BIOMASS AND CARBON SEQUESTRATION IN SILVER OAK (*Grevillea robusta* A. Cunn.) STANDS IN THE MIDLANDS OF KERALA

By

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(2010 - 17 - 109)

THESIS

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DEPARTMENT OF FOREST MANAGEMENT AND UTILIZATION
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DECLARATION

I hereby declare that this thesis entitled **"Biomass and carbon sequestration in silver oak (*Grevillea robusta* A. Cunn.) stands in the midlands of Kerala"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me for any degree, diploma, associateship, fellowship or other similar title, of any other University or society.

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Certified that this thesis, entitled **"Biomass and carbon sequestration in silver oak (*Grevillea robusta* A. Cunn) stands in the midlands of Kerala"** is a record of research work done independently by **Mr Geo Basil Paul (2010-17-109)** 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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Dedicated to My Beloved
Parents & Brother

Introduction

INTRODUCTION

One of the major issues of global concern today is rapidly increasing levels of CO_2 in the atmosphere and its potential to change the world climate. The atmospheric concentration of CO_2 has increased from approximately 315 ppm (parts per million) in 1959 to a current atmospheric average of approximately 385 ppm (Keeling et al., 2009). Current projections are for concentrations to continue to rise to as much as 500-1000 ppm by the year 2100 (IPCC, 2007). In order to mitigate this elevated carbon concentrations in atmosphere, IPCC (2001) advocated an increase in the size of the carbon pools. Increased biomass production through large scale tree planting is one among the viable actions to mitigate the rising levels of CO_2. Trees are known to maintain soil organic matter and nutrient cycling through the addition of litter and root residues to the soil. Tree plantations, especially in the tropics, play an important role in carbon sequestration through the accumulation of carbon in the wood and increase in soil carbon storage. Moreover, the availability of more wood biomass from plantations will facilitate the use of biofuels instead of fossil fuel in future. Plantations also play an important role in meeting the biomass needs of local communities and industries thus helping in conserving the natural forest carbon pools in tropics (Swamy et al., 2003).

The biomass productivity of the MPTs differs significantly with site and stand management practices (Deans et al., 1996). Primary productivity and biomass gain of a plant or in an ecosystem varies with the availability of resources and characteristics of environment in which they grow. Climate inter alia is the strongest ecological factor in determining primary production. Ecosystem productivity is an index, which integrates the cumulative effects of the many processes and interactions. Biomass estimates are useful for quantifying net primary productivity, energy pathways, nutrient and carbon cycles, and harvestable biomass yields, and in evaluating habitats and combustible fuel (IPCC, 2003; Saglan et al., 2008).

The most precise way to measure and monitor aboveground biomass (AGB) and to estimate the state and change in carbon stocks for a stand is through periodic destructive harvesting (Brown et al., 2004). However, this method is time consuming labour intensive and involves sacrifice of large number of trees belonging to different size classes. Therefore non-destructive techniques have been developed to determine AGB of forests and man-made short rotation forestry plantations (Saatchi et al., 2007). Although attempts have been made to develop prediction equations for estimating biomass of fast growing species in India (Kumar et al., 1998; Thapa, 2005), their applicability was confined to the relevant agro climatic zones. Hence, there is an imperative need to develop prediction equations for estimating biomass of plantation ecosystems.

In a given climate, the productivity (biomass) of trees is generally influenced by the availability of nutrients, which in turn depends on the pattern and role of their cycling (Rawat and Singh, 1988). Nutrient concentration within the ecosystem usually depends upon a functional balance in their intra system cycling. Nutrient distribution in the vegetation and soil compartments will provide useful information on nutrient budgeting of the ecosystem (Shanmughavel et al., 2001). Nutrient use efficiency, i.e. the amount of biomass produced per unit of a certain macro or micronutrient, is a useful measure to assess the nutrient demand and the productivity of a tree species on a site. The understanding of nutrient accumulation and storage processes will help in evolving suitable strategies of nutrient management for maximizing biomass production. The repeated harvesting under short rotation cycle leads to nutrient export and decreasing the productivity of plantations by depleting soil nutrients. The nutrient cost of biomass removal is partly dependent on the nutrient content of the parts of the tree removed. High nutrient removal in harvests mirror the high site quality deterioration potential (Shujauddin and Kumar, 2003) so it is therefore imperative to study the impact of different tree species harvesting on soil nutrient depletion.

In the light of the growing concerns over the climatic change and related issue and tree planting as a potential mitigation mechanism, there is a greater need to gather information on the carbon sequestration potential of fast growing tropical MPT's. It is estimated that global forests store 289 gigatonnes (Gt) C in the biomass alone (FAO, 2010). While sustainable management, planting and rehabilitation of forests can conserve or increase forest carbon stocks, deforestation, degradation and poor forest management reduce them. Accurate estimation of forest carbon stock and flux is a prerequisite for assessing the contribution of forest ecosystems to global carbon budgets. Vegetation carbon components are usually calculated as dry biomass multiplying by a conversion factor of carbon concentration (Gower et al., 1999). Currently, a mass-based carbon concentration of 50 per cent for woody tissues and 45 per cent for foliage and fine roots is widely accepted as a constant factor for conversion of biomass to C stock (Houghton., 1996; Gower et al., 2001). Recent studies, however, have showed that the carbon concentration varies from 44.4 per cent to 55.7 per cent depending upon tree species and biomass tissues, and using a generic conversion factor of 50 per cent will introduce as much as 10 per cent bias in C stock estimation (Bert and Danjon, 2006). Evidently, species and tissue specific carbon measurements are greatly needed for reducing uncertainties in biomass carbon estimation.

Grevillea robusta A. Cunn. ex R. Br. locally known as silver oak is a fast growing multipurpose tree that provides various goods and services that include construction material, fuel wood, shade, fodder and soil fertility improvement (Muchiri et al., 2002). This is a well-known shade tree in coffee and tea plantations and is widely intercropped in agroforestry in Eastern Africa, providing straight poles for construction, shade and firewood (Harwood, 1989). Its golden flowers are attractive to bees, making it an important honey plant and the wood is used in making railroad ties, plywood, panelling, air-freight cases and furniture, boat building etc. (Orwa et al., 2009). Due to its wide spread popularity, it has been introduced to various subtropical and tropical highland environments of eastern and central Africa, south and central America, and south Asia (Harwood, 1992a). Although the species is increasingly preferred for planting in various ecosystems, there is a paucity of information on biomass production and productivity.

Literatures relating to biomass production and carbon sequestration potential of tropical trees in general and *G. robusta* in particular is scarce. Hence a study was carried out on 20-year-old *Grevillea robusta* stands in the midlands of Kerala with the following objectives.

1. To study the aboveground biomass production potential of *G. robusta* plantation;
2. To develop biomass prediction models for 20-year-old *G. robusta*;

3. To estimate the nutrient (NPK) allocation and accumulation in the aboveground biomass of *G. robusta* plantation;
4. To quantify the carbon sequestration potential of *G. robusta* stands.

Review of Literature

REVIEW OF LITERATURE

2.1 *Grevillea robusta* A. Cunn. ex R. Br.

Grevillea robusta A. Cunn. ex R. Br. commonly known as 'silver oak' belongs to the genus *Grevillea* comprising over 357 species (Makinson, 2000) belonging to the tribe Grivilleeae, with in the dicotyledonous plant family Proteaceae, subfamily Grevilleoidae. *Grevillea robusta* is the largest species in the genus (Mc Gillivary, 1993). It is a medium sized fast growing multipurpose tree that is native to south-eastern Queensland and north-eastern New South Wales (Harwood et al., 1997).

It is an erect single-stemmed tree typically reaching an adult size of 20–30 m in height and 80 cm in diameter in its natural range (Devaraj et al., 1999). The crown is conical and symmetrical with major branches spaced at intervals of about one meter and projecting upwards at an angle of 45°. Bark on the trunk is dark grey and furrowed into a lace-like pattern. The fern-like foliage of this species is very distinctive. Leaves are 10–34 cm long and 9–15 cm wide, variably pinnate to bipinnate, with a smooth green upper surface and hairy silvery undersurface. Petioles are 1.5– 6.5 cm long.

2.1.1 Distribution

Grevillea robusta has a restricted natural range on the east coast of Australia from latitude 22° 50' 10' S (Harwood, 1992a; Mc Gillivary et al, 1993). Over the last century, silver oak, has been widely planted in subtropical and tropical highland environments of eastern and central Africa, south and central America, and south Asia (Harwood 1992a). Analysis of climate of the natural distribution of *G. robusta* and of locations where it has been grown successfully show that the species grows well within the mean annual rainfall of 700 to 2400 mm with a mean annual temperature 13-24°C (Booth and Jovanovic, 2002). It grows over an altitudinal range of 900-2500 m above sea level (Kalinganire and Zurcher, 1992). A study done by Kalinganire (1996) on the performance of *G. robusta* in plantations and on farms under varying conditions in Rwanda found that altitude and soil fertility have a major influence in the growth of *G. robusta* at altitudes above 2300m, height increment was considerably low (about 1.4 m year^{-1}). In Kerala, *G. robusta* is found in southern central and northern parts but is more frequent in Wayanad and Idukki districts (Jayaraman et al., 1992.)

2.1.2 Utilisation

Grevillea robusta has been cultivated in many countries for ornamental purposes, tea and coffee plantations as a shade and general farm planting and the last few decades increasingly as a producer of timber, poles and firewood on small farms and in large plantations (Harwood, 1992b). Over the years silver oak has been evolved in to perhaps the most preferred shade tree species in tea plantations because of its unique qualities. Its leaves effectively filter light and provide enough shade during the dry months and also the rooting pattern and architecture makes it less competitive with tea plants (Niranjana and Viswanath, 2008). It is considered a species of multiple use, cultivated in hedgerows or homogeneous forest for wood industry (carpentry, veneering, floors, firewood and pulp), honey and pollen, latex or ornamental (Harwood, 1989).

Initially, the use of this species was restricted to the humid and sub-humid areas primarily where the tea and coffee plantation grow (Harwood, 1989). Its desirable characteristics as an intercrop with other agricultural crops has led to the species spreading to semi-arid areas (Muthuri et al., 2005) that are clearly not suitable for the species according to the requirements set by Booth and Jovanovic (2002) and there have been numerous reports of fungal and insect attack in these areas (Njuguna, 2011).

2.1.2.1 A promising agroforestry crop

The most commonly cited advantages of using *G. robusta* worldwide in agroforestry systems are its fast growth rate and minimal competitiveness with crops (Jama et al., 1989; Okorio et al., 1994; Baggio et al., 1997; Lott et al., 2000a, 2000b; Takaoka, 2008). Observations of its root distribution (Jonsson et al., 1988; Mwihomeke, 1993) and measurements of water uptake (Lott et al., 1996; Howard et al., 1996) indicated that it is capable of extracting substantial quantities of water from beneath the crop rooting zone. Kalinganire (1996) in a study on the performance of *G. robusta* in plantations and on farms in Rwanda found that greater individual tree volume is produced on farms compared to plantations.

G. robusta tolerates heavy pollarding and pruning of branches and it mixes well with other crops (Muchiri et al., 2002). Furthermore, the species has a proteoid root system (cluster of roots that develop in soils deficient of phosphorous) and hence is believed to compete less for minerals with crops, making it ideal for planting on small sized farm (Akycampong et al., 1999). Its widespread popularity with farmers in East Africa suggests that adverse effects on associated crops are limited (Lott et al., 2000a). It is considered as the best support for black pepper (*Piper nigrum*) vines (Elouard et al., 2000; Ghazoul, 2007; Garcia et al., 2010). The association between coffee, pepper and *G. robusta* diversifies farm incomes, thus improves the economic resilience of planters (Nath et al., 2011). In addition to the use as soil mulch, the leaves of *G. robusta* are used by farmers of Kenya as a fodder supplement for cattle in the dry season when other fodder sources are scarce (Spiers and Stewart, 1992).

2.2 Biomass production

High Biomass production is an important consideration in all tropical tree planting programmes. This is particularly significant in view of the rising CO_2 levels and growing need to sequester it. However biomass production varies considerably owing to variations in species-site relationship, rotation age, stand density interactions and cultural treatments (Landsberg et al., 1995). Nonetheless, it is useful to know the stocks of carbon as biomass per unit area, not only to facilitate choice of species but also to assess the impact of deforestation and re-growth rates on the global carbon cycle (Deans et al., 1996). Many reports from the tropics suggest vast variations in the biomass accumulation potential among tree species (Cobb et al., 2008; Arias et al., 2011).

2.2.1 Biomass production in natural forest

At present the greatest advances in woodland production ecology is being made by studies of primary production in forests known regionally to be the most productive (Ovington, 1962). Subedi (2004) found the AGB of *Quercus semecarpifolia* forests that extends throughout the temperate region in Nepal at six different localities were 479.17, 357.53, 462.6, 356.02, 272.15 and 304.21 Mg ha^{-1}. Behera and Misra (2006) estimated the AGB of individual tree species and total biomass per unit area at four different stages of a recovering tropical dry deciduous forest dominated by *Shorea robusta,* the total AGB was found to be 30.12, 49.21, 107.54 and 261.08 Mg ha^{-1} in 2, 4, 6 and 10 year stands respectively.

2.2.2 Biomass production in plantation

A plantation may be afforested land or a secondary forest established by planting or direct seedling. A gradient exists among plantation forests from even aged single species monocultures of exotic species with various objectives to mixed species native to the site with both production and biodiversity objectives. This gradient will probably also reflect the capability of the plantation forest to maintain normal local biological diversity (FAO, 2000).

The productive capacity of many fast growing trees exhibits substantial variability. Jayaraman et al., (1992) reported that *G. robusta* at 3.0 cm. DBH with a stocking density of 2050 trees ha^{-1} can produce a biomass of 7.5 Mg ha^{-1} but at DBH 5.1 cm. with stocking density of 1950 trees ha^{-1} produce a biomass of 15.74 Mg ha^{-1}. Similar studies have been reported in many species. Ceulemans (2004) calculated the biomass of 10 year old Scots pine (*Pinus sylvestris* L.) was 13.38 kg for 4.5-5.6 m tall trees with an average DBH of 7.16 cm. In yet another study in a 7-year-old *Acacia mangium* Wild stands in Kerala, India. Kunhamu et al. (2006) reported that the biomass ranged from 5.58 Mg ha^{-1} to 97.58 Mg ha^{-1} among different girth classes. The AGB of 20 year old *Bambusa bambos* raised in hedgerows, bamboo clumps averaged 2417 kg per clump with an average per ha accumulation of 241.7 Mg ha^{-1}(Kumar et al., 2005).

Biomass production in 11 multipurpose tree species compared on sandy loam soils in Andhra Pradesh, Rao et al. (2000) found that *Dalbergia sissoo* yielded maximum biomass (214.6 Mg ha^{-1}) followed by *Leucaena leucocephala* (187.8 Mg ha^{-1}) and *Acacia auriculiformis* (162.4 Mg ha^{-1}). Gopikumar (2009) compared the biomass production potential of 12 MPTs grown in Kerala the results of the study revealed that among species studied, the total biomass production was found to be maximum for *Terminalia tomentosa* followed by *Adenanthera pavonina* while the lowest total biomass was produced by *Swietenia macrophylla*..

2.2.2.1 Biomass and age

It was revealed by many studies conducted in different species globally that the biomass production increases with increasing age. Sharma and Ambasht (1991) found that biomass production of an age sequence of Himalayan alder (*Alnus nepalensis*) plantation ranged from 106 Mg ha^{-1} in 7 year old stand to 606 Mg ha^{-1} in 56 year old stand. The biomass of 2-8-year-old plantations of *Eucalyptus terilicornis* hybrid growing in the Tarai region of central Himalaya was found to be increased from 7.7 Mg ha^{-1} in the 2-year-old to 126.7 Mg ha^{-1} in the 8-year-old plantation (Bargali et al., 1992). Lodhiyal (1995) also estimated total plantation biomass of 5-8-year-old poplar (*Populus deltoids* clone D-121) plantations growing in the Tarai belt of U.P, increased from 84.0 Mg ha^{-1} at 5 year to 170.0 Mg ha^{-1} in 8 year. In dry tropical region, it varied from 5.65 Mg ha^{-1} in 5-year-old plantation to 135.5 Mg ha^{-1} in 9-year-old plantations. In a study conducted by Jangara et al. (2010) in a 25 year old *G. robusta* plantation on a reclaimed sodic soil at Karnal in northern India, biomass accumulation in different components (Mg ha^{-1}) was: 216.943 bole > 41.380 branches > 7.590 foliage and the total aboveground net production was 17.389 Mg ha^{-1} yr^{-1}. In a 10 year old *G. robusta* stands in the mid hill of western Himalaya biomass production was found to be 345.274 Mg ha^{-1} (Gopichand and Sing, 2011). In a study conducted by Zhang et al., (2012) on differentially aged *Eucalyptus* and *Acacia* plantations in the pearl river Delta of South China found that the accumulation of biomass increased with stand age reaching 207.45 and 189.35 Mg ha^{-1} in mature *Eucalyptus* and *Acacia* plantations respectively.

Singh and Toky (1993) found the biomass in 4-year-old stands, AGB was markedly higher for *Leucaena leucocephala* (112 Mg ha^{-1}) and *Eucalyptus tereticornis* (96 Mg ha^{-1}) than for *Acacia nilotica* (53 Mg ha^{-1}) whereas in 8-year-old stands the values were 126 Mg ha^{-1}, 102 Mg ha^{-1} and 77 Mg ha-^{1} respectively. The total standing biomass of shisham (*Dalbergia sisoo*) increased with increasing age and diameter from 53.09 at 3 years to 160.04 Mg ha^{-1} at 7 years (Das and Chaturveadi, 2003). Negi et al. (1995) found the biomass production of 10 and 30-

year-old *Tectona grandis* was 74 Mg ha^{-1} and 164.1 Mg ha^{-1}. The biomass production in an age series of *Casuarenia equisetifolia* plantations in Puri, Orissa ranged from about 19 Mg ha^{-1} (5 year) to 130 Mg ha^{-1} (15 years) with 76 per cent to 83 per cent being contributed by the AGB. Vidyasagaran (2003) reported biomass production of *Casuarina equisetifolia* at an age of 2 year is 42.3 Mg ha^{-1} and at 9 years as increased to 366.82 Mg ha^{-1}, which shows that the AGB increased 9 times from 2 years to 9 years in the plantation of central Kerala.

Comparative productivity of 9-year-old *Acacia auriculiformis* and *Casuarina equisetifolia* was studied by Kushalappa (1987a) in high rainfall areas of Karnataka which revealed that the AGB of *Casuarina equisetifolia* was 68.9 Mg ha^{-1} and for *Acacia auriculiformis* it was 81 Mg ha^{-1}. Karmacharya and Singh (1992) described the AGB for *Tectona grandis* plantation which ranged from 25.7 to 76.9 Mg ha^{-1} in an age series of 4 to 30 years. whereas Adu-Anning et al. (1995) assessed the AGB accumulation of 34-year-old *Anogeissus leiocarpus*, 16-year-old *Tectona grandis* and 10-year-old *Azadiracta indica* in the Sudin Savanna of Ghana and reported as the biomass production were 29.1, 8.6 and 7.7 Mg ha^{-1} respectively. In an age series of *Anthocephalus chinensis* total biomass produced at age 12, 24 and 36 was 0.71 Mg ha^{-1}, 12.3 Mg ha^{-1} and 35.8 Mg ha^{-1} respectively (Chandra, 2011).

2.2.2 Agroforestry

Considerable species variation in biomass production was reported in a study conducted on biomass accumulation by multipurpose trees in woodlot and silvipasture experiments of three age sequences in Kerala (Kumar et al., 1998). The study revealed that biomass accumulation was highest for *Acacia auriculiformis* as 141,184 and 326 Mg ha^{-1} at 5, 7 and 8.8 years respectively. *Paraserianthus falcateria* registered the second highest biomass yield of 183 Mg ha^{-1} and *Leucaena* the lowest (93.4 Mg ha^{-1}). Singh et al. (2004) found the biomass of three clones (IC, D-121,G-3) of *Populus deltoids* at 4, 6, 8 and 10 years age in central Himalayan Tarai region varied from young (32-42 Mg ha^{-1}) to nature stands (120-170 Mg ha^{-1}). Swamy and Puri (2005) stated that at age 5 years, total stand biomass in agrisilvicultural system was 14.1 Mg ha^{-1}. Roy et al. (2006) estimated the biomass production on eight year old trees *Azadirachta indica* on farm boundaries and found as 21 Mg ha^{-1}.

Swamy et al. (2012) studied the biomass production of different tree species planted in shelterbelt agroforestry system of northern transitional zone of Karnataka and reported maximum amount of AGB for *Acacia auriculiformis* (57.65 Mg ha^{-1}) followed by *Tectona grandis* (55.57 Mg ha^{-1}) and *Azadirachta indica* (46.10 Mg ha^{-1}).

2.3 Biomass productivity

Productivity is the rate at which biomass is synthesised. Net production by an individual plant is the amount of organic matter that is synthesised and accumulates in tissue per unit time (Whittaker and Marks, 1975). Biomass productivity of trees varies with species, site relationships, rotation age and stand density interactions and cultural treatments (Landsberg et al., 1995). Considerable variations are exists in the AGB productivity of many tropical trees.

The productive capacity of many fast growing trees exhibit substantial variability. Jayaraman (1992) reported *G. robusta* as a slow grower after compairing with four fast growing species in Kerala. They noted that the dry matter production at 4.5 years (1950 trees ha^{-1}) with a mean DBH of 5.1 cm. is only 3.5 Mg $ha^{-1}yr^{-1}$ but in a 10-year-old *G. robusta* plantation grown in western Himalaya with a density of 14,000 and 10,000 trees ha^{-1} showed a productivity of 34.52 Mg ha^{-1}(Gopichand and Singh, 2011). Bargali et al. (1992) found that NPP of 2 to 8 year old plantations of *Eucalyptus tereticornis* growing in the Tarai region of central Himalaya was 8.6 Mg ha^{-1} in the 2 year old to 23.41 Mg ha^{-1} in the 8-year-old plantation. Lodhiyal (1995) reported NPP of 5 to 8-year-old poplar (*Populus deltoides* clone D-121) plantations growing on four sites on the Tarai belt of Utter Pradesh. The production increased from 16.8 Mg $ha^{-1}yr^{-1}$ in the 5 and 6-year-old to 31.8 Mg ha^{-1} in the 8-year-old plantation. Rao et al. (2000) in a study on the biomass production of some important MPTs, maximum mean annual production was found to be maximum for *Dalbergia sissoo* (23.8 Mg ha^{-1}) followed by *Leucaena leucocephala* (20.9 Mg ha^{-1}) and *Acacia auriculiformis* (18.0 Mg ha^{-1}). Vidyasagaran (2003) also reported the productivity of *Casurina equisetifolia* plantations at an age 2 years is 21.2 Mg $ha^{-1}yr^{-1}$ and at 9 years it is increased to 40.8 Mg ha^{-1} yr^{-1} in the coastal plains of central Kerala. In a seven year old *Acacia mangium* Wild. stand in Kerala, the total AGB production was 35.04 Mg ha^{-1} yr^{-1} (Kunhamu et al., 2006).

Singh and Torky (1993) recorded aboveground productivity 33 Mg ha^{-1}yr^{-1} for *Leucaena leucocephala* followed by 29 Mg ha^{-1}yr^{-1} for *Eucalyptus tereticornis* and 14 Mg ha^{-1} yr^{-1}for *Acacia tortilis* in 4-year-old stands in the arid climatic zone of Western India. Harmand et al. (2004) estimated the mean aerial woody biomass of three tree fallows, *Acacia polycantha, Senna siamea* and *Eucalyptus camaldulensis* of five year age are ranged 5-30 Mg ha^{-1} yr^{-1}, 3.81 Mg ha^{-1} yr^{-1} and 5.73 Mg ha^{-1} yr^{-1} respectively.

In a coffee and cocoa production system interplanted with *Cordia alliodora* and *Erythrina poeppigiana* of Latin America, it was estimated that the tree component alone gave about 10 Mg ha^{-1} yr^{-1} of biomass (Russo and Busowski, 1986). In a hedgerow intercropping system in Nigeria, *Gliricedia sepium* produced 3 to 4.5 Mg ha^{-1} yr^{-1}(Yamoah et al., 1986). Nigam and Roy (2006) conducted an experiment in 12 year old *Acacia tortilis* under silvopastorial system the mean woody biomass was 4.79 Mg ha^{-1} yr^{-1} and the total aerial biomass production was 4.95 Mg ha^{-1} yr^{-1}. In another study Rizvi et al. (2012) noted that in a *Eucalyptus tereticornis* based agroforestry system in North-western India, biomass productivity varied from 13.6 Mg ha $^{-1}$ for 6-year-old to 33.81 Mg ha^{-1} for 10-year-old plantations.

Sharma and Ambasht (1991) revealed the primary production of *Alnus nepalensis* plantation in Kalimpong forest division of the Eastern Himalayas was reduced to 25 Mg ha^{-1} yr^{-1} in 7 years and 13 Mg ha^{-1} yr^{-1} in 56-year-old stands. Shanmughavel et al. (2001) studied the NPP in an age series of *Bambusa bambos* plantations in India, the NPP was found to be highest in the 5th year, during which a peak of 124.1 Mg ha^{-1} yr^{-1} in NPP was obtained. Tateno et al. (2004) studied the NPP along topographic and soil N availability gradient in a cool temperate deciduous forest in Japan, the total AGB NPP ranged from 1.5 to 7.7 Mg ha^{-1}

2.2.1 Biomass partitioning

Biomass partitioning among various tree components considerably vary with species and age. The partitioning of dry matter between different components namely leaf, bole, branch wood, have significant importance in production forestry. Biomass partitioning varies considerably in different components of the tree. Generally bole fraction accounts bulk of total tree biomass. For *Eucalyptus grandis* planted at different age sequences at Kerala, India. Tandon et al. (1988) reported that percentage contribution of bole biomass varied from 28 per cent to 86 per cent over a period of 3-9 years. However the percentage contribution of leaf, twig and branches decreased with increasing age and diameter. In *Tectona grandis,* the bole fraction accounted 64.6 per cent of the total AGB at the age of 10 years, which declined to 60.2 per cent at the end of 30th year. However, branch wood proportion substantially increased from 8.3 to 35.15 per cent over the same period (Negi et al., 1995).

In four multipurpose tree species, George (1993) observed that foliage has the least biomass yields ranging from 5.2 per cent in *Leucaena* to 8.5 per cent in *Casuarina* and boles with the highest relative allocation of total biomass (ranging from 66.59 per cent for *Leucaena* to as much as 71.74 per cent for *Casuarina*). Shujauddin and Kumar (2003) found that stem wood contribution was 70 per cent and foliage contributed the least 7 per cent in 8.8 year *Ailanthus triphysa* plantation in central Kerala.

The partitioning of dry matter between different components namely, leaf, reproductive parts, bole, branch wood and roots are a matter of considerable importance in agroforestry. Patel and Singh (1996) studied biomass distribution in 10 agroforestry tree species, reported that accumulation of biomass in different tree species was highest in stem, branch, twigs, roots and least in leaves and bark. Jaimini and Tikka (2001) compared the biomass partition of the 15 multipurpose trees grown in an agroforestry system in Gujarat and found that among the trees, *Albizia lebbeck* had the maximum trunk and branch weight while *Acacia nilotica* var. *Cupressiformis* had the minimum values for these attributes, the highest twig weight per tree was observed in *Dalbergia sissoo* while minimum values was in *Moringa oleifera.*

2.3 Allometric relations

The most precise way to measure and monitor AGB, and to estimate the state and change in C stocks, for a stand is through periodic destructive harvesting (Brown et al., 2004; Saglan et al., 2008). Unfortunately, cutting and weighing a sufficient number of trees to represent the size and species distribution in an ecosystem is complex, time consuming, destructive, tedious, and labour intensive (Kale et al., 2004; Delittiet et al., 2006). In addition, destructive harvesting of trees in long-term studies and reforestation projects is not possible. Therefore, non-destructive techniques have been developed to determine AGB of forest and agroforestry tree species (Lott et al., 2000c; IPCC, 2003; Saatchi et al., 2007). These methods are based on regression models that relate biomass and growth parameters by allometry (FAO, 1997; Claesson et al., 2001).

Over the past five decades, considerable number of allometric equations have been developed to quantify the amount of AGB in individual trees and entire forest ecosystems (Jenkins et al., 2003; Navar, 2009). Even though a large number of biomass equations exist for different species and forest types, new equations need to be developed for accurate estimations of forest biomass and carbon stocks (Zapata-Cuartas et al., 2012). The financial incentives of current and future carbon markets are high, but cost-effective methodologies are an important incentive for forest managers to participate in these markets (Thomas et al., 2010).

Biomass estimation equations generally vary with species, age, bole shape and/or bole wood density (Clark and Clark, 2000; Chambers et al., 2001). Variations in these characteristics result from one or more of the following causes i.e. genetic differences between populations, environmental variability among sites, or crowding for trees that affect tree shapes (Campbell et al., 1985). Over the past decades, a number of studies have established allometric relationships to quantify biomass of aboveground components at the branch and /or tree levels for tropical trees as well (Onyekwelu, 2004; Montagu et al., 2005). For example allometric scaling equations on the basis of total tree height (H) and basal diameter have been developed for a range of agroforestry species like *Sesbania sesban* in Kenya and Negev desert in

Israel (Otieno et al., 1991), *Azadrachta indica* in India (Kumar and Tewari, 1999), and *Grevillea robusta* in Kenya (Lott et al., 2000c).

Many of these prediction equations for estimating tree components (foliage, branches, stem wood and bark) are however, site-specific (Ter-Mikaelian and Korzukhain, 1997). Furthermore, summing individual components to estimate total AGB often results in complexities to ensure the components sum to the predicted total for the tree (Parresol, 1999). Consequently, directly estimating total AGB using a single allometric equation is preferred. For instance Kumar et al. (1998) adopted a two-pronged strategy for evolving biomass equations for MPTs in a woodlot and silvo-pastoral experiment. They developed species-specific equations for a specific age class and management regime and evolved generalized biomass equations that are independent of tree age, location or management regime.

Multiple regression models were found to be suitable for predicting biomass of many species including *Casuarina equisetifolia* as reported by Dash et al. (1991) and Ghan et al. (1993). Kunhamu et al. (2006) found out regression equations linking above ground biomass dry weight, tree volume with GBH (cm) and tree height (m) in a seven year old *Acacia mangium* Wild. stand in Kerala, India. In their study, prediction equations based on single variable gave good fit with high R^2 values.

Kumar et al. (2005) brought out allometric relationships linking clump biomass and culm number with clump diameter of 20-year-old hedge rows of *Bambusa bambos* the fitted equations gave high R^2 value and gave reasonably good predictions of culm number per clump and standing stock of clump biomass. Gurumurthi and Rawat (1989) reported that both DBH and height as independent variables gave best equations for predicting biomass of *Casuarina equisetifolia.* In general the diameter and height are used as predictor variable for biomass prediction equations. In *Eucalyptus piluaris,* Montagu et al. (2005) observed that using DBH alone as the predictor variable produced the most stable relationship. The inclusion of height as second predictor variable decreased the performance of the general model with DBH alone as an independent variable. (Dudley and Foewens, 1992; Ghan et al., 1993; Tandon et al., 1993 and Rana et al., 2001).

The quadratic prediction model of leaf, branch yield with two variables (DBH and crown diameter) was a reliable predictor of leaf branch yield of thirteen agroforestry species suitable to Himalayan areas (Gupta et al., 1990). Christine (1992) estimated biomass of 6 to 7-year-old *Acacia mangium* plantations using allometric regression and found that the total biomass could be estimated within a relative error of 4 per cent. Many workers reported that standard deviation and coefficient of determination were the major criteria for the selection of best regression model (Tandon et al., 1988; Deans et al., 1996).

Logarithmic transformation of equations was observed to give best prediction for biomass in many species (Negi and Sharma, 1987 and Kushalapa, 1987b). Khan and Pathak (1996) reported the prediction of biomass in *Leucaena leucocephala* (Lam) ranging from 3.5 to 7.5 years growth, Transformate Y=log (1+x) was used for normality of data. Khan et al. (1995) did use regression analysis for biomass of three multipurpose trees, *Acacia tortilis, Hardwickia binnata* and *Leuceana leucocephala* planted under agro-silvi pasture and farm forestry experiments. Logarithmic transformation was most suitable for *Acacia tortilis* and *Hardwickia binnata* while square root transformation was most suitable for *Leuceana leucocephala.*

In allometric regressions, the parameters may not be always suitable for comparing different models because the dependent variables differ from one model to another. Therefore, it is possible to compare the different models by an index developed by Furnival (1961). Thapa (2005) developed prediction models for above ground wood of some fast growing trees *Acacia auriculiformis, Acacia catechu, Dalbergia sissoo, Eucalyptus camaldulensis, Eucalyptus tereticornis* and found that the lowest Furnival index (FI) was the main criteria for selecting a model. Among the six models tested the transformed model ln= a+b Ln DBH from a power equation W= a DBH was selected. With the exclusion of branch wood models R^2 is higher in a range of 88.7 per cent for oven dry stem wood of *Acacia catechu* to 99.3 per cent for above ground wood model of *Dalbergia sisoo.* However R^2 was less than 80 per cent in branch wood (green and oven dry) of *Acacia auriculiformis, Eucalyptus camaldulensis, and Eucalyptus teriticornis* showing moderate relationship between branch wood and DBH. In the case of *E. tereticornis* precision is more than 49 per cent which leads to low reliability in biomass estimation resulting in true biomass deviating in arrange of about 49.51 per cent to 56.74 per cent.

Kushalapa (1993) reported that in the prediction of standing biomass of *Eucalyptus* hybrid, coefficient of determination alone is not suitable for comparing different weighted and transformed model because the dependent variables differ from one model to another and therefore the best model for predicting aboveground biomass and components was selected based on equation with maximum coefficient of determination and lowest Furnivall index values.

For the prediction of the biomass of trees regression equations were used widely. Roy et al. (2006) calculated the biomass prediction equation based on regression analysis with D^2 and D^2H were developed in 8-year-old *Melia azadirachta* planted on farm boundaries. The relationship of bole and total aerial biomass was found to be strong with all the predictor variables whereas relationship of foliage was strong with D^2 and D^2H only. Rana et al. (1993) applied two regression models to asses differences in per tree biomass estimation of similar aged plantations 4, 6 and 8 to 10-year-old stands of three cotton wood clones (*Populus deltoides* 1C,D-121, G-3 clones) planted in Tarai region of central Himalaya. The mean per cent variation in biomass estimation (kg $tree^{-1}$) of different components for three ages combined are within the permissible limits. They concluded that DBH should be preferred over the model having D^2H as independent variable.

2.4. Nutrient accumulation

The nutrients accumulated in a forest ecosystem depend on the type of forest species present, density, age, basal area, altitude, climatic conditions as well as the soil conditions and the relative moisture content (Mitchell et al., 1996; Wang et al., 1996, Das and Chadurvedil, 2003). A direct result of high biomass accumulation rate is that the nutrient accumulation rates are also correspondingly high. The component wise nutrient distribution of 3 to 7-year-old plantation of shisham (*Dalbergia sissoo*) in Pusa was studied (Das and Chaturvedi, 2003). Their study revealed that nutrient content of the standing tree increased with plantation age because of an increase in dry matter accumulation. Higher amount of N, P, K, Ca and Mg was accumulated in bole and branches. In a study on the nutrient (NPK) accumulation in an age sequence of MPTs in Kerala, *Acacia auriculiformis* had the highest N accumulation rate of 1539 kg N, 1113 Kg P and 623 Kg K at 7 years of age and 998 Kg N, 49 Kg P and 478 Kg ha^{-1} K at 5 years of age when grown in association with forage grasses (Kumar et al., 1998).

Pande et al. (1987) reported the nutrient distribution in 4, 6, 8, 12 and 14-year-old plantations of *Pinus kesiya*, indicated that harvesting stem biomass (68%) at 12-year-old would remove nearly 6.9 kg N, 7 kg P, 33 kg K and 47 kg Ca. A substantial amount of nutrients was accumulated in the foliage (36 % of N, 34 % of P, 36 % of K, 9 % of Ca, and 15 % of Mg) and it is suggested that this should be left on site to minimize nutrient loss after harvesting. Morris (1992) reported biomass (Mg ha^{-1}) and nutrient content of eleven 1 to 2 years old *Pinus patula* stands in a high yielding section of Usutu forest, treating these stands as an age series sample of a single yield class, the pattern of accumulation over time at the rotation age (17 years) the biomass contained 551 kg ha^{-1} N, 73 Kg ha^{-1} P, 383 Kg ha^{-1} K, 283 Kg ha^{-1} Ca and 88 Kg ha^{-1}. Annual rate of nutrient accretion in to biomass peaked at 6 to 8 years, when the rate of canopy development was greatest.

Pande (2004) estimated the distribution of different nutrients in different life forms, their allocation in different tree components and nutrient cycling in teak forests of Satpura Plateau. The allocation of nutrients was higher for bole and lowest for leaves, irrespective of sites. The accumulation of nutrients in bole was higher for disturbed and mature sites whereas the trend was reverse for leaves. The contribution of teak in total biomass nutrients were 62.7, 70.1, 84.6 and 99.9 per cent for site I, II, III and IV respectively. Caldeira et al. (2002) quantified the nutrient content of the *Acacia mearnsii* De Wild. provenance Bodalla, Brazil at the age of 28 months they found that among the nutrient contents are contributed, 42.6 per cent of the dry matter accounted for leaves and living and dead branches, which in turn account for 74 per cent of N, 72 per cent of P, 63 per cent of K, 68 per cent of Ca, 69 per cent of Mg and 74 per cent of S of the above ground biomass. The trunk (bark and wood) represents the remaining 57.4 per cent of the total AGB. Mohsin et al. (2005) estimated the concentration of N, P, K (kg ha^{-1} yr^{-1}) in different components of

Populus deltoids at 2-3 and 6-7 ages under Agronomy system. It is observed that N, P, K in different ages decreased with increase in age of plantations.

2.4.1 Nutrient concentration

Ranasinghe (1992) studied the distribution of nutrients in *Eucalyptus camaldulensis* plantations ranging in age from two to fourteen years, at two sites in the dry zone of Sri Lanka. There were high nutrient concentrations in leaves and bark the lowest concentrations were in the bole (without bark). Shujauddin and Kumar (2003) showed that foliar N, P, K concentration is the highest, followed by branch wood, course roots and stem wood. In a study on the nutrient distribution (N, P,K, Ca, Mg, Fe, Mn, Zn, Cu and B)in middle aged *Acacia crassicarpa* plantations in South China, the results indicated that concentration of the 10 nutrient elements in different organs were in the order of leaves > bark > branch > root > stem (Bin et al., 2012). In a study on the nutrient (NPK) dynamics in 5 to 15-year-old Shisham (*Dalbergia sissoo* Roxb.) stands growing in central Himalaya. The concentrations of nutrients on different components were in the order: reproductive parts > leaf > twig > bole > bark > branch > bole wood (Lodhiyal et al., 2002).

Sharma (1993) studied the dynamics of four macro-nutrients in an age series (7, 17, 30, 46 and 56 years) of Himalayan alder (*Alnus neplensis*) plantations in the Kalimpong forest division of the eastern Himalayas, West Bengal and reported that concentrations of nutrients were in the order N>K>Ca>P in most tree components and in understorey vegetation. There was an inverse relation between nutrient concentrations of perennial parts and diameter at breast height. Xue (1996) also reported that in *Cunninghamia lanceolata,* among different nutrients N constituted highest concentration (0.07% to 1.37 %) and P the least (0.005% to 0.08%) (Singh, 1994). Similar observations are found in *Cryptomeria japonica* and in *Pinus Patula* by Singh (1982).

In a study on 5, 7, 9, 11 and 15-year-old *Pinus caribea* stands the concentration of nutrients (N, P, K, Ca and Mg) decreased in the following order: needles > branches > stembark > stemwood. (Kadeba, 1991). Bargali et al. (1992)

studied the nutrient dynamics in 2 to 8-year-old plantations of *Eucalyptus teriticornis* and reported that the concentrations changed in the order: herb > shrub > tree. Nutrient concentrations in different components of these vegetation types decreased with plantation age. Lodhiyal (1995) reported on nutrient dynamics in 5 to 8-year-old poplar *(Populous deltoids* clone 'D-121' plantation in the Tarai belt of Uttar Pradesh. They found nutrient concentrations in different layers of the vegetation were in the order: tree>shrub>herb.

In a study on the effect of stand age on the accumulation of nutrients on the above ground components of an Aleppo pine ecosystem Alifragis et al. (2001) compared 9 pine species with an age sequence of 23, 48, 70, >100 and reported that nutrient concentrations, except of Ca which mostly accumulates in high quantities in older plant matter, follow the general order: foliage > bark > branches > wood for N and K; foliage > branches > bark >wood for P; and foliage> small branches > bark > large branches > wood for Mg. With regards to age, Ca was the most abundant macronutrient in the aboveground vegetation followed by N, K, Mg the nutrient accumulation followed an increasing rate with increasing age. In a short rotation high density (1 - 4-year-old) central Himalayan Tarai Poplar plantation Lodhiyal and Lodhiyal (1996) noted that the standing state of nutrients increases with plantation age.

Nutrient allocation during the different growth stages of a stand is of particular importance in order to find out the conditions responsible for the nutrition of the stand. Furthermore, such studies provide the means to assess the effects of different management methods and to determine the rotation time, as well as, the degree of forest stand thinning (Wang et al., 1996). In addition, they provide information in order to evaluate the amount of nutrients lost during harvesting (Ranger et al., 1995).

2.4.2 Nutrient use efficiency

Sustainable production without adversely affecting site quality is an important criterion in all short rotation intensive cultural systems. Nutrient use efficiency, i.e. the amount of biomass produced per unit of a certain macro- or micronutrient, is a useful measure to assess the nutrient demand and the productivity of a tree species on a site (Shujauddin and Kumar, 2003).

Large differences may exist in nutrient use efficiency among tropical tree species (Montagini et al., 1994). So species selection that considers nutrient use efficiency therefore is a potential tool available to the foresters to alter the 'nutrient cost' associated with such systems (Kumar et al., 1998). Comparing the nutrient use efficiency and biomass production of five tropical trees, Wang et al. (1991) have shown that *Casuarina equisetifolia* with the highest growth rate had twice as efficient as *Leuceana leucocephala* for N, 3-4 times as efficient as *Albizzia lebeck* and *Leuceana leucocephala* for K and about twice as efficient as all of the studied species for Mg. In a study Merino et al. (2005) found that *Eucalyptus globulus* plantations require the highest quantity of Ca, N and Mg to produce one unit of stem wood and is the low nutrient efficient compared to *Pinus radiata* and *Pinus pinaster*. Ma et al. (2007) observed that nutrient use efficiency of Chinese fir (*Cunninghamia lanceolata*) increased significantly for all nutrients from young to mature stands.

2.5 Nutrient export through harvest

Repeated harvesting in short rotation cycles could remove considerable amounts of nutrients from the site decreasing tree productivity by depleting soil nutrients (Richter et al., 2001; Mackensen et al., 2003; Yamada et al., 2004). The amount of nutrient depletion depends on species characteristics, growth rate, tissue nutrient content, harvesting rotation period, harvesting methods used and nutrient reserves in the soil. With respect to soil nutrients reserves, it has been demonstrated that in tropical soils, it can be modified through the export of biomass (trunk and bark), confirming the need to study the impact of different tree species harvesting on soil nutrient depletion. Well reported examples for tropical species include: *Gmelina arborea* and *Pinus caribaea* (Chijicke, 1980); *Tectona grandis* (Haise and Folster, 1983); *Agathis damara* (Bruijnzeel and Wiersum, 1985); *Pinus radiata* (Birk, 1993); *Pinus caribaea* (Waterloo, 1994), *Eucalyptus hybrid* PFI -Clone 1.41 (Laclau et al., 2000), *Eucalyptus camaldulensis*, *Eucaliptus grandis* and *Dalbergia sissoo* (Hunter, 2001), *Acacia mangium, E. globulus*, and *E. grandis* (Yamada et al., 2004) and *Gmelina arborea* (Swamy et al., 2004). The above studies summarised that a number of soil nutrients, particularly potassium (K) and phosphorus (P), are susceptible to depletion by the extraction of whole bole (stems + bark).

Verma et al. (1987) studied nutrient distribution in different aged plantations of *Casuarina equisetifolia* and found that the harvesting of utilisable biomass would result in the removal of 59 per cent N, 50 per cent P, 63 per cent K, 65 per cent Ca and 66 per cent Mg of the total amount of nutrients retained in the AGB. Pande et al. (1987) found that in *Eucalyptus* hybrid, harvesting of utilizable biomass at the age of 10 years would result in the removal of 52 per cent N, 70 per cent P, 66 per cent K, 78 per cent Ca and 67 per cent Mg. Kumar et al. (2005) estimated the nutrient export (N, P, K) of hedge row raised 20-year-old *Bambusa bambos,* varied, highest in live culms, followed by leaves + twigs and dead culms. Average N, P, K and removal were 9.22, 1.22, and 14.4 kg per clump respectively. Nutrient removals increased as more biomass is harvested and the loss per unit biomass is much higher in leaves, branches and bark then for stem wood (Binkley, 1986).

Nutrient removal at harvest from the site depends on both nutrient concentration of tissue fractions and the biomass yield. Heavy nutrient drain associated with harvest has been reported by Negi et al. (1995) for *Tectona grandis* (removal of 148 Mg ha^{-1} biomass) which resulted in the loss of 247, 41, 170, 632 and 198 kg ha^{-1} of N, P, K, Ca and Mg respectively. In a 7-year-old *E. tereticornis* and *E. grandis* plantation in 4 different sites of Kerala, removal of all AGB led to potential exports on average by 312 per cent for K, 619 per cent for Ca, and 764 per cent for Mg compared with the removal of stem-wood-only (Sankaran et al., 2005).

According to Hopman et al. (1993), who analysed ecosystem in south eastern Australia, nutrient removals from wood generally represented only a small percentage of available soil reserves. Nutrient content of bark was higher compared to stem wood and therefore, export of nutrients as a result of harvesting was significantly reduced by on site debarking. The removal of forest residues from poor sites should be avoided in all cases, because it would further reduce the nutrient availability in these already nutrient poor sites (Burger, 2002).

2.6 Carbon Sequestration

The United Nations Framework Convention on Climate Change (UNFCCC) defines carbon sequestration as the process of removing C from the atmosphere and depositing in a reservoir. It entails the transfer of atmospheric CO_2, and its secure storage in long-lived pools (UNFCCC, 2007). In the current scenario there is a growing social awareness of potential environmental problems caused by global warming. This is associated with the increase in Greenhouse Effect Gases (GEG), which were first emitted during the Industrial Revolution in the nineteenth century. Even in the most optimistic of scenarios, climate change can be detrimental to several production chains, with a strong impact on developing economies which depend largely on agriculture. Carbon dioxide (CO_2) is considered to be the most important greenhouse gas that plays a vital role in global warming and climate change (USEPA, 2005). A number of studies stated that forest carbon sequestration is a viable and cost effective option for reducing global greenhouse gas emissions (Newell and Stavins, 2000; Sedjo, 2002; Richards and Stokes, 2004).

The potential role of forest tree plantations in sequestering carbon to reduce the buildup of CO_2 in the atmosphere has been recognized (IPCC, 2001). According to FAO report, the total carbon stock in Indian forests amount to 10.01 Gt C, the forest soil accounts for 50 per cent of the total soil carbon (FAO, 2006). Tree based systems accumulate large amount of biomass and sequester substantial amount of carbon in perennial tree components. Approximately 88 per cent of the total tree biomass in plantation and agroforestry systems is stored mostly in tree trunks as aboveground biomass, and the remaining as belowground (Sharrow and Ismail, 2004).

2.6.1 Intra specific variation in carbon concentrations

An extensive review of existing literature yielded a total of 253 species-specific stem wood carbon fractions, owing to 31 peer-reviewed publications; In a study conducted by Laiho and Laine (1997) on the biomass and carbon accumulation into tree stand and distribution between tree stand components in two undrained and four drained Scots pine (*Pinus sylvestris* L.) revealed that the mean dry mass weighted carbon concentration (% of dry mass) in different tree biomass components as in the order in Pines: foliage (53.8) > bark (53.1) > dead branches (52.7) > stemwood (51.8). Zhang et al. (2009) showed the mean stem carbon of the 10 Chinese temperate species (49.9 ±1.3%) as very close to the generic value (50%). However the stem carbon was significantly affected by species and varied from 43.4 per cent for aspen to 55.6 per cent Amur cork-tree. This carbon is slightly wider than that for the 41 North American tree species (46.3-55.2%) (Lamlom and Savidge, 2003). In an another study by Elias and Potwin (2003) on 32 tropical tree species it was found to be 44.4-49.4 per cent; but it is lower than that for a 50-year-old maritime pine stand (51.4-58.7%) (Bert and Danjon, 2006). In a study on the carbon sequestration potential of fast growing trees, Keeratiurai et al. (2012) found that *Anthocephalus chinensis* and the *Eucalyptus* and the *Leuceana salvadore* at concentrations of 3 years of carbon in the trunk. Average stem (48.51, 48.86, 49. 80), branch (43.24, 53.95, 45.34), leaf (47.90, 52.29, 51.03) and root (46.78, 46.93, 45.09) per cent, respectively, statistical tests showed that the average of all four of these the difference is significantly different.

Failing to account for the inter-and intra-specific variations in carbon will introduce a relative error of -6.7 per cent to +7.2 per cent in estimates of biomass carbon stock from inventory data of which > 93 per cent is attributed to ignoring the inter specific variation in carbon (Zhang et al., 2009). In a 20 year old teak plantation in Panama, the mean shoot carbon storage is 104.5 Mg ha^{-1}, leaves, flowers and fine roots 49.2 and 46.4 per cent and obtained an average of teak tree carbon concentration as 49.5 per cent (Kranzel et al., 2003). In 10 chinese temperate tree species the overall tissue carbon concentration followed an order of foliage > new branch > old branch > course root > fine root and the mean tissue carbon concentration across the 10 species varied from 47.1 ± 0.8 per cent for fine root to 51.4 per cent ± 1.0 per cent for foliage.

2.6.2 Carbon estimation

Data on carbon content of tree tissues, and in particular stem wood, are essential for accurate assessments of forest carbon sequestration. The figure of 50 per cent (w/w) carbon content of woody tissues on a mass/mass basis has been used almost universally in the literature, and has been promulgated by the governmental and scientific bodies such as the IPCC (IPCC., 1990). This figure is also assumed in essentially all ecosystem models concerned with carbon fluxes and pools (Brown, 1997). Some argue that a 50 per cent (w/w) generic value could be an oversimplification and that currently there is better information available to improve the carbon content estimations for the concept of 'carbon credits'. For example several authors found that conifers tend to have appreciably higher wood carbon content than do hardwoods (angiosperms): 51.5 per cent conifers vs. 48.4 per cent hardwoods in USA (Lamlom and Savidge, 2003), 52.6 per cent conifers. Some analysis shown that the carbon concentration may range from 47 to 59 per cent as function of tree compartment or species (Laiho and Laine, 1997; Lamlom and Savidge, 2003). Empirical data from stem cores of 59 Panamanian rainforest tree species demonstrate that wood carbon content is highly variable among co-occurring species, with an average (47.4 ± 2.51% S.D.) significantly lower than widely assumed values (Martin and Thomas, 2011).

Currently, nearly all estimates of tropical forest carbon pools and fluxes assume all tissues (i.e. wood, leaves, and roots) consist of 50 per cent carbon on a dry mass basis. In highly diverse tropical forests, overlooking species-specific wood carbon content reduces the importance of floristic composition as a potential driver of forest carbon dynamics, and may produce biases in tropical forest carbon inventories (Martin and Thomas, 2011). Generally, woody tissues in trees ≥1 cm DBH comprise the largest fraction (95%) of biomass in tropical forests (Hughes et al; 2000; Chave et al., 2003; Kriby and Potvin, 2007; Nogueira et al., 2008; Pyle et al., 2008). Yet of all wood functional traits, only wood density (WD) has been explicitly evaluated with regard to tropical forest biomass and carbon pools to date (Baker, et al., 2004).

In an extensive review on the methodological challenges in estimating carbon sequestration potential of agroforestry systems, Nair (2011) clearly stated the erroneous assumption of carbon content in biomass as 50 per cent of the dry weight. In an in-depth review of carbon allocation in trees, Cannell and Dewar (1994) claim that "there is surprisingly little understanding of the mechanisms that govern carbon allocation has fallen far behind research on processes such as photosynthesis and now severely limits our ability to construct process-based models of whole plants". This state of affairs probably prevails today, although significant success has been achieved in modelling allocation (Landsberg and Sands, 2011).

Carbon occurs in innumerable forms within forest ecosystems; however, wood represents the dominant pool wherever trees at normal stocking density are at sapling stage or larger (Savidge, 2000). At present, there are actually few research data sets on carbon content in woods (Lamlom and Savidge, 2003). A generic carbon concentration of 50 per cent (w/w) has been assumed and widely promulgated (Dewar and Cannell, 1992; Mathews, 1993; Zhang et al., 2009), but other reports supported by little if any data claimed that carbon content of wood varies, depending on the species, at least over a range from 47–59 per cent (Hollinger et al., 1993; Zhang et al., 2009). In defence of the latter reasoning, each kind of wood tends to be chemically as well as anatomically unique. Therefore, it would seem reasonable to expect that each could have characteristic carbon content (Savidge, 2000). Efforts are needed in order to increase confidence for carbon accounts in the land use sector, especially in tropical forest ecosystems that often need to turn to default values given the lack of precise and reliable site specific data to quantify their carbon sequestration and storage capacity.

Although, it is claimed that accurate carbon concentration can be estimated through elemental analysis, direct cross-study comparison of carbon concentration is problematic because of no standard sampling protocol on carbon measurements with respect to biomass sampling, sample preparation, etc. (Zhang et al., 2009). Several workers tried diverse methodologies, for example, Lamlom and Savidge (2003) measured the carbon in kiln-dried heartwood, whereas Thomas and Malczewski (2007) measured that in sapwood of increment cores with two sample preparation protocols (freeze vs. oven-dried at 105°C). It is also noted that sapwood and heartwood have peculiar chemical and structural characteristics, and thereby may have different carbon concentration. The carbon concentration in heartwood is usually greater than that in sapwood mainly due to their differences in chemical composition (Bert and Danjon, 2006; Fukatsu et al., 2008). Various temperature regimes of sample treatment also introduce sample weight loss (Lamlom and

Savidge, 2003), and there was ± 2.2% of volatile C loss when samples were dried at 105°C (Thomas and Malczewski, 2007).

Biomass production is an important consideration in all tropical tree planting programmes. This is particularly significant in view of the elevated CO_2 concentrations in the atmosphere and associated climate change. To determine the role of forests in mitigating atmospheric CO_2 content globally, as a starting point it is essential to have accurate inventory of carbon content in forest organic matter. (Dewar, 1991). Wood represents the dominant pool wherever trees at normal stocking density are at sapling stage or larger (Savidge, 2001). At present, there are actually few research data sets on carbon content in woods (Lamlom and Savidge, 2003). Examination of the role of tropical plantations as C sinks necessitates integrative approaches to evaluate not only the rates of carbon sequestration by different tree species, but also their design and management to minimize potential deleterious effects on ecosystem nutrients.

Materials and Methods

MATERIALS AND METHODS

The present investigation was carried out in 20-year-old silver oak (*Grevillea robusta* A. Cunn. ex R. Br.) stand (Plate 1) at the Instructional Farm, College of Forestry, Kerala Agricultural University, Vellanikkara, Thrissur district, Kerala. The details about the experimental site, materials used and methodology adopted are as follows.

3.1 Location

The experimental site has an elevation of 40.29 m above sea level and located at 10^0 13^1 N latitude and 76^0 13^1 E longitude.

3.1.1 Climate

Vellanikkara experiences a warm humid climate, with a mean annual rainfall of 2903 mm (mean corresponding to the twenty year period from 1991-2011), most of which is received during the South- West monsoon (June to August). The mean maximum temperature ranges from 29.6°C (July) 35.5°C (March) and the mean minimum temperature varies from 22.3°C (January) to 24.8°C (April). Temperature means corresponding to the twenty-year period from 1991 Jan. to 2011 Dec. (Fig.1).

3.1.2 Soil

The soil of the experimental site is an Ultisol (TypicPlinthustultVellanikkara Series midland laterite-Ustic moisture regimes and Isohyperthermic temperature regimes) having a P^H of 5.19.

3.2 Experimental design and treatments

The proposed experimental site forms part of an earlier field trial carried out on *Grevillea robusta*to evaluate its performance as function of density and fertilization. This was established during1991in split plots with stand density as main plot and fertilizer regimes as sub plots. (Trees were fertilised as per the treatment protocol, thrice during August 1992, Sept. 1993 and Sept. 1996). It was proposed to select sample trees according to the treatments but after careful plot by plot observation and counting, it was found that sufficient numbers of sample trees

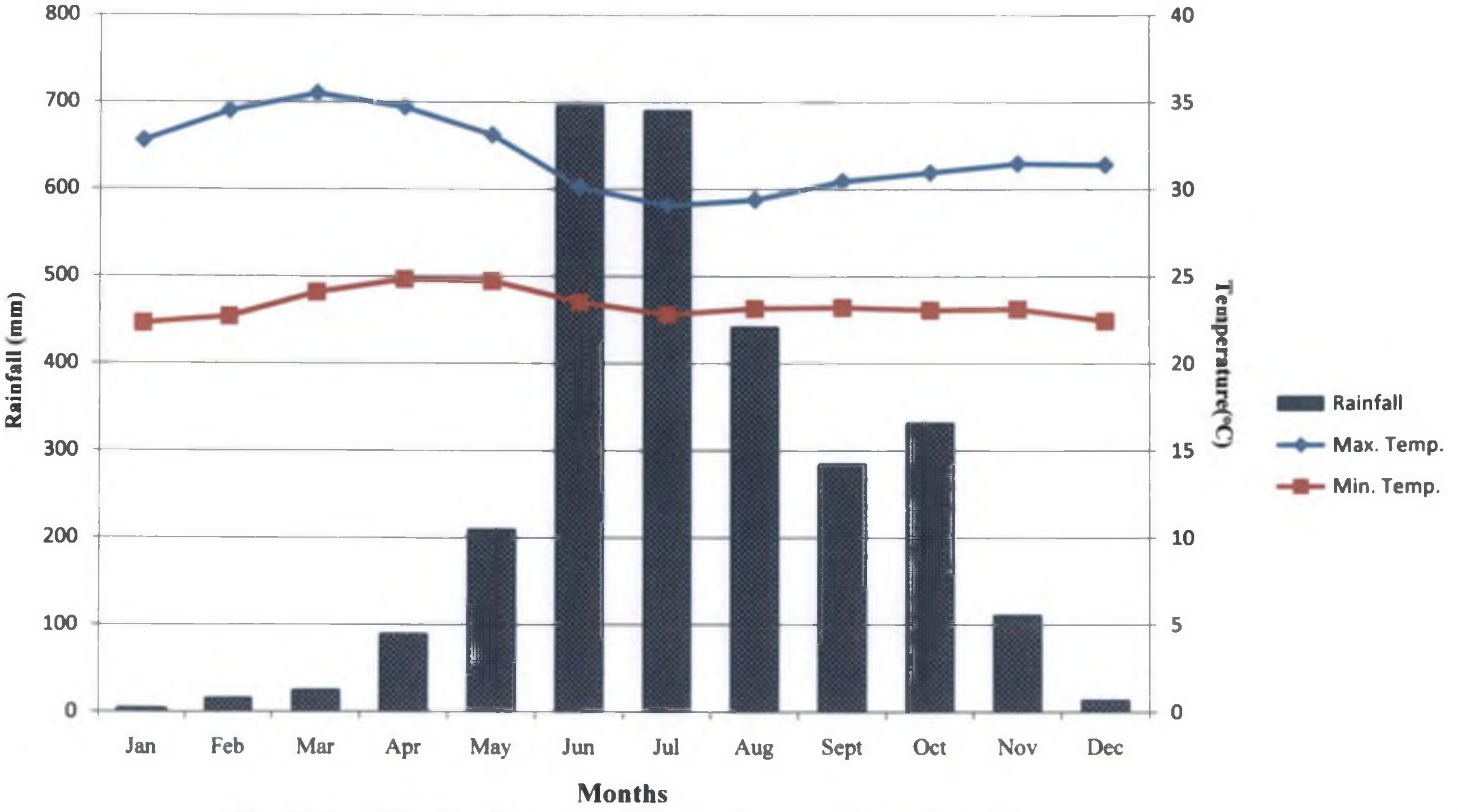

Fig. 1 Mean Weather Parameters During the experimental Period (Jan 1991 - Dec 2011)

are not available at the treatment level. Hence, it was decided to disregard the treatments and to select trees according to size class for biomass study. Accordingly the trees were grouped in to three diameter classes ranging from 5-15.0, 15.1-25.0 and above25 and 36 trees were destructively sampled in total.

3.3 Destructive sampling

The selected trees were felled at the ground level using a chainsawwithout disturbing the surviving trees, during December, 2011 (20-year-old).

The following observations were recorded on the felled trees.

1. Total height (m)
2. Height up to first crown forming branch (m)
3. Commercial bole height (m)
4. Girth at breast height (1.37 m)
5. Mid girth of 2m. billets made from the bole

After carefully recording the observations, the aboveground portions of the felled trees were separated in to stem wood (main shoot; if the main shoot is forked below BH level (1.37 m), then such branches were also treated as stem wood), branches, (above 5 cm (gob) and below 20cm (gob) twigs (below 5 cm (gob) and leaves (Plate 4). Fresh weights of all the above components (Plate 3) were recorded immediately after felling using digital spring balance (to nearest 0.1 kg).

3.4 Biomass sampling

Representative foliage and branch wood samples (ca 500g) were collected from the felled trees and were transferred to laboratory in double sealed polythene bag for moisture determination and chemical analysis.

Stem disks (ca 2cm thick) were cut (Plate 2) at base, breast height and at the base of the crown from all the trees for moisture determination and phytochemical analyses. The samples were immediately transferred to the laboratory in double sealed polythene bags and fresh weights were recorded soon. After recording the fresh weights, they were oven dried to constant weights at 70^{o}C and ground to pass

Plate1: 20-Year-old *Grevillea robusta* plantation

Plate 2: Sampling tree disks for moisture estimation

Plate 3: Weighing components using digital spring balance

Plate 4: Leaves separated for weighting

through a 2mm sieve using a Wiley mill. Estimates of biomass dry weight were obtained from the fresh weight of various tissue-types and their corresponding moisture contents. Biomass of tree parts were summed to obtain the total AGB per tree. The average oven dry biomass of component parts were summed to obtain the total AGB per tree. It was then multiplied by the number of trees per hectare and converted to stand AGB on hectare basis.

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

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

3.5 Volume estimation of felled trees

After felling, the stemwood was marked in to 2 m. sections and mid girth (ob) of each section was measured. The volume corresponding to each section was calculated using the formula $g^2/4\pi \times L$ (Where g is the mid-sectional girth and L is the length of section). Summing up all the sectional volumes will give the total volume of the tree. Volume up to the bole height (bole volume) and up to total height (total volume) were computed for each tree.

3. 6 Biomass prediction

The biomass data of all the components of 36 sample trees were used to compute the biomass on unit area basis. Equations were developed for predicting AGB and different components of tree and volume at tree level using DBH and height of trees as predictor variables. These equations are then be applied to develop estimates of stand level biomass for which such measurements are available.

The following family of equations were evaluated by using the statistical package SPSS (Version 17).

1 $Y = a_0 + a_1{*}D$

2 $Y = a_0 + a_1{*}D + a_2{*}D^2$

3 $\ln Y = a_0 + a_1{*} \ln D$

4 $\ln Y = a_0 + a_1{*}D + a_2{*}D^2$

5 $\ln Y = a_0 + a_1{*}\ln D + a_2{*}(\ln D)^2$

6 $Y = a_0 + a_1{*}D + a_2{*} D^2H_1$

7\. $Y = a_0 + a_1{*}D + a_2{*} H_1 + a_3{*}D^2H_1$

8 $\ln Y = a_0 + a_1{*}D + a_2{*} H_1$

9 $\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_1)$

10 $\ln Y = a_0 + a_1{*} D + a_2{*} H_1 + a_3{*}D^2H_1$

11 $Y = a_0 + a_1{*}D + a_2{*} D^2H_2$

12 $Y = a_0 + a_1{*}D + a_2{*} H_2 + a_3{*}D^2H_2$

13 $\ln Y = a_0 + a_1{*}D + a_2{*} H_2$

14 $\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_2)$

15 $\ln Y = a_0 + a_1{*} D + a_2{*} H_2 + a_3{*}D^2H_2$

Where

a_0, a_1, a_2, and a_3 are parameters to be estimated.

D is diameter at breast height,

H_1 is the total height

H_2 is the Bole height

Ln indicates logarithmic transformation

The best fitting models in each case was selected using adjusted R^2, Furnival index and characteristics of residuals. Non-significant terms were eliminated while fitting the models. 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 hence,

$$\text{Furnivalindex} = \sqrt{MSE}$$

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

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

The model with maximum coefficient of determination and minimum Furnival index was selected to give the best fit.

3.7 Phytochemical analysis

Triplicate samples were analysed for N, P, and K (three sub-samples were drawn from the tissue samples for this purpose). Nitrogen was estimated following the micro-kjeldahl method, phosphorous and potassium were estimated after digesting the samples in a diacid mixture (H_2SO_4 and $HClO_4$ in 9:4 ratios). Phosphorous was determined following the Vanado-molybdo phosphoric yellow colour method using Milton Roy Spectronic1001 plus (Milton Roy, Rochester, Newyork) and potassium by flame photometry (Jackson, 1958). Total nutrients for whole tree were obtained by summing results for component parts. Nutrient use efficiency was estimated by dividing component-wise biomass accumulation with the corresponding nutrient accumulation values.

3.8 Carbon content determination

For carbon concentration analysis nine (three from each diameter class) of the 36 trees were sub sampled. From each of these nine trees sampled, a quarter sector of stem disc cut from the breast height (sampling the trunk at breast height for carbon provides a good indicator of whole trunk carbon concentration (Elias and Potvin, 2002))which better represented both sapwood and heartwood for trunk carbon concentration. For leaf, twig and branchrepresentative samples(ca500g) were taken.Oven-dried the samples at 70°C at which most estimates of biomass C are conducted. Samples are finely ground and analysed using an Elementarvario CHN analyser. Duplicates of every sample were analysed.

3.9 Statistical analysis

Statistical analysis was done with the help of statistical software SPSS V.17.0. Biomass prediction equations were developed using regression analysis.

Results

RESULTS

4.1 Growth attributes of sample trees

The field studies were conducted on 36 sample trees, selected on the basis of diameter class frequency distribution. There was marked variation in growth in each diameter class. The major attributes of tree growth and volume production of *Grevillea robusta* plantation are summarised in Table 1. Overall, the highest diameter class showed greater height (19.37 m) and diameter (32.17 cm) than others. This trend reflected in volume yield too (0.24 m^3). The height increased consistently with increasing diameter class. Mean height at the lowest diameter class (5-15 cm) was 11.86 m., but on the highest diameter class (25 cm above), it was as much as 19.37 m. With regards to bole height, although it increases with respect to the increasing diameter class it does not show as much variation as total height. For instance, it increased from 7.43 m. to 11.99 m. to the highest diameter class.

The volume was estimated from the planation at different diameter class. It was observed that the total volume incresed from 0.03 to 0.24 m^3. In the initial smaller diameters to the highest, it had shown an eightfold increase (0.03 - 0.24m^3). So it can also be infered from this trend that the diamter growth and volume yield are directly linked. Bole volume also showed a similar trend as the total volume, as it increased from 0.02 m^3 to 0.11m^3 so bole volume also shows a higher varition corresponding to the increasing diamter class. The mean annual increment from the lowest diameter class to the highest diameter class shown a variation from 0.01m^3 to 0.19 m^3 with a mean MAI of 0.007 m^3.

4.2 Biomass Production and accumulation

Dry matter production of sample trees was estimated from the samples collected. It was observed that AGB and the biomass components vary between different diameter classes. Biomass of average trees among various diameter classes are depicted in Table 2 and Fig 2. Total AGB accumulation on per tree basis ranged from 44.29 kg in lower diameter class (5-15 cm) to 317.61 kg in highest class (25-35 cm). In the case of biomass components of average trees, there was a significant difference between each

Table 1. Growth variables at different diameter classes in *G.robusta* stands

Diameter class	DBH (cm)	Height (m)	Bole height (m)	Bole volume (m^3)	Total volume (m^3)	MAI (m^3)
5-15	12.09 (0.65)	11.86 (1.04)	7.43 (1.16)	0.02 (0.001)	0.03 (0.004)	0.01 (0.001)
15-25	19.95 (0.88)	16.25 (0.56)	11.04 (0.52)	0.05 (0.004)	0.08 (0.008)	0.04 (0.003)
25 above	32.17 (1.01)	19.37 (0.56)	11.99 (0.53)	0.11 (0.007)	0.24 (0.029)	0.19 (0.054)
[a]Mean	24.07 (1.42)	16.91 (0.58)	10.86 (0.44)	0.07 (0.007)	0.14 (0.020)	0.007 (0.04)

(Values shown in parenthesis are standard error of means)

([a]Values are means of 36 sample trees)

component among different diameter class. The stem portion alone produced the biomass of 38.37 kg at 5-15,105.91 kg at 15-25 and 262.11 kg at diameter class above 25. So the stem portion showed noticeably higher biomass along with an increasing diameter class. Branches showed a greater increase from the second diameter class to the highest diameter class, it indicated a biomass of 2.35, 10.33, and 37.14 kg tree^{-1} at 5-15, 15-25, and 25 above diameter classes respectively. The leaves and twigs also indicated distinct difference among various diameter classes as it increases constantly till the higher diameter class. Leaves contributed a biomass of 2.79 kg at 5-15, 8.44 kg at 15-25 and 15.10 kg at above 25 whereas twigs produced a biomass of 0.77, 2.21, and 3.26 with respect to increasing diameter class. The components showed a similar decreasing order as stem > branch > leaves > twig except in the lowest diameter class in which the leaf portion showed a slightly higher biomass (2.79 kg tree^{-1}) compared to branch biomass (2.35 kg tree^{-1}). Hence in the lowest diameter class, the components showed a different trend as stem > leaf > branch > twigs.

4.2.1 Proportional distribution of biomass

Proportional distribution of biomass components to AGB is depicted in Table 3 and Fig. 3. Among the percentage of biomass distributed to different components, stem wood constituted highest percentage biomass and twig the lowest in all diameter classes. Contribution of the biomass components to the total AGB has shown an increasing trend, among various biomass components. However, percentage of the stem wood biomass is found to be decreasing with an increasing diameter class (86.64 - 82.53 %). This may be due to the distribution of photosynthates to other components like branches, leaves and twig. Biomass of leaves also showed a marked decrease in the highest diameter class (6.31 - 4.75 %) but a nominal (0.71%) decrease in the twig biomass at highest diameter class is observed. Contrary to other components, branches showed a marked increase with regards to an increasing diameter class. This trend may be due to the distribution and accumulation of the photosynthates to stem and branches as the tree grows. The sequence of biomass distribution was in the order stem > branch > leaf > twig in all diameter classes.

Table 2. Aboveground biomass and biomass components (kg tree^{-1}) for different diameter classes in *G. robusta* stands

Diameter class (cm)	DBH (cm)	Height (m)	Biomass components (kg tree^{-1})				
			Stem wood	Branch	Twig	Leaf	Total
5-15	12.08	11.86	38.37 (6.62)	2.35 (0.56)	0.77 (0.11)	2.79 (0.75)	44.29 (7.17)
15-25	19.95	16.25	105.91 (11.50)	10.33 (1.39)	2.21 (0.37)	8.44 (1.17)	126.88 (13.49)
25 above	32.17	19.37	262.11 (20.13)	37.14 (3.99)	3.26 (0.48)	15.10 (1.37)	317.61 (23.99)
Mean	24.08	16.91	164.08 (18.23)	20.92 (3.09)	2.44 (0.29)	10.46 (1.08)	197.89 (22.08)

(Values shown in parenthesis are standard error of means)

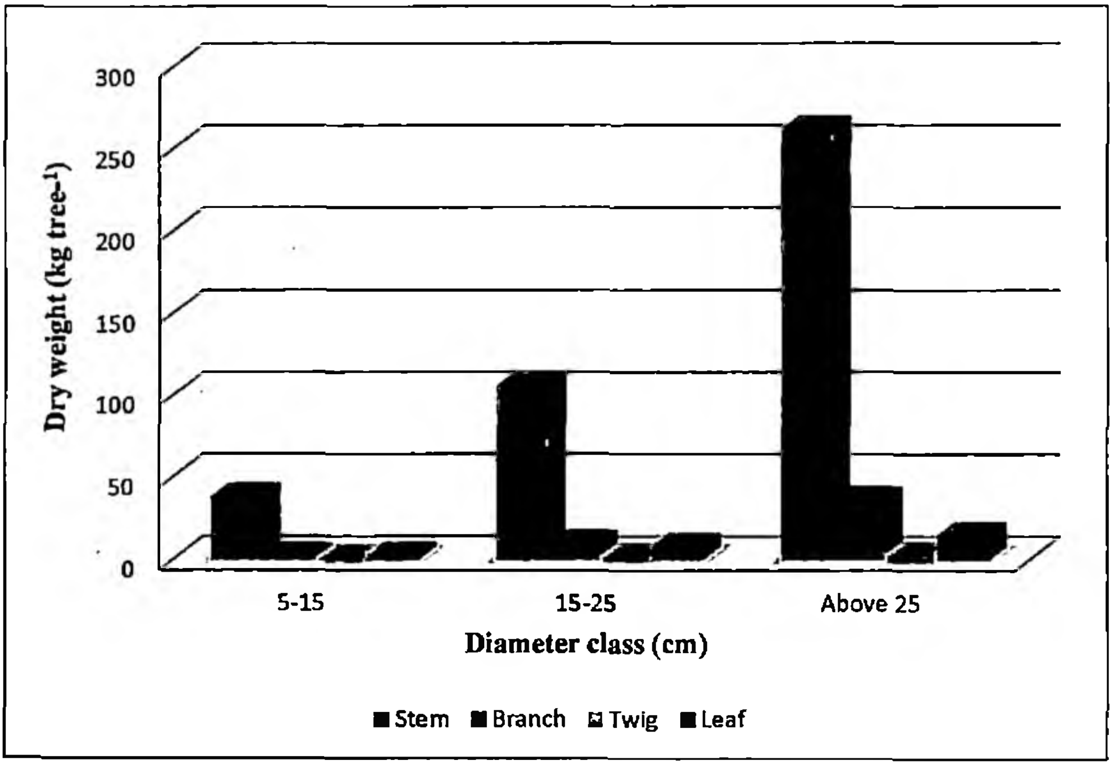

Fig. 2 Biomass production among various diameter classes in *G. robusta* stands

Table 3. Proportional distribution of biomass components to the total AGB in different diameter classes of *G. robusta* stands

Diameter class (cm)	Stem wood (%)	Branch (%)	Twig (%)	Leaf (%)
5-15	86.64	5.31	1.74	6.31
15-25	83.47	8.14	1.74	6.65
25 above	82.53	11.69	1.03	4.75
Mean	82.91	10.57	1.23	5.28

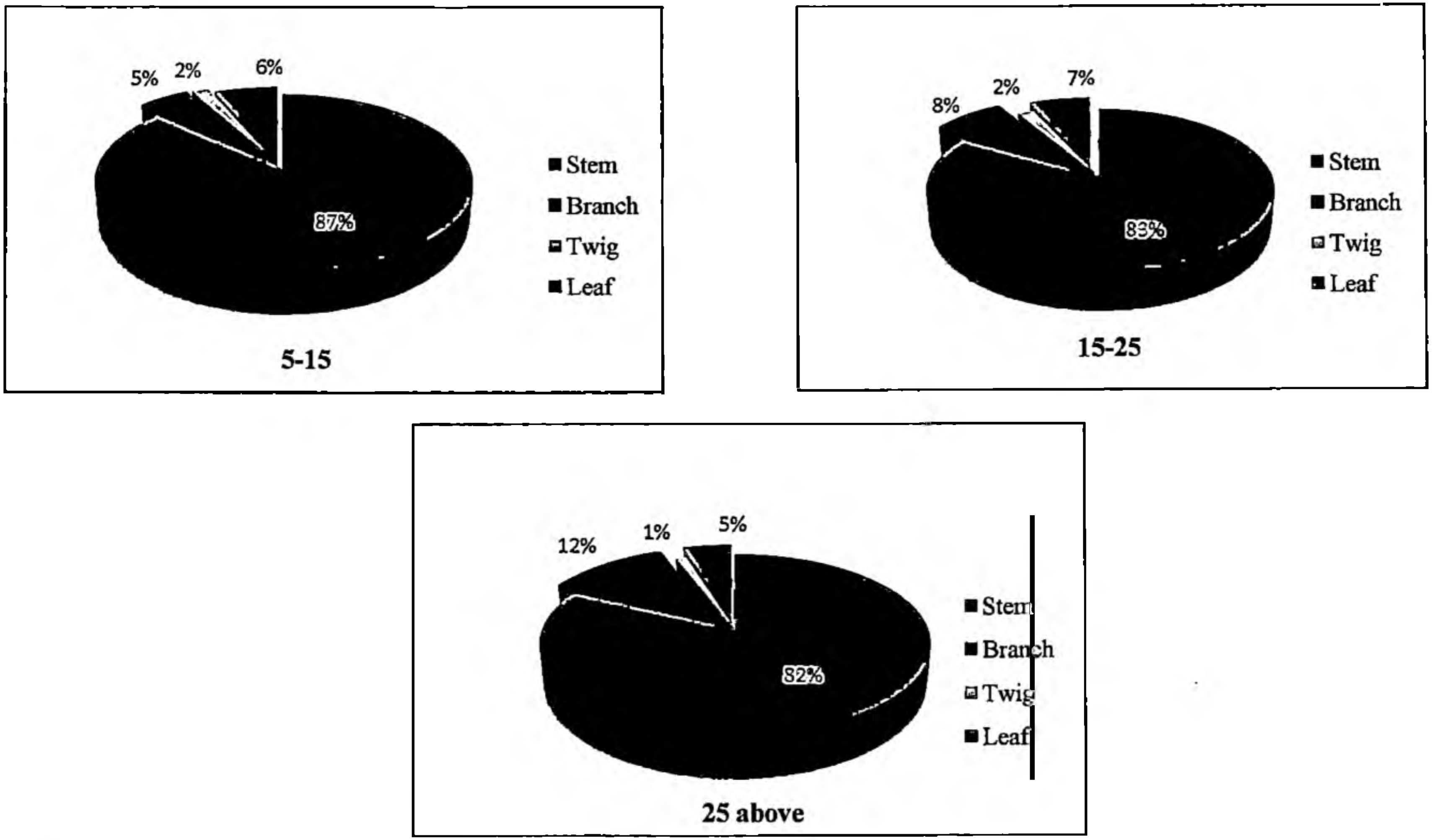

Fig. 3 Proportional distribution of various components to total dry weight in different diameter classes of *G. robusta* stands

4.2.2 Biomass production on unit area

The dry matter production per unit area is a function of age, density and growth parameters like DBH and height. As a result, conspicuous variation in the AGB and biomass of different components are observed in different diameter classes. Biomass production of different components on unit area in different diameter classes are given in Table 4. Total AGB on unit area basis varied considerably with diameter classes. However, unlike the steady increase in mean tree biomass with increasing diameter classes, the biomass accounted on unit area basis was well in terms with the number of trees per ha in different diameter classes. For instance the total AGB and biomass components followed a different trend at unit area whereas in the case of biomass components, there was a significant difference between each component towards increasing diameter class. The stem portion alone accumulated a biomass of 4.23 Mg ha^{-1} at 5-15, 28.6 Mg ha^{-1} kg at 15-25 and 19.38 Mg ha^{-1} at the highest diameter class. So the stem portion showed a different trend in unit area in which the contribution was increased in the second diameter class while it decreased in the highest diameter class. Density also may be a factor that influences the higher biomass production in the second diameter class. Branches also showed a different trend in which, the biomass production was decreased as it produces a biomass of 0.25 Mg ha^{-1}, 2.79 Mg ha^{-1} and 2.74 Mg ha^{-1} respectively at diameter class 5-15, 15-25 and 25 above. Both the leaves and twigs also indicated a significantly low biomass production among different diameter classes. Biomass components in various diameter classes had shown an increasing trend among various diameter classes, bole has acquired maximum biomass and twig has lowest. Among various diameter classes, the components showed a similar decreasing order as stem > branch > leaves > twig except in the lowest diameter class in which the leaf portion showed a slightly higher biomass (0.30 Mg ha^{-1}) compared to branch biomass (0.25 Mg ha^{-1}). So in the lowest diameter class, the components showed a different trend as stem > leaf > branch > twigs. The total aboveground biomass produced in unit area was 62.59 Mg ha^{-1}.

4.2.3 Biomass productivity on unit area

. The productivity (Mg ha^{-1} yr^{-1}) of *G. robusta* plantation was estimated and plotted in Table 5. It was seen that the productivity of biomass components between

Table 4. Aboveground biomass and biomass components of *G. robusta* stands (Mg ha^{-1})

Diameter class (cm)	Density (trees ha^{-1})	Biomass Production (Mg ha^{-1})				
		Stem wood	Branch	Twig	Leaf	Total
5-15	106	4.23	0.25	0.08	0.30	4.86
15-25	260	28.60	2.79	0.59	2.28	34.26
25 above	71	19.38	2.74	0.24	1.11	23.47
Total	437					62.59

Table 5. Component productivity of biomass in *G. robusta* stands (Mg ha^{-1} yr^{-1}).

Diameter class (cm)	Density (trees ha^{-1})	Biomass Productivity (Mg ha^{-1} yr^{-1})				
		Stem wood	Branch	Twig	Leaf	Total
5-15	106	0.204	0.012	0.003	0.014	0.234
15-25	260	1.381	0.134	0.028	0.110	1.655
25 above	71	0.936	0.132	0.011	0.053	1.133
Total	437					3.023

different diameter classes and productivity of AGB followed a similar trend in biomass production as it increased from 0.234 Mg ha^{-1} yr^{-1} at lowest diameter class to 1.655 Mg ha^{-1} yr^{-1} at second highest diameter class. The data also indicated that maximum difference in AGB was noticed in the highest diameter class. The difference in productivity between the second and third diameter class was found markedly high (0.522 Mg ha^{-1} yr^{-1}). All components in the second diameter class had shown comparatively high biomass productivity (1.381 Mg ha^{-1} yr^{-1}, 0 .134 Mg ha^{-1} yr^{-1}, 0 .028 Mg ha^{-1} yr^{-1}, 0 .110 Mg ha^{-1} yr^{-1}, 1.655 Mg ha^{-1} yr^{-1}). In the lowest diameter class, biomass components had shown less productivity than the second diameter class.

Among the biomass components, stem wood showed maximum biomass productivity while twig the lowest as indicated by biomass per unit area. At the lowest diameter class, the components showed a decreasing order of stem > leaf > branch > twig. But in the second and third diameter class, the components followed an order of stem wood > branch > leaf > twig.

4.3 Biomass Prediction

The basic data obtained from the 36 trees were used to compute the biomass prediction equation for stem, branch, twig, and leaves and total AGB. These trees showed considerable size class differentiation with DBH ranging from 9.90 cm to 39.40 cm and height from 8.65 m. to 22.40 m. Fifteen most commonly used equations were tried (Except for total height, in which equations with DBH alone are tried) of which first five of them are based on diameter at breast height (DBH) alone, next five equations were based on DBH and total height and the last five equations were based on DBH and bole height. The fifteen different models tried are given in Table 6.

When the above fifteen models were tried, it was essential to use certain criteria to select the best model. Similarly when large number of equations were proposed for constructing weight tables, difficulty may arise in deciding the most appropriate equations or a particular data. The standard error and coefficient of determination (R^2) were not sufficient for comparing different weighted and transformed models. This is due to the fact that dependent variable is changed from one model to another. However, it was made possible to compare the different models by an index developed by Furnival (1961). In all the equations either DBH alone, DBH and height, DBH and bole height together were used as independent variables and biomass of the components or total biomass or total and bole volume as dependent variable.

Different equations were tried for various components like stem wood, branch, twig, leaves and total dry weight and coefficient of determination and Furnival index values also estimated. Among the fifteen models tried, best fit was determined by coefficient of determination (R^2) and Furnival index. It was also checked that whether all the regression estimates involved in the equations was significant or not and also that whether there was significant improvement in R^2 value while incorporating additional variables as independent variables. In each case, the best for a single variable DBH and combined variables DBH and height were selected for the best fit. It indicated that single linear model (Model 1), quadratic form of models (models 2, 6. 7, 11, and 12) and exponential models (models 3, 4, 8, 9, 10, 13, 14, 15) were proved best fit for various components. The prediction equations for various components and total AGB was explained as detailed below

4.3.1. Aboveground biomass

Aboveground biomass predicted with different equations is depicted in Table 6 along with their R^2 values and Furnival Index.

Model 3 was the best fit equation with highest R^2 value and low Furnival index for the total AGB when the DBH alone as independent variable. The selected best fit model is furnished below (Appendix II)

Model 3 $\ln Y = a_0 + a_1 * \ln D$

$$\ln Y = -1.489 + 2.087 * \ln D$$

The reliability of prediction was also studied by plotting the observed and predicted values by using this equation. It proves a strong relation between DBH and total dry weight (Fig. 4).

When the DBH and total height were considered as the independent variables Model 9 proved as the best fitted equation with high R^2 value and low Furnival index (Appendix III).

Table 6. Various models tried for predicting total AGB in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1*D$	0.913	39.748
2	$Y = a_0 + a_1*D + a_2*D^2$	0.932	35.700
3	$\ln Y = a_0 + a_1* \ln D$	**0.952**	**27.594**
4	$\ln Y = a_0 + a_1*D + a_2*D^2$	0.949	29.172
5	$\ln Y = a_0 + a_1*\ln D + a_2*(\ln D)^2$	0.954	27.594
6	$Y = a_0 + a_1*D + a_2* D^2H_1$	0.917	39.408
7.	$Y = a_0 + a_1*D + a_2* H_1 + a_3*D^2H_1$	0.951	30.702
8	$\ln Y = a_0 + a_1*D + a_2* H_1$	0.947	29.553
9	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_1)$	**0.965**	**24.130**
10	$\ln Y = a_0 + a_1* D + a_2* H_1 + a_3*D^2H_1$	0.964	24.589
11	$Y = a_0 + a_1*D + a_2* D^2H_2$	0.914	40.057
12	$Y = a_0 + a_1*D + a_2* H_2 + a_3*D^2H_2$	0.939	34.195
13	$\ln Y = a_0 + a_1*D + a_2* H_2$	0.952	27.996
14	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_2)$	**0.967**	**23.183**
15	$\ln Y = a_0 + a_1* D + a_2* H_2 + a_3*D^2H_2$	0.967	23.661

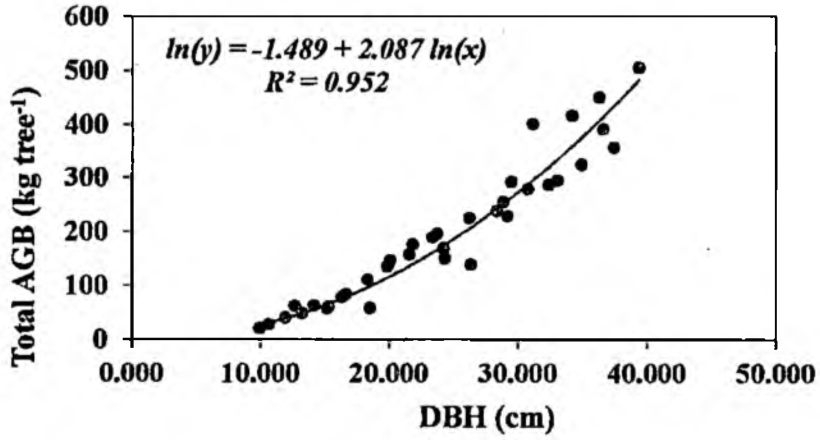

Fig. 4 Relation between DBH and total AGB in *G. robusta* stands

Model 9 $\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_1)$

$\ln Y = -2.518 + 1.646 * \ln D + 0.856 * \ln(H_1)$

When DBH and bole height were considered for prediction Model 14 had come as the best fitted equation with high R^2 value and low Furnival Index. The fitted equation is given below (Appendix IV).

Model 14 $\ln Y = a_0 + a_1 * \ln(D) + a_2 * \ln(H_2)$

$\ln Y = -1.836 + 1.863 * \ln(D) + 0.446 * \ln(H_2)$

Even though the Model 9 and 14 have higher R^2 value when compared to Model 1 the proportionate increase in R^2 value is very less compared to model 1 with an additional independent variable and also some of the coefficient was found to be non-significant.

4.3.2. Stem wood biomass

Various models tried for predicting stem wood biomass are depicted in Table 7. Among the equations with DBH alone model 3 has higher R^2 value and low Furnival index. The selected equation is given below (Appendix V).

Model 3 $\ln Y = a_0 + a_1 * \ln D$

$\ln Y = -1.559 + 2.051 * \ln D$

The reliability of prediction was also studied by plotting the observed and predicted values by using this equation (Fig. 5). It is observed that bole biomass has established good relation with DBH. Among the equations with DBH and total height, Model 9 was found to be the best equation with high R^2 value and low Furnival Index. The result of this equation is furnished as given below (Appendix VI).

Model 9 $\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_1)$

$\ln Y = -2.656 + 1.581 * \ln D + 0.913 * \ln(H_1)$

While adding bole height as an additional variable along with DBH Model 14 was found to be the best fit. The best fitted equation is given below (Appendix VII).

Model 14 $\ln Y = a_0 + a_1 * \ln(D) + a_2 * \ln(H_2)$

$\ln Y = -1.904 + 1.828 * \ln(D) + 0.443 * \ln(H_2)$

Table 7. Various models tried for predicting stem wood biomass in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1*D$	0.903	34.582
2	$Y = a_0 + a_1*D + a_2*D^2$	0.923	31.339
3	$\ln Y = a_0 + a_1* \ln D$	**0.939**	**25.550**
4	$\ln Y = a_0 + a_1*D + a_2*D^2$	0.935	26.739
5	$\ln Y = a_0 + a_1*\ln D + a_2*(\ln D)^2$	0.940	25.853
6	$Y = a_0 + a_1*D + a_2* D^2H_1$	0.911	33.681
7	$Y = a_0 + a_1*D + a_2* H_1 + a_3*D^2H_1$	0.953	24.729
8	$\ln Y = a_0 + a_1*D + a_2* H_1$	0.941	25.853
9	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_1)$	**0.954**	**22.648**
10	$\ln Y = a_0 + a_1* D + a_2* H_1 + a_3*D^2H_1$	0.954	22.989
11	$Y = a_0 + a_1*D + a_2* D^2H_2$	0.905	34.709
12	$Y = a_0 + a_1*D + a_2* H_2 + a_3*D^2H_2$	0.936	29.025
13	$\ln Y = a_0 + a_1*D + a_2* H_2$	0.943	25.244
14	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_2)$	**0.954**	**22.648**
15	$\ln Y = a_0 + a_1* D + a_2* H_2 + a_3*D^2H_2$	0.955	22.648

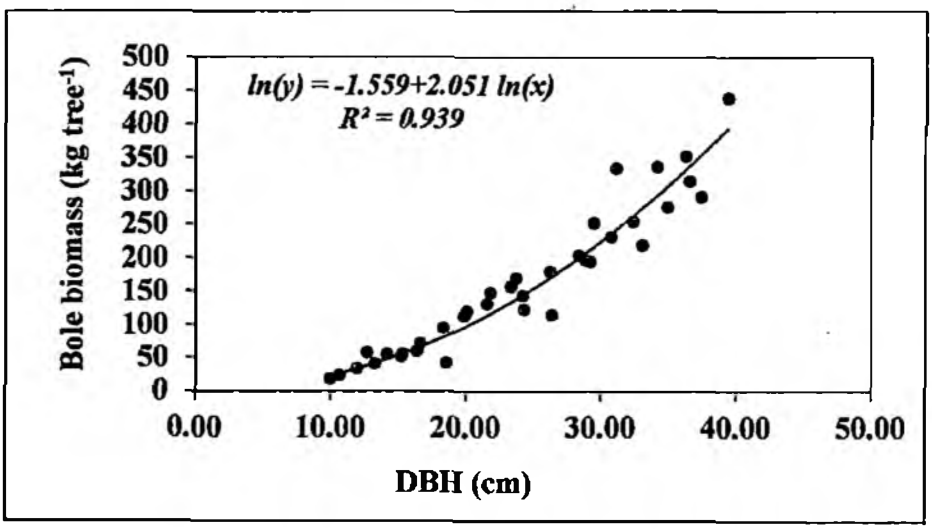

Fig. 5 Relation between DBH and stem wood biomass in *G. robusta* stands

4.3.3. Branch biomass

Prediction models were established for branch biomass with various independent variables are depicted in Table 8.

Among the equations with DBH alone model 3 was found to be suitable with high R^2 value and low Furnival Index.

The reliability of the prediction was also studied by plotting the observed and predicted values by using this equation (Fig.6). It has a good relation with DBH and branch biomass. The equation is further as below (Appendix VIII)

Model 3 $\ln Y = a_0 + a_1 * \ln D$

$\ln Y = -6.195 + 2.805 * \ln D$

It is observed that equations with DBH and total height as independent variables, Model 9 was found to be suitable for predicting branch biomass. The best fitted equation is given below (Appendix IX).

Model 9 $\ln Y = a_0 + a_1 * \ln D + a_2 * \ln H_1$

$\ln Y = -6.008 + 2.885 * \ln D - 0.156 * \ln H_1$

Among the equations with DBH and bole height, model 14 was found as a suitable equation with high R^2 value and low Furnival index. The selected equation is given as below (Appendix X)

Model 14 $\ln Y = a_0 + a_1 * \ln(D) + a_2 * \ln(H_2)$

$\ln Y = -6.318 + 2.725 * \ln(D) + 0.158 * \ln(H_2)$

4.3.4. Twig biomass

The models tried for twig biomass along with their coefficient of determination (R^2) and Furnival index are given in the Table 9.

The best model selected in which DBH alone as an independent variable was model 3 due to high R^2 value and low Furnival index. The equation is given below (Appendix XI).

Model 3 $\ln Y = a_0 + a1 * \ln D$

$\ln Y = -3.504 + 1.335 * \ln D$

The reliability of the prediction was also studied by plotting the observed and

Table 8. Various models tried for predicting branch biomass in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1{*}D$	0.742	9.558
2	$Y = a_0 + a_1{*}D + a_2{*}D^2$	0.761	9.331
3	$\ln Y = a_0 + a_1{*} \ln D$	**0.893**	**4.822**
4	$\ln Y = a_0 + a_1{*}D + a_2{*}D^2$	0.895	4.855
5	$\ln Y = a_0 + a_1{*}\ln D + a_2{*}(\ln D)^2$	0.896	4.839
6	$Y = a_0 + a_1{*}D + a_2{*}\ D^2H_1$	0.753	9.484
7	$Y = a_0 + a_1{*}D + a_2{*}\ H_1 + a_3{*}D^2H_1$	0.760	9.492
8	$\ln Y = a_0 + a_1{*}D + a_2{*}\ H_1$	0.854	5.728
9	$\ln Y = a_0 + a_1{*}\ln D + a_2{*}\ \ln(H_1)$	**0.894**	**4.888**
10	$\ln Y = a_0 + a_1{*}\ D + a_2{*}\ H_1 + a_3{*}D^2H_1$	0.895	5.501
11	$Y = a_0 + a_1{*}D + a_2{*}\ D^2H_2$	0.743	9.686
12	$Y = a_0 + a_1{*}D + a_2{*}\ H_2 + a_3{*}D^2H_2$	0.762	9.451
13	$\ln Y = a_0 + a_1{*}D + a_2{*}\ H_2$	0.863	5.559
14	$\ln Y = a_0 + a_1{*}\ln D + a_2{*}\ \ln(H_2)$	**0.894**	**4.872**
15	$\ln Y = a_0 + a_1{*}\ D + a_2{*}\ H_2 + a_3{*}D^2H_2$	0.886	5.142

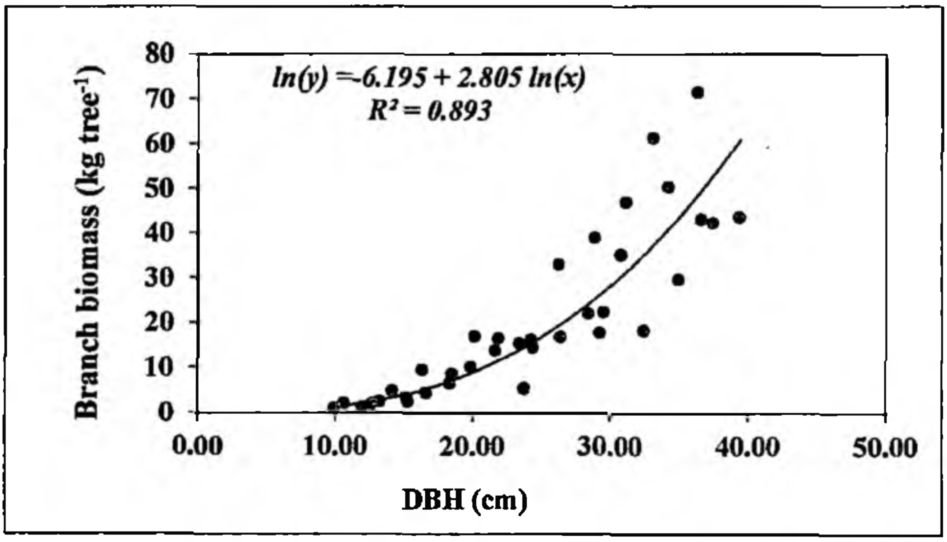

Fig. 6 Relation between DBH and branch biomass in *G. robusta* stands

predicted values by using this equation (Fig.7). It indicated weak relation with DBH. Among equations with DBH and total height as independent variable, model 9 has found to be the best prediction. (Appendix XII).

Model 9 $\ln Y = a_0 + a_1 * \ln(D) + a_2 * \ln(H_1)$

$\ln Y = -5.114 + 0.645 * \ln(D) + 1.340 * \ln(H_1)$

Among the different models tried with DBH and bole height as independent variable, model 14 was found to be suitable (Appendix XIII).

Model 14 $\ln Y = a_0 + a_1 * \ln(D) + a_2 * \ln(H_2)$

$\ln Y = -3.753 + 1.174 * \ln(D) + 0.320 * \ln(H_2)$

4.3.5 Leaf biomass

Models tried for predicting Leaf biomass are depicted in Table 10 along with coefficient of determination (R^2) and Furnival Index.

Among the different equations tried, model 5 was found to be suitable as best equation. (Appendix XIV). The reliability of the prediction
was also studied by plotting the observed and predicted values by using this equation (Fig.8).

Model 5 $\ln Y = a_0 + a_1 * \ln D + a_2 * (\ln D)^2$

$\ln Y = -12.010 + 7.360 * \ln D - 0.896 * (\ln D)^2$

Among the equations with DBH and total height as independent variable, model 10 was found to be a suitable equation (Appendix XV).

Model 10 $\ln Y = a_0 + a_1 * D + a_2 * H_1 + a_3 * D^2 H_1$

$\ln Y = -2.104 + 0.125 * D + 0.129 * H_1 - 0.0001 * D^2 H_1$

Comparing the equations with DBH and bole height as independent variable model 15 was found to be a better equation. (Appendix XVI).

Model 15 $\ln Y = a_0 + a_1 * D + a_2 * H_2 + a_3 * D^2 H_2$

$\ln Y = -1.954 + 0.145 * D + 0.150 * H_2 - 0.0001 * D^2 H_2$

Table 9. Various models tried for predicting twig biomass in *G. robusta* stands

Sl. No	Model tried	R^2	Furnival Index
1	$Y = a_0 + a_1{*}D$	0.363	1.427
2	$Y = a_0 + a_1{*}D + a_2{*}D^2$	0.366	1.446
3	$\ln Y = a_0 + a_1{*} \ln D$	**0.533**	**0.946**
4	$\ln Y = a_0 + a_1{*}D + a_2{*}D^2$	0.520	0.973
5	$\ln Y = a_0 + a_1{*}\ln D + a_2{*}(\ln D)^2$	0.543	0.950
6	$Y = a_0 + a_1{*}D + a_2{*} D^2H_1$	0.392	1.415
7	$Y = a_0 + a_1{*}D + a_2{*} H_1 + a_3{*}D^2H_1$	0.405	1.421
8	$\ln Y = a_0 + a_1{*}D + a_2{*} H_1$	0.563	0.929
9	$\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_1)$	**0.575**	**0.917**
10	$\ln Y = a_0 + a_1{*} D + a_2{*} H_1 + a_3{*}D^2H_1$	0.569	0.936
11	$Y = a_0 + a_1{*}D + a_2{*} D^2H_2$	0.364	1.447
12	$Y = a_0 + a_1{*}D + a_2{*} H_2 + a_3{*}D^2H_2$	0.369	1.464
13	$\ln Y = a_0 + a_1{*}D + a_2{*} H_2$	0.522	0.971
14	$\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_2)$	**0.543**	**0.950**
15	$\ln Y = a_0 + a_1{*} D + a_2{*} H_2 + a_3{*}D^2H_2$	0.554	0.952

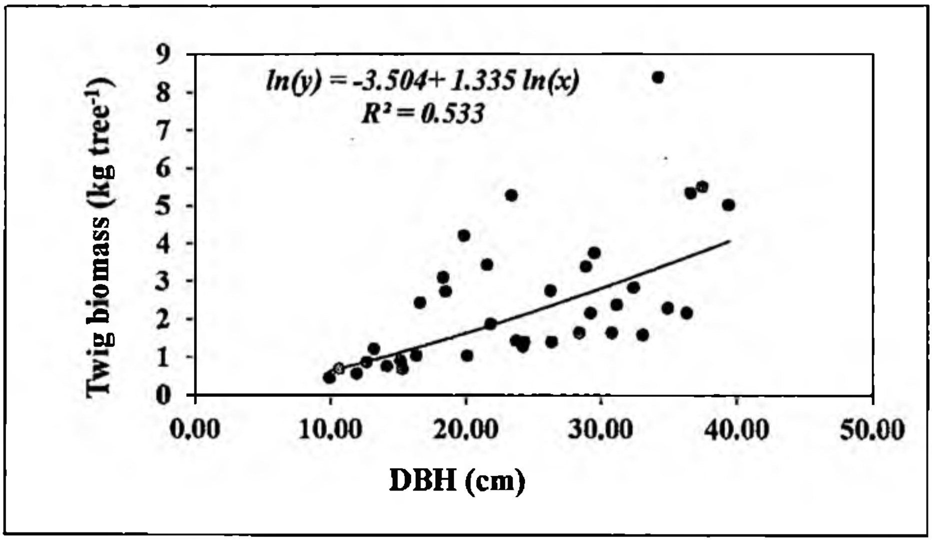

Fig.7 Relation between DBH and twig biomass in *G. robusta* stands

Table 10. Various models tried for predicting leaf biomass in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1{*}D$	0.748	3.303
2	$Y = a_0 + a_1{*}D + a_2{*}D^2$	0.749	3.345
3	$\ln Y = a_0 + a_1{*} \ln D$	0.777	3.271
4	$\ln Y = a_0 + a_1{*}D + a_2{*}D^2$	0.782	3.290
5	$\ln Y = a_0 + a_1{*}\ln D + a_2{*}(\ln D)^2$	**0.800**	**3.150**
6	$Y = a_0 + a_1{*}D + a_2{*} D^2H_1$	0.753	3.316
7	$Y = a_0 + a_1{*}D + a_2{*} H_1 + a_3{*}D^2H_1$	0.754	3.362
8	$\ln Y = a_0 + a_1{*}D + a_2{*} H_1$	0.772	3.368
9	$\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_1)$	0.809	3.078
10	$\ln Y = a_0 + a_1{*} D + a_2{*} H_1 + a_3{*}D^2H_1$	**0.818**	**3.057**
11	$Y = a_0 + a_1{*}D + a_2{*} D^2H_2$	0.748	3.199
12	$Y = a_0 + a_1{*}D + a_2{*} H_2 + a_3{*}D^2H_2$	0.755	3.357
13	$\ln Y = a_0 + a_1{*}D + a_2{*} H_2$	0.775	3.339
14	$\ln Y = a_0 + a_1{*}\ln D + a_2{*} \ln(H_2)$	0.814	3.036
15	$\ln Y = a_0 + a_1{*} D + a_2{*} H_2 + a_3{*}D^2H_2$	**0.841**	**2.850**

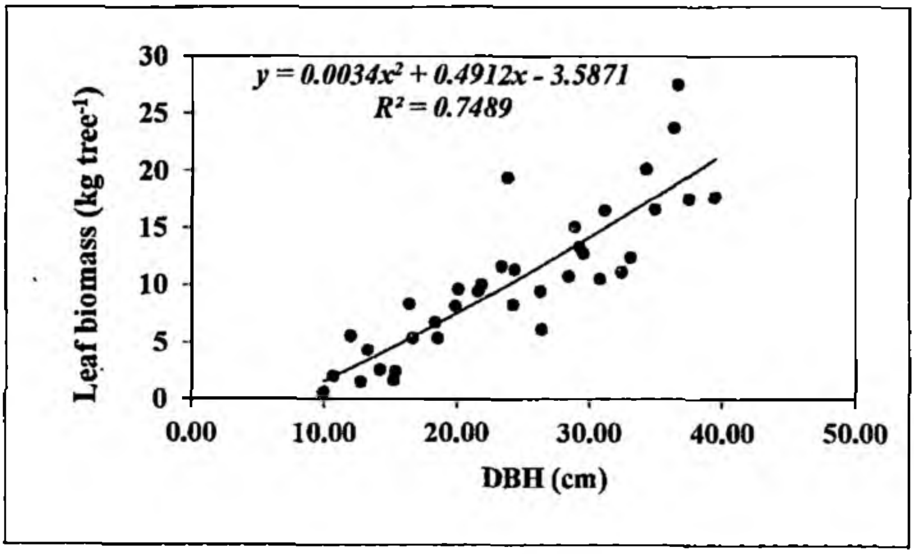

Fig. 8 Relation between DBH and leaf biomass in *G. robusta* stands

4.3.6 Total volume

The volume of all the felled trees were predicted by using different models along with their R^2 and Furnival index which presented in Table 11.

Among the equations tried, the best equation with DBH alone was model 4 with high R^2 value and low Furnival index. The selected equation is depicted as (Appendix XVII).

Model 4 $\ln Y = a_0 + a_1{*}D + a_2{*}D^2$

$$\ln Y = -4.982 + 0.140{*}D - 0.001{*}D^2$$

The reliability of prediction also studied by plotting the observed and predicted values by using this equation (Fig.9). It indicates a strong correlation with DBH and volume.

While considered the DBH and total height as independent variables the best fit equation with high R^2 value and low Furnival index was model 8. The selected equation is given as below (Appendix XVIII)

Model 8 $\ln Y = a_0 + a_1{*}\ D + a_2{*}\ H_1$

$$\ln Y = -4.573 + 0.088{*}\ D + 0.012{*}\ H_1$$

Among the equations when dbh and bole height were considered as independent variables model 14 had come as best fit with equation with high R^2 value and low Furnival index (Appendix XIX)

Model 14 $\ln Y = a_0 + a_1{*}\ln D + a_2{*}\ \ln(H_2)$

$$\ln Y = -7.897 + 2.434{*}\ln D - 0.823{*}\ \ln(H_2)$$

4.3.7 Bole volume

The bole volume of all the felled trees were predicted by using different models along with their R^2 and Furnival index are presented in Table 12

Among the equations tried, the best equation with DBH alone was model 4 with high R^2 value and low Furnival index. The selected equation is shown as (Appendix XX)

Model 4 $\ln Y = a_0 + a_1{*}D + a_2{*}D^2$

$$\ln Y = -5.590 + 0.156{*}D - 0.002{*}D^2$$

The reliability of prediction also studied by plotting the observed and predicted values by using this equation (Fig.10). It indicates a strong relation

Table 11. Various models tried for predicting total volume in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1 * D$	0.713	0.063
2	$Y = a_0 + a_1 * D + a_2 * D^2$	0.757	0.063
3	$\ln Y = a_0 + a_1 * \ln D$	0.889	0.030
4	$\ln Y = a_0 + a_1 * D + a_2 * D^2$	**0.900**	**0.028**
5	$\ln Y = a_0 + a_1 * \ln D + a_2 * (\ln D)^2$	0.900	0.028
6	$Y = a_0 + a_1 * D + a_2 * D^2 H_1$	0.722	0.063
7.	$Y = a_0 + a_1 * D + a_2 * H_1 + a_3 * D^2 H_1$	0.752	0.063
8	$\ln Y = a_0 + a_1 * D + a_2 * H_1$	**0.895**	**0.029**
9	$\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_1)$	0.892	0.030
10	$\ln Y = a_0 + a_1 * D + a_2 * H_1 + a_3 * D^2 H_1$	0.899	0.029
11	$Y = a_0 + a_1 * D + a_2 * D^2 H_2$	0.810	0.055
12	$Y = a_0 + a_1 * D + a_2 * H_2 + a_3 * D^2 H_2$	0.815	0.055
13	$\ln Y = a_0 + a_1 * D + a_2 * H_2$	0.914	0.026
14	$\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_2)$	**0.938**	**0.022**
15	$\ln Y = a_0 + a_1 * D + a_2 * H_2 + a_3 * D^2 H_2$	0.939	0.023

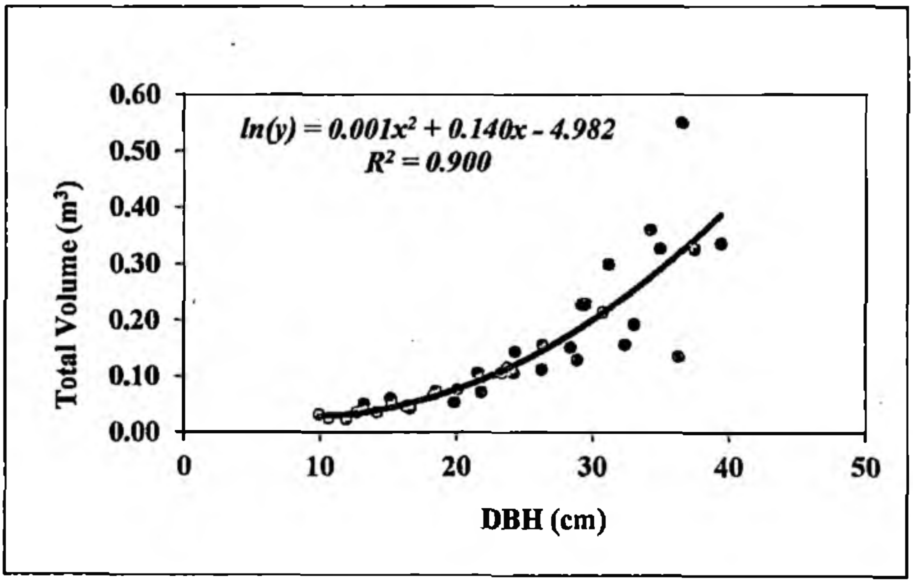

Fig. 9 Relation between DBH and total volume in *G. robusta* stands

between DBH and bole volume. While considering the DBH and height as independent variable, the best fitted equation with high R^2 value and Furnival index is found to be the Model 9 as it was selected as best equation (Appendix XXI).

Model 9 $\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_1)$

$\ln Y = -8.007 + 1.954 * \ln D - 0.328 * \ln(H_1)$

While considering DBH and bole height as independent variables the best fitted equation was model 12 (Appendix XXII).

Model 14 $\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_2)$

$\ln Y = -8.175 + 1.931 * \ln D - 0.291 * \ln(H_2)$

4.3.8 Total height

The total height of all the felled trees were predicted by using different models along with their R^2 and Furnival index which are presented in Table 13.

Among the equations tried, the best equation with DBH alone was model 2 with high R^2 value and low Furnival index. The selected equation is given below (Appendix XXIII)

Model 2 $H = a_0 + a_1 * D + a_2 * D^2$

$H = 2.826 + 0.883 * D - 0.011 * D^2$

The reliability of prediction also studied by plotting the observed and predicted values by using this equation (Fig.11). It shows a good relation with DBH and height.

4.4 Tissue Nutrient concentration

4.4.1 Nutrient concentration in biomass

The concentration of nutrients for a particular component between different diameter classes was found to be not significant (Table 14). However, concentration of N in leaf at diameter class above 25 showed higher concentration (1.930) whereas P in diameter class 15-25 (0.082) and K in diameter class 5-15 (1.265) shown higher concentration.

Table 12. Various models tried for predicting bole volume in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$Y = a_0 + a_1*D$	0.915	0.014
2	$Y = a_0 + a_1*D + a_2*D^2$	0.930	0.014
3	$\ln Y = a_0 + a_1* \ln D$	0.973	0.007
4	$\ln Y = a_0 + a_1*D + a_2*D^2$	**0.977**	**0.006**
5	$\ln Y = a_0 + a_1*\ln D + a_2*(\ln D)^2$	0.975	0.007
6	$Y = a_0 + a_1*D + a_2* D^2H_1$	0.923	0.014
7.	$Y = a_0 + a_1*D + a_2* H_1 + a_3*D^2H_1$	0.931	0.014
8	$\ln Y = a_0 + a_1*D + a_2* H_1$	0.957	0.009
9	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_1)$	**0.976**	**0.007**
10	$\ln Y = a_0 + a_1* D + a_2* H_1 + a_3*D^2H_1$	0.976	0.007
11	$Y = a_0 + a_1*D + a_2* D^2H_2$	0.945	0.014
12	$Y = a_0 + a_1*D + a_2* H_2 + a_3*D^2H_2$	0.945	0.010
13	$\ln Y = a_0 + a_1*D + a_2* H_2$	0.956	0.009
14	$\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_2)$	**0.982**	**0.006**
15	$\ln Y = a_0 + a_1* D + a_2* H_2 + a_3*D^2H_2$	0.981	0.006

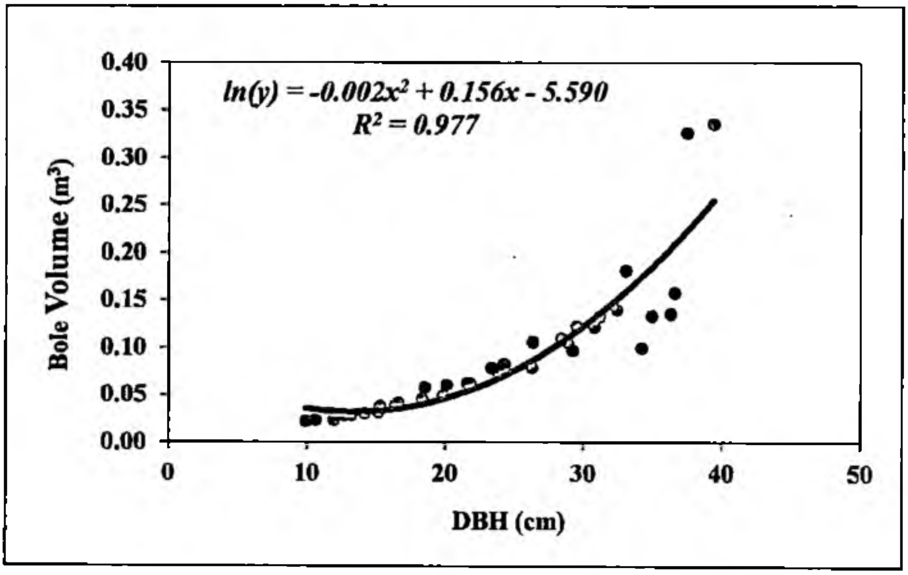

Fig. 10 Relation between DBH and bole volume in *G. robusta* stands

Table 13. Various models tried for predicting total height in *G. robusta* stands

Sl. No	Models tried	R^2	Furnival Index
1	$H = a_0 + a_1{*}D$	0.728	1.837
2	$H = a_0 + a_1{*}D + a_2{*}D^2$	**0.772**	**1.707**
3	$\ln H = a_0 + a_1{*} D$	0.689	2.154
4	$\ln H = a_0 + a_1{*} \ln D$	0.770	1.809
5	$\ln H = a_0 + a_1{*}D + a_2{*}D^2$	0.776	1.809

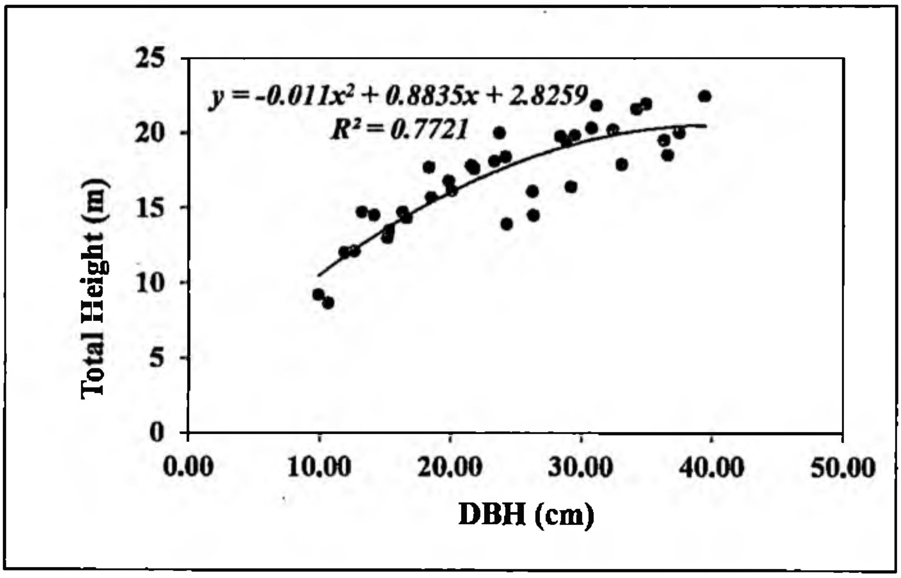

Fig. 11 Relation between DBH and Total height in *G. robusta* stands

variation in concentration was observed between components. Mean concentration of N, P, K in various components is given in Table 15 and Fig. 12.

Analyses of variance comparing nutrient concentration of different components (Table 16) have shown that there is a significant variation in the concentration of various elements between different components. Among different components leaf portion showed higher nutrient concentration compared to other components followed by twigs and branches. Nitrogen and phosphorous concentration is almost same in branch and stem portion. However percentage concentration of K is higher in branch compared to stem. Nutrient concentration for all components followed the order leaf > twig > branch > stem. Among various elements studied, nitrogen contributed highest concentration followed by potassium and least by phosphorous in all the components.

4.4.2 Nutrient accumulation and export

Nutrient accumulation on unit area basis for different diameter class was studied (Table 17) (Fig. 14, 15). It also follows the same trend as that of mean tree basis. Among different diameter classes highest nutrient accumulation was found to be in 15-25 diameter class (368.84 kg ha^{-1}) and as expected, the lowest nutrient accumulation was noticed on 5-15 diameter class (58.18 kg ha^{-1}). Consequently a higher nutrient export potential was observed in the diameter class 15-25 as stem wood alone accumulates 260 kg ha^{-1} of nutrients. This can be reduced by retaining the harvest residues like leaves and twigs right on the harvest site itself as it collectively accumulates 77 kg ha^{-1} of nutrients. Accumulation of the elements followed the order: stem > leaves > branches > twigs.

Accumulation of N, P and K in various components on a per tree basis has been given in Table (16). Nutrient accumulation was found to be highest in the stem wood (N, 136.65 kg tree^{-1}, P, 1.47 kg tree^{-1}, K, 31.50 kg tree^{-1}) and the lowest is in the twigs (N, 2.53 kg tree^{-1}, P, 0.05 kg tree^{-1}, K, 1.36 kg tree^{-1}). So the potential nutrient export through harvest may be higher as stem portion alone accumulates 169.32 kg tree^{-1} of nutrients (NPK) (Fig. 15) this nutrient export can be reduced to some extent by leaving the leaf portion right on the harvest field itself as it accumulates 30.84 kg tree^{-1}(Fig. 14) of nutrients. Branch (24.62 kg tree^{-1}) and twig (3.94 kg tree^{-1}) portion accumulates comparatively less amount of nutrients and

Table 14. Nutrient concentrations in biomass component for different diameter classes in *G. robusta* stands.

Diameter class (cm)	Components	N (%)	P (%)	K (%)
5-15	Stem wood	0.859 (0.037)	0.009 (0.001)	0.182 (0.012)
	Branch	0.851 (0.033)	0.018 (0.0003)	0.346 (0.027)
	Twig	1.001 (0.045)	0.024 (0.0007)	0.515 (0.021)
	Leaf	1.559 (0.079)	0.078 (0.002)	1.265 (0.052)
15-25	Stem wood	0.737 (0.031)	0.010 (0.0008)	0.162 (0.008)
	Branch	0.826 (0.025)	0.018 (0.0001)	0.259 (0.014)
	Twig	1.048 (0.037)	0.025 (0.0002)	0.545 (0.020)
	Leaf	1.773 (0.058)	0.082 (0.0003)	1.107 (0.051)
25 above	Stem wood	0.930 (0.059)	0.010 (0.0006)	0.246 (0.018)
	Branch	0.855 (0.033)	0.018 (0.0002)	0.257 (0.018)
	Twig	1.065 (0.053)	0.024 (0.0006)	0.633 (0.037)
	Leaf	1.930 (0.072)	0.081 (0.0004)	1.021 (0.042)

(*Values given in parenthesis are standard error*)

Table 15. Mean nutrient concentration (%) and nutrient accumulation (kg tree^{-1}) in different components of *G. robusta* stands

Components	N (%)	N (kg tree^{-1})	P (%)	P (kg tree^{-1})	K (%)	K (kg tree^{-1})
Stem wood	0.831 (0.025)	136.35	0.009 (0.0006)	1.47	0.192 (0.008)	31.50
Branch	0.843 (0.017)	17.63	0.018 (0.0001)	0.37	0.288 (0.013)	6.02
Twig	1.040 (0.025)	2.53	0.024 (0.0003)	0.05	0.560 (0.015)	1.36
Leaf	1.745 (0.043)	18.20	0.080 (0.0008)	0.83	1.136 (0.030)	11.81
Total AGB	1.11	175.01	0.032	2.72	0.544	50.69

(Values given in parenthesis are standard error of the means)

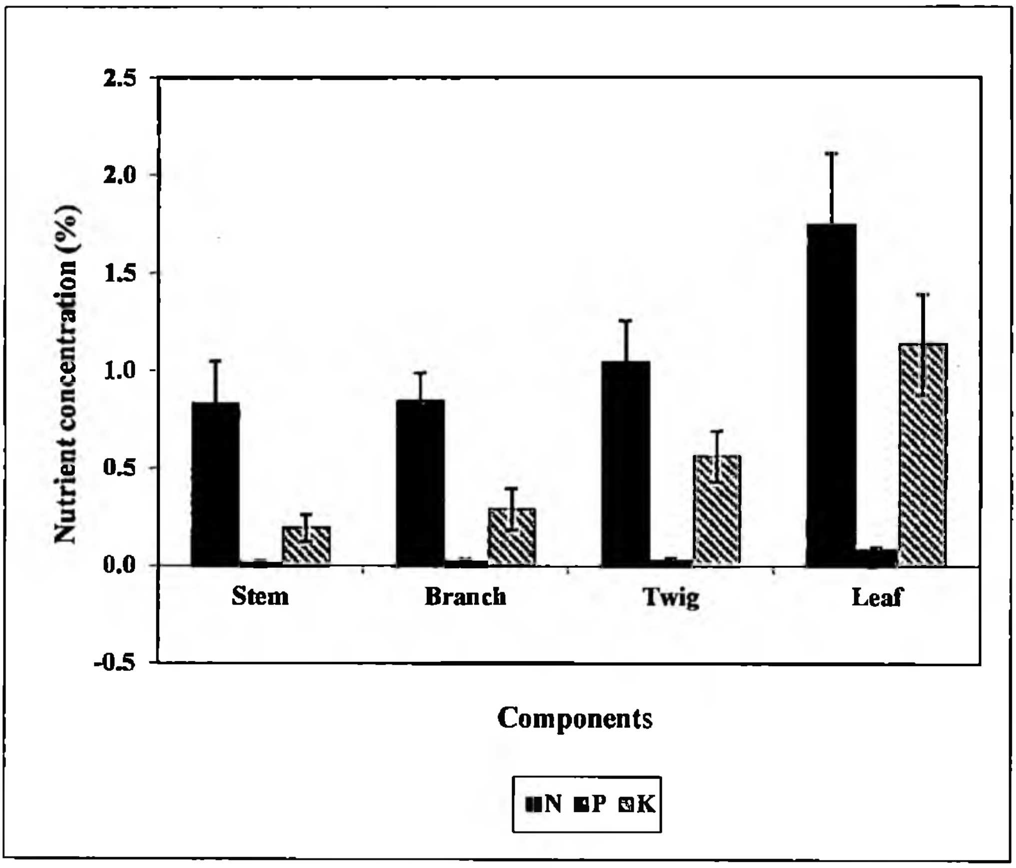

Fig. 12 Nutrient concentrations in different components of *G. robusta* stands (error bars represent standard error)

Table 16. Comparing nutrient concentration of different components

Components	N (%)	P (%)	K (%)
Leaf	1.7453[a] (0.36566)	0.27917[a] (0.043273)	1.13578[a] (0.257945)
Twig	1.0397[b] (0.21569)	0.17885[b] (0.038555)	0.55964[b] (0.130975)
Branch	0.8425[c] (0.14722)	0.16710[c] (0.028924)	0.28754[c] (0.106341)
Stem	0.8314[c] (0.21526)	0.15961[c] (0.029258)	0.19206[d] (0.068835)
F-value	215.640**	178.072**	519.847**

(*Values followed the same superscript do not differ significantly*)
(*Values in parenthesis are standard error*)

Table 17. Nutrient accumulation in various biomass components of *G. robusta* stands in different diameter classes (kg ha^{-1})

Diameter class (cm)	Density ($trees^{-1}$)	Components	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	Total (kg ha^{-1})
5-15	106	Stem wood	36.39	0.36	7.71	44.76
		Branch	2.21	0.05	0.90	3.16
		Twig	0.86	0.02	0.44	1.32
		Leaf	4.80	0.24	3.90	8.94
		Total (kg ha^{-1})	44.26	0.67	12.95	58.18
15-25	260	Stem wood	211.40	2.72	46.47	260.59
		Branch	23.11	0.51	7.25	30.87
		Twig	6.27	0.15	3.26	9.68
		Leaf	40.53	1.87	25.30	67.7
		Total (kg ha^{-1})	281.31	5.25	82.28	368.84
25 above	71	Stem wood	180.28	1.86	47.69	229.83
		Branch	23.49	0.50	7.06	31.05
		Twig	2.57	0.06	1.53	4.16
		Leaf	21.55	0.91	11.40	33.86
		Total (kg ha^{-1})	227.89	3.33	67.68	299.1

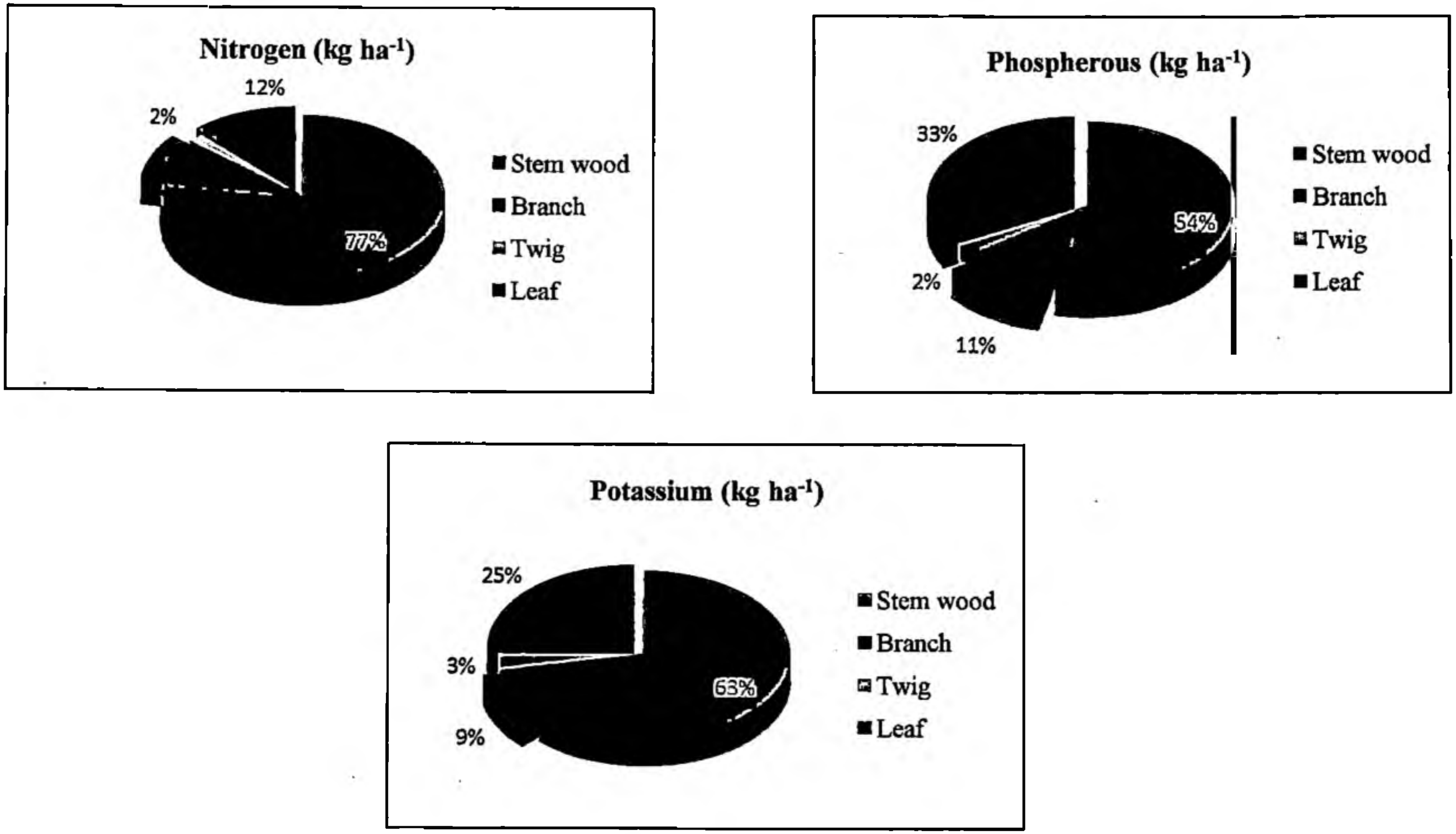

Fig. 13 Accumulation of nutrients in AGB and various biomass components in *G. robusta* stands (kg ha^{-1})

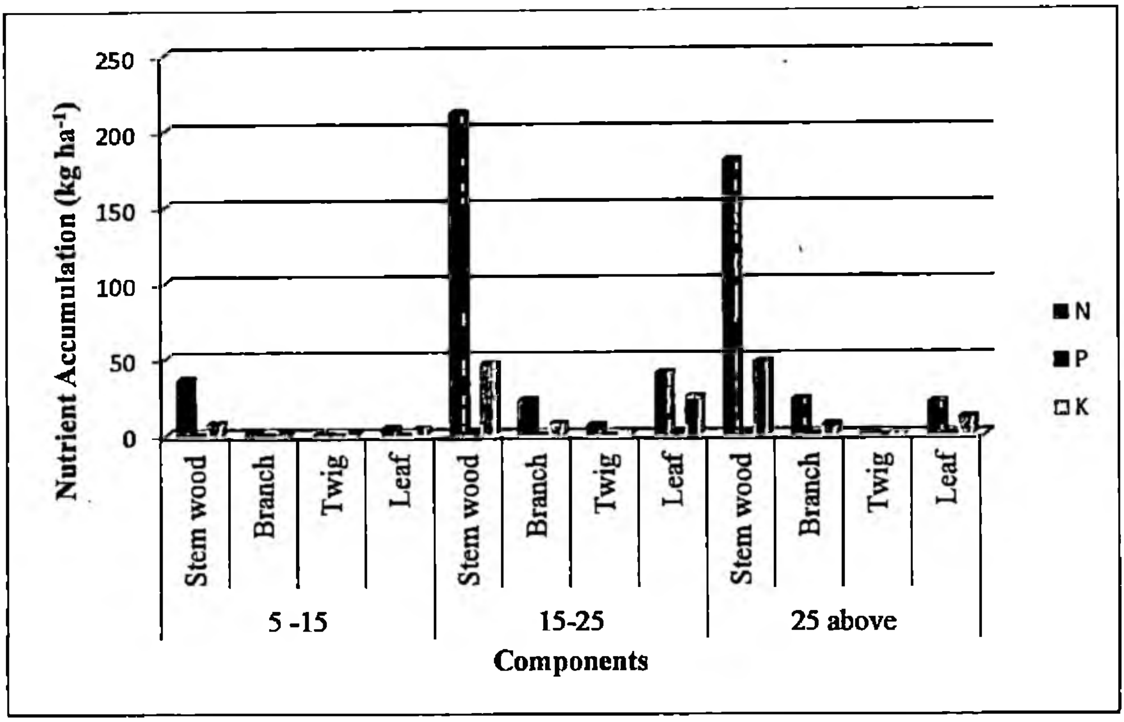

Fig. 14 Nutrient accumulation in various biomass components of *G. robusta* stands in different diameter classes (kg ha^{-1})

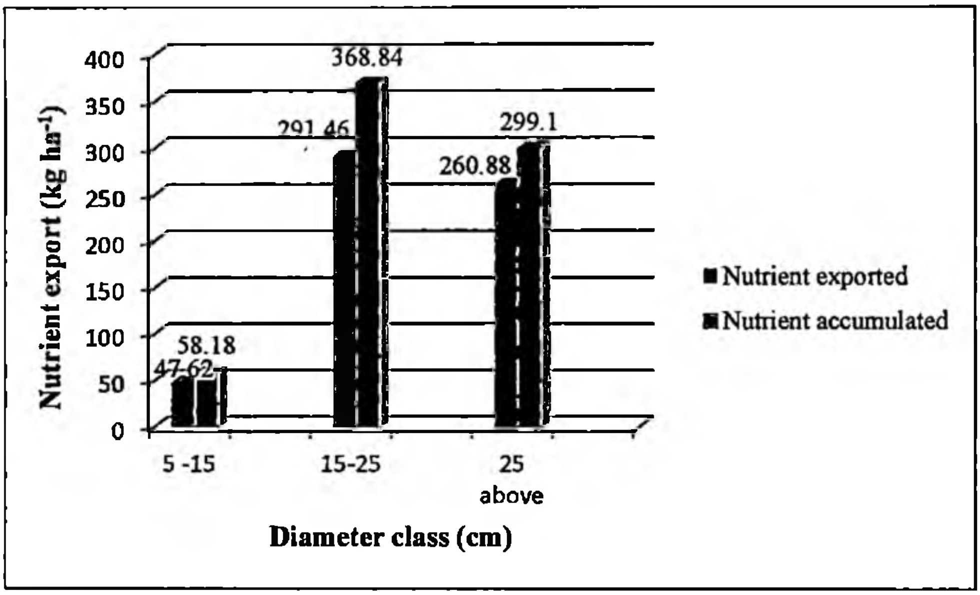

Fig. 15 Nutrient removal through harvesting of *G. robusta* stands in different diameter classes (kg ha^{-1})

contribute less to nutrient export. The nutrient accumulation follows the order stem > leaves > branches > twigs. concentration, the higher nutrient content in the stem wood may be due to high biomass production compared to foliage and twigs.

4.4.3 Nutrient use efficiency

Nutrient use efficiency is expressed as a quotient of standing biomass divided by aboveground nutrient pool. It is the total biomass synthesized per unit of nutrients utilized. The study of such nutrient use efficiency for each component indicated that among the biomass components nutrient use efficiency was maximum recorded in stem wood in all diameter class (N, 107.53 to 116.42 ; P, 10416.88 to 11651; K, 389.09 to 617.26) and least by leaf (N, 51.81 to 64.22; P, 56.37 to 90.28; K, 79.14 to 97.93). Among the nutrients, phosphorous use efficiency (PUE) was found to be maximum followed by potassium (KUE) and least by nitrogen (NUE) (Table 18) and among different components, nutrient use efficiency follows the order stem wood > branch > twig > leaf.

4.5 Carbon concentration and allocation

Table 19 and Fig. 16 show the mean aboveground carbon concentration according to tree components. It is observed from the above table that there was considerable variation in the concentration of carbon between different components. The leaf portion shows higher carbon concentration (48.36) and stem portion the lowest (45.67). On an average, carbon concentration follows the pattern: foliage > branch wood > stem wood.

Among the various components studied, the stem portion allocated maximum carbon (74.93 kg tree^{-1}) and the least by leaf (5.05 kg tree^{-1}) (Table 20, Fig. 17). Allocation of carbon to various components (Fig. 16) on a unit area basis against different diameter classes has been given in Table 20. Among different diameter classes on a unit area basis, carbon allocation in the 15-25 diameter class was found to be higher for all the components and total AGB (16079.86 kg C ha^{-1}). The stem wood portion alone allocates carbon of 24683.04 kg C ha^{-1} to the total AGB (29536.27 kg C ha^{-1}) and branch wood portion allocates 3061.59 kg C ha^{-1}.The components followed the order stem wood > branch wood > leaves.

While values of DBH of the 36 trees ranged between 12.08 cm and 32.17 cm (Table 1), total tree biomass varied from 44.29 to 197.89 kg tree^{-1} (Table 1). On an average woody tissues constitute 94.5 per cent of tree mass. Carbon taken up by the leaves is allocated to tree organs for biomass production and respiration. Because tree organs have different life span and decomposition rate, the tree carbon allocation determines the residence time of carbon in the ecosystem and its carbon cycling rate. In this study although the tissue carbon concentration was found to be maximum in leaves and least in the stem wood, the proportionate distribution of stem wood biomass to the total AGB is relatively higher (82.9 %) than that of other components (12.8 %) (Table 3) and the total carbon sequestered by the 20-year-old plantation is 27744kg ha^{-1}.

Table 18. Nutrient use efficiency of *G. robusta* stands in different diameter classes

Diameter class	Component	N	P	K
5-15	Stem wood	116.42	11651.48	549.50
	Branch	117.65	5640.79	289.38
	Twig	99.31	95.29	194.56
	Leaf	64.22	56.37	79.14
15-25	Stem wood	135.68	10525.84	617.26
	Branch	121.11	5535.75	386.25
	Twig	95.29	4075.92	183.23
	Leaf	56.37	1221.96	90.28
25 above	Stem wood	107.53	10416.88	406.51
	Branch	116.95	5494.24	389.09
	Twig	93.96	183.23	158.09
	Leaf	51.81	90.28	97.93

Table 19. Mean carbon concentration (%) and allocation in various components of *G. robusta* stands (kg C tree^{-1})

Component	Mean biomass production (kg tree^{-1})	Carbon allocation (kg C tree $^{-1}$)	Carbon concentration (%)
Stem wood	164.08	74.93	45.67 (0.895)
Branch wood (Branch + Twig)	23.36	11.06.	47.35 (0.712)
Leaf	10.46	5.05	48.36 (0.560)
Total/Mean	197.9	91.04	46.58

(Values shown in parenthesis are standard deviation)

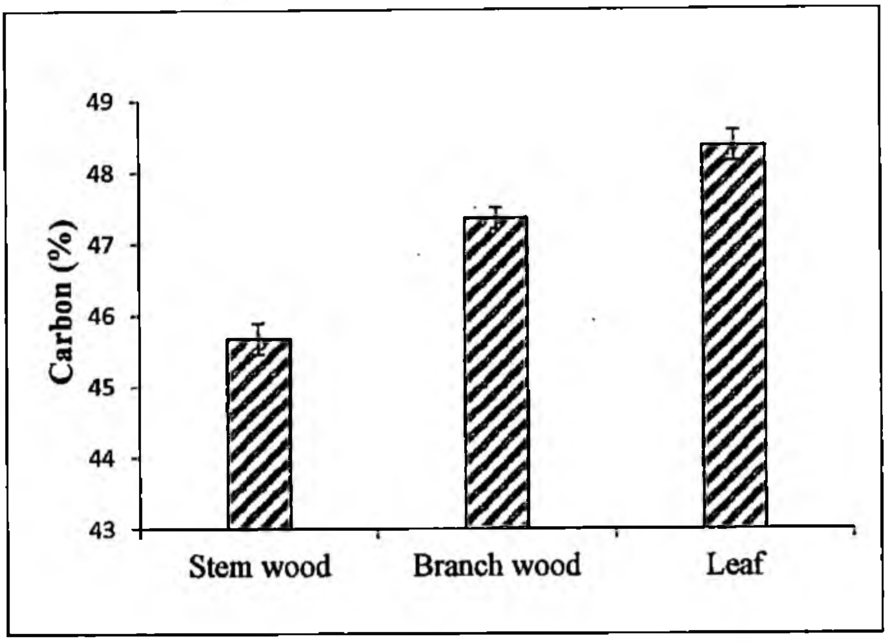

Fig. 16 Mean carbon concentration for various components of *G. robusta* stands (error bars represent standard deviation)

Table 20. Carbon allocation of *G. robusta* stands in different diameter classes (kg C ha^{-1})

Diameter class (cm)	Density (trees ha^{-1})	Carbon allocation kg ha^{-1}			
		Stem wood	Branch wood (Branch + Twig)	Leaf	Total AGB
5-15	106	2015.56	159.11	148.900	2323.57
15-25	260	13426.35	1554.91	1098.58	16079.86
25 above	71	9241.12	1347.56	544.14	11132.84
Total		24683.04	3061.59	1791.63	29536.27

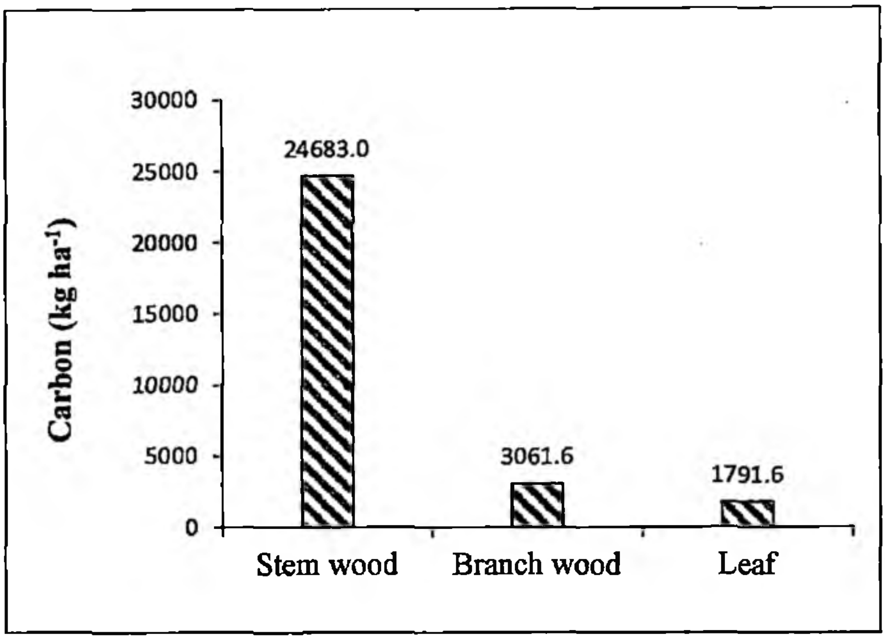

Fig. 17 Carbon allocation (kg ha^{-1}) in different components of *G. robusta* stands

Discussion

DISCUSSIONS

Estimation of aboveground biomass (AGB) is an essential aspect of studies for forecasting the productivity, volume, nutrient accumulation, carbon stocks and also for fixing rotation in tree stands (Ketterings, 2001). However, biomass production and productivity of plant or ecosystem varies considerably with the availability of resources and characteristics of the environments in which they grow (Landsberg et al., 1995). To meet current and future biomass related management objectives, there are several important issues that need to be better understood. The growth potential for plantation species needs to be quantified (Geyer, 2006). Utilisation of different stand components will vary with harvest objective. Consequently, an understanding of biomass partitioning among aboveground biomass components is needed. Estimating AGB is a useful measure for comparing structural and functional attribute of forest ecosystems across a wide range of environmental conditions (Brown et al., 1999)

Grevillea robusta locally known as silver oak is an exotic native to eastern part of Australia (Harwood et al., 1997). It is widely planted in tea plantations where it provides multiple benefits for tea plants (Niranjana and Viswanath, 2008). It is widely used in agroforestry as companion tree crop because of its widely accepted benefits like fast growth rate and minimal competitiveness with crops (Lott et al., 2000a, 2000b). Furthermore, it is considered a species of multiple use, cultivated in hedgerows or homogeneous forest for wood industry (carpentry, veneering, floors, firewood and pulp), honey and pollen, latex or ornamental (Harwood, 1989). Although *G. robusta* is indigenous to the subtropical eastern part of Australia, it has adapted quite well to various sites, several land races are now recognized in the areas of introduction (Harwood, 1992b). An attempt has been made here to study the biomass production, productivity, nutrient accumulation and carbon sequestration potential of *Grevillea robusta* stands in the midlands of Kerala.

5.1 Growth Parameters

In the present study of 20-year-old *G. robusta* stand in the midlands has acquired a mean height of 16.91 m and DBH of 24.07 cm and it is also noticed that the height increases in response to the increasing diameter class (Table 1). Several studies have also supported this trend on matching sites in the case of *Eucalyptus camaldulensis* (Prasad et al., 1984), *Albizzia lebbeck* (Pathak et al., 1992). Similar trend has been found in a 10-year-old *G. robusta* plantation in Western Himalaya in which diameter at breast height was reached 65.03 cm and height of 8.50 m (Gopichand and Singh, 2011). Significant variation in diameter and height was noticed in many experiments at different ages. Diameter and height of *Populus deltoides* clone D-121 ranged from 14.9 to 25.2 cm and height from 12.9 to 25 m at 4 to 8 years of age (Singh et al., 2004). Similarly significant variation in growth parameters at different ages was also reported in *Casuarina equesetifolia* (Lugo et al., 1990).

5.2 Aboveground biomass

Biomass accumulated per tree depends on factors like density, age of the tree and environmental conditions in which it is grown (Landsberg, 1995). In the present study biomass accumulation followed a predictable pattern, it was observed that AGB in different diameter class had shown an increase from 44.29 kg tree^{-1} in the lower diameter class to 317.61 kg tree^{-1} in the higher diameter class (Table 2). This was in tune with the trend observed in an *Acacia mangium* plantation at Thiruvazahankunnu, Kerala in which the biomass production increased from 17.49 kg in the lowest girth class to 396.31 kg in the highest class (Kunhamu et al., 2006). Similar observations are also found in *Acacia auriculiformis* and *Tectona grandis* (Swamy et al., 2012), *Anthocephalus chinensis* (Chandra, 2011), *Gmelina arborea* (Swamy and Puri, 2005) and *Dalbergia sissoo* (Lodhiyal et al., 2002).

5.3 Proportional distribution

The percentage of stem wood biomass to the total AGB was maximum in all diameter class. In the present study, it was observed that the contribution of stem wood biomass to total AGB is decreasing with an increasing diameter class. The contribution of stem wood biomass to the total AGB ranged from 82.53 to 86.64 per cent (Table 3) (Fig. 3). Similar trend (77-88 %) was observed in a plantation of multipurpose trees from, Kerala (Kumar et al., 1998). Percentage of bole biomass recorded in case of *Acacia mangium* was 65 per cent (Kunhamu et al., 2006) and 74 per cent in case of *Eucalyptus camaldulensis* (Harmand et al., 2004). High percentage of bole biomass was also reported in many species (Karmacharya and Singh, 1992, Onyekwelu, 2004 and Uri et al., 2007). In the present study, the decreasing trend in stem wood biomass in response to the increasing diameter may be due to the distribution of the photosynthates to other components like branch, leaves, and twigs (Table 3). Contrary to the stem wood biomass, contribution of branch biomass showed an increasing trend which ranged from 5.31to11.69 per cent till the highest diameter class. Reduction in stem wood percentage and corresponding increase in branch wood content is evident in the higher diameter classes. Biomass allocation for branch wood formation tends to be prominent in higher size classes most often when stem wood formation attains a peak (Kunhamu et al., 2006).

Unlike the stem wood biomass and branch biomass leaves, showed an increasing trend up to the intermediate diameter class but the twig biomass had followed almost a similar contribution in all diameter class although it had shown a slight increase in the second highest diameter class and an insignificant decrease in the highest diameter class (Table 3). The lower percentage of biomass may be due to the distribution of nutrient in branches and stem wood. Similar trend was observed in *Gmelina arborea*, in which the increase in biomass of stem wood was from 81.8 to 85.7 per cent (Onyekwelu, 2004).

5.4 Biomass production per unit area

Biomass production among diameter classes had shown wide variation. Above ground biomass per hectare basis was highest (34.26 Mg ha^{-1}) for the intermediate diameter class (15-25 cm), which incidentally represented maximum number of individuals (24.2 %). As expected, the lowest girth (5-15 cm) class showed lesser biomass accumulation to the tune of 4.86 Mg ha^{-1}. However, biomass accretion per ha basis was lower for higher girth class primarily due to the lower proportion of individuals (16.2 %). Similar trend was observed in a plantation of *Gmelina arborea* located in south-western Nigeria with a mean diameter extending from 18.4 to 34.4

cm, age from 5-21 years and a density of 837-1275 trees ha^{-1} produced a total AGB ranging from 83.2 Mg ha^{-1} to 394.9 Mg ha^{-1} (Onyekwelu, 2004). In a seven year old *Acacia mangium* plantation in five girth classes extending from 30 – 75 cm produced a total AGB of 210.24 Mg ha^{-1} and the biomass ranged from 5.58 Mg ha^{-1} to 97.58 Mg ha^{-1}(Kunhamu et al., 2006).

Leaf biomass is the important component in the tree for the photosynthesis and allocation of photosynthates to the other part of the tree. Leaf biomass produced at various diameter classes was recorded 0.30 Mg ha^{-1}, 2.28 Mg ha^{-1}, and 1.11 Mg ha^{-1}. The leaf biomass produced at age 5 years with a mean diameter of 45.87 cm in *Casuarina equisetifolia* (2.79 Mg ha^{-1}) and in *Ailanthus triphysa* (1.98 Mg ha^{-1}) with a mean diameter of 30.90 cm (Kumar et al., 1998) follows the same trend.

In the present study, total biomass production for 20-year-old *Grevillea robusta* for all diameter class was estimated to be 62.59 Mg ha^{-1}(density 437 trees ha^{-1}) and in a 10-year- old *Grevillea robusta* plantation grown at mid hills of western Himalaya with a density of 14,000 and 10,000 trees ha^{-1} and mean diameter of 65.03 cm produced a biomass of 345.27 Mg ha^{-1} (Gopichand and Singh, 2011). Estimates from regression equation for 25-year-old *Grevillea robusta* stand on a reclaimed sodic soil at Karnal, north-western India with a density of 550 trees ha^{-1} yielded 258Mg ha^{-1} of biomass combining branches and stem wood (Jangra et al., 2010). The lower production found in the present study may be due to the density and influence of agro climatic condition.

5.5 Biomass Productivity

In the present study, the total biomass productivity was found to be increasing with increasing diameter class (0.23 Mg ha^{-1} yr^{-1} to 1.13 Mg ha^{-1} yr^{-1}) and the total AGB recorded was 3.023 Mg ha^{-1} yr^{-1}(Table 5). Jayaraman et al. (1992) reported that *G. robusta* as a slow grower after comparing with four fast growing species in Kerala. They noted that productivity at 3.0 cm DBH (3.5-year-old) with a stocking density of 2050 trees ha^{-1} as 1.16 Mg ha^{-1}yr^{-1} but (1950 trees ha^{-1}) when DBH where in the productivity in average of 5.1 cm. increased to 3.5 Mg ha^{-1} yr^{-1}(4.5-year-old)

This was by in general agreement in several other studies also (Onyekwelu, 2004; Behera and Mishra, 2006).

The productivity observed in the present study are not in agreement with the results of Lugo et al. (1988) who reported that productivity of most tropical species fall in the range of 6 to 15 Mg ha^{-1} yr^{-1} for total AGB accumulation. Wang et al. (1991) nevertheless reported that AGB accumulation rates for five other tropical species were in the order of 6 to 36.2 Mg ha^{-1} yr^{-1} (age 5.5 years) implying greater variability in biomass productivity of tropical trees. As far as our results are less than the global standards shown above it can be inferred that these result are in agreement with the observations of Jayaraman et al. (1992).

5.6 Biomass prediction

The most precise way to measure and monitor AGB biomass, and to estimate the state and change in C stocks, for a stand is through periodic destructive harvesting (Saglan et al., 2008). However, cutting and weighing a sufficient number of trees to represent the size and species distribution in an ecosystem is complex and labour intensive (Kale et al., 2004; Delitti et al., 2006). In addition, destructive harvesting of trees in long-term studies and reforestation projects is not possible. Therefore, non-destructive techniques have been developed to determine aboveground biomass of forest and agroforestry tree species (Lott et al., 2000c; Claesson et al., 2001; IPCC, 2003; Brown et al., 2004; Saatchi et al., 2007). These methods are based on regression models that relate biomass growth parameters by allometry (FAO, 1997; Lott et al., 2000c; Claesson et al., 2001; Brown et al., 2004, Terakupisut et al., 2007)

Regression equation for different biomass components like stem wood, branches, twigs and leaves are developed for the best prediction (Muukkonen, 2007). Prediction equations attempted with DBH, total height and bole height of the trees. Among the fifteen equations tried, five are DBH alone as independent variable next five equations were based on DBH and total height and the last five on DBH and bole height combined. All these equations are used for predicting total biomass, biomass components and volume. Out of these, best equations were selected on DBH alone or DBH and total height/ bole height combined as independent variables, for height equations with DBH alone as independent variable was used. However, linear equations had given higher values of coefficient of determination (Ajit and Handa., 2003). Multiple regression models were also proved best fit for predicting biomass in many species (Montagu et al., 2005). Logarithmic transformation of the simple linear models was reported to give best prediction for biomass in many trees (Khan and Pathak, 1996, Specht and West, 2003., Blujdea et al., 2012)

Dry weight can be expressed as a function of DBH and height. Therefore in the present study, the two parameters were taken as independent variable and weight as a dependent variable for selecting the best model. The models with DBH as independent variable was selected as best fit due to its accurate measurement. Tree height is more indicative of site quality and remains unchanged for a single age class population. Hence, girth/diameter better serves as the biomass/volume predictor variable (Kunhamu, 2006). Dudely and Fowens (1992) observed that the time spent in field could not be greatly reduced by eliminating height measurement in stands that are relatively homogenous.

Coefficient of determination is the criteria to select the best equation in many cases (Deans et al., 1996 and Zianis, 2008). However, in allometric equation these parameters may not be always suitable for comparing different models because the dependent variable varies from one model to another. Therefore it is possible to compare different models by an index developed by Furnival (1961). In the present study the best fitted equations were selected on high R^2 value and low Furnival Index. Similar findings were reported by Gupta et al. (1990); Kushalapa (1993); Vidyasagaran (2003) and Thapa (2005).

In the present study, suitable models for various components for AGB were selected based on equations with high R^2 value and low Furnival Index. For the prediction of total AGB, the best equation selected was model 3 ($\ln Y = a_0 + a_1 * \ln D$), Model 3 came as the best fitted equation for predicting bole, branch and twig biomass also. Similarly this model was found to be suitable for predicting fast growing species like *Ailanthus triphysa* (George, 1993) and *Acacia auriculiformis* (Jamaludheen, 1994). For height prediction the best equation was model 2 ($H = a_0 + a_1 * D + a_2 * D^2$). Height prediction equations are developed for several other species also (Chhetri and Fowler, 1996; Fang et al., 1998).

Equations with DBH and height as independent variable showed different models as best fit as indicated in their maximum R^2 values and minimum Furnival index. Model 9 ($\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_1)$) was the best fit for predicting AGB, bole biomass, branch biomass and twig biomass. Allometric equation with DBH and height have been developed in many tree species elsewhere (Whitesell et al., 1988) *Eucalyptus grandis* (Halenda, 1989), *Acacia mangium* (Onyekwelu, 2004) *Gmelina arborea* (Swamy et al., 2004), (Montagu et al., 2005) *Eucalyptus piluaris.*

The equations with DBH and bole height as independent variable showed different models as best fit as shown by the coefficient of determination and Furnival index. Model 14 ($\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_2)$) was proved best fit for predicting AGB, bole biomass, branch biomass and twig biomass. Allometric equation with DBH and height have been developed in many tree species elsewhere (Trincado et al., 2007; Huang et al., 2000)

Among these selected models, the most suited equation was model model 3 ($\ln Y = a_0 + a_1 * \ln D$) with DBH alone as the predictor variable. It is chosen because it is more suitable for the prediction of the AGB, bole, branch and twig. Since this model is having DBH alone as independent variable, it was used to estimate the AGB biomass components in *G. robusta* plantation though equations with combinations of DBH and height proved best fit with relatively high R^2 value and lowest Furnival index which were relatively similar to equations with DBH alone could not be selected. Equations with height as an independent variable were not selected as best fit due to difficulty in measuring the height of the standing tree with definite accuracy. The time spent in field could be greatly reduced by eliminating height measurement in stands that are relatively homogenous. (Whittaker and Marks, 1975 and Dudely and Fowens 1992).

The reliability of the observed and predicted values are plotted in graph with dependable variables is total AGB and components like bole, branch, twig, leaf and total height. The graph showed good relation between DBH and biomass with higher R^2 value in total AGB (R^2- 0.952), bole (R^2- 0.939), branch (R^2- 0.893) except in few cases at high diameter (Fig. 4-6). Roy et al. (2006) also reported the better fitness being in the lower diameter classes of total AGB and biomass components. Similar trend of fitness in respect to aerial biomass in *Acacia nilotica* (Maguire et al., 1990) and *Leucaena leucocephala* (Khan and Pathak, 1996) have been reported. In the case of twigs, leaves and total height, comparatively low R^2 value (R^2-0.533, 0.748 and 0.772 respectively) was observed which showed their weak relation with the independent variable (Fig. 7, 8, 10). This may be because of the shedding of the twigs, leaves as reported in *Eucalyptus* hybrid (Tandon et al., 1993), *Terminalia ivorensis* (Deans et al., 1996) and in *Leucaena leucocephala (*Roy et al., 1997).

5.7 Volume prediction

Prediction of volume of standing *G. robusta* trees on the basis of easily measurable parameters such as DBH and height has been attempted using different allometric regression models. Volume prediction had been estimated and represented in many tree species in India (Sunanda and Jayaraman, 2006; Ajit et al., 2010; Gupta, et al., 2011). In the present study, for predicting total volume and bole volume, DBH alone as independent variable proved best fit equation with high R^2 value (total volume R^2-0.900, bole volume R^2- 0.977) (Fig. 9, 10) and low Furnival index was shown by model 4 ($\ln Y = a_0 + a_1*D + a_2*D^2$) (Table 13). The volume was also predicted in *Eucalyptus globulus* (Rana et al., 1993) and *Leuceana leucocephala* (Roy et al., (1997) by using the DBH as independent variable.

Fitting, diameter and height as independent variables, the best fitted equation for predicting bole volume and total volume was selected based on the high R^2 and low Furnival index. Model 8 (Table 14) was found to be suitable for predicting total volume and bole volume ($\ln Y = a_0 + a_1*D + a_2* H_1$) but the variables DBH and bole height as independent variable, the best fitted equation was model 14, ($\ln Y = a_0 + a_1*\ln D + a_2* \ln(H_2)$) with high R^2 value and low Furnival index. Variables dbh and height were calculated in different species (Singh and Dhanda, 1990) considered for developimg equations for predicting volume of *Eucalyptus* sps. (Wollmerstaditovon et al., 1992)

The relation between DBH and volume were high and close to the predicted line due to the high R^2 value (bole volume R^2- 0.900, total volume R^2- 0.977). The close relation between DBH and volume has been reported in *Eucalyptus* hybrid plantations (Dogra and Sharma, 2003) and in *Gmelina arborea* (Akindele, 2003).

5.8 Nutrient dynamics in *G. robusta*

5.8.1 Nutrient concentration

Nutrient distribution in the vegetation and soil compartments will provide useful information on nutrient budgeting of the system and the quantification of nutrient stocks in the biomass is an important issue in sustainable plantation management (Navas, 2006).

The concentration of nutrients N, P and K were highest in leaves (N, 1.74 per cent; P, .080 per cent; K, 1.13 per cent) followed by twig, branch and least in bole in decreasing order (Table 15). The foliar nutrient concentration reported in the present study on 20–year-old *Grevillea robusta* is higher than those reported by Drechsel and Zech (1991) on 3 - 4-year-old *Grevillea robusta*. The higher leaf nutrient concentration was also showed in 3 to 7-year-old *Populus deltoids* in which nutrients ranged as N, 2.49 to 2.33 per cent; P, 0.21 to 0.19 per cent and K 1.4 to 0.97 per cent (Mohsin et al., 2005). In the present study, bole constituted minimum concentration of all nutrients. Similar findings were reported in *Casuarina equisetifolia* (Jamaludheen, 1994). The highest concentration of the foliage is assumed to be good indicator for efficient nutrient return to the ecosystem. Foliar concentration also form good indices of the nutritional status of the plant.

Among the nutrients, nitrogen concentration was highest followed by potassium and the least in phosphorous, among all the components of the tree. This trend is supported by many studies (Drechsel and Zech, 1991; Mohsin et al., 2005; Specht and Turner, 2006). In the present study at 20 years, nitrogen was recorded highest followed by potassium and phosphorous. Higher concentration of N was also reported in 5-year-old *Acacia auriculiformis* (Kumar et al., 1998). The similar observation has been observed in *Acacia auriculiformis* and *Ailanthus triphysa*, (Jamaludheen, 1994), *Dalbergia sissoo* (Lodhiyal et al., 2002). It is also noted that site and soil conditions may have a strong influence on tissue nutrient concentrations. Deviations in nutrient concentration of tissue fractions are therefore not extraordinary (Shujauddin and Kumar, 2003).

5.8.2 Nutrient accumulation and export

Nutrient accumulation and export have become an important consideration in all fast growing short rotation plantations where nutrients are removed through frequent harvest (Hopman et al., 1993). Heavy nutrient drain is an adverse impact on long-term site quality and sustained production. Nutrient removal at harvest is a function of both nutrient concentration and of the different tissue fractions and biomass yield and leaves were the most costly tissues to build registering the highest concentration of N, P and K followed by branch wood and stem wood respectively (Shujauddin and Kumar, 2003). The quantification of nutrients stocks in the AGB is an important concern in sustainable plantation management. Depending on rotation length and harvest practices, the amount of nutrients lost through biomass removal can crucially determine the future success of productive plantations (Montagnini and Jordan, 2005).

Nutrient accumulation varied in various components of the tree according to the nutrient concentration. In this study, the accumulation of nutrients ranged as N, 44.26 to 227.89 kg ha^{-1}, P, 0.67 to 3.33 kg ha^{-1}, K, 7.71 to 67.68 kg ha^{-1} (Table 17). Similar studies in other fast growing species also had shown the trend of variation in nutrient accumulation in different components *Pinus radiata, Pinus pinaster, Eucalyptus globulus* (Merino et al., 2005). *Eucalyptus tereticornis* and *Eucalyptus grandis* (Sankaran et al., 2005).

In biomass components maximum accumulation of nutrients was found to be in the stem wood (N, 428.07 kg ha^{-1}; P, 4.94 kg ha^{-1}; K, 101.87 kg ha^{-1}) (Table 17). This trend of higher nutrient accumulation in stem wood was supported by several other studies in fast growing species like a *Eucalyptus tereticornis* (Bargali, 1995), *Dalbergia sissoo* (Das and Chaturvedi, 2003) and *Gmelina arborea* (Swamy and Puri, 2005). Among the nutrients, maximum accumulation was observed for nitrogen and least by phosphorous in the total AGB. Similar observations were reported in *Tectona grandis* (Negi et al., 1995) *Acacia mearnsii* (Caldeira et al., 2002), *Casuarina equesetifolia* (Vidyasagaran, 2003), *Gmelina arborea* and *Terminalia amazonica* (Arias et al., 2011).

Despite the lower nutrient concentrations, the higher nutrient content in the stem wood was primarily on account of the wide gap between the biomass production compared to foliage and twigs. The total nutrients exported is found to be higher in the intermediate diameter class (291.46 kg ha^{-1}) and as expected the lowest was in the lowermost diameter class (47.62 kg ha^{-1}) but the percentage nutrient export had shown a different trend. It was found to be higher in the highest diameter class (87.22) and the lowest was in the intermediate diameter class (79.02 %). So it was clear that the higher total nutrient export found in the intermediate diameter class was due to the higher proportion of individuals. This trend were in agreement with the studies on *Eucalyptus camaldulensis*, *Eucalyptus grandis*, *Dalbergia sissoo* (Hunter, 2001), *Acacia mangium, Eucalyptus globulus, Eucalyptus grandis* (Yamada et al., 2004). Leaves on the other hand, despite their higher nutrient concentration could accumulate fewer nutrients mainly due to lower leaf biomass production. However, it is important to note that leaf biomass can bring substantial nutrient turnover to the soil through litter. In the present study accumulation of nutrients in the leaves was N, 66.88 kg ha^{-1}; P, 3.02 kg ha^{-1}; and K, 40.6 kg ha^{-1}. Hence considering the potential nutrient loss on account of harvest, effort should be made to see that maximum foliage and harvest left over.

5.8.3 Nutrient use efficiency

Sustainable production without adversely affecting site quality is a key design criterion in all short rotation intensive cultural systems. Species selection that considers nutrient use efficiency, therefore, is a potential tool available to the forester to alter the 'nutrient costs' associated with such systems (Wang et al., 1991; Kumar et al., 1998). In general, species with high nutrient use efficiencies should be preferred for tropical biomass plantations. Within a species, however, a further alteration in nutrient rates at harvest can be achieved by either adjusting the types of tissues removed from the site or by silvicultural manipulation of the stands, which in turn, alters growth and nutrient accumulation patterns (Shujauddin and Kumar, 2003).

In the present study among the nutrients, the study of such nutrient use efficiency for each component indicated that among the biomass components nutrient use efficiency was maximum recorded in stem wood in all diameter class (N, 107.53 to 116.42 ; P, 10416.88 to 11651; K, 389.09 to 617.26) and least by leaf (N, 51.81 to 64.22; P, 56.37 to 90.28; K, 79.14 to 97.93). Similar trend was observed in *Acacia auriculiformis*, *Ailanthus triphysa*, *Casuarina equisetifolia* (Kumar et al., 1998), *Cunningamia lanceolata* (Xue et al., 2007) but among different components branch portion showed higher nutrient use efficiency. The nutrient use efficiencies calculated for *Grevillea robusta* were within the range reported for other tropical tree species (Wang et al., 1991; Hiremath et al., 2002), although our calculation did not account for the amount of N, P and K in the litter and belowground biomass.

5.9 Intra specific carbon concentration

Accurate knowledge of carbon content in live wood is essential for converting estimates of forest AGB in to forest C stocks. Quantifying wood carbon content in tree species from a range of forest types is critical for understanding the potential of forests for carbon capture and storage (Martin and Thomas, 2011). Previous measurements on carbon are mostly made for wood (Lamlom and Savidge, 2003; Thomas and Malczewski, 2007) because woody tissues account for the majority of biomass carbon stock (Laiho and Laine, 1997; Wang et al., 2003) and net primary production in forest ecosystems (Gower et al., 2001). This study showed the mean stem carbon concentration of a 20-year-old *G. robusta* (47.12%) was less (2.88%) than the generic carbon concentration of 50 per cent. The carbon concentration in various components was, stem wood (45.67%), leaf (48.36%), branches (47.35%). The carbon concentration follows the order: leaves > branch > stem wood. Similar observations are found on 10 Chinese temperate species (Zhang et al., 2009) in which the tissue carbon overall followed an order foliage > new branch > old branch > stem > coarse root > fine root and the mean tissue carbon across the 10 species varied from 47.1 ± 0.8% (mean ± SE) for fine root to 51.4 ± 1.0% for foliage. Similar trend was noticed in *Pinus pinaster* (Bert and Danjon, 2006), *Acacia crassicarpa* and

Xylia xylocarpa (Meupong et al., 2010), *Eucalyptus* K7 and *Leuceana leucocephala* (Keeratiurai et al., 2012).

Trees with different characteristics of metabolism and growth have various carbon containing compounds (Kozlowski, 1992), the inter specific variations in carbon concentration are also influenced by site conditions, stand characteristics (e.g., tree age, social status), management practice, etc. (Elias and Potvin, 2003; Bert and Danjon, 2006; Fukatsu et al., 2008).

5.10 Carbon allocation

Carbon allocation is a major issue in plant ecology, controlling the flows of carbon fixed in photosynthesis between respiration and biomass production, and between short and long lived and aboveground and belowground tissues. Incomplete knowledge of carbon allocation currently hinders accurate modelling of tree growth and forest ecosystem metabolism (Friedlingstein et al., 1999; Gower et al., 2001, Landsberg, 2003; Ryan et al., 2004). carbon allocation is a major issue in plant ecology, controlling the flows of C fixed in photosynthesis between respiration and biomass production, and between short- and long-lived and aboveground and belowground tissues (Epron et al., 2011).

The potential role of forest tree plantations in sequestering carbon to reduce the build-up of CO_2 in the atmosphere has been recognized (Houghton et al., 2007). According to FAO report, the total carbon stock in Indian forests amount to 10.01 Gt C, the forest soil accounts for 50 per cent of the total soil carbon (FAO, 2006). On the basis of Comprehensive Mitigation Analysis Process (COMAP) model, Ravindranath et al. (2008) have shown a large stock of carbon in forest soils of India. Tree based systems accumulate large amount of biomass and sequester substantial amount of carbon in perennial tree components. Approximately 88 per cent of the total tree biomass in plantation and agroforestry systems is stored mostly in tree trunks as aboveground biomass (Sharrow and Ismail, 2004). In the present study on a 20-year-old *Grevillea robusta* carbon allocation was found to be higher in the stem wood (24683 kg C ha^{-1}) and the lowest in the leaves (1791 kg C ha^{-1}). Due to the high proportion of the woody tissues to the total AGB (94.5 %) woody tissues alone accumulates a carbon of 27744.63 kg C ha^{-1}. Similar trend in which higher accumulation of carbon in woody tissues is reported in several other species also (*Anthocephalus chinensis*, *Eucalyptus* K7, *Leuceana salvador* (Keeratiurai et al., 2012); *Populus deltoids* (Coleman et al., 2004); *Tectona grandis* (Kraenzel et al., 2003)).

Summary

SUMMARY

The present study was conducted on biomass production and carbon sequestration in a 20-year-old *Grevillea robusta* plantations with respect of the objectives mentioned and the salient features summarised herein.

1. The plantation showed a substantial variability in growth between different diameter classes. The mean diameter ranged from 12.09 cm to 24.07 cm and height ranged from 11.86 m to 19.37 m. Both the diameter and height increased with the diameter class.
2. The observation on AGB of sample trees and biomass components showed an increase with increasing diameter class. Among the diameter class the total AGB ranged from 44.29.kg tree^{-1} to 317.61 kg tree^{-1}.
3. The proportional distribution of the stem wood to the total AGB was found to be decreasing (86.64-82.53 %) with increasing diameter class. Biomass of leaves also showed a marked decrease in the highest diameter class (6.31 - 4.75 %) whereas an insignificant (0.71%) decrease in the twig biomass at highest diameter class is observed. Contrary to other components, branches showed a marked increase in biomass with regards to an increasing diameter class.
4. The biomass was found to be highly influenced by diameter and height. The increase of biomass ranged from 44.29 to 317.61 kg tree^{-1} till the highest diameter class.
5. Biomass production on unit area (Mg ha^{-1}) increased till the second highest diameter class. Generally the biomass is influenced by diameter and height. The increase of biomass ranged from 4.86 Mg ha^{-1} to 23.47 Mg ha^{-1}. The significant increase from the lowest to intermediate diameter class has been noticed (4.86 – 34.26 Mg ha^{-1}), but in the highest diameter class it decreased to 23.47 t ha^{-1} and the total AGB production was 62.59 Mg ha^{-1}.
6. Productivity showed similar trend as productivity of AGB is found to be increasing with an increasing diameter class, it increased from 239.56 to 1134 kg ha^{-1}.

7. Different prediction models developed with respect to DBH and height for AGB and biomass components. Accordingly, the best fit equations were selected. The selection was based on equation with maximum R^2 and minimum Furnival Index.
8. With respect to DBH as independent variable, the total aboveground biomass, the best equation was model 3 ($\ln Y = a_0 + a_1 * \ln D$). This model was found to be best fitted for predicting bole, branch and twig biomass also. But for leaf and height prediction model 5 ($\ln Y = a_0 + a_1 * \ln D + a_2 * (\ln D)^2$) and model 2 ($H = a_0 + a_1 * D + a_2 * D^2$) were proved to be best fitted. Whereas for predicting the total volume and bole volume, model 4 ($\ln Y = a_0 + a_1 * D + a_2 * D^2$) was proved to be the best fitted with high R^2 value and low Furnival index.
9. With respect to DBH and height as as independent variable, the total aboveground biomass, the best equation was model 9 ($\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_l)$). This model was found to be best fitted for predicting bole, branch and twig biomass also. But for leaf model 10 ($\ln Y = a_0 + a1 * D + a_2 * H_l + a_3 * D^2 H_l$) was found to be best fitted. Whereas for predicting the total volume model 8 ($\ln Y = a0 + a_1 * D + a_2 * H_l$) and for bole volume, model 9 ($\ln Y = a_0 + a_1 * \ln D + a_2 * \ln(H_l)$) was found to be the best fitted with high R^2 value and low Furnival index.
10. Though some equations were proved to be more fit with combination of DBH and height/bole height, R^2 value and Furnival index were relatively similar to equations with DBH alone could not be selected, it is difficult to measure height of the standing trees with definite accuracy. Hence, equations with DBH alone were selected for predicting the AGB and biomass components.
11. The present investigation also revealed that in the case of AGB, bole, and branch the observed values were very close to the predicted values except for a few deviations in higher diameters. But in twigs and leaves noticed a weak relation between biomass and DBH. The best equation with coefficient of determination and Furnival index was given highest statistical precision in prediction estimation.
12. Total volume was also estimated which ranged as 0.04 to 0.28 (m^3). The model developed for volume with respect to DBH was model 4 ($\ln Y = a_0 + a_1 * D + a_2 * D^2$) and model 8 for DBH and height ($\ln Y = a_0 + a_1 * D + a_2 * H_l$).
13. Investigation on nutrient concentrations was found to be not significantly different between various diameter classes. However, significant variation in nutrient concentration observed among components. Leaves had the maximum concentration of the nutrients and bole had the lowest.

14. Among the nutrients nitrogen concentration was highest followed by potassium and phosphorous was minimum among all components.
15. In nutrient accumulation, among the nutrients, nitrogen accumulated maximum followed by potassium and phosphorous.
16. Nutrient use efficiency was found to be maximum in bole and minimum in leaf. Among the nutrients, efficiency of phosphorous was maximum followed by potassium and nitrogen.
17. The mean carbon concentration (46.58) was found to be lower than the assumed values and it is also found that failing to account the variation can introduce an error of 3.42 per cent.
18. Investigations on the intra specific variation carbon concentration revealed a higher carbon concentration in the leaves (48.36) followed by branches and bole.
19. The carbon allocation has increased from 2323.57 to16079.86 kg C ha^{-1} but in the highest diameter class it decreased to 11132.84kg C ha^{-1} and the total AGB accumulation was 29536.27 kg C ha^{-1}.

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Appendices

APPENDICES

Appendix I. Mean weather parameters during the experimental period (Jan 1991-Dec 2011) recorded by the department of meteorology, college of horticulture, Kerala Agricultural University.

Months	**Temperature (°C)**		**Rainfall(mm)**
	Maximum	**Minimum**	
January	32.79	22.3	1.47
February	34.51	22.7	15.12
March	35.5	24.09	24.4
April	34.7	24.83	88.86
May	33.12	24.72	209.04
June	30.11	23.53	695.25
July	29.06	22.8	689.59
August	29.39	23.15	441.28
September	30.45	23.21	284.01
October	30.95	23.07	331.31
November	31.47	23.12	110.48
December	31.4	22.44	13.14
Mean	31.95	23.33	241.99
Total Rainfall (mm)			2903.95

Appendix II ANOVA for fitting the regression equation for predicting total AGB

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	23.329	2	11.665	453.916	.000[a]
Residual	.848	33	.026		
Total	24.177	35			
Independent variables: (Constant), lnD					

Appendix III ANOVA for fitting the regression equation for predicting total AGB

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	23.329	2	11.665	453.916	.000[a]
Residual	.848	33	.026		
Total	24.169	35			
Independent variables: (Constant), $\ln H_1$, lnD					

Appendix IV ANOVA for fitting the regression equation for predicting total AGB

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	23.372	2	11.686	479.137	.000[a]
Residual	.805	33	.024		
Total	24.169	35			
Independent variables: (Constant), $\ln H_2$, lnD					

Appendix V ANOVA for fitting the regression equation for predicting stem wood biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	22.232	1	22.232	525.594	.000[a]
Residual	1.438	34	.042		
Total	23.670	35			
Independent variables: (Constant), lnD					

Appendix VI ANOVA for fitting the regression equation for predicting stem wood biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	21.693	2	10.846	140.723	.000^a
Residual	2.544	33	.077		
Total	24.327	35			
Independent variables: (Constant), H_1, D					

Appendix VII ANOVA for fitting the regression equation for predicting stem wood biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	22.578	2	11.289	341.185	.000^a
Residual	1.092	33	.033		
Total	23.670	35			
Independent variables: (Constant), $\ln H_2$, lnD					

Appendix VIII ANOVA for fitting the regression equation for predicting branch biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	41.570	1	41.570	284.943	.000^a
Residual	4.960	34	0.146		
Total	46.530	35			
Independent variables: (Constant), lnD					

Appendix IX ANOVA for fitting the regression equation for predicting branch biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	41.580	2	20.790	138.600	.000^a
Residual	4.950	33	.150		
Total	46.530	35			
Independent variables: (Constant), lnD, $\ln H_1$					

Appendix X ANOVA for fitting the regression equation for predicting branch biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	41.614	2	20.807	139.667	.000^a
Residual	4.916	33	.149		
Total	46.530	35			
Independent variables: (Constant), lnH$_2$, lnD					

Appendix XI ANOVA for fitting the regression equation for predicting twig biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	9.421	1	9.421	38.740	.000^a
Residual	8.268	34	.243		
Total	17.689	35			
Independent variables: (Constant), lnD					

Appendix XII ANOVA for fitting the regression equation for predicting twig biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	10.174	2	5.087	22.338	.000^a
Residual	7.515	33	.228		
Total	17.689	35			
Independent variables: (Constant), lnD H$_1$					

Appendix XIII ANOVA for fitting the regression equation for predicting twig biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	9.601	2	4.801	19.587	.000^a
Residual	8.088	33	.245		
Total	17.689	35			
Independent variables: (Constant), lnH$_2$, lnD					

Appendix XIV ANOVA for fitting the regression equation for predicting leaf biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	20.343	2	10.171	66.027	.000[a]
Residual	5.084	33	.154		
Total	25.427	35			
Independent variables: (Constant), lnD, $(\ln D)^2$					

Appendix XV ANOVA for fitting the regression equation for predicting leaf biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	20.797	3	6.932	47.918	.000[a]
Residual	4.630	32	.145		
Total	25.427	35			
Independent variables: (Constant), D^2H_1					

Appendix XVI ANOVA for fitting the regression equation for predicting leaf biomass

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	21.379	3	7,126	56.335	.000[a]
Residual	4,048	32	.126		
Total	25.427	35			
Independent variables: (Constant), $\ln H_2$, lnD					

Appendix XVII ANOVA for fitting the regression equation for predicting total volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	21.825	2	10.912	149.297	.000[a]
Residual	2.412	33	.073		
Total	24.237	35			
Independent variables: (Constant), D, D^2					

Appendix XVIII ANOVA for fitting the regression equation for predicting total volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	21.693	2	10.846	140.723	.000[a]
Residual	2.544	33	.077		
Total	24.327	35			
Independent variables: (Constant), H_1, D					

Appendix XIX ANOVA for fitting the regression equation for predicting total volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	22.736	2	11.368	249.986	.000[a]
Residual	1.501	33	.045		
Total	0.507	35			
Independent variables: (Constant), H_2, D, D^2H_2					

Appendix XX ANOVA for fitting the regression equation for predicting bole volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	16.902	2	8.451	714.221	.000[a]
Residual	.390	33	.012		
Total	17.292	35			
Independent variables: (Constant), D, D^2					

Appendix XXI ANOVA for fitting the regression equation for predicting bole volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	16.873	2	8.437	664.930	.000[a]
Residual	.419	33	.013		
Total	17.292	35			
Independent variables: (Constant), lnH_1, lnD					

Appendix XXII ANOVA for fitting the regression equation for predicting bole volume

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	16.978	2	8.489	890.230	.000[a]
Residual	.315	33	.010		
Total	17.292	35			
Independent variables: (Constant), $\ln H_2$, $\ln D$					

Appendix XXIII ANOVA for fitting the regression equation for predicting Total height

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	325.831	2	162.915	55.906	.000[a]
Residual	96.165	33	2.914		
Total	421.996	35			
Independent variables: (Constant), D, D^2					

Appendix XIV Marketable wood obtained from (Kg tree^{-1}) table

GBH	Biomass	GBH	Biomass	GBH	Biomass	GBH	Biomass
31	26.8	56	92.0	81	198.8	106	348.5
32	28.6	57	95.5	82	204.0	107	355.4
33	30.5	58	99.0	83	209.2	108	362.4
34	32.5	59	102.6	84	214.5	109	369.4
35	34.5	60	106.3	85	219.8	110	376.5
36	36.6	61	110.0	86	225.3	111	383.7
37	38.7	62	113.8	87	230.8	112	391.0
38	41.0	63	117.7	88	236.3	113	398.3
39	43.2	64	121.6	89	242.0	114	405.7
40	45.6	65	125.6	90	247.7	115	413.1
41	48.0	66	129.7	91	253.5	116	420.7
42	50.5	67	133.8	92	259.3	117	428.3
43	53.0	68	138.0	93	265.2	118	436.0
44	55.6	69	142.3	94	271.2	119	443.7
45	58.3	70	146.6	95	277.3	120	451.5
46	61.0	71	151.0	96	283.4	121	459.4
47	63.8	72	155.5	97	289.6	122	467.4
48	66.7	73	160.0	98	295.9	123	475.4
49	69.6	74	164.6	99	302.2	124	483.5
50	72.6	75	169.3	100	308.6	125	491.7
51	75.7	76	174.1	101	315.1	126	499.9
52	78.8	77	178.9	102	321.6	127	508.2
53	82.0	78	183.7	103	328.3	128	516.6
54	85.3	79	188.7	104	334.9	129	525.1
55	88.6	80	193.7	105	341.7	130	533.6

BIOMASS AND CARBON SEQUESTRATION IN SILVER OAK (*Grevillea robusta* A. Cunn.) STANDS IN THE MIDLANDS OF KERALA

By

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ABSTRACT OF THE THESIS

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ABSTRACT

The present study was conducted in College of Forestry, Kerala Agricultural University, Vellanikkara on biomass production and carbon sequestration potential of a 20-year-old *Grevillea robusta* A. Cunn. plantation standing in the midlands of Kerala. The study reveals the biomass production and productivity, volume production, nutrient export through harvest, and carbon allocation of the above plantation. The mean aboveground biomass production was 197.89 kg $tree^{-1}$. Whereas on unit area basis it was 62.59 Mg ha^{-1}.The percentage contribution of various components to AGB was in the order: stem wood > branch > leaves > twig. Diameter profoundly influenced the biomass production on per tree basis, whereas on unit area, it was influenced mainly by density. Equations were developed for predicting AGB and biomass components with respect to DBH alone, DBH and total height/bole height together. With respect to the DBH alone as independent variable, for the total AGB, stem, branch, twig the best fit equation was $\ln Y = a_0 + a_1 * \ln D$. However, in leaves, the equation selected was $\ln Y = a_0 + a_1 * \ln D + a_2 * (\ln D)^2$ with high R^2 value and lowest Furnival index. For predicting the total volume and bole volume the best fit equation was $\ln Y = a_0 + a_1 * D + a_2 * D^2$. Studies on nutrient dynamics revealed that (N P K) among the components, leaves had the maximum concentration of the nutrients and stem wood the lowest. The nutrient accumulation in various biomass components was found to be in the decreasing order: stem wood > leaves > branch > twig. The maximum nutrients accumulated in stem wood (169.32 kg $tree^{-1}$) and minimum in twigs (3.94 kg $tree^{-1}$). Among the nutrients, N accumulated maximum followed by K and P. Stands showed a greater accumulation of nutrients with high potential of nutrient export through harvest. The mean carbon concentration was found to be 46.58 per cent and among components, the leaf portion had the maximum concentration (48.36 %) of carbon and stem wood the lowest (45.67 %). The carbon sequestration potential of 20-year-old *G. robusta* plantation was 27744 kg ha^{-1}.