand thinning in general improved the understorey light regimes. This, however, varies with the intensity of thinning and the time elapses after thinning. In the present study too, such trend was obvious. In younger plantations, the remaining tree crown expanded rapidly during early years. This was observed in the present study as well. However, in the long term, the trees tend to occupy the free space gradually and the canopy gets closed after few years after thinning reducing the PAR availability (Breda *et al*., 1995). This may necessitate the need for second thinning in stands (Zeide, 2004). However, with due regard the rotation age, second thinning in *A. mangium* stand is not a prudent action (Awang and Taylor, 1993). Table 29 indicates that the canopy closure has not fully occurred in two-third thinned stand. Still, the understorey PAR availability is less compared to that of the short term effects (Kunhamu, 2006). The PAR availability in the two-third thinned plot alone can support some intercrops.

Changes in PAR with thinning also influence the understorey productivity along with several other factors. Prospects of intercropping are more in higher understory regimes. Hence, in the present study chances of intercropping are more in heavily thinned plots. Such studies in the same stand during early periods of thinning observed that yield in the understorey ginger (*Zingiber officinate*) was the highest under the heavily thinned plots consequent to its highest understorey PAR incidence (Kunhamu *et al*., 2008).

5.13. Wood properties

5.13.1. Physical properties

The wood physical properties did not vary with regard to thinning, however the decline in the basic density value in the thinned plots compared to that of the unthinned plot can be attributed to opening up tree canopy which increases the rate of growth but reduces the wood density (Evans and Turnbull 2004; Wistara *et al.*, 2016). The heavily thinned *Acacia salicana* wood density was 3.8% lesser than that of the unthinned plot (Hegazy *et al.*, 2014). This effect of thinning is of temporary nature and many studies have indicated that wood basic density is not significantly influenced by thinning. Wood density in *Eucalyptus nitens* did not vary at 22- year old which was thinned at a sixth year from planting (Medhurst *et al.*, 2012). In other work by Lin *et al.* (2012) concluded the row thinning in 24-years old *Cryptomeria japonica* did not significantly influence wood physical and mechanical properties. Also, wood properties of *Cupressus lusitanica* in Tanzania did respond not to different thinning schedule (Malende and Ringo, 1987). In India, thinning schedules in teak did not influence wood properties including heartwood percentage, specific gravity and density (Tewari, 1999).

Perez and Kanninen (2005) concluded that impact of thinning on the wood properties such as heartwood percentage and density tends to be temporary in nature and in the long run the effect gets nullified, based on his work on different thinning schedule in teak plantations of Costa Rica. So, in the effect of thinning after long period got subdued in the present study too as thinning was carried back some 10 years back. The other physical properties followed the same trend of the basic density. To further support, the results, study by Zhang (1995) which aimed to understand the effect of growth rate on wood specific gravity and mechanical properties in softwood, diffuse porous wood and porous wood. The study revealed that the diffuse porous wood is very little influenced by an enhancement in growth rate while the porous wood was least influenced. Similar sort of finding has also been reported in *Swietenia macrophylla, Khaya senegalensis* and *Paulownia fortunei* where increased growth rate did not influence wood properties. (Perera *et al.*, 2012). *A. mangium* being a diffuse porous wood (Anoop *et al.*, 2012) the enhancement in the growth rate had very little influence on the wood property.

On the whole, the mean basic wood density for 20-year-old *A. mangium* was 575.50 kg m^{-3}which was higher than the value reported for 14-year-old stand in similar site condition to that of the present study (Jajo, 2015). The basic density value showed an increasing trend with an increase in age following a similar trend to the results of Chowdhury *et al.* (2005). The many other studies in other species have reported an increase in density with increase in age (Lim and Gan, 2011).

The pioneering work on wood properties on *A. mangium* in Kerala by Dhamaodaran and Chacko (1999) have stated that lack of mature trees for wood property estimation was on the shortcoming in their study. The present study has sorted out this shortcoming. Wood density parameter can vitally shed some light on the other wood features including mechanical properties as it has a direct relationship (Hegazy *et al.,* 2014). For instance, Yang and Evans (2003) predicted the MOE of Eucalyptus using the density and microfibril angle as a parameter. Hence the increase in the density of 20-year-old *A. mangium* wood shall significantly enhance the structural utilisation of the wood.

The higher moisture content compared to other Acacia has been one of the curtailments in the utilisation of *A. mangium.* This has been commented as wet-heartwood (Yamamoto *et al*., 2003) or as soft core (Dhamodaran and Chacko, 1999) which may fall apart and cause hollow holes in the heartwood. This is a negative trait with regard to utilisation. However, all these reports are from a young aged *A. mangium* stand of age around 8 to 14 year to the maximum. In the present study, the mean moisture content (37.51±3.1) was relatively very low compared to the values reported from the previous studies. Further, there was relatively less incidence of the soft core in the disc that was dried. The shrinkage values were also lower compared to the results published from humid tropics as well as other parts of the globe.

5.13.2. Heartwood and sapwood percentage

The increase in heartwood and sapwood across treatment as shown in figure 13 and 14 is an implication of the diameter increment due to thinning which is revealed in figure 8. Even though the gradual increase in DBH due to thinning treatment has directly impacted on the heartwood area, the heartwood percentage and heartwood to sapwood ratio was not influenced by thinning treatment. Hence, it clear that the thinning has no implication on the heartwood production. The heartwood percentage increased with increase in the axial position and so did the sapwood percentage. This is an expected usual trend. A study by Lim and Gan (2011) in 16 and 20-year-old *A. mangium* plantation in Malaysia also concluded that the sapwood percentage increase with an increase in height. This indicated that sapwood-heartwood percentage follow a particular pattern (figure 15). All these results invariably lead to the conclusion that there is a higher probability of Mangium wood being used for structural timber purpose.

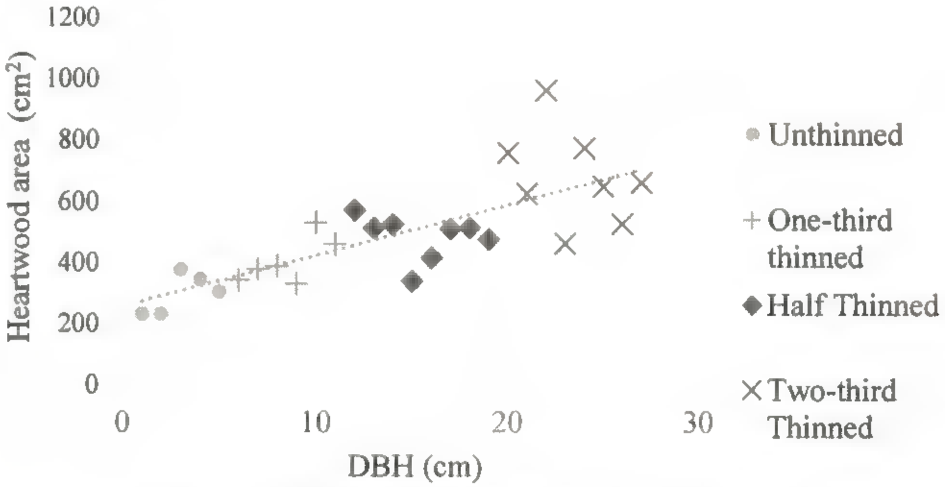


Figure 13. Variation in heartwood area in 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

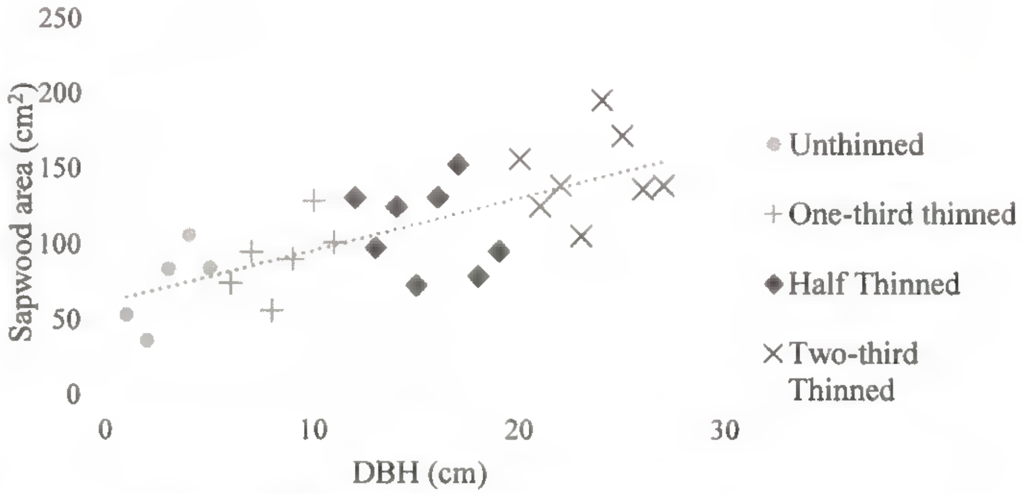


Figure 14. Variation in sapwood area in 20-year-old *Acacia mangium* as influenced by stand thinning at Thiruvazhamkunnu, Kerala, India.

5.14. Managerial implications

Observations on the long term effects of thinning in 20-year-old *A. mangium* showed interesting findings that provide valuable inputs on the management of *A. mangium*. The manifold increase of individual tree volume at heavy thinning regimes ascertains the need for such thinning for quality sawlog production. However, this may not be true for biomass production where the sawlog quality is subsidiary to the total production. The higher biomass production in the moderately thinned stand observed in the present study converges to the conclusion that this thinning regime would be ideal where the objective is biomass production for pulpwood. The findings also suggest a two pronged strategy for density management in *A. mangium* wherein closer spacing can be maintained for six to seven years followed by a heavy thinning of 50 to 75%. The materials realised from thinning can be utilised as source for pulpwood. Often it is observed that thinning for quality sawlog production end up with decrease in the stand level carbon sequestration. However, our study showed an enormous increase in belowground biomass and consequent soil carbon stocks that levelled the possible loss in carbon stocks through heavy thinning. Yet another observation is the improvement in the understorey PAR with heavy thinning, suggesting the possibility of intercropping after thinning. However, our study does not give a concrete indication on the optimal time of thinning for best productivity for various management objectives that calls for further studies in this line.

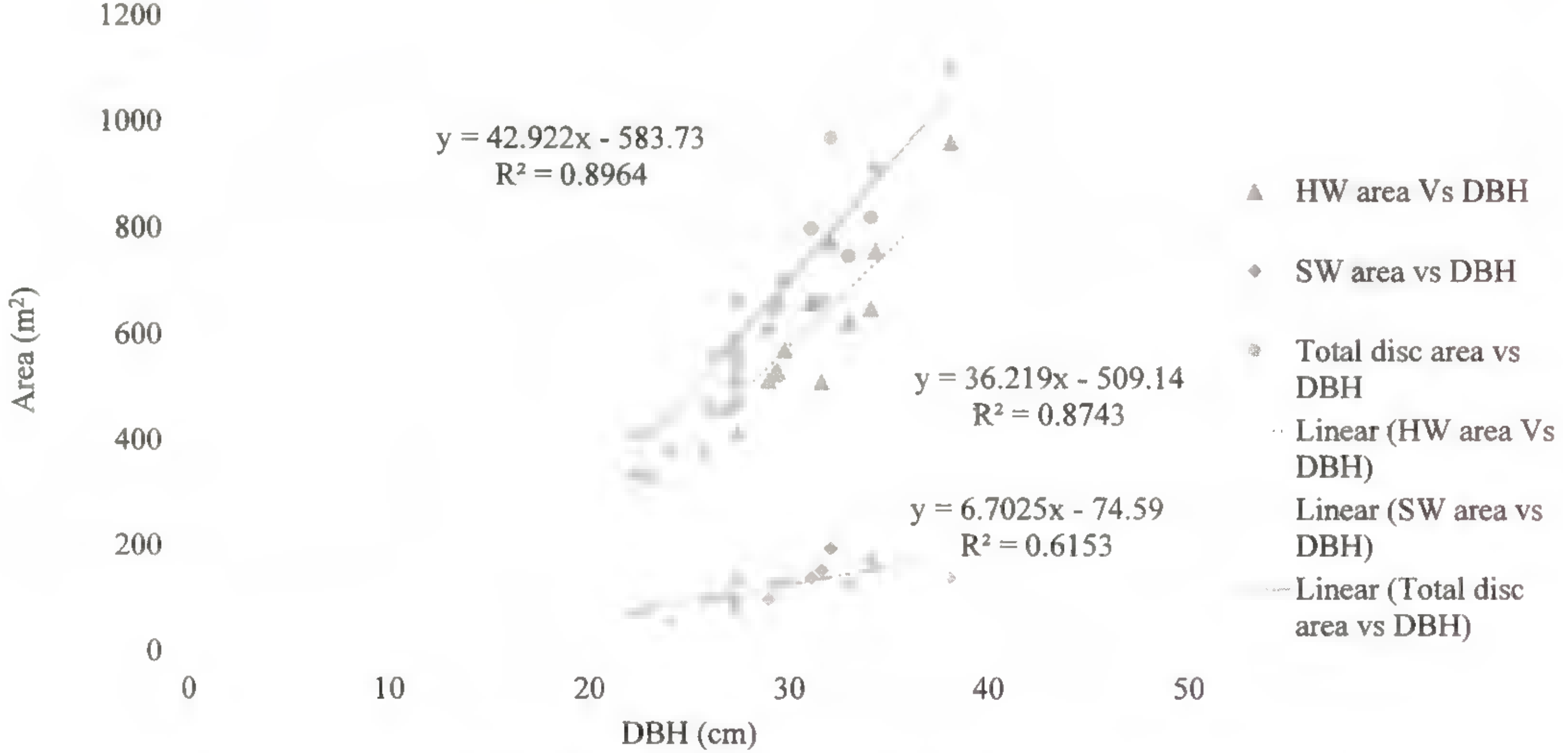


Figure 15. Relationship between total, heartwood, sapwood area with DBH of 20-year-old *Acacia mangium* subjected to stand thinning

Summary

VI. SUMMARY

Effective stand management practices like thinning are indispensable for optimal productivity and product quality of plantations. In light of rising need for the development of production forestry, thinning proved to be an essential silvicultural strategy for production of quality wood material for various management objectives. Trees being long rotations stand thinning may have shorter as well as long terms effects on the product quality. However, long term impacts of such stand management practices have not been studied so far in the tropics especially for fast growing tree species. The present investigation entitled "Long term effect of thinning on productivity and wood properties for 20-year-old *Acacia mangium* Willd. stands" was undertaken in this background to investigate the long term effect of thinning on the growth and biomass allocation pattern. As thinning on long-term can alter the resource utilisation potential of the site, information on such silvicultural management tools help us in meeting current goals and objectives. Furthermore, quantitative information about the progress of these previously thinned stands over the long-term may prove to be useful in addressing whether past silvicultural treatments, often guided by timber management objectives, are addressing contemporary stand management issues. The study also probed into the possible effects of thinning on carbon sequestration potential, soil nutrient utilisation, and understorey photosynthetically active radiation (PAR) as well as wood properties which are the areas that are not explored till date. The salient findings of the study are summarised below:

1. The overall improvement in radial growth due to thinning observed on short term basis was persisted even after 13 years of thinning. There was a significant difference in diameter growth between the two-third thinning (30.68 cm) and unthinned treatments (19.32 cm).
2. The insensitivity of height to thinning was evident in the present study. The maximum average height of 20-year-old *A. mangium* ranged from 21.77 to

23.23 m. The present study concludes that the long term effects of thinning on height growth were only marginal.

3. Crown growth parameters showed an insignificant response after a long period of thinning indicating the possible levelling in canopy expansion potential over the time.
4. The mean tree basal area showed profound responses even after 13 years of stand thinning. The two-fold increase in mean basal area at two-third thinned plots testifies the positive response to thinning. However, the trend was not discernible when the basal area was computed on stand basis. The advantage in mean tree basal area in the heavily thinned stands seems to be confounded by the larger number of trees per ha in the low thinned stands.
5. Thinning in general had increased stem taper with two-third thinned stand showing the highest taper value compared to the unthinned stands.
6. Mean tree volume production followed the same trend as a basal area with a two-fold increase in the heavily thinned plots. However, the lower volume production on stand basis observed for the heavily thinned stands shows the better trade-off through the premium prize discernible for the larger sized trees from this thinning regime.
7. Both aboveground and belowground biomass production showed a consistent increase with increasing intensity of thinning. The maximum tree level belowground biomass production recorded in the two-third thinned plot (225.20 kg tree^{-1}) was almost 7.3 times more than the unthinned stands (35.11 kg tree^{-1}). This indicates the prominent advantage of longer time elapses after thinning on belowground biomass production.
8. The patterns of biomass partitioning followed the order of stemwood>roots>branchwood>foliage>twigs which was not affected by thinning. However increased allocation towards belowground biomass production was observed at later stages after thinning in heavily thinned stands.

Even though the thinning tends to increase the foliage biomass, in the long term this effect was marginal.

9. The stand level biomass accumulation followed a divergent trend with one - third thinned plots showing marginally higher value compared to other thinning treatments. This could be attributed to the more number of trees per ha. The longer periods after thinning has led to a confounding effect on the stand level total biomass between the treatments. This clearly is in agreement with the principle of equitable distribution of site resources.
10. Stand level carbon sequestration ranged from 133.99 (unthinned) to 156.30 Mg ha^{-1} (1/3rd thinning) which however did not vary between the thinning intensities. It can be concluded that the loss in the carbon stock due to thinning gets compensated in the long run.
11. Regression equations developed to predict the aboveground tree biomass, total aboveground biomass, total volume and bole volume using DBH as independent variable showed simple linear and quadratic equations as better predictors with reasonably high R^2 values and lower furnival index. Single variable (dbh) based equations yielded reliable results suggesting that time spent on tree height measurements can be saved without compromising the accuracy.
12. Long-term effects of thinning had no influence on soil bulk density, pH, and available phosphorus and exchangeable potassium. However, all the thinning regimes registered significantly higher soil carbon stock compared to contiguous treeless control plot. The total nitrogen content also followed the same trend.
13. Marked differences were observed in the root morphometric data between the thinning treatments. The maximum rooting depth of 2.25 m was recorded for two-third thinned plot which was on par with (1.93m) half thinned plot. A

similar trend was observed for the lateral root spread also, with the lowest root spread attached to unthinned plots (0.9 m).

14. Even though the maximum rooting intensity was found in the surface layer of the soil irrespective of the thinning intensities, thinning had reduced the root competition substantially.
15. The understory PAR showed a consistent increase with an increase in the intensity of thinning with almost 50% transmittance recorded in the 2/3rd thinned plots during the month of March. Results imply the possibility of intercropping in the heavily thinned treatments. Also, the lower belowground competitive advantage in this thinning regime may contribute to intercropping prospects.
16. The thinning had no influence on wood physical properties. The mean basic wood density for 20-year-old *A. mangium* was 575.50 kg m^{-3}which was higher than the value reported for an unthinned 14-year-old *A. mangium* stand. The mean moisture content (37.51±3.1 %) was relatively low compared to the values reported for younger aged stands. Further, there was relatively less incidence of soft core and lower shrinkage values which lead to the conclusion that there is a higher probability of mangium wood being used for structural timber purpose at a longer rotation of 20 years and beyond.
17. This study primarily concentrated on wood production from the point of view of volume and dimensions. The relative merits of different thinning intensities may also depend on the size–price relationship of logs for various end uses as well as on the interest rate used to discount the costs and incomes over time. The economical consequences of different thinning schedules remain a topic of further study.

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Abstract

LONG TERM EFFECT OF THINNING ON PRODUCTIVITY AND WOOD PROPERTIES FOR 20-YEAR-OLD *Acacia mangium* Willd. STANDS

by

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VIII. ABSTRACT

The focus of forest management in India has moved from timber production to conservation and eco-restoration. Hence, plantations are the viable scope for meeting our ever increasing wood demand. Effective stand management practices are indispensable for deriving optimal productivity from these plantations. Thinning is generally recognised as an important silvicultural tool for creating qualitative and quantitative improvement in plantation productivity. However, its temporal effect varies with species and thinning regime. In this context, the present study was undertaken by destructive sampling of trees and assessing the aboveground and belowground biomass, soil parameters, understorey PAR and wood physical properties in a 20-year-old *Acacia mangium* stand that was subjected to stand thinning 13 years ago.

The results indicated that the impact of stand thinning on radial growth, mean tree basal area and mean tree volume was still persisting even 13 years after thinning. The highest response was from two-third thinning intensity (533 trees ha^{-1}) followed by half thinned stand (800 trees ha^{-1}). The tree level biomass followed the same pattern with the maximum aboveground (663.67 ±121.03 kg tree^{-1}) and belowground (225.20 ±20.62 kg tree^{-1}) biomass production recorded from the two-third thinning intensity. However on stand basis, the effect of thinning on volume and biomass did not show significant variation across treatments, probably due to the confounding effect of the higher number of trees in the low density stands. This trend was visible in stand carbon sequestration potential also. Even though two-third thinning intensity had maximum carbon sequestration at tree level (405.62 kg C tree^{-1}), the stand level carbon sequestration did not vary with thinning treatments.

Long-term effects of thinning had no influence on soil bulk density, pH, and available phosphorus and exchangeable potassium. However, all the thinning regimes registered significantly higher soil carbon stock compared to contiguous treeless control plot. Total nitrogen content also followed the same trend. Understorey

Photosynthetically Active Radiation (PAR) availability observed in this study revealed reduced availability across all thinning regime except for the heavily thinned stand suggesting the possibility for intercropping.

Thinning also had an impact on the root spread on a long term basis. The maximum spread of 2.84 m was recorded in the two-third thinning treatment which was significantly higher compared to other thinning intensities. Characterization of spatial root distribution pattern using logarithmic spiral trenching method suggested restricted root spread for the unthinned stand, while better root spread was observed with increased intensity of thinning. The results indicate that influence on thinning on wood physical properties are not significant across treatments. The wood density of 20-year-old *A. mangium* was 570.50 (kg m^{-3}) albeit, was higher compared to mangium wood of relatively younger ages. Mean moisture content (37.51±3.1 %) and shrinkage values were relatively very low compared to the values reported from previous studies. Furthermore, the incidence of the soft core which was relatively less indicates better seasoning of the harvested wood. Understanding the long-term effects of stand management activities on productivity will help in taking better management decisions. On the whole, the study revealed that, since long term effects of thinning were significant for most of the productivity traits, thinning intensity regimes have a strong influence/bearing on stand management objectives.