CARBON SEQUESTRATION POTENTIAL OF TEAK PLANTATIONS OF KERALA

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CERTIFICATE

This is to certify that the research work presented in the thesis entitled **"Carbon Sequestration Potential of Teak Plantations of Kerala"** is based on the authentic record of original work done by Mr. Sreejesh, K.K (Reg. No. 3983) under my supervision and guidance at Kerala Forest Research Institute, Peechi, Thrissur in partial fulfillment of the requirements of the degree of Doctor of Philosophy and that no part of this work has previously formed the basis for the award of any degree, diploma, associateship, fellowship or any other similar title or recognition. All the relevant corrections and modifications suggested by the audience during the pre-synopsis seminar and recommendation by the Doctoral Committee of the candidate has been incorporated in the thesis.

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DECLARATION

The research work presented in the thesis entitled **"Carbon Sequestration Potential of Teak Plantations of Kerala"** submitted in partial fulfillment of the requirements of the degree of Doctor of Philosophy of Cochin University of Science and Technology, is a bonafide record of the research work done by me under the supervision of Dr. Thomas P Thomas, Scientist F & HoD (Rtd.), Soil Science Department, Kerala Forest Research Institute, Peechi, Thrissur. No part of this work has previously formed the basis for the award of any degree, diploma, associateship, fellowship or any other similar title or recognition.

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Abstract

Carbon storage potential of teak plantation was estimated by studying plantations in Nilambur undergoing prescribed thinning schedules. Nilambur in Kerala State has the reputation of establishing the first teak plantation in India. The area has a humid tropical climate with around 300 cm annual rainfall received from the two monsoons. The soil is well drained coarse textured oxisol with high content of sesquioxides. An average teak tree at Nilambur was found to attain a height of 6.93 m and dbh of 6.3 cm at 5 year which was seen to increase to 22.83 m and 45.85 cm, respectively at the final felling stage of 50 years. Biomass was found to increase from 65.38 kg tree^{-1} *at the first stage to 1085.70 kg tree*$^{-1}$ *at the final stage of felling. Significant increase in growth and biomass production was noted after 30th year of plantation.*

Carbon sequestration in various compartments of teak followed the pattern bole > branch > root > bark in the initial stages and bole > root > branch > bark in the latter stages. Carbon sequestration increased with age and at 50 years 332.88 kg tree^{-1} *carbon was found to be stored in bole, 60.63 in branch, 80.06 in root and 26.57 kg tree*$^{-1}$ *in bark compartment giving a total of 508.14 kg tree*$^{-1}$ *of carbon.*

Allometric models to predict carbon sequestration with height and dbh as independent variable and carbon sequestered as dependent variable were tested to obtain the best fit model. The best regression model for predicting carbon sequestered in the bole compartment was $\sqrt{Y} = 1.502 + 0.344\,D$, *that for bark* $\sqrt{Y} = 1.163 + 0.082\,D$, *for branch* $\ln Y = 1.308 \ln D - 1.116$, *for root* $\sqrt{Y} = 0.858 + 0.170\,D$, *for above ground compartment* $\sqrt{Y} = 2.113 + 0.379\,D$ *and that for predicting the total carbon sequestered in the teak in all its vegetative parts was* $\sqrt{Y} = 2.289 + 0.415\,D$.

Carbon sequestration potential of teak plantations in Kerala was calculated based on the estimated carbon sequestration at prescribed felling stages and the area prescribed for felling in 2014. The calculated figure was 0.21 million tons of carbon which was equivalent to Certified Emission Reduction (CER) potential of 0.81 million units corresponding to 61.48 crores of rupees at current exchange rates.

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Chapter 1

General Introduction

1. General Introduction

Climate change due to global warming and other related factors has become a serious issue which is affecting the earth's ecosystem adversely. Global warming has been attributed to the presence of increasing amount of water vapour, carbon dioxide, methane, nitrous oxide etc., in the atmosphere which permits sunlight to pass through freely but absorb and trap the extra-terrestrial radiation that is reflected back from the earth's surface (Walker *et al.,* 1999; Corpuz, 2014). Since these gases trap the infrared radiation resulting in heating of the atmosphere similar to the greenhouse, these gases were named as greenhouse gases (Nowak and Crane, 2002; Jung, 2005). The greenhouse effect was first described in 1827 by the French scientist Fouriere. Later Arrhenius, the Sweedish scientist pointed out that increasing amount of carbon dioxide emissions after the industrial revolution has changed the greenhouse gas composition markedly leading to excessive rise in atmospheric temperature. Increase in the CO_2 concentration in the atmosphere has been reported to be from 270 ppm prior to the industrial revolution to 394 ppm in December 2012 and to 401.30 ppm to date (Mauna Loa observatory, 2015).

The greenhouse gases differ in their capacities to increase temperature which is termed the Global Warming Potential (GWP) of the particular gas. GWP of CO_2 is 1, that of methane 21 and nitrous oxide 310 on a hundred year time horizon (Schimel, 1995). This shows that gases such as methane and nitrous oxide are much more harmful than carbon dioxide. However, CO_2 accounts for 64% of the increase in atmospheric heat since it is released into the atmosphere at enormous levels (Maslin, 2004) due to combustion of fuels mainly fossil fuels the consumption of which has been increasing in geometric proportion post industrial revolution. Fossil fuel burning and deforestation/forest degradation together has been responsible for the unprecedented increase of carbon dioxide during the last two centuries (Schulze *et al.,* 2002). Carbon dioxide emitted is partitioned between the atmosphere (around 50%), the ocean (around 30%) and the terrestrial biosphere (around 20%) (Kasting, 1998); that stored in the biosphere often referred to as the "missing carbon sink" (Scholes *et al.,* 1999)

1.1 International agreements and obligations

The United Nations Environmental Programme (UNEP) and the World Meteorological Organisation (WMO) together established the Inter-Governmental Panel on Climate Change (IPCC) in 1988 to formulate guidelines that can help to reduce the release of greenhouse gases into the atmosphere. The United Nations Conference on Environment and Development (UNCED) organized the first Earth Summit in Rio de Janeiro, Brazil in the year 1992 in which 162 countries of the world adopted a treaty known as the United Nations Framework Convention on Climate Change (UNFCCC). The year 1990 was taken as the base year and the developed countries were expected to reduce their greenhouse emissions to 1990 levels by the year 2000.

The UNFCCC at the third Conference of Parties (COP) held in December 1997 at Kyoto, Japan initiated certain protocols legally binding the industrialized countries (Annex I countries) to cut the greenhouse gas emissions by 5.2% compared to the 1990 levels during the first commitment period of 2008-2012 (Schulze *et al.*, 2002). The Kyoto Protocol (KP) includes reduction of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6), hydro fluorocarbons (HFCs) and per fluorocarbons (PFCs). The Kyoto Protocol came into force only on 16th February 2005 after agreement by Russia on 18th November 2004. Thus 163 countries emitting 61.6% of total CO_2 emissions of Annex I countries agreed to the Kyoto Protocol. The KP identified flexibility mechanisms such as Joint Implementation (JI), Clean Development Mechanism (CDM) and Emission Trading (ET) to meet their target in reducing emissions. CDM includes carbon sequestration through reforestation, afforestation and reducing deforestation as items that qualify for emission reduction credits.

Removal of greenhouse gases from the atmosphere can be achieved through sequestration. Carbon sequestration is the transfer of atmospheric CO_2 into the pools with a longer mean residence time in such a manner that it is not re-emitted into the atmosphere in the near future (Lal, 2004). Carbon emissions from different types of land uses and land use change has been estimated to be around 1.65 Gt (Giga ton) carbon per year, 80% of which come from developing countries especially those having large area of tropical forest including Brazil, Indonesia, Malaysia, Papua New Guinea, Gabon, Costa Rica, Cameroon, Republic of Congo and Democratic Republic of Congo. Plantation forestry activities, deforestation and forest degradation account for these emissions. Land Use, Land Use Change and Forestry (LULUCF) has thus entered the Kyoto Protocol. Forest loss to the tune of 13 million hectares per year and forest degradation of 7.3 million hectares per year has been mentioned in the 2007 IPCC report.

The UNFCCC conference of parties 11 which met in Montreal in 2005 to review and supplement the CDM included Reducing Emission from Deforestation (RED) as eligible for carbon credits. It was further expanded to accommodate emissions from forest degradation and RED was modified as Reducing Emission from Deforestation and Degradation (REDD) on suggestion from Indonesia (Kanninen, 2010). RED and REDD carbon credits are fundamentally different from credits accruing from afforestation/reforestation activities because it is not from growing trees but from avoiding deforestation and reducing forest degradation that the credits are obtained.

The COP 13 of 2007 adopted the Bali Road Map further widening the REDD concept by including forest conservation, sustainable forest management and increasing forest area carbon stocks along with it and was named REDD$^+$. The developing world gets the benefit as they have more forest area. UNFCCC is responsible for REDD$^+$ policy formulation and implementation guidelines. The recently concluded COP 21 in Paris seems to have addressed the lacunae in implementation of all the previous decision since the Annexure I countries that were reluctant to oblige have themselves offered emission reductions to save the planet.

India's share in CO_2 emission is 5.81% compared to China emitting 28.03% and the USA emitting 15.9% of the world's total emission as per data of 2015 (Statista, 2015). Energy sector contribute 61% emissions, agriculture sector 28%, industrial processes 8%, waste disposal 2% and LULUCF sector contributes 1% carbon dioxide emissions.

Forests sequester carbon dioxide from the atmosphere through photosynthesis. This carbon is distributed in the living plants and on death gets transformed to carbon which is stored in the soil (Sang *et al.*, 2013; Kaul *et al.,* 2010). Forests capture carbon and also act as carbon reservoirs. A young forest during its early fast growth period sequester large amounts of carbon while an old forest acts more as a reservoir while adding less carbon annually. It can hold large amounts of carbon as biomass over long period of decades and even centuries (Luyssaert *et al.*, 2008). The capacity to sequester carbon varies with species, site, spacing, climate, age etc; (Vucetich *et al.*, 2000; Pussinen *et al.*, 2002; Terakunpisut *et al.,* 2007; Kaul *et al.*, 2010). Carbon sequestration capacity of forests can be supplemented by afforestation of additional land area. The importance of forest in mitigating climate change has prompted countries to maintain carbon budgets of their forest resource. It is estimated that during the period 1995-

2050 afforestation/reforestation activities can sequester 1.1 to 1.6 Pg per year of which the tropics would contribute 70% (IPCC, 2007).

Afforestation and reforestation are attractive since they produce wood along with sequestering carbon. Different carbon budget models that can account forest carbon dynamics have been proposed some of which take into consideration the carbon stored in the forest ecosystem and also that contained in the harvested wood (Masera *et al.*, 2003). Afforestation/ reforestation based CDM projects are being implemented in developing countries (Samek *et al.,* 2011) prompting screening of fast growing trees with high storage potential (Paquette and Messier*,* 2010).

Terrestrial vegetation is considered to store around 466 Gt of carbon, 75% of which is in the forest ecosystems mainly in the stem, branches, foliage and roots of trees. Forest soils account for 39% of all carbon stored in soils (Bolin and Sukumar, 2000). The high carbon sequestration capacity of forest coupled with the long residence time of carbon is receiving greater attention (Winjum and Schroeder, 1997) at present.

India, known for its diverse forest and mega biodiversity, ranks 10th among the most forested nations of the world (FAO, 2006). It has 76.86 million hectare of its geographical area (23.4%) under forest and tree cover (FSI, 2009). Sequestered carbon has increased from 6244.78 million tons in 1995 to 6621.55 million tons in 2005 with an annual increment of 37.68mt of carbon or 138.15 million tons of CO_2 equivalents. The total forest carbon stock of India as estimated by FAO (2006) has increased during 1986-2005 period to 10.01 Gt of carbon. On a global scale carbon sequestration by forest vegetation has been reported to be 283 Gt of carbon in its biomass and 38 Gt in dead wood giving a total of 321 Gt of carbon storage (FAO, 2006).

Forest plantations assist in greenhouse effect mitigation by sequestering carbon from the atmosphere. At the same time, timber production from these plantations relieves pressure on natural forests for the resource (Updegraff *et al.,* 2004). Asia and South America together account for 89% of forest plantations with a planting rate of 4.5 million hectare per year (Fang *et al.*, 2007). Forest plantations of several species such as teak, eucalyptus, acacia, poplar etc., have been raised successfully within and outside forest reserves in India.

The cumulative area under forest plantations in India up to 2005-2006 as estimated by the National Afforestation and Ecodevelopment Board (NAEB) of the Ministry of Environment and Forests of the government of India was 42.17 million hectare (Pandey, 2008). Carbon sequestration potential of different plantation species vary widely (Negi *et al.,* 2003). Estimates of tree cover outside forest in India using remote sensing gave a figure of 2.68 billion trees contributing average tree carbon density of 4 Mg C ha^{-1}; the average density in forest was 43 Mg C ha^{-1} (Kaul *et al.*, 2010).

1.2 Carbon sequestration by teak

Teak (*Tectona grandis* Linn. f.) is one of the world's high quality timber with fine grain, durability and appealing colour and hence in great demand in specific markets of luxury applications including furniture, ship building and decorative components. Teak occurs naturally in the geographical region situated between 9^0 to 26^0 N latitude and 73^0 to 104^0 E longitude which include India, Myanmar, Laos and Northern Thailand. It has also been introduced to South East Asia, Indonesia, Sri Lanka, Vietnam, Malasysia and the Soloman Islands as well as Africa and Latin America (Phillips, 1995). Teak planting in India began during the 1840s and the first plantation in India was raised at Nilambur, Kerala (Tewari, 1992).

Tectona grandis is a large deciduous tree with a clean cylindrical bole attaining a height of around 25m. It occurs mostly in moist and dry deciduous forests below 1000 m elevation. It grows best in hot humid climates with annual rain fall of 1250 – 3750 mm and temperature of 13 - 17^0C minimum and 39-43^0C maximum. Natural teak occurs on hilly undulating terrain of basalt, granite, gneiss, charnockite, schist, limestone and sandstone. Its potential is best expressed on well drained deep alluvium. In Nilambur, Kadambi (1972) noted the following factors helpful for high quality of teak, viz. high SiO_2/R_2O_3 ratio in the soil, alluvial site, adequate Ca and Mg in the soil, good moisture availability, sandy loam texture and good drainage. It is a light demanding species and does not tolerate shade.

Teak performs well in plantations though mixed plantations may not yield good result. The first teak plantation was started in 1680 in Sri Lanka (Pandey and Brown, 2000). Teak plantations started in India with the first plantation established in Nilambur in the year 1842. Area under teak plantation increased gradually in many countries reaching 900,000 ha by 1970 (Kadambi, 1972; Tewari, 1992). Further increase occurred leading to 1.7 million ha in 1980 (Pandey, 1983) and 2.2 million hectare by 1990 (Krishnapillay, 2000; Bhat *et al.*, 2008). Recent figures show that out of 187 million ha of global forest plantations, teak plantations constitute about 5.7 million ha; most of the area (>90%) occur in Asia (Shukla and Viswanath, 2014) of which 44% is located in India.

In Asia, teak is grown in rotations of 60 years or more while in tropical America, plantations are harvested at 20 to 30 years. Teak was worked on a 70 year rotation but the same has been subsequently reduced to 50 years in certain parts of India. The rotation age has been brought down in Nilambur to 50 years in the recent past. Teak trees grown in plantations on good soils may reach an average of 60 cm diameter at breast height (dbh), and 30 m in height in about 50 years.

Productivity of teak on a plantation scale varies widely depending on the site quality. Mean annual increment of biomass has been reported to vary from 2.0 m^3 ha^{-1} yr^{-1} in poor sites to 17.6 m^3 ha^{-1} yr^{-1} in fertile sites (Pandey and Brown, 2000). The minimum and maximum total biomass (above ground + below ground) was found to be 0.007 Mg $tree^{-1}$ (4 cm dbh and 5 m height) and 2.997 Mg $tree^{-1}$ (50 cm dbh and 25 m height) for *T. grandis* (Bohre *et al.,* 2013).

Forest plantations can sequester carbon from the atmosphere (Kraenzel *et al.,* 2003) though they do not do so permanently on account of harvest or natural death (Harmon *et al.*, 1990). An area of 2.4 million ha of teak in the world would have the potential to sequester 240 million tons of carbon. Chaturvedi and Raghubanshi (2015) reported average carbon accumulation of 532 kg C m^{-2} yr^{-1} in teak across the mono and multi-specific stands. Carbon storage by teak increases with age of the plantation from 51.32 t ha^{-1} in 19 year old plantations to 101.40 t ha^{-1} in 33 year old teak plantations (Sahu *et al.,* 2013). Derwisch *et al.* (2009) reported average above ground carbon storage of 2.9 Mg ha^{-1} in the first year to 40.7 Mg ha^{-1} in the 10th year of teak plantation in Western Panama. Carbon sequestration potential has been found to increase with high input management. It has been reported that there has been an improvement in carbon sequestration from 0.816 Mg ha^{-1} without any management to 1.76 Mg ha^{-1} with high input management in 5 year old teak plantations (Koppad and Rao, 2013).

The Kerala Forest Department was reported to have about 75,000 ha under teak, out of which, approximately 64 per cent is in the first rotation and the remaining 36 per cent is in the second and third rotation stages (Prabhu, 2003). Prospects of teak have further increased due to its ability to sequester carbon in addition to the high quality timber that it yields.

Though several studies have brought out its carbon sequestering role, no serious work on plantation teak of Kerala has been reported so far. The present study is an attempt in this direction with the following specific objectives.

1.3 Objectives of the study

1. *To estimate the carbon content in different compartments of teak plantation including the soil*
2. *To develop nondestructive predictors of carbon storage by teak in plantations*
3. *To estimate the carbon sequestration potential of teak plantations in Kerala*

Chapter 2

Study Area

2. Study Area

Teak (*Tectona grandis* Linn. f.) is the most important forest plantation species of Kerala in every respect. The study was carried out in Nilambur, Kerala where the first teak plantation in India was raised in the year 1842 by the British. The present study was taken up to assess the carbon storage potential of teak plantations in the respective felling schedules in selected plantations at Nilambur.

Nilambur in Malappuram district of Kerala lies between 11^{0}26'70" and 11^{0}36'61" N latitudes 76^{0}22'58" and 76^{0}45'10" E longitudes. Nilambur forest area is large in size and hence divided into Nilambur North forest division with an area of 39,592.491 ha and Nilambur South forest division with 36,515.27 ha area. Nilambur, Edavanna and Vazhikadavu ranges constitute the Nilambur North division while Karulai and Kalikavu ranges constitute the Nilambur South Divisions. The study sites were located in Nilambur, Edavanna and Karulai ranges depending on the availability of respective felling stages of 5, 10, 15, 20, 30, 40 and 50 year old trees.

2.1 Climate

The climate is humid tropical with both South West and North East monsoons. The South West monsoon brings maximum rain during June - September which is supplemented by the North East monsoon during the months of October – November. Summer rains are also not uncommon. On an average, the area receives around 2500 mm rain fall, 60-70% of which is contributed by the South-West monsoon 20-30% by the North-East monsoon and the rest received during the summer months. Temperature fluctuates between 21 to 38^{o}C and the humidity varies from 60 to 90 percent.

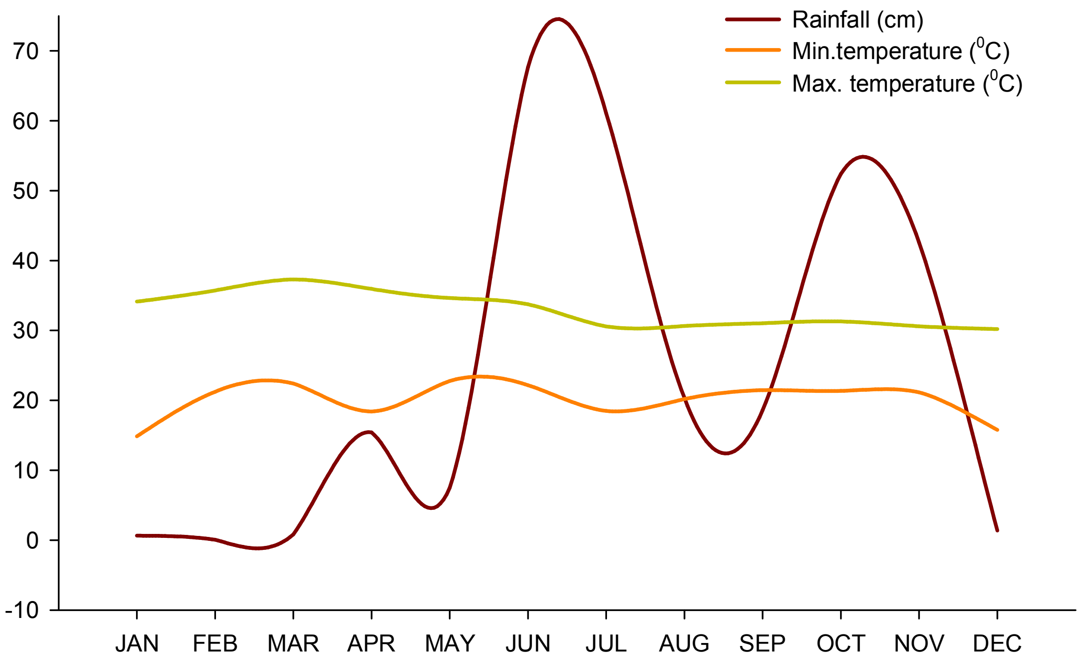

Figure 2.1. Mean rain fall and temperature of the study area

2.2 Elevation

The altitude increases as one travels towards North East of Nilambur from 50 m to 2000 m above MSL and the topography becomes rugged, undulating with moderate to steep slopes as one travels from the foothills to the Western Ghats. All aspects are met with in the landscape. The area is well drained with multitude of perennial as well as seasonal water courses.

2.3 Geology and Soil

The geology of the region is constituted by crystalline rocks of archean ages, the most common being gneiss which is mostly granitic and is easily recognizable by the alternate bands of pale and dark bands, the pale bands being dominated by quartz and feldspar and the darker shades by predominantly biotite. The soil formed from the gneissic parent material is coarse textured, acidic and with low exchange capacities because during the weathering process under the influence of hot humid tropical climate most of the silica and bases had been leached down resulting in iron-aluminium-manganese rich surface horizons of soil. These soils are often referred to as lateritic/ferrallitic soils indicating its genesis through the process called laterisation. The soil strata have well developed profiles due to intensive leaching. Appreciable amount of gravel are found in the soil mass providing good internal drainage. Accumulation of humus in the topsoil gives it dark reddish brown to dark brown colour, which changes to different shades of red in the sub-soil due to de-hydration of sesquioxides. The surface soil has a granular structure, which favours aeration, infiltration and root development.

2.4 Location of sites

Silviculture of teak has been standardised long back and has undergone modifications. The present schedule of felling operation is with a mechanical thinning at the age of 5 years which is followed by selective silvicultural thinning at 10, 15, 20, 30, 40 and 50 years of age. Teak plantations in different thinning regimes and at final felling were surveyed in Nilambur forest division and seven sites corresponding to the felling schedule on comparable site quality selected for the study; all the selected plantations were of site quality II or III. Study sites were located in Edavanna, Nilambur and Karulai ranges. The specific sites were Chathumpurai in Nilambur range for 5 year teak, Kalkulam in Karulai range for 10 year, Panayamkode in Nilambur range for 15 year, Elenchery in Edavanna range for 20 year, Edakode in Edavanna for 30 year, Kallenthode in Karulai range for 40 year and Pulimunda in Karulai range for 50 year teak plantation.

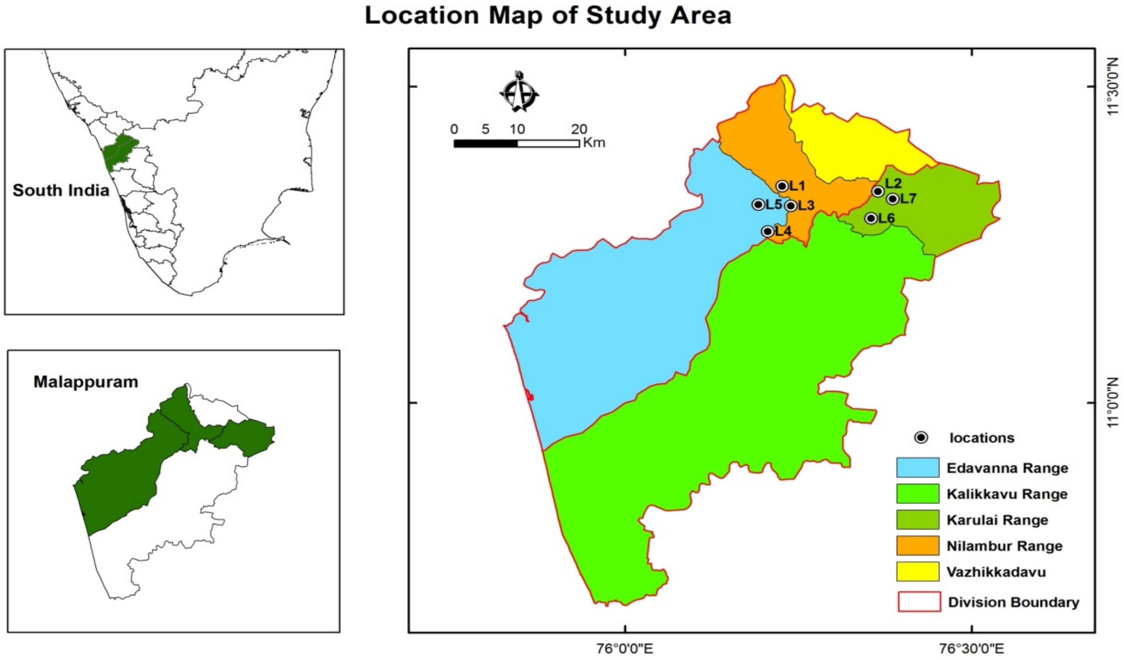

Figure 2.2. Location of sites

Chapter 3

Biomass Production of Teak

3. Biomass Production of Teak

3.1 Introduction

Biomass is the mass of living or dead organic matter often expressed as dry matter. It is expressed in kg per tree when individual tree is referred or kg per unit area when the biomass of an area is considered. Forest biomass is a function of density, height and basal area of trees in a locality. Biomass differs with site, succession, species composition and disturbance levels of the ecosystem (Whitmore, 1984; Brunig, 1983, Kuyah *et al.,* 2013).

Trees in general have dimensions that are related with one another (Gould, 1966). The height, girth, diameter and biomass follow a definite relation that are similar for most trees irrespective of its size provided there is no great variation in site conditions (King, 1996; Archibald and Bond, 2003; Bohlman and O'Brien, 2006; Dietze *et al.*, 2008). Biomass is calculated by multiplying the volume with density; density differs within trees depending on the longitudinal position as well as the radial position. It also differs between compartments of a tree such as wood, bark, branches, stump, roots and leaves (Andrews and Siccama, 1995; Colin-Belgrand *et al.,* 1996; Guilley *et al.,* 2004; Chave *et al.*, 2005; Saint-Andre *et al.,* 2005; Augusto *et al.,* 2008; Berges *et al.,* 2008; Henry *et al.,* 2010; Knapic *et al.,* 2011).

Biomass of teak (*Tectona grandis*) was dependent on height and dbh and the net biomass production was found to be 13.99 Mg ha^{-1} yr^{-1} (Bohre *et al.,* 2013). Karmacharya and Singh (1992) had reported a net production of 14 Mg ha^{-1} yr^{-1} in dry tropical regions of India.

Teak was found to attain a dbh of 15.06 cm at the age of 9 years and a dbh of 27.70 cm at 12 years in farmers' field (Bhore *et al.,* 2013); a dbh of 18 cm was reported in forest plantations of 20 years age by Buvaneswaran *et al.* (2006) in Tamil Nadu. Shukla (2009) reported a mean dbh of 15.04 cm for

7.5 year old teak grown as plantation in Madhya Pradesh. Significantly better growth was reported in agro forestry than sole plantation by Mutanal *et al.* (2000).

The net biomass accumulation in 10 year old teak was found to be 279.89 Mg ha^{-1} (Bohre *et al.,* 2013). Variations in biomass (Above ground + below ground) from 0.007 Mg tree^{-1} (5 m height and 4 m dbh) to 2.997 Mg tree^{-1} (25 m height with 50 m dbh) were reported by Bohre *et al.* (2013).

Mixed plantation had significantly greater diameter and height than the sole plantation. Bole biomass of 2.69 to 3.79, 4.79 to 6.95 and 8.36 to 12.2 kg tree^{-1} was found in 4, 6 and 8 year plantations respectively (Sharma *et al.*, 2010). Growth and dry matter production of teak increases with age. At the age of 20 years, teak was found to attain a height of 23.1 m with a diameter of 23.1 cm. The fast growth during the initial years was found to slow down after 15 years (Parameswarappa, 1995). Sahu *et al.* (2013) reported total biomass of 206.48 Mg ha^{-1} in 23 year old teak plantation of which the above ground contributed 173.53 Mg ha^{-1} and the below ground 32.92 Mg ha^{-1} of biomass. The distribution in bole, branch, leaf and root was found to be 104.64, 46.33, 22.56 and 32.95 Mg ha^{-1} respectively. Heque and Usman (1993) observed significantly greater diameter and height in mixed plantation than in sole plantation of 26 years.

Increase in height, dbh and biomass with age has been reported by most of the workers. The average height of 2, 8, 9, 10 and 19 year old plantations were reported to be 2.41, 5.20, 7.25, 8.15 and 11.70 m respectively with corresponding dbh of 3.8, 7.6, 10.8, 12.4 and 17.4 cm. The biomass accumulation in the respective years were 12.97, 88.84, 202.87, 279.89 and 706.37 Mg ha^{-1} with mean annual increments of 6.48, 11.10, 22.54, 27.99 and 37.18 Mg ha^{-1} yr^{-1} (Bhore *et al.,* 2013).

Total biomass of teak at 19 years of age was found to be 119.37 Mg ha^{-1}, at 23 years 210.48 Mg ha^{-1} and at the age of 33 years it was 235.14 Mg ha^{-1} (Sahu *et al,* 2013). The above ground biomass increased from 99.08 Mg ha^{-1} at 19 years to 197.88 Mg ha^{-1} at 33 years, the respective figures for below ground biomass were 20.29 and 37.27 Mg ha^{-1}.

Teak during its initial growth years allocates more resources to the root system to optimize nutrient uptake that is necessary to support fast growth during this period (Prasad and Mishra, 1984; Pandey, 2009). Biomass of teak plantations with high input management was reported to be almost double of that obtained from poorly managed plantations. The wood biomass was found to be 19.47 and 59.55 Mg ha^{-1} in 5 and 10 year old plantation with high input while that from low input areas were only 8.87 and 31.52 Mg ha^{-1} respectively. Wood density was slightly higher in poorly managed plantations though the difference was not statistically significant and the better managed plantation was as good as the other one in strength properties (Koppad and Rao, 2013).

3.2 Methodology

3.2.1 Biomass sampling

Teak plantations of different ages corresponding to the prescribed thinning schedules and the final felling were selected after ascertaining the actual felling programme from the forest officials so that measurements and sampling of biomass could be carried out in the field. In each site, sampling locales were selected that represented the average growth of the plantation. Diagonal transects of 100 m length were laid out and 50 trees adjacent to the transects were marked for biomass estimation. Girth at breast height of these trees was measured and the trees were grouped into four girth classes.

Sample trees for each girth class were selected as being nearest to the average of each class (Ovington *et al.*, 1967).

Three trees from each girth class were felled and biomass estimated by actual measurements of logs and branches; both over bark and under bark girth was recorded. Sample discs from each cut end of logs and branches were taken for density, moisture and carbon estimation.

Bole

The sample trees were cut at the ground level with the help of power saw and total length measured after removing all the branches and twigs from the main stem. The bole was cut into 6 m billets and the length of each billet was recorded. The girths, both over bark and under bark, at the thinner and thicker end of each billet as well as the middle portion were also measured. The length of the trunk up to 5 cm diameter was considered as bole. Dry weight of different components was calculated on the basis of fresh and dry weight of the representative samples. Cross-sectional discs of 2 cm thickness were collected from either ends of all the billets to estimate moisture, density and carbon content. The collected discs were immediately placed in plastic bags and were packed well in order to avoid moisture loss. These samples were taken to the laboratory for further analysis. The fresh weights of the samples collected were measured immediately after arriving in the laboratory. The samples were oven dried at 70^{o}C for 48 hours after recording the fresh weight.

The density of wood and bark was measured on oven dry weight to green volume basis. The volume was measured by water displacement method, using top pan balance. Disc basic density was computed as weighted average value of blocks in relation to the volume of wood they represented in the discs.

Similarly, the average density for wood/branch was calculated by giving preference to the disc densities in relation to the volume they represented in the stem/branch. Total volume (m^3) of bole (with and without bark) for each billet was calculated using the Smalian formulae (Clutter *et al.,* 1983).

$$V = \frac{(A1 + A2)}{2} \times L$$

Where, V is the volume of the log in m^3, A1 is the area of the small end of the log in m^2, A2 is the area of the large end of the log in m^2 and L is the length of the log in m.

Biomass per hectare was calculated by multiplying weight of each sample tree with the number of trees in their respective girth class and adding the above values to get the total biomass.

Bark

Bark of the bole alone was considered for estimating the bark biomass in the current study. The difference between volume over bark and under bark of the bole was assumed as the bark volume. Volume of bark was multiplied by its density to obtain bark biomass.

Branch

The branches were grouped into four diameter classes as class 1: 0 – 5 cm, class 2: 5 -10 cm, class 3: 10 – 15 cm, and class 4: >15 cm. The length and middle girth of each branch in these subdivisions were recorded separately. Sub samples from all the diameter classes were taken for laboratory analysis. Samples of different diameters were taken from different branches to represent the architecture of a standard branch. The fresh weights of the samples collected were determined and the samples got dried in an oven at 70°C for 48 hours.

Below ground

Root systems of the selected twelve trees in each site were excavated manually by the skeleton method (Dry excavation), *i.e.* digging along the course of the roots in the soil mass. The stump along with the exposed roots was pulled out with the help of a tractor. Total fresh weight of core stump, lateral roots and secondary roots was measured in the field. Representative samples were obtained by taking several random sections from the stump and the roots. The samples were immediately placed in plastic bags and were packed well in order to reduce the moisture loss. Fresh weight was determined in the field and dry weight estimated in the laboratory by drying at 70°C for 48 hours in an electric oven.

Biomass of various compartments was worked out by estimating dry matter of samples by oven drying to constant weight and extrapolation to the whole biomass. Weight of the wood biomass was calculated by multiplying volume of biomass and specific gravity (SG) of the wood, as per the below mentioned formula where specific gravity (SG) is the ratio of oven dry weight and green volume of the pieces of wood samples.

Biomass (g) = Volume of biomass (m^3) x Specific gravity (SG)

where, SG = Oven dry weight / Green volume

Plates 3.1 Biomass sampling- Above ground

Plate 3.2 Biomass sampling – Below ground

3.3 Results

3.3.1 Biomass production of 5 year teak

As mentioned earlier in chapter 2, field studies were confined to sample plots of 7 teak plantations in the Nilambur North and South Forest Divisions of Kerala. Three trees from four different girth classes were sampled for detailed observation from each of these teak plantations. The basic data on various parameters like diameter at breast height (dbh) and height along with dry weight of various biomass components of sample trees are given in table 3.1. It is seen that these plantations show considerable variation in their growth parameters within the same age groups as well as between age groups. Height increased with increase in girth class. Significant differences were noted with increase in girth except between the second and third girth class. Maximum height of 9.67 m was recorded in >25 cm girth class.

3.3.1.1 Above ground biomass

The above ground biomass production among various tree girth classes were calculated by adding the biomass of above ground compartments such as bole, branch and bark and is shown in the same table 3.1. It was observed that the lowest above ground biomass of 49.33 kg tree^{-1} recorded in the girth class <15 cm was significantly different from other girth classes. Trees in the girth classes 15-20, 20-25 and >25 cm showed no significant difference in their above ground biomass at this age.

The bole biomass of girth class <15 cm was found to vary significantly from trees belonging to 15-20, 20-25 and >25 cm girth classes. The girth class >25 cm showed the highest bole production (45.27 kg tree^{-1}) and the lowest was by the trees in <15 cm girth class (34.57 kg tree^{-1}). However, significant variation in bole biomass production was not observed between the trees belonging to 15-20, 20-25 and >25 cm girth classes.

The biomass production in branch compartment showed a maximum value of 9.01 kg tree^{-1} in girth class >25 cm and a lower value of 7.94 kg tree^{-1} in girth class <15 cm but significant difference in branch biomass between trees of different girth classes was not observed in teak at this age.

Table 3.1. Biomass production of 5 year teak

Girth class (cm)	Height (m)	dbh (cm)	Mean dry matter production (kg tree^{-1})						Root: shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<15	4.43^{a} ±0.23	3.87^{a} ±0.32	34.57^{a} ±2.36	7.94^{a} ±0.64	6.82^{a} ±0.77	49.33^{a} ±3.74	7.25^{a} ±0.28	56.59^{a} ±4.01	0.150^{a} ±0.006
15-20	6.63^{b} ±0.45	5.73^{a} ±0.37	40.13^{b} ±0.16	9.10^{a} ±0.13	8.39^{ab} ±0.22	57.62^{b} ±0.50	7.69^{ab} ±0.24	65.31^{b} ±0.74	0.137^{a} ±0.003
20-25	7.00^{b} ±0.29	6.79^{b} ±0.28	41.34^{b} ±1.01	8.96^{a} ±0.99	8.71^{b} ±0.06	59.01^{b} ±0.61	$8.13b^{c}$ ±0.06	67.14^{b} ±0.67	0.140^{a} ±0.001
>25	9.67^{c} ±0.44	9.02^{c} ±0.53	45.27^{b} ±1.08	9.01^{a} ±0.56	9.42^{b} ±0.16	63.70^{b} ±0.88	8.80^{c} ±0.15	72.50^{b} ±1.03	0.140^{a} ±0.001
Mean	6.93 ±0.58	6.36 ±0.58	40.33 ±1.30	8.75 ±0.31	8.34 ±0.34	57.42 ±1.77	7.97 ±0.19	65.38 ±1.95	0.142 ±0.002

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The bark biomass was highest (9.42 kg tree^{-1}) in the girth class >25 cm while it was not significantly different with that of trees in adjacent girth classes. However, trees in the smaller girth classes recorded lesser bark biomass production.

3.3.1.2 Below ground biomass

It was seen that the below ground biomass in the trees of the adjacent girth classes did not differ significantly though it was lower in the smaller girth classes and greater in the larger girth classes as expected. The below ground biomass increased from 7.25 kg tree^{-1} in girth class <15 cm to 8.80 kg tree^{-1} in girth class >25 cm.

3.3.1.3 Root –shoot ratio

The root to shoot ratio of trees belonging to various girth classes showed that the trees of girth class <15 cm had the highest root-shoot ratio of 0.15 and the minimum value 0.137 was in girth class 15-20 cm. Though the root: shoot ratio varies with the girth classes, they were not statistically dissimilar.

3.3.1.4 Total biomass

The total biomass of teak tree in various girth classes computed by adding the biomass in different components showed that the total biomass production was lowest (56.59 kg tree^{-1}) in trees of girth class <15 cm which was significantly different from the girth classes of 15-20, 20-25 and >25 cm. The teak trees in the girth classes of 15-20, 20-25 and >25 m showed no significant difference in their total biomass at this age.

3.3.1.5 Mean tree biomass production and partitioning

The average biomass production of teak trees at the age of five year regardless of their girth classes revealed that a teak tree attained an average height of 6.93 m with a mean dbh of 6.36 cm. The above ground biomass was 57.42 kg tree^{-1} on an average while the below ground biomass production was 7.97 kg tree^{-1} contributing a total biomass of 65.38 kg tree^{-1}. It was seen that the mean bole production was 40.33 kg tree^{-1} at this age while the branch and bark recorded an average biomass of 8.75 and 8.34 kg tree^{-1} respectively.

The percentage distribution in various compartments of five year teak showed that the bole contributed the maximum of 61.68% of the total biomass. The percent contribution of various other compartments such as branch, bark and root to the total biomass was 13.39, 12.75 and 12.19% respectively. The biomass partitioning in different components was in the order of bole > branch > bark > root. The mean root-shoot ratio for 12 trees of various girth classes recorded a value of 0.142 at 5 years growth.

3.3.2 Biomass production of 10 year teak

The biomass production in different components of sample trees from various girth classes of 10 year old plantations are shown in Table 3.2. It was seen that these plantations showed considerable variation in their growth parameters between various girth classes. The sample trees showed variation in height though they were not statistically significant. Trees with girth <40 cm had a height of 7.67 m whereas trees with girth >50 cm recorded a height of 10.67 m on an average.

3.3.2.1 Above ground biomass

Considerable variation existed in the above ground biomass as well as its components within a plantation. For example the smallest tree of <40 cm girth had an above ground biomass of 105.56 kg tree^{-1} whereas the biggest tree of the same plantation with >50 cm girth had an above ground biomass of 148.53 kg tree^{-1}.

The distribution of bole biomass of teak in various girth classes showed that the maximum bole production (103.24 kg tree^{-1}) was in the trees of girth class >50 cm and was found to vary significantly from trees in <40, 40-45 and 45-50 cm girth classes. The trees in girth classes of <40, 40-45 and 45-50 cm did not differ significantly in their bole biomass.

The biomass of branch compartment had the maximum value of 28.49 kg tree^{-1} in girth class >50 cm and a smaller value of 13.55 kg tree^{-1} in girth class <40 cm but significant difference in branch biomass between trees of various girth classes was not observed in teak at this age.

The bark biomass was highest (16.81 kg tree^{-1}) in the girth class >50 cm while it was not significantly different with that of trees in adjacent girth classes. However, trees in the smaller girth classes recorded lower value for bark biomass production.

Table 3. 2. Biomass production of 10 year teak

Girth class (cm)	Height (m)	dbh (cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<40	7.67^{a} ±0.88	12.42^{a} ±0.00	79.12^{a} ±1.64	13.55^{a} ±1.03	12.88^{a} ±0.26	105.56^{a} ±0.93	18.40^{a} ±0.38	123.95^{a} ±1.30	0.173^{a} ±0.003
40-45	9.00^{a} ±0.58	13.48^{ab} ±0.28	80.73^{a} ±1.58	27.27^{a} ±5.45	12.25^{a} ±0.74	120.25^{ab} ±7.61	17.62^{a} ±1.01	137.87^{ab} ±8.57	0.143^{ab} ±0.003
45-50	9.00^{a} ±1.00	15.08^{bc} ±0.53	89.75^{a} ±3.92	27.67^{a} ±5.85	14.61^{ab} ±0.64	$132.04b^{c}$ ±1.73	20.87^{ab} ±0.91	152.91^{bc} ±1.31	0.157^{ab} ±0.009
>50	10.67^{a} ±0.67	17.30^{c} ±1.08	103.24^{b} ±3.69	28.49^{a} ±3.30	16.81^{b} ±0.60	148.53^{c} ±6.96	24.01^{b} ±0.86	172.53^{c} ±7.77	0.163^{b} ±0.003
Mean	9.08 ±0.47	14.57 ±0.61	88.21 ±3.14	24.24 ±2.63	14.14 ±0.59	126.59 ±5.25	20.23 ±0.83	146.82 ±5.98	0.159 ±0.004

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

3.3.2.2 Below ground biomass

The below ground biomass of trees of adjacent girth classes did not differ significantly. However, below ground biomass was lower in the smaller girth classes and higher in the larger girth classes as expected. The minimum below ground biomass value was 18.40 kg tree^{-1} in girth class <40 cm and maximum was 24.01 kg tree^{-1} in girth class >50 cm.

3.3.2.3 Root: Shoot ratio

The root: shoot ratio was also computed using the below ground and above ground biomass data for ten year old teak trees in various girth classes. It was higher (0.173) in the trees belonging to girth class <40 cm and the lowest value (0.143) was found in 40-45 cm girth class.

3.3.2.4 Total biomass

It can be seen from the table that the total biomass production was maximum (172.53 kg tree^{-1}) in trees of girth class >50 cm and were significantly different from trees of girth classes <40 and 40-45 cm. The teak trees in the adjacent girth classes showed no significant difference in their total biomass at this age.

3.3.2.5 Mean tree biomass production and partitioning

It can also be seen from the table 3.2 that the teak reached a mean height of 9.08 m and dbh of 14.57 cm at 10 years. The average above ground biomass production was 126.59 kg tree^{-1} while the below ground compartment recorded a mean biomass of 20.23 kg tree^{-1} which together contributed a value of 146.82 kg tree^{-1} for total biomass production at this age. The different compartments such as bole, branch and bark recorded mean biomass of 88.21 kg tree^{-1}, 24.24 kg tree^{-1} and 14.14 kg tree^{-1} respectively. Even though there was an increase in the biomass between five year and ten year old teak, significant difference was not observed among the various compartments of these age groups.

It was observed that the bole contributed the maximum of 60.08% to the total biomass. The percent contribution of various compartments such as branch, bark and root to the total biomass was 16.51, 9.63 and 13.78% respectively. The biomass partitioning in different components of teak in this age was in the order of bole > branch > root > bark. The mean root-shoot ratio of trees in various girth classes of teak was 0.159 at the age of 10 years.

3.3.3 Biomass production of 15 year teak

The data on various parameters like height and dbh along with dry weight of various biomass components of 15 year old trees are given in Table 3.3. It was seen that trees from these plantations showed considerable variation in their growth parameters between girth classes. The sample trees showed variation in height with respect to their girth classes and a maximum height of 14 m was recorded in the trees of girth class >60 cm and the lowest girth class of <40 cm recorded a height of 10.37 m.

3.3.3.1 Above ground biomass

The sample trees exhibited considerable variation in their above ground biomass as well as in their biomass components within a plantation. For instance, the smallest above ground biomass of 123.82 kg tree^{-1} was recorded in the girth class <40 cm whereas the maximum above ground biomass production of 198.23 kg tree^{-1} was recorded in the girth class >60 cm.

The distribution of bole biomass of teak in various girth classes showed that the maximum bole production (137.50 kg tree^{-1}) was in the trees of girth class >60 cm and the lowest value of 83.08 kg tree^{-1} was recorded in <40 cm girth class. The lower girth classes (<40 cm & 40-50 cm) differed significantly from the higher group of 50-60 cm and >60 cm girth in above ground biomass production.

The biomass production in branch compartment showed a maximum value of 40.19 kg tree^{-1} in trees of girth class >60 cm and a lesser value of 28.09 kg tree^{-1} in girth class <40 cm but significant difference in branch biomass between trees of various girth class was not observed in teak at this age also.

Table 3.3. Biomass production of 15 year teak

Girth class (cm)	Height (m)	dbh (cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<40	10.37^{a} ±0.20	12.25^{a} ±0.24	83.08^{a} ±0.68	28.09^{a} ±3.48	12.65^{a} ±0.46	123.82^{a} ±3.86	26.73^{a} ±1.13	150.54^{a} ±2.97	0.217^{a} ±0.018
40-50	10.67^{a} ±1.45	14.18^{a} ±0.40	90.55^{a} ±3.74	31.88^{a} ±3.35	14.52^{ab} ±1.36	136.96^{a} ±4.13	30.19^{a} ±1.20	167.15^{a} ±4.06	0.220^{a} ±0.012
50-60	11.67^{ab} ±0.33	17.94^{b} ±0.56	111.60^{b} ±4.03	36.03^{a} ±2.95	16.68^{b} ±0.60	164.31^{b} ±7.03	38.48^{b} ±1.39	202.79^{b} ±8.37	0.237^{a} ±0.003
>60	14.00^{b} ±0.00	20.49^{c} ±0.94	137.50^{b} ±6.69	40.19^{a} ±2.54	20.55^{c} ±1.00	198.23^{c} ±6.23	47.41^{c} ±2.30	245.64^{c} ±8.45	0.240^{a} ±0.006
Mean	11.68 ±0.54	16.22 ±1.00	105.68 ±6.64	34.05 ±1.90	16.10 ±0.97	155.83 ±8.91	35.70 ±2.50	191.53 ±11.34	0.228 ±0.006

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The bark biomass was highest (20.55 kg tree^{-1}) in the girth class >60 cm and it was significantly different from that of trees in lower girth classes. However, trees in the smaller girth class recorded lower value for bark biomass production and were statistically similar in adjacent groups.

3.3.3.2 Below ground biomass

It was seen that the below ground biomass was lower in the smaller girth classes and maximum in the larger girth classes as expected. The lowest below ground biomass value was 26.73 kg tree^{-1} was in girth class <40 cm and maximum was 47.41 kg tree^{-1} in girth class >60 cm. The smaller girth classes of <40 cm and 40-50 cm did not differ significantly but the higher girth classes of 50-60 cm and >60 cm was found to differ significantly from the lower group as also between themselves.

3.3.3.3 Root : shoot ratio

The root shoot ratio was also computed using the below ground and above ground biomass data for fifteen year old teak trees in various girth classes. Table 3.3 provides the relationship between the above ground and below ground biomass. The root shoot ratio was higher (0.240) in the trees belonging to girth class >60 cm and lowest value 0.217 was found in <40 cm girth class. However no significant difference was noted between the girth classes.

3.3.3.4 Total biomass

With regard to total biomass of sample trees of fifteen year old teak, it was found that there was significant variation between different girth classes. It can be seen from the table that the total biomass production was maximum (245.64 kg tree^{-1}) in trees from girth class >60 cm and was significantly different from all the smaller girth classes. The teak trees in the girth classes <40 and 40-50 cm showed no significant difference in their total biomass at this age while those in the 50-60 cm group differed from all other groups.

3.3.3.5 Mean tree biomass production and partitioning

It can also be seen from the table 3.3 that teak reached a mean height of 11.68 m and dbh of 16.22 cm which were significantly different from the previous age group. The average above ground biomass production was 155.83 kg tree^{-1} while the below ground compartment recorded a mean biomass of 35.70 kg tree^{-1} which together contributed a value of 191.53 kg tree^{-1} for total biomass production. The different compartments such as bole, branch and bark recorded mean biomass of 105.68 kg tree^{-1}, 34.05 kg tree^{-1} and 16.10 kg tree^{-1} respectively. Even though there was an increase in the biomass between ten year and fifteen year aged teak, a significant difference was not observed among the various compartments of these age groups. This is because of the interpolation of the trees of lower girth classes in one age group with the trees of higher girth classes in the other group.

The average of biomass partitioning in various girth classes of fifteen year teak is shown in table (3.3). It was observed that the bole contributed the maximum of 55.18% to the total biomass. The percent contribution of other compartments such as branch, bark and root to the total biomass was 17.78, 8.41 and 18.64% respectively. The biomass partitioning indifferent components of teak in this age was in the order of bole > branch > root > bark. The mean root-shoot ratio for trees in various girth classes of teak was 0.228 at the age of fifteen years.

3.3.4 Biomass production of 20 year teak

The data on various parameters like diameter at breast height (dbh) and height along with dry weight of various biomass components of sample trees are given in Table 3.4. It is seen that trees from these plantations show considerable variation in their growth parameters with girth classes. The sample trees showed variation in height with respect to their girth classes and a maximum height of 16 m was rerecorded in the trees of girth class >70 cm and the lowest (12.23 m) was in <50 cm girth class.

3.3.4.1 Above ground biomass

The distribution of above ground biomass of twenty year old teak in various girth classes showed that significant variation existed between trees. The teak tree at 20 years reached an average above ground biomass of 275.03 kg tree^{-1} in girth class >70 cm and showed significant difference with trees from other girth classes. The above ground biomass of trees from the remaining girth classes were found to have less variation with trees of adjacent girth class.

The different compartments contributing to the above ground biomass also exhibited variation with girth class. Bole of higher girth classes (60-70 cm and >70 cm) differed significantly from the lower ones as also between themselves. Trees of >70 cm dbh produced 198.40 kg tree^{-1} of bole.

The biomass production in branch compartment showed a maximum value of 49.57 kg tree^{-1} in trees of girth class >70 cm and a smaller value of 21.38 kg tree^{-1} in girth class <50 cm but significant difference in branch biomass between trees of adjacent girth class was not observed in teak at this age.

Table 3. 4. Biomass production of 20 year teak

Girth class (cm)	Height (m)	dbh (cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<50	12.33^{a} ±0.67	14.46^{a} ±0.46	92.68^{a} ±4.58	21.38^{a} ±1.64	13.08^{a} ±0.19	127.14^{a} ±5.49	31.60^{a} ±1.56	158.74^{a} ±7.00	0.247^{a} ±0.007
50-60	13.00^{a} ±0.58	17.09^{b} ±0.28	113.32^{a} ±3.57	29.22^{ab} ±4.51	15.45^{a} ±0.49	158.00^{ab} ±5.21	38.63^{ab} ±1.22	196.63^{ab} ±5.96	0.243^{a} ±0.009
60-70	13.83^{ab} ±0.60	20.80^{c} ±0.32	145.67^{b} ±6.76	41.22^{ab} ±3.06	20.67^{b} ±1.14	207.56^{b} ±10.53	47.64^{b} ±3.27	255.19^{b} ±13.26	0.230^{a} ±0.010
>70	16.00^{b} ±0.58	25.80^{d} ±0.84	198.40^{c} ±13.42	49.57^{b} ±9.62	27.05^{c} ±1.83	275.03^{c} ±24.06	67.64^{c} ±4.58	342.66^{c} ±28.56	0.250^{a} ±0.006
Mean	13.79 ±0.49	19.54 ±1.30	137.52 ±12.51	35.35 ±4.04	19.06 ±1.69	191.93 ±17.83	46.38 ±4.27	238.30 ±22.05	0.243 ±0.004

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

Bark biomass was similar to bole as regards to variation with girth classes. It increased with increasing girth and significant difference was observed in the upper girth classes greater than 60 cm. the bark biomass almost doubled in the >70 cm category as compared with the <50 cm girth class.

3.3.4.2 Below ground biomass

Below ground biomass also followed the same trend of bole and bark as regards increase with girth class. The biggest girth classes differed significantly from the smaller ones and recorded more than double the biomass of 31.60 kg tree^{-1} obtained in the smallest girth class of <50 cm.

3.3.4.3 Root –shoot ratio

The root shoot ratio was also computed using the below ground and above ground biomass data for twenty year old teak trees in various girth classes. The root: shoot ratio was highest (0.250) in the trees belonging to girth class >70 cm while it was almost the same (around 0.24) the lower girth classes.

3.3.4.4 Total biomass

Total biomass increased progressively with increasing girth as can be seen from the table. The higher girth classes were significantly different from each other as also from the lower ones. Maximum biomass of 342.66 kg tree^{-1} was recorded in >70 cm category.

3.3.4.5 Mean tree biomass production and partitioning

It can be seen from the table 3.4 that the 20 year old teak reached a mean height of 13.79 m and dbh of 19.54 cm which were significantly different from the previous age group. The average above ground biomass production was 191.93 kg tree^{-1} while the below ground compartment recorded a mean biomass of 46.38 kg tree^{-1} which together contributed a value of 238.3 kg tree^{-1} for total biomass production at this age. The different compartments such as bole, branch and bark recorded mean biomass of 137.52 kg tree^{-1}, 35.35 kg tree^{-1} and 19.06 kg tree^{-1} respectively. Even though there was an increase in the biomass between fifteen year and twenty year aged teak, a significant difference was not observed among the various compartments of these age groups. This is because of the interpolation of the trees of lower girth classes in one age group with the trees of higher girth classes in the other group.

The average biomass partitioning in various girth classes of fifteen year old teak is described below. It can be seen that the bole contributed the maximum of 57.71% of the total biomass. The percent contribution of various compartments such as branch, bark and root to the total biomass were 14.83, 8.00 and 19.46% respectively. The biomass partitioning indifferent components of teak was in the order of bole > branch > root > bark. The trees in various girth classes had a root: shoot ratio of 0.243 on an average.

3.3.5 Biomass production of 30 year teak

The data on various parameters like dbh and height along with dry weight of various biomass components of sample trees are given in Table 3.5. It is seen that trees from these plantations show considerable variation in their growth parameters between girth classes. The sample trees showed variation in height with respect to their girth classes and a maximum height of 18.33 m was recorded in the trees of girth class >90 cm and the lowest (11.67 m) was in <70 cm girth class.

3.3.5.1 Above ground biomass

The distribution of above ground biomass of thirty year old teak in various girth classes showed that significant variation existed between trees. The teak tree attained an average above ground biomass of 441 kg tree^{-1} in girth class >90 cm and showed significant difference with trees from other girth classes. The above ground biomasses of trees from the girth class such as 70-80 and 80-90 cm were found to have less variation.

It is seen from table 3.5 that the trees belonging to various girth classes showed considerable variation in their above ground biomass as well as in their biomass components within the same age group. The trees in girth class <70 cm and 70-80 cm showed no significant difference in their bole production but they were different from trees in 80-90 and >90 cm girth class. The maximum bole production recorded was 347.86 kg tree^{-1} which were from trees of girth class >90 cm and it was nearly three times the bole production in lowest girth class (127.12 kg tree^{-1}) of <70 cm.

Table 3.5. Biomass production of 30 year teak

Girth class (cm)	Height (m)	dbh(cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<70	11.67^{a} ±0.33	19.74^{a} ±0.97	127.12^{a} ±5.69	24.59^{a} ±2.67	13.84^{a} ±0.91	165.55^{a} ±8.55	44.24^{a} ±1.52	209.78^{a} ±10.01	0.270^{a} ±0.006
70-80	13.00^{a} ±1.00	22.51^{a} ±1.56	173.27^{a} ±16.12	34.30^{ab} ±1.62	20.09^{b} ±1.69	227.66^{a} ±17.71	45.83^{a} ±6.78	273.49^{a} ±24.21	0.203^{b} ±0.017
80-90	16.67^{b} ±0.33	28.34^{b} ±0.84	237.21^{b} ±13.01	46.48^{ab} ±9.31	26.36^{c} ±1.44	310.05^{b} ±6.62	81.70^{b} ±4.48	391.75^{b} ±10.75	0.260^{b} ± 0.010
>90	18.33^{b} ±0.33	34.82^{c} ±1.22	347.86^{c} ±14.98	54.51^{b} ±12.67	38.65^{d} ±1.66	441.02^{c} ±27.30	119.82^{c} ±5.16	560.84^{c} ±32.23	0.273^{b} ±0.009
Mean	14.92 ±0.85	26.35 ±1.82	221.36 ±25.59	39.97 ±4.85	24.73 ±2.84	286.07 ±31.94	72.90 ±.57	358.97 ±41.31	0.252 ±0.010

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The biomass production in branch compartment showed a maximum value of 54.51 kg tree^{-1} in trees of girth class >90 cm and a minimum value of

24.59 kg tree^{-1} in girth class <70cm. Significant difference in branch biomass between trees of adjacent girth class was not observed at this age.

Biomass of bark recorded significant increase with girth classes was significantly different from each other. It increased remarkably from 13.84 kg tree^{-1} in the lowest girth class of <70 cm to 38.65 kg tree^{-1} in the highest girth class of >90 cm.

3.3.5.2 Below ground biomass

The below ground biomass also increased with increasing girth class from <70 cm recording a value of 44.24 kg tree^{-1} to >90 cm with 119.82 kg tree^{-1} of biomass. Significant difference was noted in the higher girth classes beyond 80 cm.

3.3.5.3 Root –shoot ratio

The root-shoot ratio varied from 0.203 to 0.273 in different classes with no definite trend with increasing girth class. The ratios were non significant also.

3.3.5.4 Total biomass

The net production of total biomass in sample trees of thirty year old teak showed that there is significant variation between different girth classes. It can be seen from the table that the total biomass production was maximum (560.84 kg tree^{-1}) in trees from girth class >90 cm and was significantly different with trees from the girth classes <70, 70-80 cm and 80-90 cm. The teak trees in the girth classes <70 and 70-80 cm showed no significant difference in their total biomass at this age.

3.3.5.5 Mean tree biomass production and partitioning

It can be seen from the table 3.5 that teak reached a mean height of 14.92 m and dbh of 26.35 cm which were significantly different from the previous age group. The average above ground biomass production was 286.07 kg tree^{-1} while the below ground compartment recorded a mean biomass of 72.90 kg tree^{-1} which together contributed 358.97 kg tree^{-1}of total biomass. The different compartments such as bole, branch and bark recorded mean biomass of 221.36 kg tree^{-1}, 39.97 kg tree^{-1} and 24.73 kg tree^{-1} respectively. Even though there was an increase in the biomass between twenty year and thirty year aged teak, significant difference was not observed among the various compartments of these age groups.

It was observed that the bole contributed the maximum of 61.67% of the total biomass. The percent contribution of various compartments such as branch, bark and root to the total biomass was 11.13, 6.89 and 20.31% respectively. The biomass partitioning of different compartments of teak was in the order of bole > branch > root > bark. A mean root-shoot ratio of 0.252 was obtained for 30 year old teak.

3.3.6 Biomass production of 40 year teak

The data on various parameters like dbh and height along with dry weight of various biomass components of sample trees are given in Table 3.6. It is seen that trees from these plantations showed considerable variation in their growth parameters between various girth classes. Height of trees increased only marginally with increasing girth class and the increase was not significant. It increased from 18.33 in <110 cm girth class to 19.33 in >120 cm girth class.

3.3.6.1 Above ground biomass

The distribution of above ground biomass of forty year old teak in various girth classes showed that significant variation existed between trees belonging to different classes. Above ground biomass was found to increase progressively from 421.31 kg tree^{-1} in <110 cm girth class to 683.12 kg tree^{-1} in the biggest girth class of >140 cm.

It is seen from table 3.6 that the trees belonging to various girth classes showed considerable variation in their above ground biomass as well as in their biomass components within the same age group. Bole biomass increased significantly from the smallest girth class of <110 cm to the subsequent classes up to 140 cm where after the increase though remarkable was not statistically significant.

Table 3. 6. Biomass production of 40 aged teak

Girth class (cm)	Height (m)	dbh (cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<100	18.33^{a} ±0.33	30.89^{a} ±1.02	311.13^{a} ±11.30	72.85^{a} ±6.52	37.33^{a} ±3.63	421.31^{a} ±5.55	85.78^{a} ±5.09	507.09^{a} ±10.05	0.203^{a} ±0.012
100-120	18.83^{a} ±0.17	35.91^{b} ±0.49	384.08^{b} ±14.05	75.24^{a} ±9.39	40.90^{a} ±4.62	500.22^{b} ±23.18	94.64^{a} ±6.87	594.86^{b} ±18.13	0.190^{a} ±0.021
120-140	19.33^{a} ±0.67	40.32^{c} ±0.46	477.91^{c} ±11.74	103.02^{a} ±18.76	44.39^{a} ±1.09	625.32^{c} ±6.02	130.58^{b} ±3.20	755.90^{c} ±2.95	0.207^{a} ±0.007
>140	19.33^{a} ±0.67	43.52^{d} ±0.53	538.52^{c} ±24.05	94.57^{a} ±7.53	50.03^{a} ±2.23	683.12^{d} ±18.83	147.13^{b} ±6.57	830.25^{d} ±25.39	0.217^{a} ±0.003
Mean	18.96 ±0.25	37.66 ±1.46	427.91 ±27.13	86.42 ±6.27	43.16 ±1.96	557.49 ±31.67	114.53 ±7.97	672.02 ±39.14	0.204 ±.0006

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The biomass production in branch compartment showed a maximum value of 94.57 kg tree^{-1} in trees of girth class >140 cm and the lowest value of 72.85 kg tree^{-1} in girth class <100 cm. Significant difference in branch biomass between trees of various girth class was not observed in this age.

Bark biomass, though not significantly different between girth classes increased gradually from 37.33 kg tree^{-1} in <100 cm girth class to 50.03 kg tree^{-1} in the highest girth class of >140 cm.

3.3.6.2 Below ground biomass

Below ground biomass of 40 year old teak was found to increase with increasing girth class; significant difference occurring only at the 120-140 cm girth class where after the increase was not significant. It was found to increase from 85.78 kg tree^{-1} in <100 cm girth class to 147.13 kg tree^{-1} in >140 cm girth class.

3.3.6.3 Root : shoot ratio

The root: shoot ratio was also computed using the below ground and above ground biomass data for forty year old teak trees in various girth classes. Table 3.6 provides the relationship between the above ground and below ground biomass. The root shoot ratio was highest (0.217) in the trees belonging to girth class >140 cm and the lowest value of 0.190 was found in 100-120 cm girth class.

3.3.6.4 Total biomass

The net production of total biomass in sample trees of forty year old teak showed that there was significant variation between different girth classes. It can be seen from the table that the total biomass production was maximum (830.25 kg tree^{-1}) in trees from girth class >140 cm which was significantly higher than that from the girth classes of <100 cm, 100-120 cm and 120-140 cm.

3.3.6.5 Mean tree biomass production and partitioning

It was observed that 40 year old teak reached a mean height of 18.96 m and dbh of 37.66 cm which were significantly different from the previous age group. The average above ground biomass production was 557.49 kg tree^{-1} while the below ground compartment recorded a mean biomass of 114.53 kg tree^{-1} which together contributed a value of 672.02 kg tree^{-1} for total biomass production at this age. The different compartments such as bole, branch and bark recorded mean biomass of 427.91 kg tree^{-1}, 86.42 kg tree^{-1} and 43.16 kg tree^{-1} respectively. Even though there was an increase in the biomass between thirty year and forty year aged teak, significant difference was not observed among various compartments of these age groups.

It was observed that the bole contributed the maximum of 63.68% of the total biomass. The percent contribution of various compartments such as branch, bark and root to the total biomass was 12.86, 6.42 and 17.04% respectively. The biomass partitioning indifferent components of teak in this age was in the order of bole > branch > root > bark. The mean root-shoot ratio was 0.204 in 40 year old teak.

3.3.7 Biomass production of 50 year teak

The data on various parameters like dbh and height along with dry weight of various biomass components of sample trees are given in Table 3.7. It is seen that trees from these plantations show considerable variation in their growth parameters between various girth classes. Trees were found to attain a height of 21.67 m in the smallest girth class of <120 cm. There was an increase of around 2 m in the next class of 120-140 cm girth where after no increase in height was recorded in the successive higher girth classes. DBH on the other hand recorded significant increase with increasing girth.

3.3.7.1 Above ground biomass

The distribution of above ground biomass of fifty year old teak in various girth classes showed that significant variation existed between trees. The teak tree attained an average above ground biomass of 1312 kg tree^{-1} in girth class >160 cm and showed significant difference with trees from other girth classes.

Table 3. 7. Biomass production of 50 year teak

Girth class (cm)	Height (m)	dbh (cm)	Mean biomass (kg tree^{-1})						Root: Shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
<120	21.67^{a} ±0.88	36.73^{a} ±0.42	443.95^{a} ±22.69	139.83^{a} ±8.40	41.24^{a} ±2.11	625.02^{a} ±31.00	121.30^{a} ±6.20	746.32^{a} ±37.09	0.193^{a} ±0.003
120-140	23.33^{a} ±0.88	39.81^{b} ±0.92	543.53^{a} ±31.55	137.42^{a} ±5.47	50.49^{a} ±2.93	731.44^{a} ±30.90	148.50^{b} ±8.62	879.94^{a} ±39.46	0.203^{a} ±0.003
140-160	23.33^{a} ±0.88	47.72^{c} ±1.29	698.03^{b} ±17.12	161.50^{a} ±16.87	65.62^{b} ±1.44	925.15^{b} ±4.69	192.19^{c} ±4.27	1117.30^{b} ±6.88	0.210^{a} ±0.006
>160	23.00^{a} ±1.15	58.96^{d} ±2.20	1035.60^{c} ±48.70	178.06^{a} ±25.57	98.26^{c} ±6.40	1312.00^{c} ±49.11	267.14^{d} ±7.55	1579.10^{c} ±45.41	0.203^{a} ±0.012
Mean	22.83 ±0.46	45.81 ±2.65	680.29 ±69.00	154.20 ±8.51	63.90 ±6.72	898.39 ±80.21	182.28 ±16.88	1080.70 ±96.76	0.203 ±0.004

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The trees from the smaller girth classes of <120 and 120-140 cm showed no significant difference in their bole production but they were different with trees in 140-160 and >160 cm girth classes. The maximum bole production recorded was 1035 kg tree^{-1} which were from trees of girth class >160 cm and was nearly two times more than the bole production of 443.95 kg tree^{-1} in the lowest girth class of <120 cm.

The biomass production in branch compartment showed a maximum value of 178.06 kg tree^{-1} in trees of girth class >160 cm and a lower value of 139.83 kg tree^{-1} in girth class <120 cm. Significant difference in branch biomass between trees of adjacent girth class was not observed at this age.

In girth class >160 cm, trees recorded maximum value (98.26 kg tree^{-1}) for their bark biomass production and have showed a decreasing trend in lower girth classes and were statistically dissimilar. The bark biomass recorded in the trees of girth class <120 cm were almost half that of trees from girth class >160 cm and the recorded value was 41.24 kg tree^{-1}.

3.3.7.2 Below ground biomass

The below ground biomass of fifty year old teak showed that the trees of various girth classes exhibited significant difference and was lower in the smaller girth classes and maximum in the larger girth classes. The minimum below ground biomass value was 121.30 kg tree^{-1} in girth class <120 cm and maximum was 267.14 kg tree^{-1} in girth class >160 cm.

3.3.7.3 Root-shoot ratio

The root shoot ratio was also computed using the below ground and above ground biomass data for fifty year old teak trees in various girth classes. Table 3.7 provides the relationship between the above ground and below ground biomass. The root shoot ratio was highest (0.210) in the trees belongs to girth class 140-160 cm and the lowest value (0.193) was found in <120 cm girth class. No significant difference could be observed in root: shoot ratio of different girth classes.

3.3.7.4 Total biomass

The net production of total biomass in sample trees of fifty year old teak was showed that there is significant variation from different girth class. It can be seen from the table that the total biomass production was maximum (1579.10 kg tree^{-1}) in trees from girth class >160 cm and was significantly different with trees from the girth classes <120, 120-140 cm and 140-160 cm. The teak trees in the girth classes <120 and 120-140 cm showed no significant difference in their total biomass at this age.

3.3.7.5 Mean tree biomass production and partitioning

It was observed that teak reached a mean height of 22.83 m and dbh of 45.81 cm at 50 years which were significantly different from the previous age group. The average above ground biomass production was 898.39 kg tree^{-1} and that by the below ground compartment was 182.28 kg tree^{-1} together contributing 1080.7 kg tree^{-1} of total biomass at 50 years. The different compartments such as bole, branch and bark recorded mean biomass of 680.29 kg tree^{-1}, 154.2 kg tree^{-1} and 63.90 kg tree^{-1} respectively. There was significant increase in biomass of all compartments from 40 to 50 year.

It was observed that the bole contributed the maximum of 62.95 % of the total biomass. The percent contribution of various compartments such as branch, bark and root to the total biomass was 14.27, 5.91 and 16.87 % respectively. The biomass partitioning indifferent components of teak at 50 years was in the order of bole > branch > root > bark. The mean root-shoot ratio for trees in various girth classes of 50 year teak was 0.203

3.4 Discussion

3.4.1 Biomass at tree level

Biomass studies are important for forecasting the productivity, nutrient dynamics and also for assessing carbon sequestration in tree stands. Different plant communities have different rates of biomass production based on their photosynthetic efficiency (Rai, 1984). An attempt is made here to assess the biomass production of *Tectona grandis* of different ages growing in Kerala.

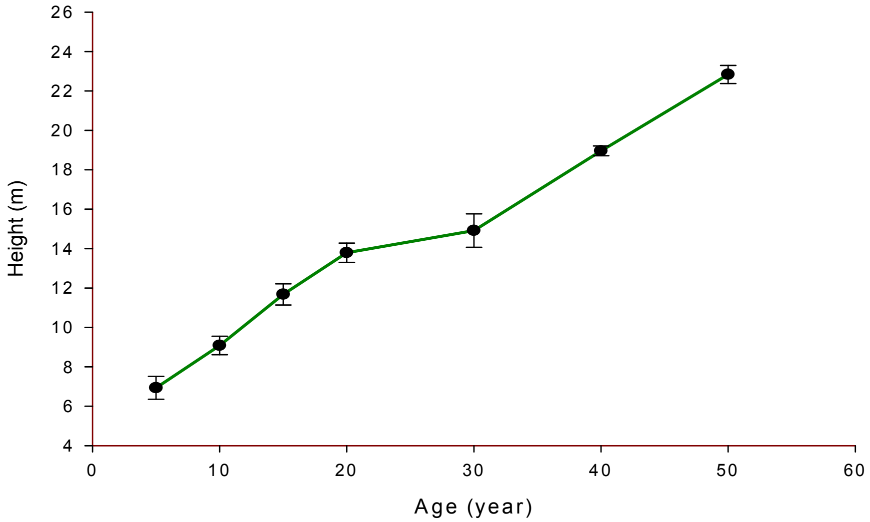

Figure 3.1. Variation in height growth of teak with age

Growth and biomass production of teak at prescribed felling cycles of 5, 10, 15, 20, 30, 40 and 50 years follows the trend shown in figures 3.1 to 3.6. It can be seen from the figure 3.1 that height of teak trees increased linearly and regularly with age till 20th year where after the height increase was very slow till the 30th year. The height increment from 30th to 40th and 50th year was again linear and regular. The increase from 5th to 10th year was 31%.

The respective figures for the consecutive stages were 29, 18, 8, 27 and 20%. The maximum height increment was during the initial stages and final stages. Minimum increment of 8% occurred from 20th to 30th year.

Diameter at breast height was seen to increase steadily (figure, 3.2) with age though maximum increase was noted during the 5th to 10th year and from 30th to 40th year. The percentage increase during the succeeding stages starting from the 5th year was 129%, 11, 20, 35, 43 and 22%. The highest increase of 129% occurred during the initial 5th to 10th year.

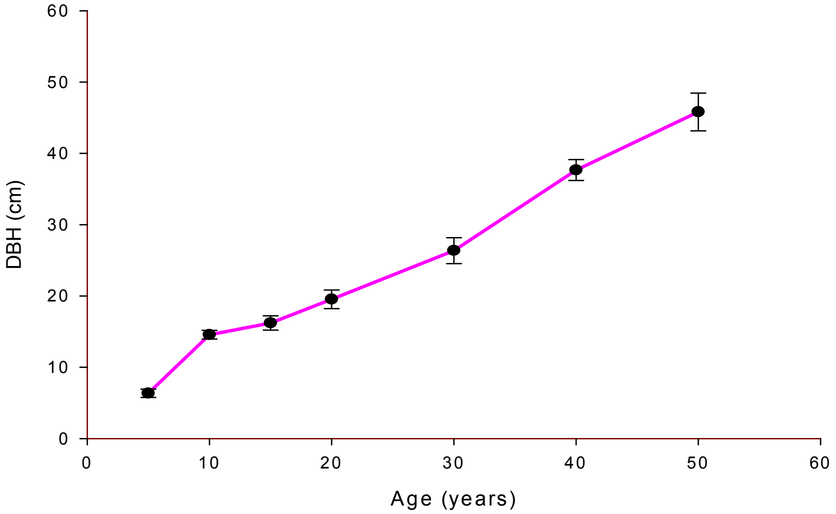

Figure 3.2. Variation in dbh of teak with age

The steady increase in height up to 20th year was not sustained after the 20th year till the 30th year which could be due to opening up of canopy and reduced competition from adjacent trees after thinning at 5th, 10th 15 and 20th ages. Branching out of wood has been encouraged at this juncture. The tree has been shown to resume the initial growth pattern after 30th year with appreciable increase in height. Diameter increase followed almost a uniform pattern of increase without showing any appreciable effect of thinning operations except that the increase from 5 to 10 year was exceptionally high.

The results were in agreement with the findings of Negi *et al.* (1990). They have reported dbh of 21.1 cm for 20 year old teak in central region of India and we got values of 19.54 cm at the same age. Bohre *et al.* (2013) studied teak trees of 2, 8, 9, 10 and 19 year in Madhya Pradesh and reported dbh of 3.8, 7.6, 10.8, 12.4,17.8 cm and corresponding heights of 2.41, 5.10, 7.25, 8.15, 11.70 m at the respective ages indicating lower growth in that region compared to Kerala.

Similar results were reported from Panama teak plantation by Kraenzel *et al.* (2003) with dbh values varying from 16.9 to 43.8 cm in 20 year old trees; variation in the present study being observed from 14.46 to 25.80 cm in different girth classes. Suryawanshi *et al.* (2014) reported dbh of 9.55 cm and height of 10.73 m for young teak trees in Maharashtra. Mean height of 23 m of 47 year old teak in West Bengal were reported by Banerjee and Prakasam (2013). Karmacharya and Singh (1992) reported gbh of 13.5 cm, 28.6 cm and 32.7 cm and height of 6.8 m, 12.6 m and 20 m in 4, 14 and 30 year old teak of Varanasi, North India. Thapa and Gautam (2004) from Nepal reported mean height of 9.2 m at 6.5 years of *T. grandis.* Shukla and Viswanath (2014) determined the average dbh of a 12 year old intensively managed teak plantation as 22.63 cm, while that in unmanaged teak plantation was only 12.05 cm. Jain and Ansari (2013) from Jabalpur, India reported average dbh of 0.6 cm, 2.36, 4.79, 8.85, 10.51, 13.95 cm for 1.5, 3.5, 7.5, 13.5, 18.5 and 23.5 year old teak plantation while the corresponding height was 1.60 m, 3.27, 4.18, 8.83, 11.46 and 14.38 m respectively. Perez and Kanninen (2005) obtained dbh of 11.5 cm, 21.8, 29.7, 38.3, 44 and 47.8 cm of 4, 8, 12, 18, 24 and 30 year old teak plantation with respective heights of 9.4 m, 16.8, 22.2, 27.5, 30.6 and 32.4 m from Costa Rica.

Nunifu (1999) from Ghana reported mean dbh of 5.96 cm, 7.92, 10.78, 18.21 21.06 and 23.58 cm in 6, 9, 17, 26, 31 and 38 year old teak trees which had heights of 5.51, 6.78, 8.07, 13.86, 14.76 and 19.85 m respectively.

Sharma *et al.* (2011) observed taller teak (9.67 m) in agroforestry system as compared to sole plantation which could record a height of 8.42 m only. Buvaneswaran *et al.* (2006) observed 14 m height in a 20 year old forest (sole) plantation whereas in farmers fields 13 m height was attained at 12 years of age. Shukla (2009) reported that mean girth at breast height was only 15.04 cm in 7.5 year old teak under sole plantation. Heque and Osman (1993) measured height and dbh in 26 year old plantation in pure teak and in mixed plantation. It was found that teak had significantly greater diameter and height in the mixed plantation than in sole plantation.

The similarities in diameter and height obtained by several investigators as compared to the present study may be attributed to the similarity in edapho-climatic conditions in the teak grown regions. The height varied within the girth classes indicating that vertical growth of trees varied between sites due to variation in several growth factors. Such variations were observed in all age classes too. Teak trees grown in plantations on good soils may reach an average of 60 cm diameter at breast height (dbh) and 30 m height in about 50 years (Pandey and Brown, 2000).

Height and diameter growth were the factors considered in assessing biomass of the above ground portions. Figure (3.3 and 3.4) shows total biomass along with its partitions into above ground, below ground, bole, branch and bark. It can be deciphered from the figure that the combined effect of height and dbh on biomass especially the total biomass, above ground biomass and bole biomass gets reflected in almost a parabolic relation with increasing age. The increase is more in the initial stages and latter stages with a slowdown in between. The percent increase in total biomass with age was 125%, 30, 24, 51, 87 and 61% at 5, 10, 15, 20, 30, 40 and 50 years respectively. The above ground biomass had a similar pattern with 120% increase from 5th to 10th year followed by 23%, 23, 49, 95 and 61 % increases at the succeeding ages. Bole has also not much different; the increase at 10th year was 119% followed by 20%, 30, 61, 93 and 59% at the succeeding stages.

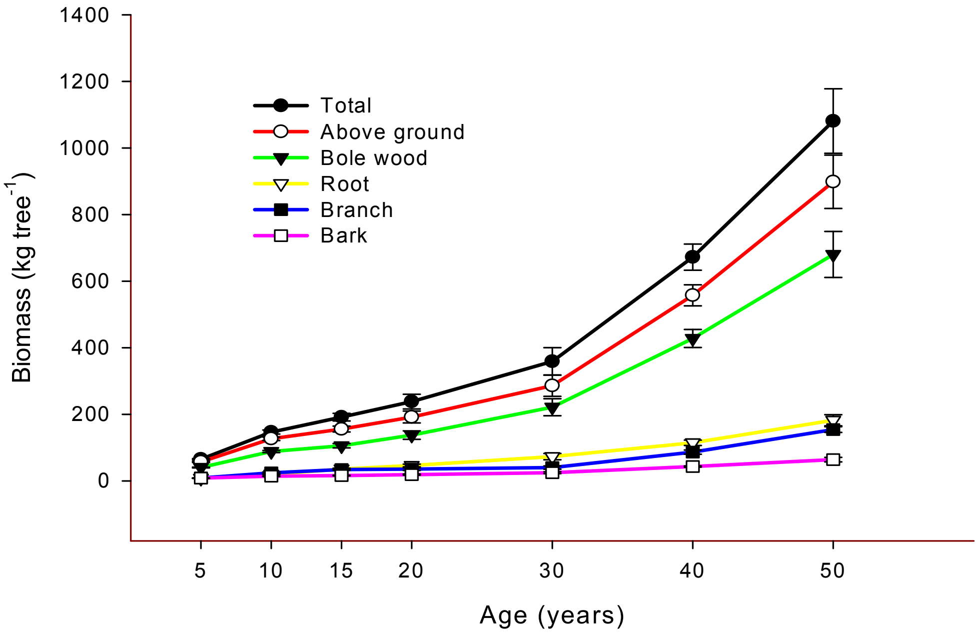

Figure 3.3. Biomass accumulation in various compartments of different aged teak

Biomass contribution from root and branch was not much different at different selected ages though root contributed more from 15th year onwards while in the initial period the contribution by branches exceeded that by roots. This may be due to the fact that small roots were not taken into account in the present study which might have been proportionately more in the initial ages. Increase in root and branches were appreciable only after the 30th year; an increase of 57% in the case of root and 116% in the case of branches occurred from 30th to 40th year. The respective figures were 59% and 78% from 40th to 50th year. Bark biomass did not exhibit any remarkable difference with the growth of tree. The increase was slightly more from 5th to 10th and 30th to 40th year only.

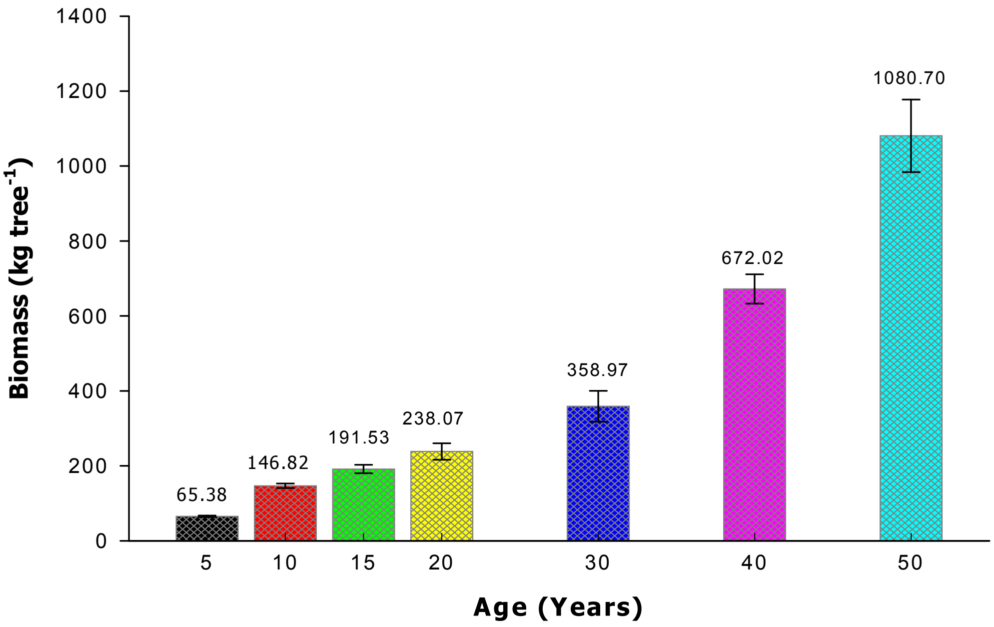

Figure 3.4. Total biomass production in various aged teak trees

The rate of increase of total biomass with age is depicted in figure (3.5). It can be seen that there was a sharp increase in the rate of biomass accumulation in the initial 5 to 10 year period. A sharp fall in the rate was seen up to the 15th year, the decrease followed till the 20th year where after the rate become steady till the 30th year. A very sharp increase was observed from 30th year to the final felling stage of 50th year. The respective values for the rate of biomass accumulation were 13.08, 14.68, 12.77, 11.92, 11.97, 16.80 and 21.61 at 5, 10, 15, 20, 30, 40 and 50 years respectively. The initial biomass increase may due to the combined effect of mechanical thinning at 5th year during which half the population of trees were removed enhancing the remaining half to access sunlight, carbon dioxide, water and nutrients more freely. The successive silvicultural thinning removes only lesser number of selected weaker trees and thinning are carried out 10 years gap afterwards. By the 30th year maximum thinning of trees would have occurred (2152 trees out of the initially planted 2500) resulting in adequate facility for exploitation of resources necessary for faster growth of the trees which gets reflected in the high rate of biomass accumulation during the later stages.

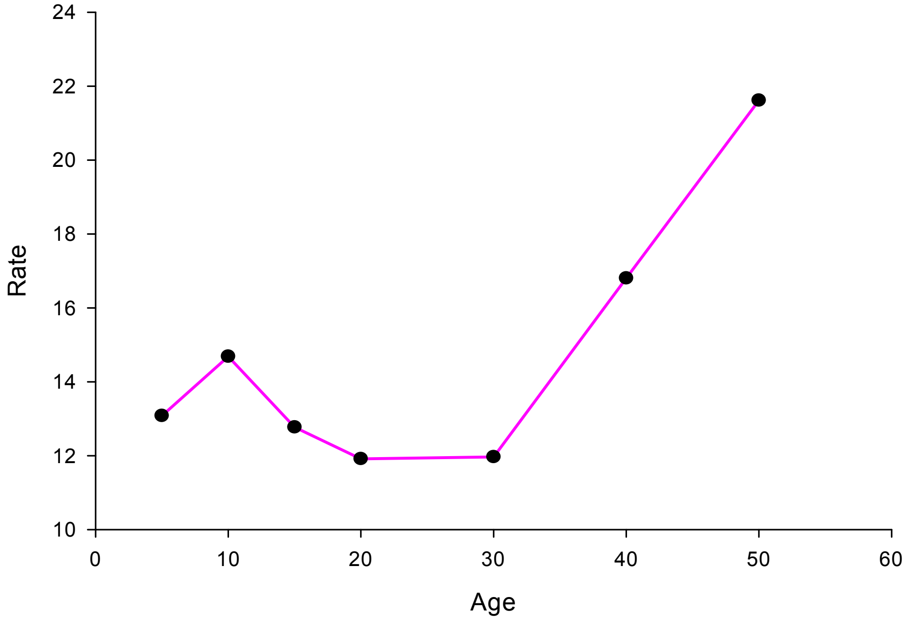

Figure 3.5. Rate of biomass accumulation in teak

Appuhamy *et al.* (2009) reported total biomass of 21.82 kg tree^{-1} and 88.87 kg tree^{-1} in 5 and 10 year old teak trees from Sri Lanka. Thapa and Gautam (2004) from Nepal obtained bole biomass of 58.8 kg tree^{-1} from 7.5 year teak.

Karmacharya and Singh (1992) reported mean bole biomass of 7.8, 25.8 and 121 kg tree^{-1} from 4, 14 and 30 year old teak trees of Uttar Pradesh. They found a slow biomass build up in the initial years followed by a rapid increase in the later 14 to 30 years. They also found that the bole contributed 78% of the above ground biomass.

Jain and Ansari (2013) from Jabalpur, India reported average above ground biomass of 1.39, 4.94, 12.90, 49.22, 71.78 and 141.38 kg tree^{-1} from 1.5, 3.5, 7.5, 13.5, 18.5 and 23.5 year old teak plantation. An intensively managed teak plantation was found to produce 217 kg per tree biomass at 12th year which was much higher than an unmanaged plantation with 116 kg per tree of biomass production (Shukla and Viswanath, 2014)

3.4.2 Biomass at plantation level

Teak silviculture standardised over a long period starting from the first plantation established at Nilambur in the 1840s follow time tested prescriptions especially of felling schedules and final felling age. The first mechanical thinning at 5 year removes alternate trees along rows and columns resulting in a reduction by half of the planted 2500 saplings. Further reduction in stand density occurs with subsequent felling at designated periods. This results a definite number of trees remaining in the plantation at each stage after felling.

There was an increase in the standing biomass from 5th to 10th year after which it undergoes a reduction in the initial years starting from the 10th year to the 30th year. Gradual but steady increase in biomass occurs after the 30th year. The total biomass at 5th, 10th, 15th, 20th, 30th, 40th and 50th years were 163.46 Mgha^{-1}, 183.53 Mg ha^{-1}, 153.61 Mg ha^{-1}, 128.21 Mg ha^{-1}, 124.92 Mg ha^{-1}, 164.64 Mg ha^{-1} and 172.91 Mg ha^{-1} respectively (figure, 3.6).

The initial increase from 5th to 10th year was due to fast growth consequent to the 5th year mechanical thinning resulting a stand density of 1250 trees only at the 10th year.

The bole contributed maximum towards the total biomass and its pattern of change with age resembles exactly the pattern of total biomass. The contribution of bole towards total biomass was the maximum with 100.81 Mg ha^{-1} at the 5th year, 110.26 at 10, 84.76 at 15, 73.99 at 20, 77.03 at 30, 104.84 at 40 and 108.85 Mg ha^{-1} at 50th year age.

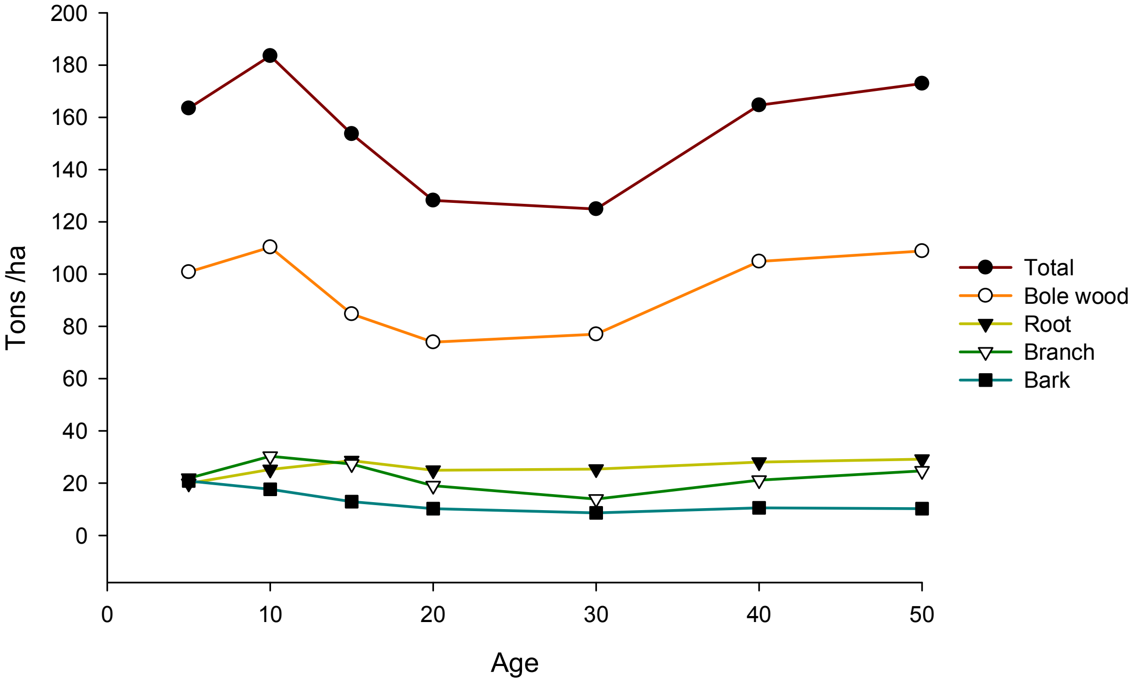

Figure 3.6. Biomass production of teak in plantation scale

The root compartment contributed its share without much difference during growth except that there was an increase in the initial period up to the 15th year. The respective figures at various stages were 19.92 Mg ha^{-1}, 25.28, 28.63, 24.95, 25.37, 28.06 and 28.16 Mg ha^{-1} respectively. The initial increase can be attributed to both proliferation and thickening of roots after which a dynamic equilibrium seems to be maintained between production and decomposition of roots. The fine root portion was not taken into account in the present study.

The branch component of the tree contributed slightly more than the roots up to the 15th year where after it declined steadily till the 30th year after which it started climbing up continuously. The decrease during the middle portions tallies with the bole pattern and explainable by the decrease in stand density caused by periodic felling. The increase at the later stages can be due to diameter increments of mature branches. Branch compartments contributed 21.88 Mg ha^{-1} of biomass at the 5th year. The contribution in the later stages of 10, 15, 20, 30, 40 and 50 years were 30.31, 27.31, 19.02, 13.91, 21.17 and 24.67 Mg ha^{-1} respectively.

Bark was found to contribute the least towards total biomass and the pattern showed a slight but constant decrease till the 20th year stagnating thereafter. The biomass of bark at respective felling stages were found to be 20.84, 17.67, 12.91, 10.26, 8.61, 10.58 and 10.22 Mg ha^{-1} starting from the 5th to 50th year.

The above ground contribution tacking in to account the contribution by bole, branch and bark together was 143.54 Mg ha^{-1} when 2500 trees were considered at the 5th year just before felling followed by 158.24 Mg ha^{-1} from 1250 trees at the 10th year, 124.26 Mg ha^{-1} at 15th year with 802 trees, 103.26 Mg from 538 trees at 20th year, 99.55 Mg from 348 trees at 30th year, 136.59 Mg at 40th year from 245 trees and 143.74 Mg ha^{-1} contributed by 160 standing trees at the 50th year of final felling.

The results obtained from the present study revealed slightly higher biomass production in Nilambur, Kerala as compared to other parts of India. It was seen that the above ground biomass production of 103.26 Mg ha^{-1} obtained in 20 year old teak of the present study was slightly greater than the AGB of 97.53 Mg ha^{-1} obtained in Chhattisgarh region (Sahu *et al.*, 2013) and 90.70 Mg ha^{-1} obtained in Uttar Pradesh (Negi *et al.*, 1990). Bole biomass obtained in Kerala (73.99 Mg ha^{-1}) was similarly higher than that obtained in Chhattisgarh (59.49) and Uttar Pradesh (58.10). Below ground biomass of 24.95 Mg ha^{-1} obtained in the present study was also slightly than 19.96 Mg ha^{-1} obtained in Chhattisgarh and 17.90 Mg ha^{-1} obtained from Uttar Pradesh.

But the trend got reversed at 30th year and biomass yield obtained in the present study was found to be lesser than that obtained by Negi *et al.* (2003) from Uttar Pradesh. The above ground biomass obtained in the present study of 99.55 Mg ha^{-1} was much lower than 164.1 Mg ha^{-1} obtained in Uttar Pradesh. Bole compartment yielded 77.03 Mg ha^{-1} which was lower than the yield of 98.8 Mg ha^{-1} reported from Uttar Pradesh. Below ground biomass also followed the trend with 25.37 Mg ha^{-1} compared to the Uttar Pradesh value of 28.5 Mg ha^{-1}. This may be due to differences in thinning schedules with wider intervals in the latter site.

3.5 Summary

Mean biomass production of teak at prescribed felling stages is summarized below in table 3.8. A five year teak was found to attain a height of 6.93 m on an average. At 50thyear the average height obtained was 22.83 m. Significant differences between felling stages were noticed except the 20thand 30th year which did not differ significantly. Diameter at breast height was found to increase from 6.3 cm at the 5th year to 45.85 cm at the 50th year. Significant differences did not occur between 10th, 15 and 20th year teak. Dry matter yield was mostly contributed by bole to the tune of 40.33 kg tree^{-1} at the first mechanical thinning which was seen to increase to 680.29 kg tree^{-1} at the final felling stage. The increase in bole biomass at successive stages did not differ significantly in the initial stages up to 20th year; significant differences were noted from 30th year onwards. Branch component contributed 8.75 kg tree^{-1} at 5th year and 154.20 kg tree^{-1} at 50th year. The increase was significant from the 40th year onwards only. Bark component was found to contribute 8.34 kg tree^{-1} at the initial stage which increased to 63.90 kg tree^{-1} at the final stage of felling. The latter two stages alone differed from the previous ones significantly.

Table 3.8. Mean biomass production in various compartments among different aged teak tree

Age (Years)	Height (m)	dbh (cm)	Mean dry matter production (kg tree-1)						Root: shoot ratio
			Bole	Branch	Bark	Above ground	Below ground	Total	
5	6.93^{a} ±0.58	6.36^{a} ±0.58	40.33^{a} ±1.30	8.75^{a} ±0.31	8.34^{a} ±0.34	57.42^{a} ±1.77	7.97^{a} ±0.19	65.38^{a} ±1.95	0.142^{a} ±0.002
10	9.08^{b} ±0.47	14.57^{b} ±0.61	88.21^{a} ±3.14	24.24^{ab} ±2.63	14.14^{ab} ±0.59	126.59^{a} ±5.25	20.23^{ab} ±0.83	146.82^{a} ±5.98	0.159^{a} ±0.004
15	11.68^{c} ±0.54	16.22^{b} ±1.00	105.68^{a} ±6.64	34.05^{b} ±1.90	16.10^{ab} ±0.97	155.83^{ab} ±8.91	35.70^{ab} ±2.50	191.53^{a} ±11.34	0.228^{c} ±0.006
20	13.79^{d} ±0.49	19.54^{b} ±1.30	137.52^{ab} ±12.51	35.35^{b} ±4.04	19.06^{ab} ±1.69	191.93^{ab} ±17.83	46.38^{b} ±4.27	238.30^{ab} ±22.05	0.243^{cd} ±0.004
30	14.92^{d} ±0.85	26.35^{c} ±1.82	221.36^{b} ±25.59	39.97^{b} ±4.85	24.73^{b} ±2.84	286.07^{b} ±31.94	72.90^{c} ±.57	358.97^{b} ±41.31	0.252^{d} ±0.010
40	18.96^{e} ±0.25	37.66^{d} ±1.46	427.91^{c} ±27.13	86.42^{c} ±6.27	43.16^{c} ±1.96	557.49^{c} ±31.67	114.53^{d} ±7.97	672.02^{c} ±39.14	0.204^{b} ±.0006
50	22.83^{f} ±0.46	45.81^{e} ±2.65	680.29^{d} ±69.00	154.20^{d} ±8.51	63.90^{d} ±6.72	898.39^{d} ±80.21	182.28^{e} ±16.88	1080.70^{d} ±96.76	0.203^{b} ±0.004

Values in the table are Mean± SE, n=3, p= 0.05 level, Values with same superscripts do not differ significantly and are homogenous within a column

The below ground compartment consisting mainly of woody root portion also contributed 7.97 kg tree^{-1} biomass at the first felling stage. It increased consistently to 182.28 kg tree^{-1} at the final felling stage of 50 years. Significant difference in root growth was observed only from the 30th year onwards. Considering all the compartments together, it was seen that an average teak tree at 5 year growth add a total biomass of 65.38 kg tree^{-1} which was seen to increase with age to a figure 1080.70 kg biomass per tree. Significant difference in growth and biomass production could be noted beyond the 30th year only.

Chapter 4

Carbon Sequestration by Teak

4. Carbon Sequestration by Teak

4.1 Introduction

Carbon is a constituent of living organism. It is also found in nonliving substances such as coke, oil and gas and also the air. Plants absorb carbon dioxide during photosynthesis and turn it into biomass. The contribution by forest in carbon sequestration is commendable. India with 69.2 million hectare forest cover (FSI, 2013) including a wide range of forest types from wet to dry forest in temperate to tropical climate has high capacity in absorbing and retaining carbon. Living trees continue to absorb and store carbon and thus at as carbon sinks. Mature forest store carbon within its biomass (Harmon *et al.*, 1990). An effective management approach is to selectively fell mature trees that no more act as sink and plant new ones which can sequester more carbon in its younger years.

Carbon is also stored in harvested wood, wood products and dead organic matter. 195 million tons of carbon was reported to be stored in harvested wood products in the house hold sector and 62 million tons locked in commercial sector. 24 million tons of carbon is being locked annually in harvested wood products (FSI, 2013). But still carbon is always stored more efficiently in forest stands than in wood products (Karjalainen *et al.,* 2002).

Forest covers an area of 11265 km^2 which is 28.99% of the geographical area of Kerala state (FSI, 2013). It consists of different types of forests namely tropical wet evergreen, tropical, moist deciduous, tropical dry deciduous, littoral and swamp forests, tropical thorn and mountain wet forest (Champion and Seth, 1968). The highest carbon stock is found in tropical wet evergreen forest with 161.93 Mg ha^{-1} carbon followed by mountain moist temperate forest which sequesters 139.84 Mg carbon per hectare. Littoral and swamp forest store 116.25 Mg ha^{-1} while the tropical dry deciduous forest contains 114.05 Mg of carbon. The division into pools of carbon gives the figures as 59% soil organic carbon, 30% in above ground biomass, 8% in below ground biomass and 3% in litter (FSI, 2013). Plantations account for 145.54 Mg of carbon in medium density areas to 179.09 Mg in high density areas.

Carbon sequestration potential of trees differs with species and the silvicultural practices adopted. *Albizi aprocera* has been shown to sequester higher quantity of carbon (189.93 Mg ha^{-1}) compared to *Casuarina equisetifloia* with its capacity to store 185.85 Mg ha^{-1} and Eucalyptys which could sequester 114.36 Mg ha^{-1} carbon (Swamy *et al.,* 2003). These values conform with those of tropical forests which vary from 132 to 174 Mg ha^{-1} of carbon sequestration potential (Dixon *et al.,* 1994).

Teak (*Tectona grandis*) has been shown to sequester carbon more efficiently than most other species. As the teak grows, its height, dbh and biomass increases faster in the initial period. Biomass of tree components also increase with age of the tree, the contribution of different components to the total biomass is highly variable depending on many factors (Sahu *et al.,* 2013). Carbon sequestration in the biomass follows the same trend; higher the biomass, higher the carbon storage.

4.2 Methodology

The biomass samples from different compartments of teak that were oven dried at 60^0C were chipped using chisel. These were further dried and powdered using Wiley mill to fine state. The powdered samples were stored in plastic vials. The carbon content in these samples were determined using CHNS Elemental Analyser (EUROEA3000) which helps in accurate estimation of the elements carbon, hydrogen, nitrogen and sulphur of organic compounds, which are generally combustible at 1800^0C based on the principle of "Dumas method" which involves the complete and instantaneous oxidation of the sample by "flash combustion”. The combustion products are separated by a chromatographic column and detected by the thermal conductivity detector (T.C.D.), which gives an output signal proportional to the concentration of the individual components of the mixture. Ten mg samples were placed in tin capsules and put inside the auto sampler cap from where they are purged with a continuous flow of helium and then dropped at constant intervals into a vertical quartz tube (reactor column) maintained at 1020 degree Celsius. When the samples are dropped inside the furnace, the helium stream enriched with pure oxygen melts both the sample and its container by flash combustion. Quantitative combustion is then achieved by passing the mixture of gases over a catalyst layer. The sample gas pulses and a separate reference stream of helium pass through a detector; differences in thermal conductivity between the two streams are displayed as visible peaks and recorded as numerically integrated areas.

Carbon content in different compartments of teak were thus estimated and expressed as percentage. These figures were utilized to calculate the carbon sequestration in different compartments by multiplication with respective biomass values.

4.3 Results

The carbon sequestered in various compartments of teak was estimated by multiplying the carbon content of each component with the respective biomass. Though there was only slight increase in carbon content with growth of teak, the biomass increase with age was high and hence, the carbon sequestration calculated exhibited significant difference with age and between girth classes in the same age group. The variation within and between different thinning regimes are described below.

4.3.1 Carbon sequestration by 5 year teak

Table 4.1 shows the carbon content in various compartments of five year old teak. The carbon content was less dependent on the girth class of trees. It can be seen that the carbon content was maximum in the bole compartment which was followed by root, branch and bark respectively.

Table 4.1. Carbon content in 5 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<15	45.21^{a}±0.65	40.86^{a}±0.63	37.97^{a}±0.32	42.53^{a}±0.32
15-20	45.20^{a}±0.62	40.51^{a}±0.68	38.00^{a}±0.58	42.47^{a}±0.24
20-25	44.90^{a}±0.46	41.23^{a}±0.92	36.93^{a}±0.64	41.50^{ab}±0.29
>25	45.47^{a}±0.27	40.90^{a}±0.07	37.68^{a}±0.66	39.03^{b} ±1.31
Overall	45.19^{a}±0.23	40.87^{a}±0.29	37.65±0.27	41.38±0.52

The trees of the various girth classes in five year old teak plantation showed no significant difference in carbon content in their bole, branch and bark;

the only significant difference was in the root compartment of trees in the highest girth class. Mean carbon percent of trees of various girth classes was recorded as 45.19% for bole, 40.86 for branch, 37.65 for bark and 41.38 for root compartment.

The carbon sequestration of teak in various girth classes at five year age is shown in the table 4.2. Above ground carbon sequestration was estimated by adding the carbon sequestered in various above ground compartments such as bole, branch and bark as in the case of above ground biomass estimation. It was seen from the table that the five year old teak could store carbon in its above ground parts to the tune of 21.47 kg tree^{-1} in girth class <15 cm which was found to vary significantly from that of trees belonging to 15-20, 20-25 and >25 cm girth classes. Trees of girth class >25 cm had the highest above ground carbon sequestration of 27.82 kg tree^{-1}. Significant variation in above ground carbon sequestration was not observed between the trees belonging to 15-20, 20-25 and >25 cm girth classes.

Table 4.2. Carbon sequestration by 5 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<15	15.62^{a} ±1.07	3.25^{a} ±0.31	2.60^{a} ±0.31	21.47^{a} ±1.68	3.09^{a} ±0.11	24.55^{a} ±1.79
15-20	18.14^{b} ±0.28	3.69^{a} ±0.06	3.19^{a} ±0.10	25.01^{b} ±0.30	3.27^{a} ±0.12	28.28^{b} ±0.37
20-25	18.56^{b} ±0.41	3.69^{a} ±0.42	3.22^{ab} ±0.04	25.47^{b} ±0.06	3.37^{a} ±0.03	28.84^{b} ±0.04
>25	20.58^{b} ±0.45	3.68^{a} ±0.24	3.55^{b} ±0.09	27.82^{b} ±0.43	3.43^{a} ±0.12	31.25^{b} ±0.51
Mean	18.22 ±0.60	3.58 ±0.13	3.14 ±0.13	24.94 ±0.78	3.29 ±0.06	28.23 ±0.83

It was found that the bole carbon recorded a minimum value of 15.62 kg tree^{-1} in trees of girth class <15 cm which was significantly different from trees of other three girth classes. The maximum value for carbon sequestration was 20.58 kg tree^{-1} and was reported in trees of girth class >25 cm. However, trees coming under girth classes 15-20 cm, 20-25 cm and >25 cm expressed homogeneity in their carbon sequestration and were statistically dissimilar.

The carbon sequestration in the branches of five year old teak recorded minimum value of 3.25 kg tree^{-1} in girth class <15 cm but variation with higher girth classes was not observed in this age.

The carbon sequestration in bark of five year old teak trees was 2.60 kg tree^{-1} in girth class <15 cm while it was 3.19 kg tree^{-1}, 3.22 kg tree^{-1} and 3.55 kg tree^{-1} in trees of girth class 15-20 cm, 20-25 and >25 cm respectively. Significant difference in bark carbon sequestration was observed only between the trees of girth class <15 cm and >25 cm.

The root carbon sequestration of a teak in its fifth year recorded a minimum value of 3.09 kg tree^{-1} in girth class <15 cm and a maximum value of 3.43 kg tree^{-1} in girth class >25 cm. However, the trees between various girth classes recorded less variation and was non significant.

It can be seen from the table that the total carbon sequestration was lowest (24.55 kg tree^{-1}) in trees from girth class <15 cm and were significantly different with trees from the girth classes 15-20, 20-25 and >25 cm. Even though the maximum value for total carbon sequestration (31.25 kg tree^{-1}) was observed in trees of girth lass >25 cm, the teak trees studied in the girth classes such as 15-20, 20-25 and >25 cm showed no significant difference in their carbon sequestration at this age.

The average above ground carbon sequestration of teak at the age of five year recorded a value of 24.94 kg tree^{-1} while the below ground carbon sequestration was 3.29 kg tree^{-1} which together give a total carbon sequestration of 28.23 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 18.22 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 3.58 kg tree^{-1} and 3.14 kg tree^{-1} respectively.

4.3.2 Carbon sequestration by 10 year teak

Carbon content was highest in bole followed by branch, root and bark in decreasing order as was the case in 5 year teak (table 4.3). No significant difference was noted between girth classes in any of the compartments. Mean carbon percentage of different girth classes was 45.43% in bole, 42.17 in branch, 39.76 in bark and 45.8% in the root compartments. Sight increase in carbon content occurred in all the compartments as compared to the previous stage.

Table 4.3. Carbon content in 10 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<40	45.73^{a}±0.24	42.17^{a}±0.60	40.33^{a}±0.44	42.83^{a} ±0.38
40-45	45.37^{a}±0.63	42.30^{a}±0.47	40.83^{a}±1.01	41.50^{a}±0.29
45-50	45.00^{a}±0.67	42.17^{a}±0.17	40.05^{a}±0.59	42.27^{a}±0.59
>50	45.61^{a}±0.19	42.04^{a}±0.14	38.63^{a}±0.33	40.80^{a}±0.50
Mean	45.43±0.22	42.17±0.17	39.96±0.37	41.85±0.30

Carbon sequestration by 10 year teak in different sections of the tree as related to girth classes is given in table 4.4 below. The portion above ground increased markedly from the lowest girth of <40 cm (47.11 kg tree^{-1}) upwards to the >50 cm girth class with 65.56 kg tree^{-1}. Significant increase occurred beyond 45 cm girth. Bole carbon also increased with increasing girth, though significant difference was noted in the largest girth class only. It was seen to increase successively from 36.19 kg tree^{-1} to 47.10 kg tree^{-1}.

Table 4.4. Carbon sequestration by 10 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<40	36.19^{a} ±0.87	5.73^{a} ±0.51	5.20^{a} ±0.13	47.11^{a} ±0.49	7.88^{a} ±0.23	55.00^{a} ±0.72
40-45	36.64^{a} ±1.13	11.52^{a} ±2.26	4.99^{a} ±0.18	53.14^{ab} ±3.39	7.30^{a} ±0.37	60.45^{ab} ±3.72
45-50	40.34^{a} ±1.16	11.65^{a} ±2.43	5.85^{ab} ±0.24	57.84^{bc} ±1.19	8.83^{ab} ±0.47	66.67^{bc} ±0.78
>50	47.10^{b} ±1.86	11.97^{a} ±1.35	6.50^{b} ±0.29	65.56^{c} ±3.25	9.80^{b} ±0.47	75.36^{c} ±3.70
Mean	40.07 ±1.43	10.22 ±1.10	5.63 ±0.20	55.91 ±2.28	8.45 ±0.33	64.37 ±2.55

Branch compartment observed to sequester 5.73 kg tree^{-1} carbon in <40 cm girth category and it increased with girth to 11.97 kg tree^{-1} in the >50 cm class though the increase in none of the classes were significant. Carbon sequestered in bark exhibited remarkable increase only beyond the third girth class. Significant difference was noted in the highest girth of >50 cm only. The values ranged from 4.99 to 6.50 kg tree^{-1} in different classes.

The below ground portion constituting of roots did not differ much with increasing girth except the >50 cm girth trees whose carbon sequestration of 9.80 kg tree^{-1} differed significantly from the lower girth classes.

The sum of carbon sequestered in different compartments revealed that there was remarkable increase with increasing girth classes. It increased from 55.0 kg tree^{-1} carbon in the <40 cm category to 75.36 kg tree^{-1} in the highest girth class of >50 cm which was statistically significant also.

At this age a mean teak tree recorded above ground carbon sequestration of 55.91 kg tree^{-1} while the below ground carbon sequestration was 8.45 kg tree^{-1} which all together contributed a total carbon sequestration of 64.37 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 40.07 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 10.22 kg tree^{-1} and 5.63 kg tree^{-1} respectively.

The percentage of carbon sequestration distribution in various compartments of ten year old teak showed that the bole contributed 62.25% to the total carbon content which was greater than the other compartments. The percent contribution of other compartments such as branch, bark and root to the total carbon sequestration were 15.87%, 8.75% and 13.13% respectively. The carbon sequestration partitioning indifferent components of teak in this age was in the order of bole > branch > root > bark.

4.3.3 Carbon sequestration by 15 year teak

At 15 year, the carbon content of different compartments exhibited a slightly different pattern with the root compartment registering higher values than branches in most of the girth classes (table 4.5). The pattern in bole and bark was similar to the previous stages. Significant difference was noted in bark and root compartments in some of the girth classes. The mean values of carbon in bole, branch, bark and root were 45.99, 42.29, 40.69 and

42.70% respectively and these values were slightly higher than that obtained in 10 year old teak.

Table 4.5. Carbon content in 15 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<40	$46.64^{a}\pm0.43$	$42.40^{a}\pm0.57$	$41.40^{b}\pm0.72$	$43.29^{b}\pm0.37$
40-50	$45.37^{a}\pm0.22$	$42.00^{a}\pm0.76$	$40.82^{ab}\pm0.29$	$43.13^{ab}\pm0.49$
50-60	$46.03^{a}\pm0.79$	$42.60^{a}\pm0.49$	$41.51^{b}\pm0.41$	$42.95^{ab}\pm0.42$
>60	$45.90^{a}\pm0.15$	$42.17^{a}\pm0.10$	$39.02^{a}\pm0.61$	$41.42^{a}\pm0.29$
Mean	45.99±0.24	42.29±0.24	40.69±0.38	42.70±0.28

Carbon sequestered by 15 year old teak in different above ground and below ground compartments is given in table 4.6 and described below. It can be seen that there was marked increase in above ground storage with girth, though not significant in the lower girth classes; the higher girth classes differed significantly. The values increased from 55.91 kg tree^{-1} in the lowest <40 cm category to 88.08 kg tree^{-1} in the highest >60 cm girth class.

Bole carbon storage followed the same trend as above with significant increase beyond 50 cm girth. It was seen to increase from 38.74 kg tree^{-1} in <40 cm girth trees to 63.12 kg tree^{-1} in the >60 cm class.

Branches were found to store 11.93 kg tree^{-1} of carbon in the smallest girth class which was seen to increase up the classes to 16.95 kg tree^{-1} with no significant difference in any of the girth classes.

There was considerable variation in bark carbon between girth classes. It was seen to increase from 5.25 kg tree^{-1} to 8.01kg tree^{-1} up the girth classes. The increase was significant in the larger girth classes

Table 4.6. Carbon sequestration by 15 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<40	38.74^{a} ±0.37	11.93^{a} ±1.55	5.25^{a} ±0.27	55.91^{a} ±1.46	11.57^{a} ±0.57	67.49^{a} ±1.00
40-50	41.09^{a} ±1.78	13.39^{a} ±1.40	5.94^{ab} ±0.59	60.41^{a} ±2.01	13.02^{a} ±0.51	73.43^{a} ±2.19
50-60	51.37^{b} ±2.04	15.32^{a} ±1.10	6.92^{bc} ±0.21	73.61^{b} ±3.27	16.53^{b} ±0.61	90.14^{b} ±3.86
>60	63.12^{c} ±3.27	16.95^{a} ±1.06	8.01^{c} ±0.32	88.08^{c} ±2.96	19.63^{c} ±0.89	107.71^{c} ±3.81
Mean	48.58 ±3.05	14.40 ±0.80	6.53 ±0.35	69.51 ±3.93	15.19 ±0.99	84.70 ±4.89

Below ground carbon storage followed the same pattern of above ground and below ground in the sense that statistically significant increase was noted in the larger girth classes beyond 50cm only. The lowest girth class trees were found to sequester 11.57 kg tree^{-1} of carbon which subsequently increased to 19.63 kg tree^{-1}in trees with >60 cm girth.

It can be seen from the table that the total carbon sequestration was lowest (67.49 kg tree^{-1}) in trees from girth class <40 cm and were significantly different with trees from the girth classes 50-60 cm and >60 cm. The maximum value for total carbon sequestration (107.71 kg tree^{-1}) was observed in trees of girth class >60 cm. The upper girth classes of 50-60 cm and >60 cm differed significantly between and also from the lower girth classes.

The average carbon sequestration of teak trees at the age of fifteen year regardless of their girth classes recorded above ground carbon sequestration of 69.51 kg tree^{-1} while the below ground carbon sequestration was 15.19 kg tree^{-1}contributinga total carbon sequestration of 84.70 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 48.58 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 14.4 kg tree^{-1} and 6.93 kg tree^{-1} respectively.

4.3.4 Carbon sequestration by 20 year teak

At 20 year, the carbon content decreased from bole to branch, root and bark progressively with highest value in bole and lowest in bark (table 4.7). The mean values were 45.03, 43.72, 40.93 and 42.81% in bole, branch, bark and root respectively. There was no significant difference between girth classes in carbon content of bole, branch and root; significant difference was seen in bark carbon content of different girth classes. Slight increase in carbon content was noted in all the compartments as compared to the previous stage.

Table 4.7. Carbon content in 20 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<50	$46.30^{a}\pm0.44$	$43.20^{a}\pm0.35$	$41.87^{b}\pm0.32$	$43.30^{a}\pm0.60$
50-60	$46.27^{a}\pm0.29$	$43.51^{a}\pm0.51$	$41.53^{b}\pm0.39$	$43.20^{a}\pm0.15$
60-70	$46.23^{a}\pm0.58$	$44.05^{a}\pm0.47$	$40.78^{ab}\pm0.72$	$42.96^{a}\pm0.74$
>70	$45.33^{a}\pm0.35$	$44.14^{a}\pm0.43$	$39.54^{a}\pm0.27$	$41.79^{a}\pm0.55$
Mean	46.03 ± 0.22	43.72 ± 0.22	40.93 ± 0.33	42.81 ± 0.30

Carbon sequestered by 20 year old teak in different above ground and below ground compartments is given in table 4.8 and described below.

Teak at 20th year was found to sequester 57.78 kg carbon per tree in the smallest trees with girth of <50 cm. it was found to increase with increasing girth up to 122.51 kg tree^{-1} in trees belonging to the highest girth class of >70 cm. Significant increase was noted beyond 60 cm girth.

Bole alone could store from 42.88 kg tree^{-1} to 89.96 kg tree^{-1} with increasing girth. Significant difference was seen beyond 60 cm girth.

Carbon stored in branches increased from 9.22 kg tree^{-1} in <50 cm to 21.86 kg tree^{-1} in the >70 cm category, significant difference occurred only in the last category.

Table 4.8. Carbon sequestration by 20 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<50	42.88^{a} ±1.80	9.22^{a} ±0.63	5.48^{a} ±0.09	57.58^{a} ±2.10	13.69^{a} ±0.79	71.27^{a} ±2.84
50-60	52.45^{ab} ±1.98	12.74^{ab} ±2.02	6.42^{a} ±0.25	71.61^{ab} ±2.77	16.69^{ab} ±0.58	88.30^{ab} ±3.20
60-70	67.42^{bc} ±3.96	18.12^{ab} ±1.14	8.41^{b} ±0.32	93.96^{b} ±5.31	20.43^{b} ±1.11	114.39^{b} ±6.09
>70	89.96^{c} ±6.22	21.86^{b} ±4.17	10.69^{c} ±0.69	122.51^{c} ±10.52	28.23^{c} ±1.65	150.74^{c} ±12.17
Mean	63.18 ±5.61	15.49 ±1.79	7.75 ±0.63	86.42 ±7.85	19.76 ±1.71	106.17 ±9.53

Bark compartment was found to store 5.48 kg tree^{-1} in the smallest girth class which increased to 10.69 kg tree^{-1} in the biggest class of >70 cm. The increase in the latter classes was significantly differed from the former.

Carbon sequestered by the below ground compartment of roots also increased with increasing girth class; the increase being from 13.69 kg tree^{-1} in <50 cm girth to 28.23 kg tree^{-1} in the >70 cm girth class. Significant difference was seen in the bigger girth classes.

It can be seen from the table that the total carbon sequestration was lowest (71.27 kg tree^{-1}) in trees of girth class <50 cm which was significantly different from trees of girth classes 60-70 cm and >70 cm. The maximum value for total carbon sequestration (150.74 kg tree^{-1}) was observed in trees of girth class >70 cm which was significantly different from that of teak trees in the girth classes of <50 cm, 50-60 and 60-70 cm.

At this age a mean teak tree recorded above ground carbon sequestration of 86.42 kg tree^{-1} while the below ground carbon sequestration was 19.76 kg tree^{-1} together contributing a total carbon sequestration of 106.17 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 63.18 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 15.49 kg tree^{-1} and 7.75 kg tree^{-1} respectively.

4.3.5 Carbon sequestration by 30 year teak

Carbon content of 30 year teak followed the same pattern of highest mean percentage in bole (47.73%) followed by branch (44.33%), root (43.53%) and bark (41.25%) in decreasing order (table 4.9). though differences were observed between girth classes in carbon content of different compartments, none of these were significantly different from each other. Carbon content was slightly more than that obtained in 20 year teak in all the compartments.

Table 4.9. Carbon content in 30 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<70	46.45^{a}±1.01	45.12^{a}±0.49	41.32^{a}±0.82	44.22^{a} ±1.18
70-80	49.08^{a}±0.25	43.32^{a}±0.69	42.60^{a}±1.07	44.79^{a}±0.32
80-90	47.14^{a}±0.22	45.04^{a}±0.49	41.56^{a}±1.08	42.52^{a}±0.21
>90	48.24^{a}±0.51	43.85^{a}±0.48	39.53^{a}±0.17	42.61^{a}±0.99
Mean	47.73±0.39	44.33±0.33	41.25±0.50	43.53±0.45

Carbon sequestered by 30 year old teak in different above ground and below ground compartments is given in table 4.10 and described below.

It can be seen that considerable increase in carbon sequestration occurred with girth increments. Remarkable increase could be observed up the girth classes from 75.97 kg tree^{-1} of <70 cm girth trees to 206.95 kg tree^{-1} of trees with a girth of >90 cm. significant changes were noted beyond 80 cm girth.

Bole carbon storage was observed to increase significantly in successive girth classes. The values were found to increase from 59.16 kg tree^{-1} in <70 cm girth to 167.85 kg tree^{-1} in >90 cm girth class.

The contribution by branches towards carbon sequestration increased from 11.09 kg tree^{-1} to 23.82 kg tree^{-1} up the girth categories with no significant difference in any of the girth classes.

Bark compartment was found to store 5.71 kg tree^{-1} of carbon in the smallest girth class of <70 cm and it recorded remarkable increase in subsequent classes to 15.28 kg tree^{-1} in the highest one of >90 cm girth. The increase was significant except between the first two classes.

Table 4.10. Carbon sequestration by 30 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<70	59.16^{a} ±3.88	11.09^{a} ±1.20	5.71^{a} ±0.35	75.97^{a} ±4.98	19.59^{a} ±1.09	95.55^{a} ±6.06
70-80	85.11^{b} ±8.33	14.84^{a} ±0.52	8.59^{b} ±0.94	108.54^{a} ±9.13	20.57^{a} ±3.17	129.11^{a} ±12.18
80-90	111.76^{c} ±5.68	20.95^{a} ±4.24	10.92^{b} ±0.37	143.63^{b} ±2.60	34.72^{b} ±1.74	178.35^{b} ±4.08
>90	167.85^{d} ±7.74	23.82^{a} ±5.36	15.28^{c} ±0.68	206.95^{c} ±13.38	51.08^{c} ±2.63	258.03^{c} ±16.00
Mean	105.97 ±12.47	17.67 ±2.11	10.13 ±1.09	133.77 ±15.09	31.49 ±3.98	165.26 ±18.98

Carbon sequestered by the roots taken as the below ground compartment also increased with increasing girth classes from 19.59 kg tree^{-1} in the smallest class to 51.09 kg tree^{-1} in the largest group. Significant increase occurred only beyond 80 cm girth.

It can be seen from the table that the total carbon sequestration was lowest (95.55 kg tree^{-1}) in trees from girth class <70 cm and were significantly different with trees from the girth classes 80-90 cm and >90 cm. The maximum value for total carbon sequestration (258.03 kg tree^{-1}) was observed in trees of girth class >90 cm and was significantly different with the teak trees studied in the girth classes such as <70 cm, 70-80 and 80-90 cm.

At this age a mean teak tree recorded above ground carbon sequestration of 133.77 kg tree^{-1} while the below ground carbon sequestration was 31.49 kg tree^{-1} together contributing a total carbon sequestration of 165.26 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 105.97 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 17.9 kg tree^{-1} and 10.13 kg tree^{-1} respectively.

4.3.6 Carbon sequestration by 40 year teak

Bole had the highest carbon content in 40 year teak also and it decreased in branch, root and bark in order similar to the previous stages. No significant difference was present between girth classes in any of the compartments (table 4.11). The mean carbon content was 48.14% in bole, 44.38% in branch, 41.46% in bark and 43.71% in the roots. There was slight increase in carbon content from that recorded at 30th year of growth.

Table 4.11. Carbon content in 40 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<100	48.85^{a}±0.86	44.22^{a}±1.18	40.56^{a}±0.34	43.23^{a}±0.68
100-120	46.90^{a}±0.64	43.94^{a}±0.80	42.68^{a}±0.33	44.00^{a}±0.21
120-140	48.60^{a}±0.68	44.77^{a}±0.29	42.03^{a}±0.53	45.23^{a}±1.20
>140	48.21^{a}±0.14	44.62^{a}±0.05	40.56^{a}±0.76	42.38^{a}±0.59
Mean	48.14±0.35	44.38±0.33	41.46±0.36	43.71±0.45

Carbon sequestered by 40 year old teak in different above ground and below ground compartments is given in table 4.12 and described below. It can be observed that the above ground portion could sequester 199.42 kg tree^{-1} of carbon in trees with less than100 cm girth. The storage of carbon increased with girth to 322.12 kg tree^{-1} in trees belonging to the upper most girth class of >40 cm. significant difference was seen beyond 120-140 cm girth class with the previous classes.

Table 4.12. Carbon sequestration by 40 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<100	152.17^{a} ±7.96	32.10^{a} ±2.29	15.14^{a} ±1.49	199.42^{a} ±5.44	37.11^{a} ±2.49	236.53^{a} ±6.66
100-120	180.06^{a} ±5.92	33.19^{a} ±4.60	17.47^{a} ±2.04	230.72^{a} ±11.33	41.62^{a} ±2.94	272.35^{b} ±9.84
120-140	232.11^{b} ±2.45	46.20^{a} ±8.57	18.66^{a} ±0.56	296.96^{b} ±5.67	59.11^{b} ±2.73	356.07^{c} ±3.21
>140	259.61^{b} ±11.30	42.19^{a} ±3.34	20.32^{a} ±1.26	322.12^{b} ±9.21	62.41^{b} ±3.50	384.53^{c} ±12.70
Mean	205.99 ±13.13	38.42 ±2.88	17.90 ±0.84	262.31 ±15.29	50.06 ±3.51	312.37 ±18.52

Bole was no different from the above ground compartment in pattern of increase with girth. Significant difference occurred beyond 120-140 cm girth and the carbon storage was found to increase from 152.17 kg tree^{-1} in the <100 cm category to 257.61 kg tree^{-1} in the highest class of >140 cm.

Carbon storage in branches did not differ significantly with girth increase; the values were found to increase from 32.10 kg tree^{-1} in <100 cm girth trees to 42.19 kg tree^{-1} in the >140 cm category.

Bark compartment behaved like the branch; no significant difference occurred with girth increment. Trees in the <100 cm class had 15.14kg tree^{-}

^{1} of carbon in bark which increased gradually to 20.32 kg tree^{-1} in >140 cm girth class.

Below ground carbon storage was similar to bole in significant difference with girth class; significant difference occurred beyond 120 cm girth. Carbon stored in the roots increased from 37.11 kg tree^{-1} in the smallest girth class to 62.41 kg tree^{-1} in the highest girth class.

It can be seen from the table that the total carbon sequestration was lowest (236.53 kg tree^{-1}) in trees of girth class <100 cm and were significantly different with trees from the girth classes 100-120 cm, 120-140 cm and >140 cm. The maximum value for total carbon sequestration (384.53 kg tree^{-1}) was observed in trees of girth class >140 cm.

At this age a mean teak tree recorded above ground carbon sequestration of 262.31 kg tree^{-1} while the below ground carbon sequestration was 50.06 kg tree^{-1} together contributing a total carbon sequestration of 312.37 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 205.99 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 38.42 kg tree^{-1} and 17.9 kg tree^{-1} respectively.

4.3.7 Carbon sequestration by 50 year teak

Fifty year teak had a mean carbon content of 48.85% in bole, 44.45% in branch, 41.78% in bark and 44.24% in root compartment (table 4.13). Bole recorded greater carbon content and bark had the lowest values as was the case in earlier stages; branch and root had almost similar content in all the girth classes except the >160 cm girth class. No significant difference was observed in any of the compartments with girth class. The increase in carbon content with age of teak continued at this stage also with slightly higher values.

Table 4.13. Carbon content in 50 year teak

Girth class (cm)	Carbon (%)			
	Bole	Branch	Bark	Root
<120	$47.69^{a}\pm1.44$	$44.15^{a}\pm1.05$	$41.09^{a}\pm0.67$	$45.53^{a}\pm0.94$
120-140	$48.99^{a}\pm1.29$	$44.77^{a}\pm0.30$	$43.48^{a}\pm0.85$	$44.72^{a}\pm0.79$
140-160	$49.56^{a}\pm0.31$	$44.40^{a}\pm1.17$	$41.99^{a}\pm1.20$	$44.06^{a}\pm1.21$
>160	$49.15^{a}\pm0.25$	$44.49^{a}\pm0.30$	$40.54^{a}\pm0.15$	$42.64^{a}\pm0.48$
Mean	48.85±0.47	44.45±0.35	41.78±0.48	44.24±0.50

Table 4.14 depicts the carbon sequestered in different compartments of 50 year teak. It can be seen that above ground carbon storage increased significantly with increasing girth in all successive classes. There was an increase from 289.70 kg tree^{-1} in the <120 cm girth class to 627.96 kg tree^{-1} in the highest girth category of >160 cm.

Bole was no different from the above ground compartment in statistically significant difference between girth classes; significant increase was noted in successive girth classes. Trees in <120 cm girth category were found to sequester 211.17 kg tree^{-1} of carbon while those in the upper most category of >160 cm could store 332.88 kg tree^{-1} of carbon.

Storage of carbon by branches were found to increase from 61.59 kg tree^{-1} in <120 cm girth class to 79.34 kg tree^{-1} in >160 cm girth class but no significant differences were noted in branch carbon with increasing girth.

Carbon sequestration by bark compartment increased from 16.43 kg tree^{-1} to 39.89 kg tree^{-1} as the girth class increased from <120 cm to >160 cm. significant difference occurred beyond 140 cm only.

Table 4.14. Carbon sequestration by 50 year teak

Girth class (cm)	Carbon sequestered (kg tree^{-1})					
	Bole	Branch	Bark	Above ground	Below ground	Total
<120	211.17^{a} ±6.69	61.59^{a} ±2.57	16.93^{a} ±0.70	289.70^{a} ±7.22	55.34^{a} ±3.98	345.03^{a} ±11.10
120-140	265.56^{b} ±10.22	61.50^{a} ±2.24	21.96^{ab} ±1.39	349.01^{b} ±9.49	66.28^{a} ±2.75	415.29^{b} ±12.13
140-160	346.01^{c} ±10.38	72.09^{a} ±9.32	27.54^{b} ±0.85	445.65^{c} ±1.78	84.73^{b} ±3.57	530.38^{c} ±4.07
>160	508.77^{d} ±21.36	79.34^{a} ±11.85	39.84^{c} ±2.68	627.96^{d} ±21.00	113.89^{c} ±3.09	741.85^{d} ±18.46
Mean	332.88 ±34.34	68.63 ±4.00	26.57 ±2.66	428.08 ±38.97	80.06 ±6.84	508.14 ±45.63

Below ground carbon storage contributed by roots increased with increasing girth from 55.34 kg tree^{-1} in the lowest girth class of <120 cm to 113.89 kg tree^{-1} in the >160 cm girth class. Significant difference was observed only beyond 140 cm in this case also.

It can be seen from the table that the total carbon sequestration was lowest (345.03 kg tree^{-1}) in trees from girth class <120 cm and were significantly different with trees from the girth classes 120-140 cm, 140-160 cm and >160 cm. The maximum value for total carbon sequestration (741.85 kg tree^{-1}) was observed in trees of girth class >160 cm.

At this age a mean teak tree recorded above ground carbon sequestration of 428.08 kg tree^{-1} while the below ground carbon sequestration was 80.06 kg tree^{-1} together contributing a total carbon sequestration of 508.14 kg tree^{-1}. It was seen that the mean bole carbon sequestration was 332.88 kg tree^{-1} at this age while the branch and bark recorded an average carbon sequestration of 68.63 kg tree^{-1} and 26.57 kg tree^{-1} respectively.

4.4 Discussion

4.4.1 Carbon content

Carbon content in different compartments of teak at prescribed thinning schedules is given in figure 4.1. It is clear that there is increase in carbon percentage as the tree grows though the pattern differs between compartments. Highest carbon percentage was obtained in bole which was followed by branch, root and bark in decreasing order. The pattern of increase in the case of bole is continuous though a sudden spurt is visible during 20-30 year period and a flattening just before that. This can be due to an increase in the rate of hardening during the 20-30 year periods, the hardening mostly from high carbon compounds such as lignin, cellulose etc.

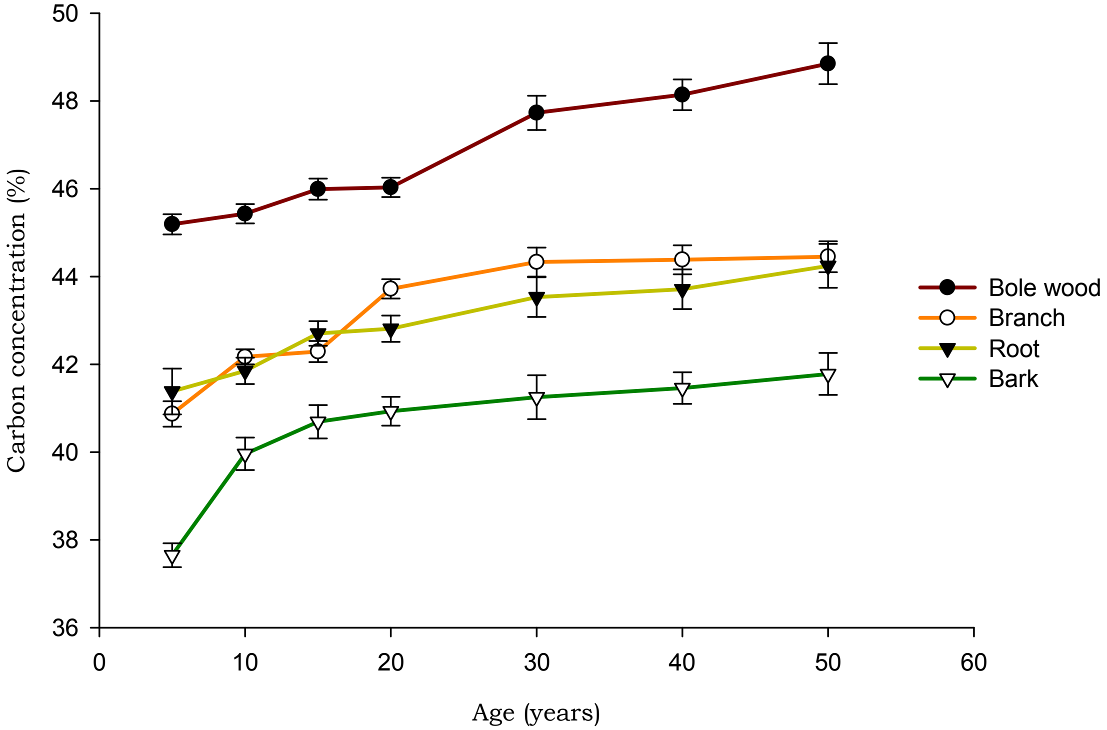

Figure 4.1. Carbon content in different compartments of teak

The overall pattern of carbon content in the branches showed an increase from 5th year to 20th year followed by a slow increment till the 30th year after which it stabilizes. The initial increase can be assumed to be caused by greater photosynthetic activity due to opening up of canopy through the mechanical thinning. In the later stages though selective felling further encourages growth of individual trees it does not make much difference in the carbon concentration percentage.

In the case of root the concentration of carbon was seen to increase till the 15th year only where after there was only gradual increment. Thickening of root would have been faster in the initial growth stages up to 15th year after which there was a lesser rate of increase which would have got reflected in the carbon content. The carbon content in bark increased sharply from 5th to 10th year which was followed by a lesser rate in the succeeding years.

It was found that the carbon content in teak varies with compartments and also with various regions in India. Jha (2005) reported higher carbon concentration (52.98) in bole compartment in North Himalayas than that obtained in the present study (47.73%) while Sahu *et al.* (2013) obtained a lower value (43.50%) in Chhattisgarh. The branch carbon content in the current study was 44.73 which were lower than those reported from both Himalaya (56.79) and Chhattisgarh (45.67%). Carbon percentage in the root compartment (43.63%) was found to lie between that obtained from both the other places. Species with high lignin content tend to display high carbon content and wood carbon density (gC/cm^3) showed high inter-specific variation, mainly due to differences in wood specific gravity (Gogate, 1995). Lamlom and Savidge (2006) also stated that the volatile carbon fraction in wood may contribute substantially to variation in total wood Carbon content. Low molecular weight organic substances in wood include a wide variety of alcohols, aldehydes, ketones, phenolics, furans, terpenoids, isoprenoids, and other compounds.

4.4.2 Carbon sequestration

Carbon sequestration by teak per tree is shown in the figure 4.2 and 4.3. It can be seen that the above ground contributed maximum of which bole was the major contributor. Carbon sequestration increased gradually till the 30th after which the increase was substantial. The figure 4.2 gives the impression that it may go on increasing further. Increase in bole is faster the 30th year and hence the increase in sequestered carbon stock in the root and branch also increase with age though the rate is less as compared to the bole. Here also the rate of change is more after 30th year.

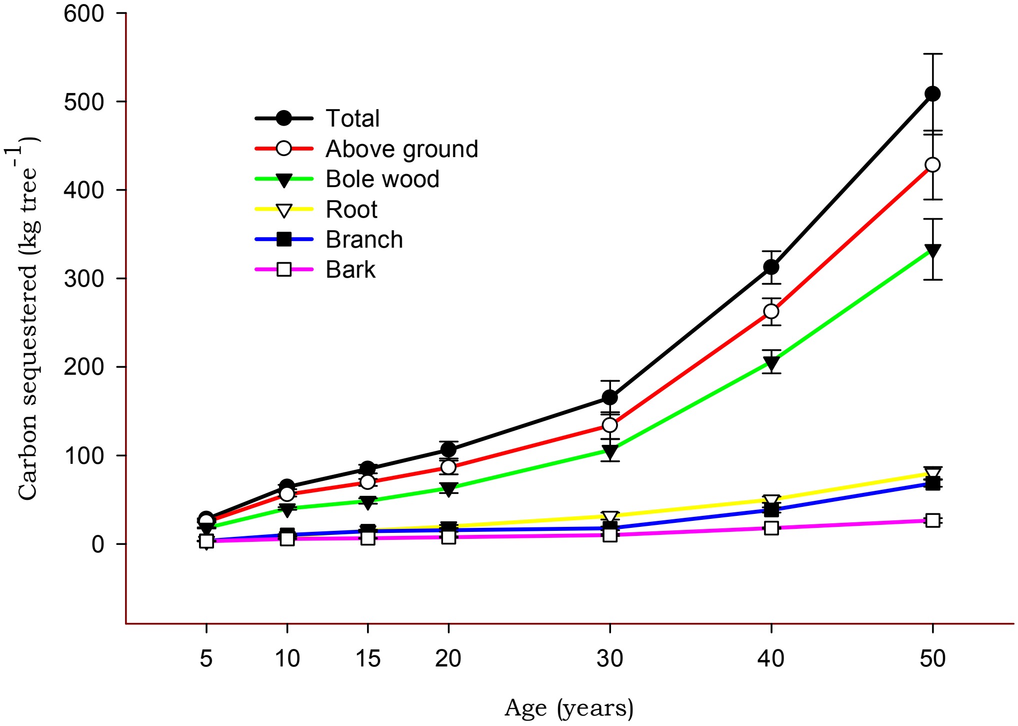

Figure 4.2. Carbon sequestered in various compartments of teak

In the case of bark, there is no appreciable difference in carbon content with increasing age. Above ground portion consisting of bole, branch and bark and the total figure including roots in addition to the above ground debits the same trend as bole though with higher values. Root and branch portion on hardening store remarkable quantity of carbon. Bark of teak is thick, soft and fragile composed of carbohydrates, glycosides, tannins, resins alkaloids etc. with comparatively lesser carbon percentage results in lower carbon sequestration as compared to the other compartments.

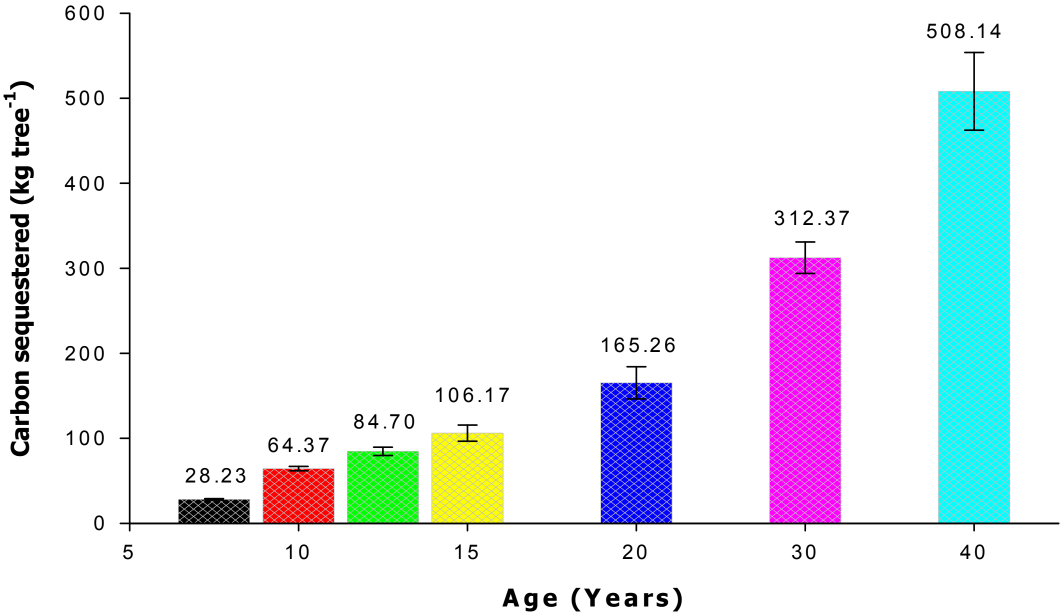

Figure 4.3. Total carbon sequestered in teak

The contribution of different compartments towards carbon stock in a teak tree expressed in percentage is shown in figure 4.4 and 4.5. It can be seen that bole contributed most of the carbon stock in a teak tree which is almost three fold of the root compartment. The contribution by bole decreases initially but picks up after 15th year after which its share increases steadily though gradually. The proportionate decrease in the beginning is due to the increasing trend by root and branch in the same period.

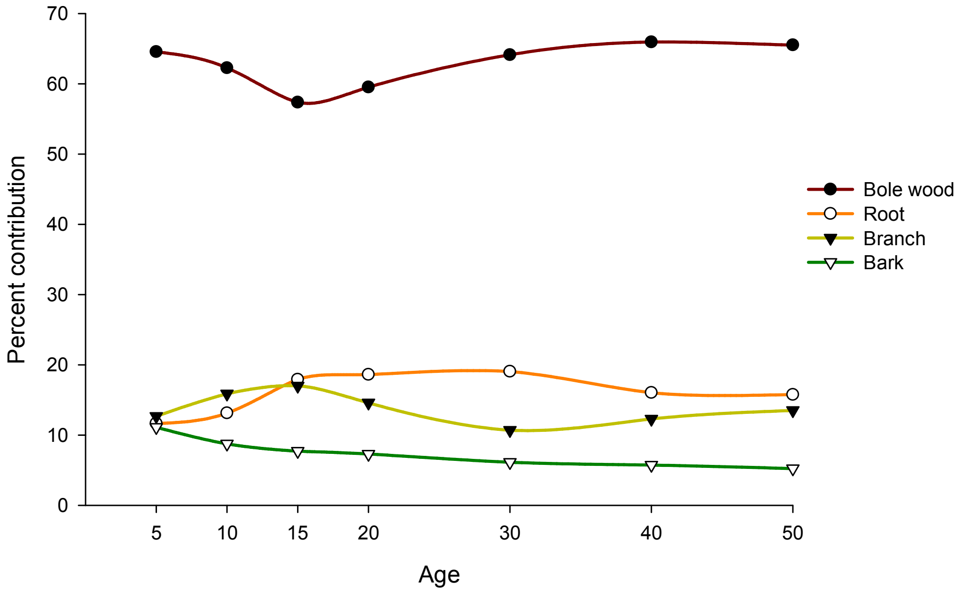

Figure 4.4. Carbon partitioning in teak compartments with age

The contribution by root is almost steady after the 15th year while that by the branches decreases gradually from 15th to the 40th year after which a slight increase is noted. The contribution by the bark towards the total carbon stock is the least and it has a decreasing trend in the beginning which is very slow and continuous without much difference in the later stages.

Carbon sequestration by teak differs with the age and growth pattern in different sites (Sreejesh *et al.*, 2013). It was reported to increase gradually from 55.23 kg tree^{-1} at 18th year to 83.75 kg in 19th year, 130.43 kg in 24th year and 337.45 kg tree^{-1} in the 47th year in West Bengal (Banerji and Prakasm, 2013). A five year tree in Sri Lanka was found to store 10.96 kg tree^{-1} carbon which was seen to increase to 44.35 kg tree^{-1} by the 10th year

(Appuhamy, 2009). The biomass of 406.67 Mg ha^{-1} with carbon storage of 101.7 Mg ha^{-1} has been reported by Chanan and Iriany (2014) in the younger teak plantations. Across age group highest carbon concentration of 45.695 was observed in the wood, while the branches had 48.25% and the fine roots had a concentration of 35.32 percent.

The percentage contribution of different compartments *viz.,* bole, branches, root and bark towards the total carbon exhibited similar trend in all age classes.

The bole contribution was 64% in the 5th year which gradually got reduced to 62% in the 10th year, 57% in the 15th year, and 59% in the 20th year after which the bole regained its initial position of 64% by the 30th year and was seen to stabilize at 66% by the final felling stage of 50 years. The other compartments were highly variable at different ages. The contribution by root was less in the initial period with around 12% up to the 10th year after which there was a remarkable increase to around 19% till the 30th year after which it was seen to stabilize at 16 percent. The contribution by the bark and branch were almost the same at the 5th year with around 12 percent. It was seen to follow a definite proportion later with the bark contributing around half of what the branches contribute; branch contribution increasing first from 13 to 17 and then decreasing gradually from 17 to around 11 percent.

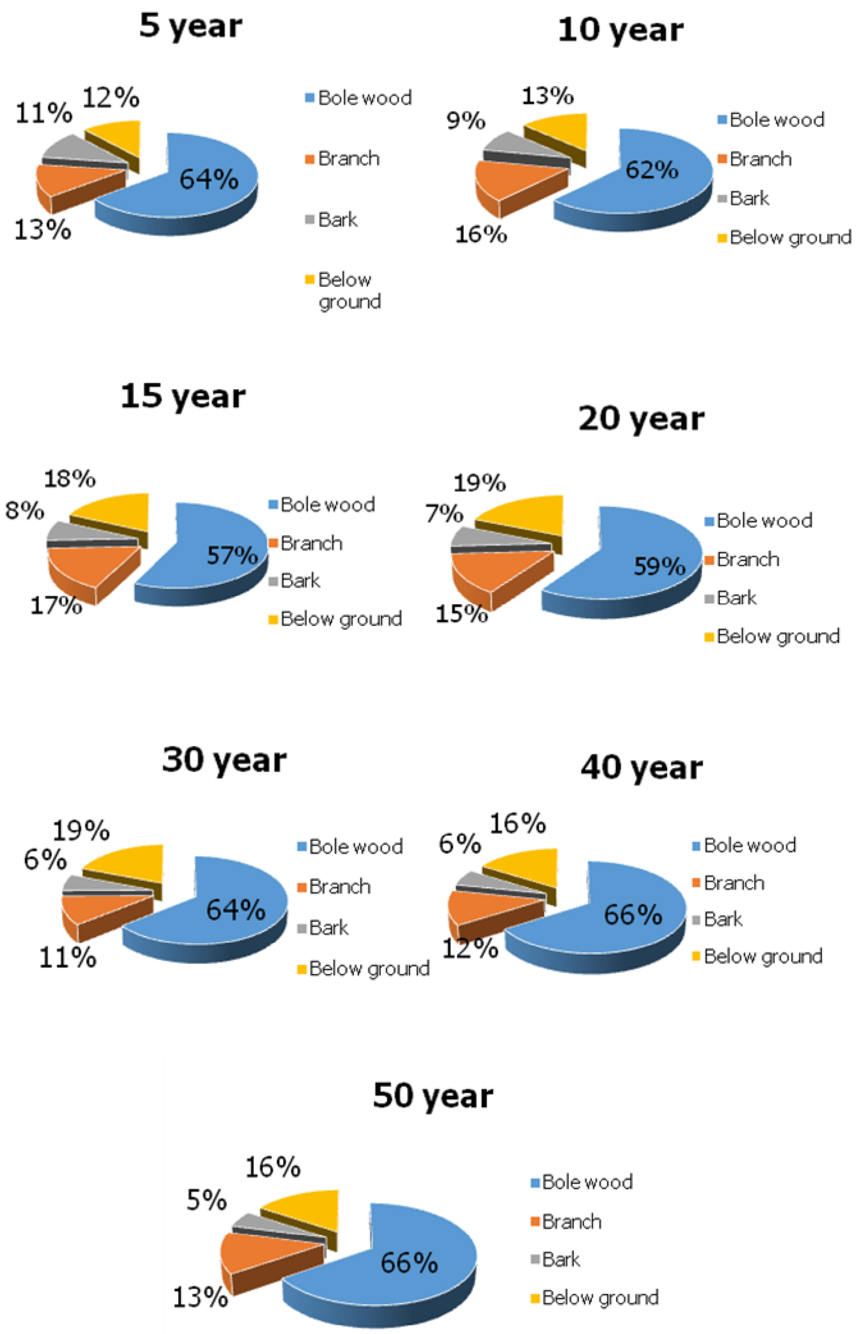

Figure 4.5. Carbon partitioning in teak compartments with age

Reddy *et al.* (2014) studied the variation in carbon sequestration potential of teak plantations of different ages (10, 15 and 20 years) growing in different agro climatic regions of South India by classifying into zones of varying wetness and found that the Northern transition zones yielded significantly higher biomass compared to the hilly zones and the dry zones. Total above ground carbon sequestered was to be 247.47 Mg ha^{-1}, 157.60 Mg ha^{-1} and 103.73 Mg ha^{-1} in the respective zones.

The reason for such variations can be attributed to edapho-climatic factors. The poor sites with low biomass yield naturally results in lower carbon content in the tree and the soil while better sites would definitely give higher dry matter and carbon. The above mentioned sites with lower yield are those with lesser precipitation and lower productivity as compared to the better ones. Kerala state blessed with humid tropical climate and well drained soils are capable of supporting reasonably good growth of teak though site degradation due to continuous rotation of the same species at the same site definitely leads to deterioration of site quality resultant lower yield. These are reflected in the present results also as can be seen from the variation across sites and ages.

Higher biomass and carbon production with increasing precipitation of forest trees has been documented by Brown and Lugo (1982) and Murphy and Lugo (1986 a) while better height and above ground biomass of teak was reported by Watanabe *et al.* (2009) with increase in precipitation.

4.4.3 Carbon storage at plantation level

Figure (4.6) depicts carbon storage by teak plantation on per hectare basis at the prescribed felling stages. Bole contributed maximum followed by root, branches and bark towards the total carbon storage. The pattern of carbon storage with increasing age was similar to the biomass variation that has been described earlier. The contribution by bole was found to be 45.56 Mg ha^{-1} at the 5th year with 2500 standing trees taken in to account before felling at that stage. The respective figures at subsequent felling stages of 10, 15, 20, 30, 40 and the final felling at 50th year were 50.08, 38.96, 33.99, 36.88, 50.47 and 53.26 Mg ha^{-1} of carbon with corresponding number of 1250, 802, 538, 348, 245 and 160 trees per hectare. The contribution by root at the respective stages was 8.23, 10.57, 12.18, 10.63, 10.96, 12.27 and 12.81 Mg per hectare. The contribution by branch was 8.95, 12.77, 11.55, 8.33, 6.15, 9.41 and 10.98 Mg ha^{-1} of carbon at the respective felling periods. Bark contributed 7.84, 7.04, 5.24, 4.17, 3.52, 4.39 and 4.25 Mg of carbon per hectare during different stages respectively.

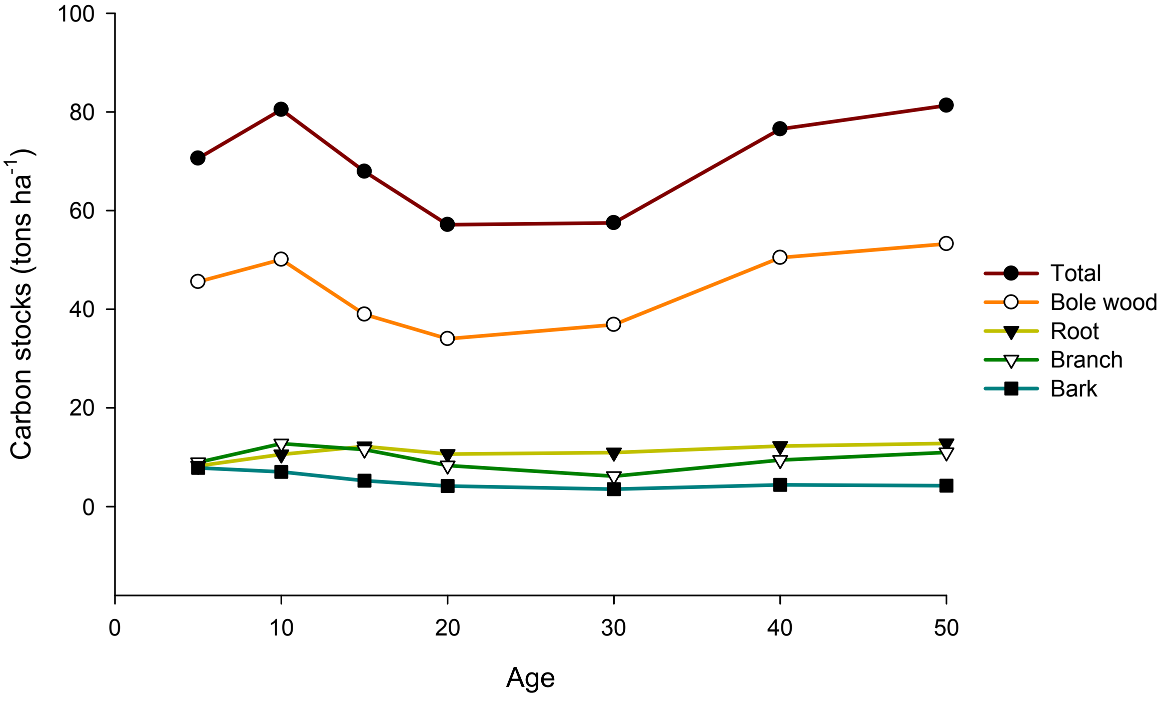

Figure 4.6. Carbon stocks in teak compartments with age

Carbon sequestration by teak on a plantation scale was studied by several investigators. Their results indicate increasing carbon storage with increasing age. Pestri *et al.* (2007) obtained a figure of 39.5 Mg ha^{-1} of above ground carbon at the 6th year of growth, 40.82 Mg at the 10th year, 33.86 in the 15th year, 55.23 in the 23rd year and 41.13 Mg ha^{-1} at the 24th year. Jha *et al.* (2003) obtained 15.8 Mg of carbon from a hectare of teak plantation in Uttar Pradesh, India at the 5th year which increased to 35.4 Mg the 11th year 38.9 in the 18th year, 61.5 Mg by the 24th year and 73.2 Mg carbon per hectare by the 30th year. A teak plantation in Western Panama was found to store 2.9 tons of carbon per hectare in the first year which gradually increased to 40.7 Mg ha^{-1} at the 10th year (Derwisch *et al.,* 2009). A 23 year old plantation had 52.70% carbon while at 33 years the carbon content increased negligibly to 52.85% of carbon. Carbon storage at the harvest age of 20 years in Panama was found to vary from 86.6 Mg ha^{-1} to 122.2 Mg ha^{-1} in the above ground portion (Kraenzel *et al.,* 2003). The carbon storage by teak plantation in Thailand was found to be 50.51 Mg ha^{-1} in a 19 year old teak plantation and 85.27 Mg ha^{-1} in 33 year old plantation (Pestri *et al.* 2007). These figures vary between themselves and with the results of the present study but the differences are not very significant because the number of trees removed at each felling stage is not the same everywhere. Site factors including climate and soil would also have influenced the yield. The above ground carbon content in the present investigation was higher than that obtained by both Pestri *et al.* (2007) and Jha (2015) in general indicating higher potential of carbon sequestration in Kerala.

The below ground biomass was also found to increase with age, the values obtained by Jha (2015) being 7.25 Mg of carbon at the 19th year, 12.24 Mg at the 23rd year and 13.31 Mg at the 33rd year. These figures were slightly higher than our results in the latter stages of growth. The bole carbon was found to be 26.24, 45.92 and 50.51 Mg per hectare at the same age. Branches contributed 11.66 Mg, 22.01 Mg and 26.42 Mg carbon during the above said age.

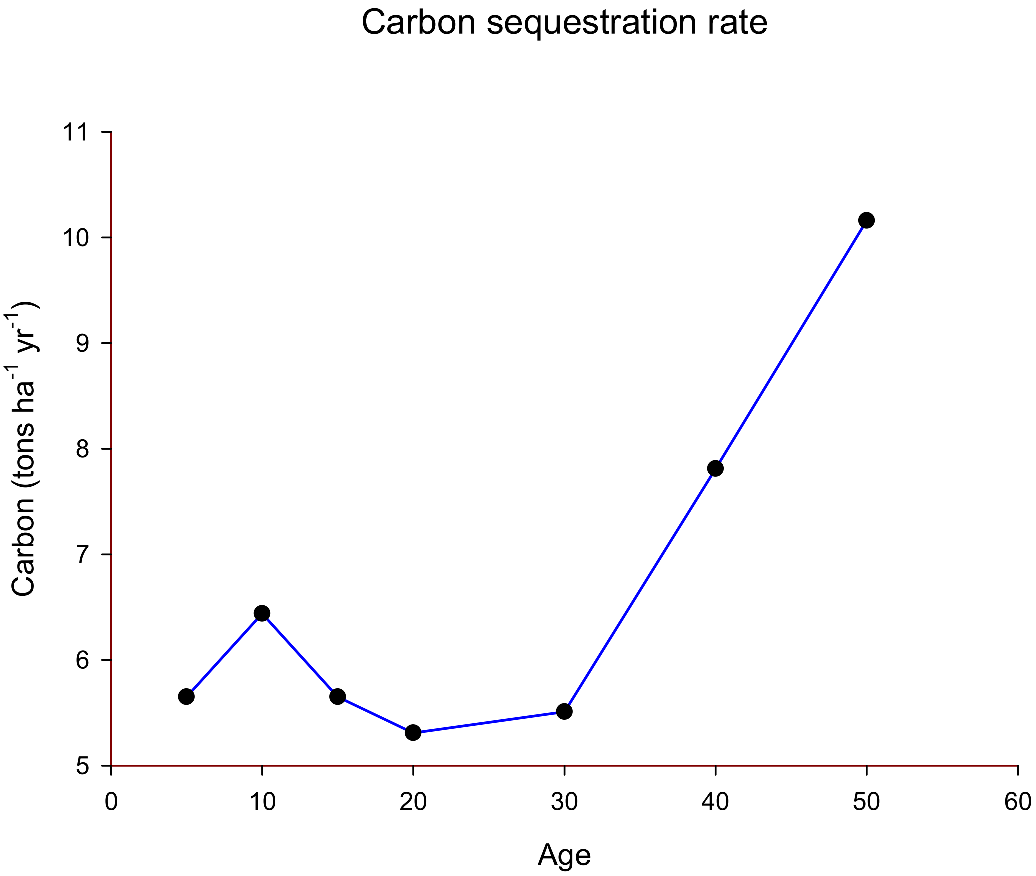

Figure 4.7. Carbon sequestration rate in teak tree

The rate of carbon sequestration from the fifth year to the fiftieth year through the prescribed felling stages is given in figure 4.7. It can be seen that though there is an initial increment in the carbon sequestration rate from 5th to the 10th year, the latter stages registered a decrease up to the 20th year where after a gradual climb has been observed. A steep climb followed indicating significant increase in the rate of carbon sequestration. This is naturally expected because the trend follows that of biomass accretions which depends on the density of trees per hectare and the content of carbon in the biomass which depends on the density of the compartments.

4.5 Summary

Carbon sequestered in various compartments of teak at prescribed felling stages is summarized below. Bole contributed maximum towards total carbon in teak. The contribution by branches came next but only up to the 10th year beyond which stage, roots were found to contribute more than the branches. The contribution by bark was the least among the four compartments.

Table 4.15. Mean carbon content in various compartments of teak

Age (Years	Mean carbon content (kg tree-1)					
	Bole	Branch	Bark	Above ground	Below ground	Total
5	18.22^{a} ±0.60	3.58^{a} ±0.13	3.14^{a} ±0.13	24.94^{a} ±0.78	3.29^{a} ±0.06	28.23^{a} ±0.83
10	40.07^{a} ±1.43	10.22^{ab} ±1.10	5.63^{ab} ±0.20	55.91^{a} ±2.28	8.45^{ab} ±0.33	64.37^{a} ±2.55
15	48.58^{a} ±3.05	14.40^{b} ±0.80	6.53^{ab} ±0.35	69.51^{ab} ±3.93	15.19^{ab} ±0.99	84.70^{a} ±4.89
20	63.18^{ab} ±5.61	15.49^{b} ±1.79	7.75^{ab} ±0.63	86.42^{ab} ±7.85	19.76^{bc} ±1.71	106.17^{ab} ±9.53
30	105.97^{b} ±12.47	17.67^{b} ±2.11	10.13^{b} ±1.09	133.77^{b} ±15.09	31.49^{c} ±3.98	165.26^{b} ±18.98
40	205.99^{c} ±13.13	38.42^{c} ±2.88	17.90^{c} ±0.84	262.31^{c} ±15.29	50.06^{d} ±3.51	312.37^{c} ±18.52
50	332.88^{d} ±34.34	68.63^{d} ±4.00	26.57^{d} ±2.66	428.08^{d} ±38.97	80.06^{e} ±6.84	508.14^{d} ±45.63

A five year teak was seen to sequester 18.22 kg tree^{-1} in its bole, 3.58, 3.14 and 3.29 kg tree^{-1} in branch, bark and root respectively. Carbon sequestration capacity of teak was found to increase with age and reach a figure of 332.88 kg tree^{-1} in bole, 68.63 in branch, 26.57 in bark and 80.06

kg tree^{-1} in the root compartment. On the whole a teak tree at final feeling stage was found to sequester 508.14 kg of carbon.

Chapter 5

Soil Carbon Sequestration

5. Soil Carbon Sequestration

5.1 Introduction

Soil has greater carbon storage capacity than vegetation and atmosphere (Bellamy *et al.*, 2005) giving it a major role in global carbon sequestration (Lal, 2002). Globally the soil stores 2300 Peta gram (Pg) of carbon which is 3 times the atmospheric storage (770 Pg) and 3.8 times the storage of 610Pg in biotic pools (Lal, 2002). The upper one metre soil is reported to store twice the amount of atmospheric carbon amounting to 1502 Pg of carbon (Jobbagy and Jackson, 2000). Delgado and Follett (2002) reported greater storage in the soil equivalent to 3.2 times the atmospheric carbon and 4 times the carbon in terrestrial vegetation.

Temperate evergreen forest has been found to sequester 20.4 kg m^3 of carbon in the 1st three metre of soil; 47% of which is in the 0-20 cm depth and 23% in the 20-40 cm depth of soil (Jobbagy and Jackson, 2000). Indian forests have been estimated to store 4.13 Pg carbon in the 50 cm soil and 6.81 Pg carbon when the top one metre soil depth was considered (Chhabra *et al.*, 2002). Other estimates by Dadhwal *et al.* (1997) and Jha *et al.* (2003) gave the figures as 6.72 to 9.8 Pg C of soil organic carbon. The national average of soil organic carbon in the forest soil was estimated as 183 Mg carbon per hectare (Jha *et al.*, 2003).

Trees contribute substantially to soil organic carbon due to higher biomass in both above ground and below ground (Lal and Bruce, 1999; Nair *et al.*, 2009; Promraksa, 2014). Soil carbon is constituted by both organic and inorganic sources. Inorganic sources do not change with management or land use but the organic pool is affected by land use. Even a 5% increase in the organic pool with management techniques can cause a decrease in the atmospheric carbon by up to 16% (Pastian *et al.,* 2000; Delgado and Follett

2002). The balance between addition and decomposition determines the soil organic carbon content.

Continuous mono cropping at same site can lead to soil degradation of several kinds. It may lead to decline in soil fertility due to proportional uptake of certain nutrients and also may cause soil compaction during periodic operations encouraging soil erosion. Declining soil fertility including decrease in soil organic carbon in successive rotations of teak raised as plantations in Kerala have been reported by Alexander *et al.* (1981) and Balagopalan and Jose (1982).

A knowledge of the portion of soil organic carbon into different pools such as active, slow and passive pools provide information that is necessary to interpret changes in the organic carbon fractions with respect to the ecosystem dynamics (Gartzia-Bengoetxea *et al.*, 2009; von Lutzow *et al.,* 2007). Labile soil organic carbon though cannot be specifically defined physically and chemically is constituent of simple carbohydrates and other compounds including amino acids and a part of microbial biomass. It is separated through chemical fractionations that rely on the solubility in acid or base media (Tirol-Padre and Ladha, 2004). Decomposed organic fractions interact with mineral particles especially clay minerals and soil aggregates forming stable associations. Such strongly held fractions are less susceptible to further decompositions and release (Kogel-Knabner *et al.,* 2008). Macro aggregates (>250μm diameter) of soil can store soil organic carbon for short period while micro aggregates (<250μm) are capable of retaining soil organic carbon fractions for longer periods (Carter, 2002; Six *et al.*, 2002; Edward and Bremener, 1967). The finer soil separates, silt and clay (<53μm) also fix soil carbon for longer periods.

Soil organic carbon pools have been investigated by many workers (Franzluebbers and Arshad, 1996; Turner *et al.*, 2005; Yang *et al.*, 2007;

Tan *et al.*, 2009). Soil carbon fractions with rapid turnover rate are termed as labile organic carbon (Harrison *et al.,* 1993). Parton *et al.* (1987) defined the active carbon fractions as that part of the soil organic carbon with a turn over time of few years (<5 years) as compared with the recalcitrant carbon which has a turn over time of 200 to 1500 years. The slow fraction is considered to have a mean residence time of 20 to 40 years.

5.2 Methodology

5.2.1 Estimation of Soil Organic Carbon

In all the 7 plantations, composite soil samples were collected from 0-20, 20-40, 40-60, 60-80 and 80-100 cm depth. The collected soil samples were air dried in shade and powdered to fine soil particles using pestle and mortar. The soil thus prepared was first sieved through 0.5 mm sieve and stored in soil bags. A small portion of each sample was sieved through 0.2 mm sieve for analysis of organic carbon and total carbon. 20 mg of the processed soil is placed in tin capsules and the carbon estimated using CHNS analyser as was done in the case of different compartments of teak.

Soil organic carbon stock in a soil layer was determined using the formula given below (Batjes, 1996) where bulk density of the soil was measured by core sampling techniques.

$$Qi = CiDiEi$$

Where, Qi – Soil organic carbon stock (Mg m^{-3}), Ei – Depth (m), Ci – Carbon content (g g^{-1}), Di – Bulk Density (gcm^{-3})

5.2.2 Fractions of Soil Carbon

Describing the cycling of C through soils often requires the partitioning of soil organic C (SOC) among pools with varying turnover times. A three pool model is frequently used where the organic C compounds persist in an “active” pool, “slow” pool and in a “passive” pool.

5.2.2.1 Active carbon

The active carbon in the soil represents the labile carbon pool with a residence time of < 5 years in the soil. It was estimated by the oxidation of soil with 333 mM potassium permanganate method proposed by Blair *et al.* (1995). 2.0 g of soil was taken in centrifuge tube and oxidized with 25 ml of 333 mM $KMnO_4$ by shaking in a mechanical shaker for 1 hour. The tubes were centrifuged for 5 minutes at 4000 rpm and 1.0 ml of supernatant solution was diluted to 250 ml with double distilled water. The concentration of $KMnO_4$ was measured at 565 nm wavelength using spectrophotometer. The change in concentration of $KMnO_4$ is used to estimate the amount of carbon oxidized assuming that 1.0 mM of MnO_4 was consumed in the oxidation of 0.75 mM of carbon.

5.2.2.2 Passive carbon

Passive SOC was measured by using acid hydrolysis (Leavitt *et al.,* 1997), taking more than 5 g of soil into a test tube containing 6 N HCl, boiled the soil for 16 hours and then washed the samples to pH=7.0 with distilled water, dried the samples in an oven at 60°C, and the carbon of these samples was determined using CHNS analyser.

5.2.2.3 Slow carbon

The slow carbon was estimated as the difference between total carbon and the sum of active and passive SOC.

Plate 5.1 Soil carbon sampling

5.3 Results

5.3.1 Soil carbon stock in 5 year teak

The soil carbon estimated in five year teak plantation is shown in the table 5.1. It was seen that the total carbon content was maximum in the surface layer of 0-20 cm which decreased drastically with depth. While in contrast to this, the bulk density of soil showed minimum value in surface and it increased in deeper layers. The soil carbon concentration in various layers showed significant difference at $p=0.05$ level but such variation was less prominent in the case of bulk density. The carbon concentration in the soil layers decreased from 1.90% in 0-20 cm depth to 0.52% in 80-100 cm layer but the bulk density was minimum (1.20 g cm^{-3}) in the surface layer of 0-20 cm and maximum (1.31 g cm^{-3}) in the 80-100 cm depth. The total soil carbon stocks in a hectare of teak plantation was found to be 45.56 Mg ha^{-1} in 0-20 cm soil layer and the carbon stocks in sub soil layers were 34.18 Mg ha^{-1}, 22.97 Mg ha^{-1}, 18.06 Mg ha^{-1}, and 13.64 Mg ha^{-1} respectively. When all the depths were taken together, it was seen that soil carbon stored in 0-100 cm depth of five year old teak plantation was 134.40 mega gram per hectare.

Table 5.1. Soil carbon stock in 5 year teak plantation

Soil depth (cm)	Bulk density (gcm^{-3})	Soil carbon (%)	Soil carbon (Mgha^{-1})	Cumulative soil carbon (Mgha^{-1})
0-20	1.20^{a}±0.019	1.90^{a}±0.070	45.56^{a}±1.89	45.56^{a}±1.89
20-40	1.24^{ab}±0.016	1.38^{b} ±0.047	34.18^{b}±1.31	79.74^{b}±2.99
40-60	1.25^{ab}±0.015	0.92^{c}±0.057	22.97^{c}±1.39	102.70^{c}±4.16
60-80	1.26^{ab}±0.015	0.72^{d}±0.043	18.06^{d}±1.05	120.76^{d}±5.14
80-100	1.31^{b}±0.028	0.52^{e}±0.045	13.64^{d}±1.20	**134.40^{d}±5.65**

5.3.2 Soil carbon stock in 10 year teak

The soil carbon content in 0-20 cm layer of 10 year old plantation was estimated to be 1.93% with a bulk density of 1.21 g cm^{-3} which gives a carbon stock of 46.63 Mg ha^{-1} in the surface soil layer (table 5.2). The carbon concentration decreased significantly with depth to 0.53% in the deepest layer of 80-100 cm while the bulk density increased to 1.31 g cm^{-3} giving a carbon stock of 13.95 Mg ha^{-1} in this layer. The cumulative carbon stock in ten year old teak plantation was calculated to be 140.96 Mg ha^{-1} when all the depths were taken together.

Table 5. 2. Soil carbon stock in 10 year teak plantation

Soil depth (cm)	Bulk density (gcm^{-3})	Soil carbon (%)	Soil carbon ($Mgha^{-1}$)	Cumulative soil carbon ($Mgha^{-1}$)
0-20	1.21^a±0.015	1.93^a±0.074	46.63^a±1.91	46.63^a±1.91
20-40	1.23^a±0.015	1.55^b±0.085	37.79^b±1.93	84.42^b±3.54
40-60	1.25^a±0.015	0.98^c±0.026	24.36^c±0.60	108.78^c±3.80
60-80	1.30^b±0.007	0.70^d±0.040	18.23^d±0.66	127.78^d±3.77
80-100	1.31^b±0.012	0.53^d±0.029	13.95^d±0.77	**140.96^e±3.70**

5.3.3 Soil carbon stock in 15 year teak

The soil carbon content in 0-20 cm layer of 15 year old plantation was found to be 2.28% with a bulk density of 1.16 g cm^{-3} contributing a carbon stock of 52.82 Mg ha^{-1} in the surface soil layer (table 5.3). The carbon concentration decreased significantly with depth to 0.65% in the deepest layer of 80-100 cm. The bulk density in the corresponding depth was 1.28 g cm^{-3} resulting in carbon stocks of 16.68 Mg ha^{-1} in that layer. The cumulative carbon stock in the fifteen year aged teak plantation was calculated to be 163.93 Mg ha-1 when all the depths were taken together.

Table 5.3. Soil carbon stock in 15 year teak plantation

Soil depth (cm)	Bulk density (gcm-3)	Soil carbon (%)	Soil carbon (Mgha-1)	Cumulative soil carbon (Mgha-1)
0-20	1.16ᵃ±0.023	2.28ᵃ±0.060	52.82ᵃ±1.33	52.82ᵃ±1.33
20-40	1.20ᵃ±0.022	1.80ᵇ±0.055	43.31ᵇ±1.42	96.13ᵇ±2.65
40-60	1.23ᵃᵇ±0.018	1.19ᶜ±0.045	29.21ᶜ±1.32	125.35ᶜ±3.81
60-80	1.22ᵃᵇ ±0.019	0.90ᵈ±0.045	21.91ᵈ±1.26	147.26ᵈ±4.98
80-100	1.28ᵇ±0.021	0.65ᵉ±0.026	16.68ᵉ±0.78	**163.93ᵉ±5.41**

5.3.4 Soil carbon stock in 20 year teak

Twenty year old teak plantation had 2.2% carbon in 0-20 cm soil layer with a bulk density of 1.13 g cm-3 which gave a carbon stock of 49.87 Mg ha-1 in the surface soil layer (table 5.4).

Table 5.4. Soil carbon stock in 20 year teak plantation

Soil depth (cm)	Bulk density (gcm-3)	Soil carbon (%)	Soil carbon (Mgha-1)	Cumulative soil carbon (Mgha-1)
0-20	1.13ᵃ±0.018	2.20ᵃ±0.057	49.87ᵃ±1.82	49.89ᵃ±1.82
20-40	1.19ᵃᵇ±0.016	1.88ᵇ±0.066	44.61ᵇ±1.49	90.45ᵇ±4.20
40-60	1.22ᵃᵇ±0.016	1.19ᶜ±0.046	29.20ᶜ±1.24	123.16ᶜ±3.20
60-80	1.36ᵇ±0.107	0.90ᵈ±0.046	24.77ᶜ ±2.89	147.92ᵈ±4.92
80-100	1.33ᵇ±0.011	0.71ᵉ±0.046	19.01 ±1.25	**166.93ᵉ±5.94**

There was progressive decrease in soil carbon with depth, the 80-100 cm soil layer registering a bulk density of 1.33 g cm^{-3} and a carbon stock of 19.01 Mg ha^{-1}. Considering all the soil layers, the cumulative carbon stock was worked out to be 166.93 Mg ha^{-1} in twenty year teak.

5.3.5 Soil carbon stock in 30 year teak

An increase in soil carbon content continued to occur in 30 year teak as compared to the previous periods resulting in a carbon content of 2.34% in 0-20 cm soil layer that had a bulk density of 1.16 g cm^{-3}. The carbon stock was calculated to be 53.99 Mg ha^{-1} in the surface soil layer (table 5.5). The sub surface layers registered consistent decrease in soil carbon while the bulk density increased down the profile. The deepest layer had a carbon stock of 21.34 Mg ha^{-1}, the carbon content being 0.76% and the bulk density 1.40 g cm^{-3}. The cumulative carbon stock taking in to account all the depths was found to be 175.30 Mg ha^{-1} in 30 year old teak plantation.

Table 5.5. Soil carbon stock in 30 year teak plantation

Soil depth (cm)	Bulk density (gcm^{-3})	Soil carbon (%)	Soil carbon ($Mgha^{-1}$)	Cumulative soil carbon ($Mgha^{-1}$)
0-20	1.16^a±0.023	2.34^a±0.055	53.99^a±1.80	53.99^a±1.80
20-40	1.23^b±0.016	1.86^b±0.061	45.62^b±1.72	99.61^b±2.87
40-60	1.24^b±0.015	1.24^c±0.059	30.73^c±1.53	130.34^c±3.96
60-80	1.25^b±0.014	0.94^d±0.078	23.61^d±1.86	153.54^d±5.27
80-100	1.40^c±0.019	0.76^e±0.069	21.34^d±1.85	**175.30^e±6.75**

5.3.6 Soil carbon stock in 40 year teak

The soil carbon in 40 year teak increased further to 2.5% in 0-20 cm layer that had a bulk density of 1.19 g cm^{-3} yielding a carbon stock of 60.17 Mg ha^{-1} in the surface soil layer (table 5.6). The carbon concentration decreased significantly with depth to 0.79% at the lowest layer of 80-100 cm and the bulk density increased to 1.39 gcm^{-3} resulting in a carbon stock of 22.00 Mg ha^{-1} in that layer. The cumulative carbon stock of forty year teak plantation was calculated to be 185.13 Mg ha^{-1} when all the depths were taken together.

Table 5.6. Soil carbon stock in 40 year teak plantation

Soil depth (cm)	Bulk density (gcm^{-3})	Soil carbon (%)	Soil carbon (Mgha^{-1})	Cumulative soil carbon (Mgha^{-1})
0-20	1.19^{a}±0.015	2.52^{a}±0.089	60.17^{a}±2.48	60.17^{a}±2.48
20-40	1.23^{ab}±0.014	1.90^{b}±0.054	46.64^{b}±1.55	106.81^{b}±3.74
40-60	1.26^{b}±0.012	1.27^{c}±0.036	31.92^{c}±0.91	138.73^{c}±4.38
60-80	1.25^{b}±0.016	0.97^{d}±0.050	24.40^{d}±0.90	163.13^{d}±5.04
80-100	1.39^{c}±0.018	0.79^{e}±0.037	22.00^{e}±1.03	**185.13^{e}±5.94**

5.3.7 Soil carbon stock in 50 year teak

The surface 0-20 cm of 50 year old teak plantation was found to have 2.65% carbon and a bulk density of 1.20gcm^{-3}. The carbon stock was estimated to be 63.79 Mg ha^{-1} in the surface soil layer (table 5.7). The carbon concentration decreased significantly with depth to 0.83% in 80-100 cm and the bulk density in the layer being 1.43 g cm^{-3} carbon stock was worked out to be 23.82 Mg ha^{-1}. The cumulative carbon stock in fifty year teak plantation was calculated to be 197.48 Mg ha^{-1} considering all the depths together.

Table 5.7. Soil carbon stock in 50 year teak plantation

Soil depth (cm)	Bulk density (gcm^{-3})	Soil carbon (%)	Soil carbon (Mgha^{-1})	Cumulative soil carbon (Mgha^{-1})
0-20	1.20^{a}±0.013	2.65^{a}±0.063	63.79^{a}±1.98	63.79^{a}±1.98
20-40	1.23^{ab}±0.011	2.11^{b}±0.053	51.81^{b}±1.47	115.60^{b}±3.26
40-60	1.23^{ab}±0.009	1.31^{c}±0.040	32.26^{c}±0.87	147.86^{c}±3.87
60-80	1.27^{b}±0.017	1.02^{d}±0.040	25.80^{d}±1.11	173.66^{d}±4.76
80-100	1.43^{c}±0.022	0.83^{e}±0.022	23.82^{e}±1.28	**197.48^{e}±5.77**

The carbon stocks in 0-100 cm depth of soil was found to increase consistently with teak growth in plantations; it increased from 134.40 Mg ha^{-1} in five year plantation to 197.48 Mg ha^{-1} in fifty year plantations.

5.3.8 Soil carbon fractions in surface soil of teak plantations

The results of the soil fractions are shown in the table 5.8 and figure 5.1. Soil carbon fractions studied in different teak plantations showed significant variations. The total carbon content in the 0-40 cm layer of five year plantation was 1.90% which increased with age of plantation to 2.65% in the fiftieth year. A similar trend of increase with age was observed in the case of passive carbon fraction which increased from 0.78% to 1.74% though slight variations were also observed. It was found to constitute 41% of the total soil carbon at age 5 to 66% at age 50 of the teak plantation. Such a specific trend was not observed in the case of active and slow carbon pools with age of the teak plantations.

Table 5.8. Soil carbon fractions (%) in teak plantation

Age	Carbon content in surface soil (%)			
	Total carbon	Active carbon	Slow carbon	Passive carbon
5	1.64 ±0.060	0.30 ±0.015	0.66 ±0.071	0.67 ±0.025
10	1.74 ±0.066	0.41 ±0.021	0.30 ±0.023	1.03 ±0.060
15	2.04 ±0.054	0.59 ±0.054	0.13 ±0.072	1.32 ±0.062
20	2.05 ±0.053	0.53 ±0.026	0.46 ±0.025	1.06 ±0.027
30	2.10 ±0.048	0.52 ±0.047	0.27 ±0.012	1.31 ±0.073
40	2.21 ±0.078	0.43 ±0.025	0.62 ±0.066	1.16 ±0.050
50	2.38 ±0.057	0.66 ±0.040	0.16 ±0.040	1.56 ±0.023

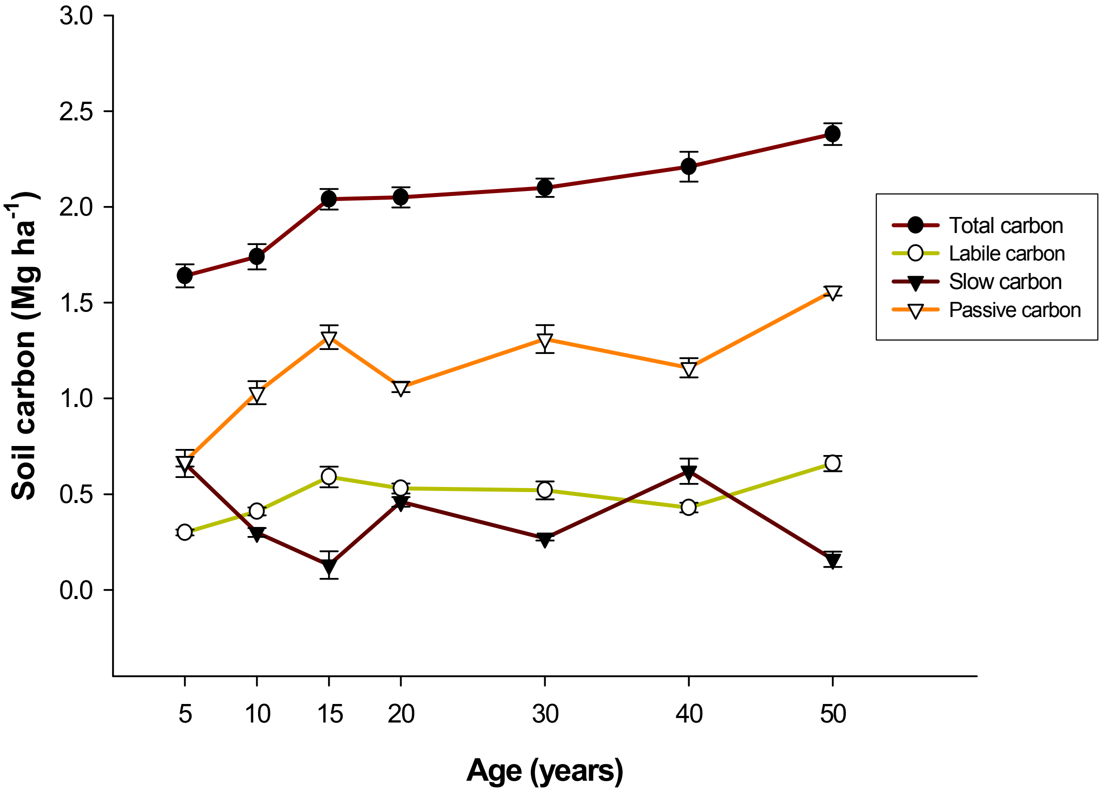

Figure 5.1. Variation in soil carbon pools with age of teak plantation

The active carbon pool determines almost all the ecosystem functions in soil and was found not to vary significantly between age 10 and final felling. No specific trend was observed in the case of slow carbon pools with age of the teak plantations. The slow carbon pool was found to decrease from 0.66% at 5 year to 0.13% at 15 year of age.

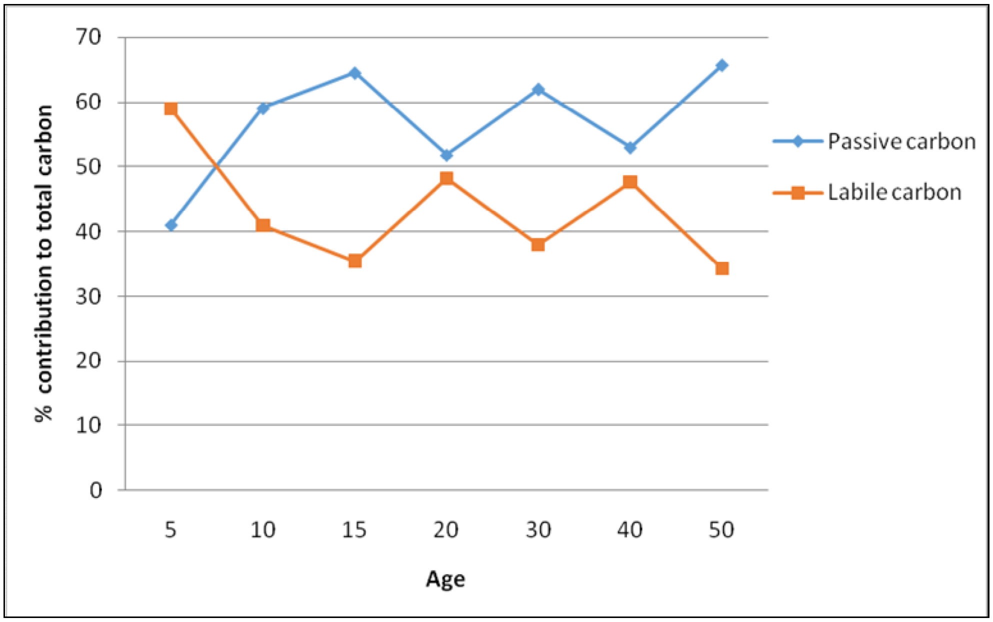

Figure 5.2. Interconversion carbon pools

The results indicate that slow and passive pools are in a state of dynamic equilibrium. For example, figure 5.1 depicts that an increase in passive pool inadvertently leads to a decrease in slow pool and vice versa. It also shows that this interconversion leads to release of some carbon fraction into the active pool, thus helping it to sustain the ecosystem functions. The study shows that there is an increased conversion of labile (active and slow) to the recalcitrant passive fractions with age of teak plantation (figure 5.2). It was found that the recalcitrant or passive carbon fraction increased from 41% to 66% during the growth of teak. The passive carbon pool was more than double the active and slow pools combined in 50 year old plantations.

5.4 Discussion

5.4.1 Soil carbon stocks

Carbon content in the soils of teak plantations at successive felling stages is depicted in the figure 5.3. It can be seen that there was a continuous replenishment of total soil carbon with increasing age though there were slight variations between different stages of growth. The total soil carbon content in 0-100 cm depth was found to increase from 134.40 Mg ha^{-1} to 140.96, 163.93, 166.93, 175.30, 185.13 and 197.48 Mg ha^{-1} in the succeeding stages up to 50th year. There was a cumulative increase of around 47% from the 5th year to the 50th year of teak growth. However, caution is warranted to consider factors other than age of teak that might have exerted its influence on the pattern of soil carbon stocks obtained as these plantations existed at different sites though care was given to minimize the variation between sites as far as possible.

The carbon inputs in the soil are more when the plantation gets older due to higher litter fall and rapid decomposition (Sreejesh *et al.*, 2011; Forrester *et al*, 2012). Gupta and Pandey (2008) from Uttarakhand reported that 15 year old teak plantation recorded 38.97 Mg ha^{-1} soil carbon with an annual addition of 1.10 Mg C ha^{-1}. Net increase of soil carbon with age was also observed in the forest plantations of Ethiopia (Dungait *et al.*, 2012). Studies by Bouwman and Leemans (1995) and Page-Dumroese *et al.*, 2006 have also reported that the age of plantations has an important role in the soil carbon stocks by way of litter inputs as well as the fine roots influencing the organic carbon in soil.

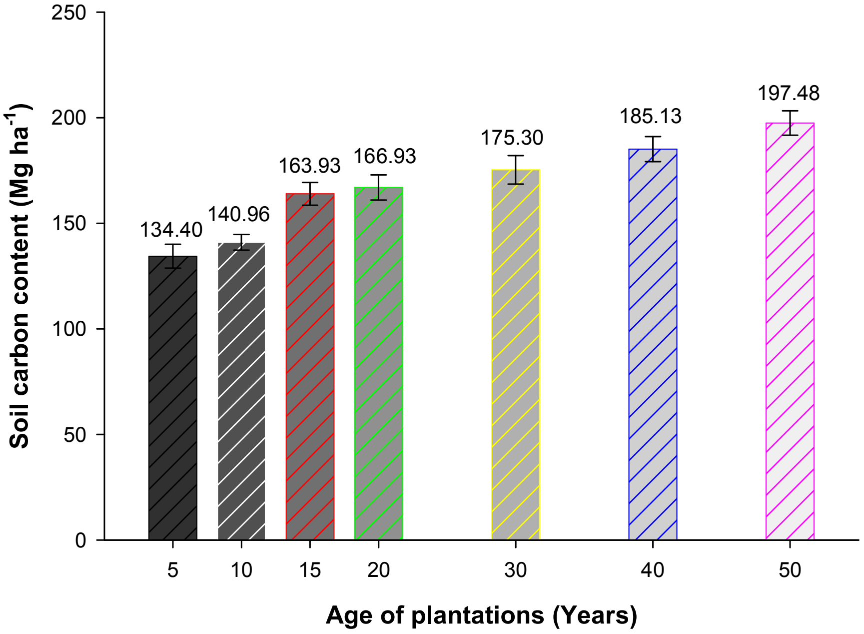

Figure 5.3. Soil carbon variation with age of teak plantation

The increase in soil carbon with age of teak plantation was more prominent in the 0-20 cm and 20 - 40 cm depths as shown in the figure 5.4. Within the depth range of 40 - 60 cm, substantial changes in soil carbon was observed only up to the 15th year wherein the values are seen to be stabilized indicating insignificant further carbon additions or retentions in this depth with age. A similar stabilization point for the 60-80 cm depth was observed in the 20th year. There was a gradual but steady increase in organic carbon in the lowest soil layer of 80-100 cm considered in the study.

There was no appreciable change in total carbon from 5th to 10th year in either the surface (0- 20 cm) or subsurface layers (below 20 cm). The first mechanical thinning in the 5th year, a recommended silvicultural practice in the teak plantations, removes half the trees resulting in subsequent lesser litter fall in the coming years. Opening the area by mechanical thinning helps in decreasing competition for light, water and nutrients between the teak plants and enables the tree to grow faster in the succeeding years thereby contributing greater quantities of organic matter to the soil from above ground and below ground portions of the tree. This increased carbon additions exerts its impact on the total soil carbon with age of plantation especially in the surface (0-20 cm) and the immediate 20-40 cm layer.

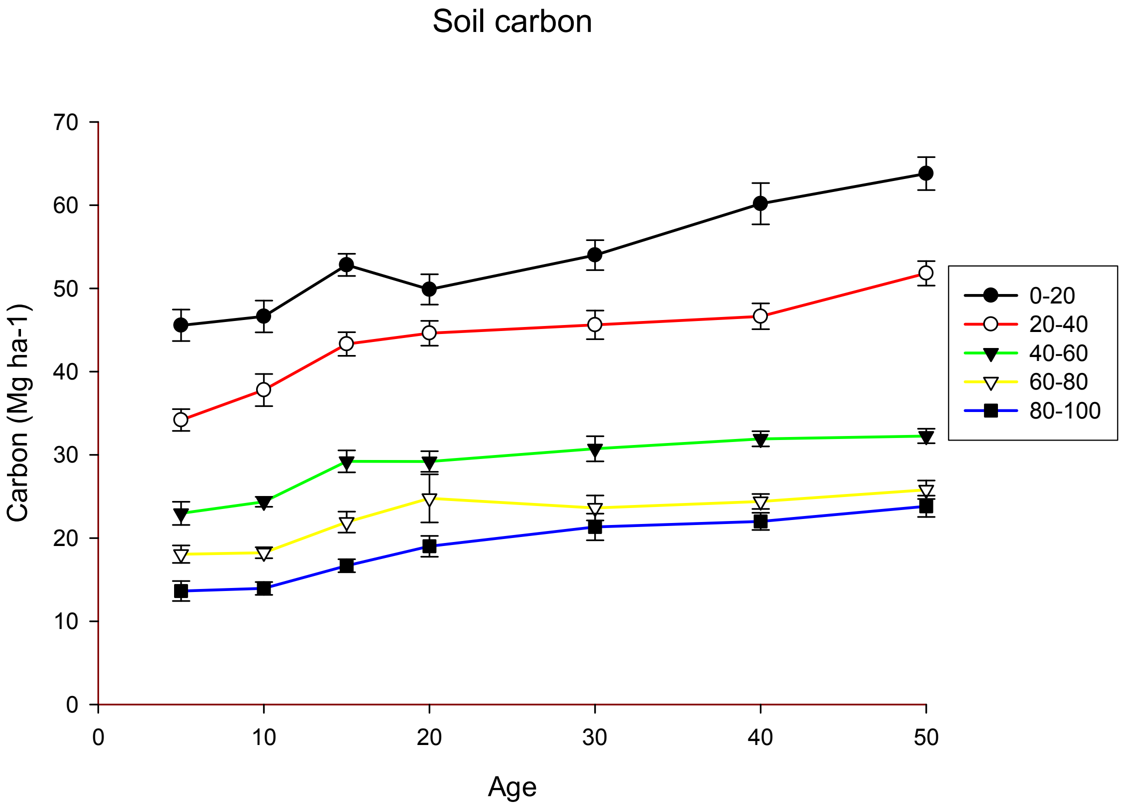

Figure 5.4. Depth wise distribution of soil carbon with age of teak plantation

The carbon content of soil decreased drastically with depth (figure 5.5). This is because additions of organic matter from various sources occur at or above the surface soil which on decomposition moves down the profile enriching the total soil organic carbon deposits at different depths (Lal, 2005a; Manlay *et al.*, 2007). The pattern of decrease of soil carbon with depth followed almost a similar pattern from 5 year to 50 year old plantation.

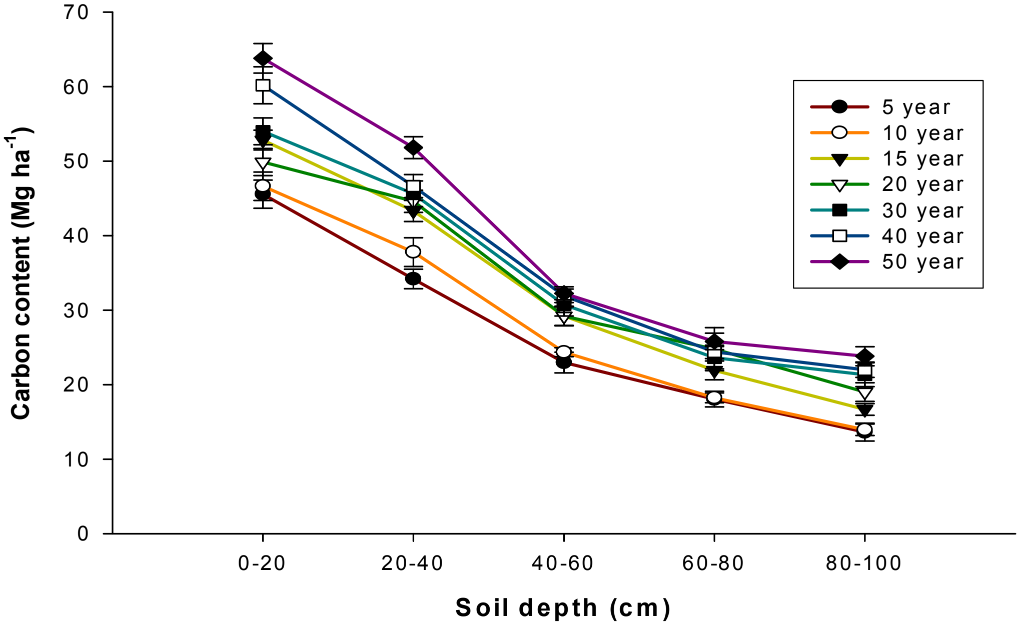

Figure 5.5. Pattern of soil carbon decrease with depth

Geetha (2005a) reported soil carbon storage of 108 to 124 Mg ha^{-1} in one metre top soil of 30 year old teak plantation, the contribution by 0-15 cm top soil being 32-38 Mg C ha^{-1}. Tangsinmankong *et al.* (2007) reported wide variation of 78.8 to 157 Mg C ha^{-1} in the 1m soil layer of teak plantation; the carbon storage in the 0-15 cm layer varied from 26.7 to 37.2 Mg C ha^{-1} in Thailand. Adalarasan *et al.* (2007) reported 5.52 Mg C ha^{-1} in the above ground biomass of 12 year teak plantation with a soil organic carbon of 6.71 Mg C ha^{-1} giving a ratio of 1.22 between SOC and biomass carbon. Post *et al.* (1990) had reported a higher ratio of 2.5 to 3 between SOC and biomass carbon.

5.4.2 Soil carbon pools

The passive carbon in soil represents nonreactive polymers or those held up strongly with in the lattice structure of clay minerals, both silicates and amorphous types. Several studies have indicated that organic matter protection against decomposition can occur in soil by mechanisms like chemical and physical stabilization and biochemical recalcitrance (Christensen, 1987; Stevenson, 1994). Chemical stabilization of organic matter is the result of chemical or physicochemical binding between organic matter and soil minerals (Feller and Beare, 1997;Hassink, 1997). However, the study area with lateritic soils rich in low activity clays are expected to provide only a minimum of this type of chemical protection. Hence the stabilization of carbon in these soils will be mainly due to physical stabilization by soil aggregates or biochemical recalcitrance by increased polymerization (Jastrow, 1996; Six *et al.,* 2000a). Aggregates physically protect SOM by forming physical barriers between microbes and enzymes and their substrates (Elliott and Coleman, 1988). Teak during the initial period undergoes intensive thinning which leads to high disturbances. With age, the impact of initial thinning disturbances gets reduced and provides sufficient time for the soil particles to aggregate and trap the carbon within them. Further, being in the humid tropics with consistently high temperature and rainfall the organic matter gets highly polymerized and thereby less reactive. The litter of older teak trees has high quantities of non reactive highly polymerized biochemical constituents like lignins, humin, etc. These are biologically less decomposable and hence the passive carbon pool enlarges with age of teak plantation. The high litter fall of teak plantation with age though enriches the soil carbon in surface layers, its biochemical stability leads to increase in recalcitrant carbon concentration (passive pool) over time (Six *et al.*, 2002).

5.5 Summary

The content of carbon in the soil was more in the surface as compared to the subsurface horizons; a gradual decrease occurred with depth up to 100 cm. It was observed that 134.40 ton C ha^{-1} was sequestered in the 5 year old plantation. The soil carbon was found to increase slowly but consistently with the age of the plantations, the 50th year plantation sequestering 197.48 ton per hectare of carbon in 0-100 cm of soil.

The fractions of soil carbon in the surface soil were found to be distributed between the active fraction, slow fraction and the passive carbon fraction. Passive carbon pool was found to increase gradually from 0.67% in the 5th year to 1.56% in the 50th year. The active carbon fractions increased from 0.30% at five year to 0.66% in 50th year plantation. The slow carbon fraction was highly variable with values ranging from 0.16% to 0.66% in different plantations irrespective of age of the plantation. There is an increased conversion of labile carbon pools to recalcitrant pools with age of teak plantation.

Chapter 6

Nondestructive Predictors of Carbon Storage by Teak

6. Nondestructive Predictors of Carbon Storage by Teak

6.1 Introduction

Biomass is an essential aspect of studies on carbon cycle (Cairns *et al.*, 2003). There are two methods to calculate forest biomass, one is direct method and the other is indirect method (Salazar-Iglesias *et al.*, 2010). Direct methods, also known as destructive methods, involve felling of trees to estimate biomass. Indirect methods of estimation of stand biomass are based on allometric equations using measurable parameters. Biomass and carbon prediction equations often make use of reliable relationships between easily measurable attributes of trees in a given location because individual estimates are impractical. The use of circumference or girth at breast height alone (expressing the basal area) for above-ground biomass estimation is common to many studies. Diameter at breast height (dbh) is one of the universally used predictors, because it shows a high correlation with all tree biomass components and it is easy to obtain accurate estimates (Razakamanarivo *et al.*, 2012; Antonio *et al.,* 2007).

Allometry relates non-easy to measure tree characteristics to easily collected data on some characteristic such as height, dbh or age. Since tree growth varies considerably with site, climate etc., allometric equations have to be carefully selected using regression techniques so that reasonable estimates are obtained (Henry *et al.*, 2013). Such equations employ tree diameter and/or height to arrive at total tree biomass from which carbon storage is calculated. Accuracy of 95% is often achieved in comparable conditions (Montagnini, *et al.*, 1995, Fang *et al.*, 2007; Correia *et al.*, 2010). Allometric equations relating biomass of tropical forest with easily measurable tree characteristics at predetermined age was attempted by destructive sampling at actual harvesting by several workers (Negi *et al.,* 1990; Feldpausch *et al.*, 2011; Chaturvedi *et al.,* 2012; Lima *et al.*, 2012; Chaturvedi and Raghubanshi, 2013; Durkaya *et al.,* 2013; Jansons *et al.,* 2013; Jain and Ansari, 2013). Biomass has been found to have strong relation with basal area (Rai, 1981; Rai and Proctor, 1986; Brunig, 1983; Murali and Bhat, 2005) and height (O'Neill and De Angelis, 1988) while Cannell (1984) reported strong relation with wood density.

Above ground biomass has been shown to be highly correlated with tree diameter and hence allometric equations with only diameter as input has been accepted as a good estimator of above ground biomass (Brown and Lugo, 1992, Chakrabarti and Gaharwar, 1995; Brown and Schroeder 1999; Nelson *et al.,* 1999; Clark *et al.*, 2001; Djomoa *et al.*, 2011). Such predictions may not be accurate in the case of individual trees; they work well when several trees are considered together and the results aggregated.

Biomass varies due to several factors including climate, topography, soil fertility and moisture, wood density and site disturbances (Sicard *et al.,* 2006; Fearnside, 1997; Luizao *et al.,* 2004; Slik *et al.*, 2008, Henry *et al.*, 2010). These variables are considered while developing allometric equations for estimation of above ground biomass in tropical regions (Chave *et al.,* 2005; Alvarez *et al.,* 2012; Vieilledent *et al.*, 2012).

New prediction equations are needed wherever appropriate equations are not available. Generic model encompassing dbh, height and wood specific gravity with sufficient calibration is advised for the tropical forest systems by Sandeep *et al.* (2015). This will necessitate destructive sampling and biomass estimation of few trees and relating the volume or biomass to nondestructive measures of diameter and/ or height of trees through regression analysis (Jayaraman, 1999).

The least square regression is a common approach to develop biomass models (Cunia and Briggs, 1985; Keith *et al.,* 2000; Zianis *et al.,* 2005). The dbh is commonly used as a single input variable to biomass estimation (Brown *et al.,* 1989; Zianis *et al.,* 2005*).* Addition of other input variables including height (Harding and Grigal, 1985; Ter-Mikaelian and Korzukhin, 1997) was also used for obtaining good result. In some studies, a combined variable of dbh and height (Spurr's combined variable) is often used for getting better prediction results (Picard *et al.*, 2012). Linear least square regression assumes that the relationship between two variables is linear. A nonlinear relationship can be straightened by transforming one or both of the variables (Jayaraman, 1999; Picard *et al.,* 2012).

Transformations of data mainly by logarithmic transformations have been recommended by many forest scientists while estimating growth parameters (Baskerville, 1972; Parde, 1980; Liski *et al.*, 1998; Snorrason and Einarsson 2006; Bjarnadottir *et al.*, 2007; Johansson, 1999, Deans *et al.*, 1996 and Sabatia *et al.*, 2008). Logarithmic transformation of simple linear model has been found to improve prediction of biomass in many species (Kushalapa, 1993; Grewal, 1995 and Williams *et al.*, 2005). The basic assumption is that allometric regression can estimate the relationship between any two characteristics of a tree (Vidyasagaran and Paramathma, 2014).

Allometric models are selected based on the goodness of fit indicated by R^2, mean of residuals indicating the magnitude of associated errors and root mean square error or standard error of the fitted regression. However, the model is analysed based on the Furnival index (Furnival, 1961) if it has different transformed response variable (Vanclay, 1994). The index adjusts the standard error of the regression to facilitate comparison. Furnival index is obtained by multiplying square root of mean square errors with inverse of geometric mean (Jayaraman, 1999). Allometric models with maximum coefficient of determination and smallest Furnival index is selected to give the best fit.

6.2 Methodology

Biomass equation in several areas of forest research such as in silviculture, ecology or wood science necessitates determination of biomass of trees. Since the measurement of biomass is destructive, one may resort to pre-established biomass/carbon prediction equations to obtain an estimate of these characteristics. These equations are found to vary from species to species and even for a given species. Whenever, an appropriate equation is not available, a prediction equation will have to be established new. This will involve determination of actual biomass/carbon of a sample set of trees and relating them to nondestructive measures like diameter at breast height and height of trees through regression analysis.

Destructive sampling was employed for generating data on various parameters as mentioned in earlier chapters. These data collected from sample trees on their biomass and carbon content along with the dbh and height were utilized to develop prediction equations through regression techniques. The various allometric models used in the study are listed below.

$$Y = a + b\,D \quad \text{(I)}$$

$$Y = a + b\,D + c\,D^2 \quad \text{(II)}$$

$$\ln Y = a + b\,D \quad \text{(III)}$$

$$\ln Y = a + b \ln D \quad \text{(IV)}$$

$$\sqrt{Y} = a + b\,D \quad \text{(V)}$$

$$Y = a + b\,D^2H \quad \text{(VI)}$$

$$\ln Y = a + b\, D^2H \text{……………………(VII)}$$

$$\sqrt{Y} = a + b\, D^2H \text{……………………(VIII)}$$

Y= Carbon content (kg), D = diameter at breast height (cm), H = Height of the tree (m), a, b and c = regression coefficients

The model I is the simple linear regression while the model II is quadratic or parabolic in nature. The model III is the power model with logarithmic transformation in the dependent variable and the model IV is exponential family with logarithmic transformation in both the response and explanatory variable. In model V square root transformation is applied in the dependent variable. In Models VI, VII and VIII, a combined form of dbh and height (Spurr's combined variable) was used as the explanatory variable with various transformations in both dependent and independent variables.

Following transformation, the best model was selected based on the goodness of fit as indicated by R^2 (coefficient of determination), mean of the residuals (magnitude of errors associated with regressions) and root mean square error or standard error of fitted regression. The residual analyses were used to determine the lack of fit and biasness (West, 1980; Wan Razali, 1988). However, this method of selection seemed acceptable for simple models involving one or two functions (Alder, 1995) and having same response or dependent variable (equations I and II). Thus, the index of fit is the standard error of the regression. In contrast, transformed models (equations III, IV, V, VI, VII and VIII) were analysed using the Furnival index (Furnival 1961) as these models had different transformed response variables. The index adjusts the standard error of the regression in order to facilitate comparison.

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

Where MSE is the mean sum of squares due to error, y^{-1} is the reciprocal of the derivative of transformed variable

The Furnival index (FI) was calculated by multiplying the standard error of the fitted regression with the geometric mean and the reciprocal of the derivative of transformed variable with respect to the untransformed variable (Zuhaidi, 2013).

6.3 Results

Allometric equations were developed for bole, bark, branch, root, above ground and total carbon content through several forms of dependent and independent variables. Results showed good relationship of carbon content with dbh and height. The R^2 values of the developed prediction models for bole, bark, branch, root, above ground and total carbon content were more than 0.80 and at the same time, F-test showed that the performance of the equations was significant.

6.3.1 Nondestructive predictors of carbon storage by 5 year teak

The prediction models for bole carbon content (table 6.1) showed that all models performed reasonably well with sufficiently high coefficients of determination. Even though the R^2 value was maximum in the model-IV (0.868) the Furnival index of this prediction model was comparatively high (0.810) and hence it was not selected as the best model. The exponential model and quadratic model also had high R^2 values (0.836 & 0.857); however, the quadratic model had a lower FI value (0.779) also. Therefore the model-II was considered as the best fit regression model for predicting the bole carbon content in five year old teak tree.

In the case of bark compartment, the quadratic model and the exponential model using the functions of dbh as explanatory variables had the maximum R^2 values (0.912 & 0.917). While comparing the Furnival index values it was found that the quadratic model had the lowest FI value (0.375) and hence this model was the best one for the prediction of bark carbon at this age.

Table 6.1. Regression models for predicting carbon sequestered in 5 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.836	0.834	57.253	12.251	0.940		0.834
	II	$Y = a + b D + c D^2$	0.857	0.779	34.048	8.676	2.138	-0.091	0.779
	III	$\ln Y = a + b D$	0.805	0.052	46.308	2.560	0.053		0.992
	IV	$\ln Y = a + b \ln D$	0.868	0.043	73.149	2.301	0.331		0.810
	V	$\sqrt{Y} = a + b D$	0.821	0.104	51.585	3.555	0.111		0.893
	VI	$Y = a + b D^2H$	0.699	1.131	26.579	16.139	0.006		1.131
	VII	$\ln Y = a + b D^2H$	0.641	0.017	20.613	2.782	0.000		1.281
	VIII	$\sqrt{Y} = a + b D^2H$	0.670	0.141	23.363	4.018	0.001		1.204
Bark	I	$Y = a + b D$	0.883	0.063	68.778	2.540	0.114		0.522
	II	$Y = a + b D + c D^2$	0.912	0.055	47.563	1.928	0.289	-0.012	0.375
	III	$\ln Y = a + b D$	0.872	0.020	62.155	0.963	0.034		0.532
	IV	$\ln Y = a + b \ln D$	0.917	0.016	99.898	0.736	0.243		0.543
	V	$\sqrt{Y} = a + b D$	0.877	0.018	65.435	1.607	0.031		0.532
	VI	$Y = a + b D^2H$	0.754	0.091	28.580	3.094	0.001		0.487
	VII	$\ln Y = a + b D^2H$	0.733	0.029	25.754	1.131	0.000		0.488
	VIII	$\sqrt{Y} = a + b D^2H$	0.744	0.026	27.133	1.760	0.000		0.492
Branch	I	$Y = a + b D$	0.044	0.456	1.511	3.048	0.083		0.456
	II	$Y = a + b D + c D^2$	0.116	0.439	1.723	1.322	0.662	-0.044	0.438
	III	$\ln Y = a + b D$	0.061	0.127	1.710	1.110	0.025		0.449
	IV	$\ln Y = a + b \ln D$	0.123	0.123	2.544	0.949	0.177		0.435
	V	$\sqrt{Y} = a + b D$	0.052	0.120	1.609	1.744	0.023		0.446
	VI	$Y = a + b D^2H$	-0.058	0.480	0.395	3.471	0.000		0.480
	VII	$\ln Y = a + b D^2H$	-0.051	0.135	0.468	1.234	9.376E		0.476
	VIII	$\sqrt{Y} = a + b D^2H$	-0.055	0.127	0.431	1.858	8.47E		0.477
Above ground	I	$Y = a + b D$	0.798	1.215	44.465	17.276	1.206		1.215
	II	$Y = a + b D + c D^2$	0.851	1.043	32.465	10.758	3.390	-0.167	1.043
	III	$\ln Y = a + b D$	0.756	0.057	35.053	2.892	0.050		1.358
	IV	$\ln Y = a + b \ln D$	0.842	0.046	59.570	2.637	0.319		1.109
	V	$\sqrt{Y} = a + b D$	0.777	0.131	39.404	4.206	0.123		1.299
	VI	$Y = a + b D^2H$	0.606	1.696	17.938	22.372	0.007		1.696
	VII	$\ln Y = a + b D^2H$	0.547	0.078	14.300	3.106	0.000		1.921
	VIII	$\sqrt{Y} = a + b D^2H$	0.577	0.181	15.987	4.728	0.001		1.809
Below ground	I	$Y = a + b D$	0.866	0.068	59.098	2.680	0.113		0.520
	II	$Y = a + b D + c D^2$	0.850	0.071	26.434	2.836	0.069	0.003	0.367
	III	$\ln Y = a + b D$	0.867	0.019	59.693	1.018	0.032		0.519
	IV	$\ln Y = a + b \ln D$	0.833	0.021	45.914	0.822	0.219		0.507
	V	$\sqrt{Y} = a + b D$	0.867	0.018	59.421	1.651	0.030		0.516
	VI	$Y = a + b D^2H$	0.910	0.055	91.449	3.205	0.001		0.530
	VII	$\ln Y = a + b D^2H$	0.902	0.016	83.959	1.168	0.000		0.531
	VIII	$\sqrt{Y} = a + b D^2H$	0.906	0.015	87.642	1.792	0.000		0.529
Total	I	$Y = a + b D$	0.798	1.292	44.333	20.093	1.281		1.292
	II	$Y = a + b D + c D^2$	0.850	1.112	32.150	13.204	3.588	-0.176	1.112
	III	$\ln Y = a + b D$	0.758	0.053	35.516	3.037	0.047		1.538
	IV	$\ln Y = a + b \ln D$	0.843	0.043	60.018	2.800	0.298		1.256
	V	$\sqrt{Y} = a + b D$	0.778	0.131	39.616	4.528	0.122		1.382
	VI	$Y = a + b D^2H$	0.597	1.822	17.319	25.520	0.008		1.822
	VII	$\ln Y = a + b D^2H$	0.544	0.073	14.103	3.238	0.000		1.986
	VIII	$\sqrt{Y} = a + b D^2H$	0.570	0.182	15.607	5.050	0.001		1.925

The statistics used to construct the branch carbon prediction equations revealed that all the equations were having very low R^2 values and the f-statistic used for testing the validity of the model showed that the models were non-significant and not able to predict the branch carbon content from its height and dbh or its various functions. The computation of Furnival index was also irrelevant in this situation.

Among the models that were tried for predicting the above ground carbon content, the highest R^2 value was recorded in exponential family model IV (0.88) but the FI value was comparatively higher (3.795) and hence it could not be selected as the best prediction model. The quadratic model using various functions of dbh as independent variable gave a minimum FI value (2.673) and a larger value for determination coefficient (0.862) and it was listed as the best fit regression equation for predicting above ground carbon content in 5 year teak tree.

The best model for below ground carbon prediction in five year old teak was the quadratic model with higher coefficient of determination (0.850) and lower Furnival index value (0.367). The prediction models VI, VII, VIII had maximum R^2 values but they had a higher Furnival index also hence rendering them poor models.

It was observed that in the case of total carbon content prediction, first five regression models tried were having higher values of coefficient of determination and minimum value of Furnival index. However the model II having the lowest Furnival index (1.112) was taken as the most suitable prediction model for total carbon content in this age.

6.3.2 Nondestructive predictors of carbon storage by 10 year teak

The coefficient of determination values in the various regression models that were tried had a maximum of 0.913 in the model VII using Spurr's combined variable (D^2H) as the independent variable for bole carbon prediction (table 6.2). This model also had a low value of Furnival index (1.259) and so it was considered the best prediction model. Other models also had higher R^2 values but the comparatively higher FI values did not permit their consideration as good models.

Among the eight models tried, the models having Spurr's combined variable as the independent variable showed maximum values for determination coefficient in the case of bark. The model VI had the least value of Furnival index (0.297) and higher value for determination coefficient (0.818) and hence it was selected as the most suitable prediction model for bark carbon content at this age group. In other models, even though they were having higher values of determination coefficient, the residuals departed from the linearity in these models which resulted in a comparatively higher Furnival index values. Therefore they could not be considered as good prediction models.

The statistics used to construct the branch carbon prediction equations revealed that all the equations were having very low R^2 values and the f-statistic used for testing the validity of the model showed that the models were non-significant and were not able to predict the branch carbon content from its height and dbh or its various functions. The computation of Furnival index was also not relevant in this situation.

Table 6.2. Regression models for predicting carbon sequestered in 10 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.876	1.742	79.061	8.079	2.165		1.742
	II	$Y = a + b D + c D^2$	0.865	1.823	36.123	17.143	1.001	0.039	1.823
	III	$\ln Y = a + b D$	0.865	0.044	71.325	2.920	0.052		1.780
	IV	$\ln Y = a + b \ln D$	0.860	0.045	68.319	1.558	0.796		1.780
	V	$\sqrt{Y} = a + b D$	0.871	0.137	75.515	3.851	0.169		1.739
	VI	$Y = a + b D^2H$	0.922	1.381	131.743	28.751	0.006		1.381
	VII	$\ln Y = a + b D^2H$	0.913	0.035	116.896	3.413	0.000		1.259
	VIII	$\sqrt{Y} = a + b D^2H$	0.919	0.109	125.425	5.445	0.000		1.382
Bark	I	$Y = a + b D$	0.789	0.320	42.098	1.344	0.294		0.319
	II	$Y = a + b D + c D^2$	0.767	0.336	19.079	2.428	0.151	0.005	0.336
	III	$\ln Y = a + b D$	0.761	0.059	35.987	0.990	0.050		0.306
	IV	$\ln Y = a + b \ln D$	0.755	0.060	34.959	-0.316	0.763		0.354
	V	$\sqrt{Y} = a + b D$	0.776	0.069	39.022	1.484	0.061		0.334
	VI	$Y = a + b D^2H$	0.818	0.297	50.579	4.125	0.001		0.297
	VII	$\ln Y = a + b D^2H$	0.787	0.056	41.762	1.465	0.000		0.306
	VIII	$\sqrt{Y} = a + b D^2H$	0.804	0.064	46.099	2.058	0.000		0.299
Branch	I	$Y = a + b D$	0.195	3.419	3.668	-3.309	0.928		3.418
	II	$Y = a + b D + c D^2$	0.169	3.474	2.119	-44.135	6.310	-0.174	3.474
	III	$\ln Y = a + b D$	0.257	0.339	4.795	0.722	0.105		3.236
	IV	$\ln Y = a + b \ln D$	0.286	0.332	5.413	-2.202	1.670		3.165
	V	$\sqrt{Y} = a + b D$	0.229	0.530	4.264	0.885	0.155		3.269
	VI	$Y = a + b D^2H$	0.030	3.752	1.344	7.108	0.002		3.752
	VII	$\ln Y = a + b D^2H$	0.082	0.377	1.986	1.877	0.000		3.596
	VIII	$\sqrt{Y} = a + b D^2H$	0.057	0.586	1.666	2.604	0.000		3.619
Above ground	I	$Y = a + b D$	0.798	1.215	44.465	17.276	1.206		1.215
	II	$Y = a + b D + c D^2$	0.851	1.043	32.465	10.758	3.390	-0.167	1.043
	III	$\ln Y = a + b D$	0.756	0.057	35.053	2.892	0.050		1.358
	IV	$\ln Y = a + b \ln D$	0.842	0.046	59.570	2.637	0.319		1.109
	V	$\sqrt{Y} = a + b D$	0.777	0.131	39.404	4.206	0.123		1.299
	VI	$Y = a + b D^2H$	0.606	1.696	17.938	22.372	0.007		1.696
	VII	$\ln Y = a + b D^2H$	0.547	0.078	14.300	3.106	0.000		1.921
	VIII	$\sqrt{Y} = a + b D^2H$	0.577	0.181	15.987	4.728	0.001		1.809
Below ground	I	$Y = a + b D$	0.866	0.068	59.098	2.680	0.113		0.520
	II	$Y = a + b D + c D^2$	0.850	0.071	26.434	2.836	0.069	0.003	0.367
	III	$\ln Y = a + b D$	0.867	0.019	59.693	1.018	0.032		0.519
	IV	$\ln Y = a + b \ln D$	0.833	0.021	45.914	0.822	0.219		0.507
	V	$\sqrt{Y} = a + b D$	0.867	0.018	59.421	1.651	0.030		0.516
	VI	$Y = a + b D^2H$	0.910	0.055	91.449	3.205	0.001		0.530
	VII	$\ln Y = a + b D^2H$	0.902	0.016	83.959	1.168	0.000		0.531
	VIII	$\sqrt{Y} = a + b D^2H$	0.906	0.015	87.642	1.792	0.000		0.529
Total	I	$Y = a + b D$	0.798	1.292	44.333	20.093	1.281		1.292
	II	$Y = a + b D + c D^2$	0.850	1.112	32.150	13.204	3.588	-0.176	1.112
	III	$\ln Y = a + b D$	0.758	0.053	35.516	3.037	0.047		1.538
	IV	$\ln Y = a + b \ln D$	0.843	0.043	60.018	2.800	0.298		1.256
	V	$\sqrt{Y} = a + b D$	0.778	0.131	39.616	4.528	0.122		1.382
	VI	$Y = a + b D^2H$	0.597	1.822	17.319	25.520	0.008		1.822
	VII	$\ln Y = a + b D^2H$	0.544	0.073	14.103	3.238	0.000		1.986
	VIII	$\sqrt{Y} = a + b D^2H$	0.570	0.182	15.607	5.050	0.001		1.925

In the case of above ground carbon prediction model, it was found that the models VI, VII and VIII using functions of height as independent variable gave minimum R^2 values and higher Furnival index. The other five models resulted in higher R^2 values and out of these, the exponential model with logarithmic transformation of carbon content as dependent variable and logarithmic transformation of dbh as independent variable had the least Furnival index. Therefore the model VI with R^2 value of 0.827 and FI value of 3.035 was preferred as the most suitable model for above ground carbon prediction at this age.

In the case of below ground compartment, the R^2 values were maximum in the models using Spurr's combined variable as explanatory variable such as model VI, VII and VIII (0.971, 0.979 & 0.975) but the FI values were slightly higher compared to other regression models. The quadratic model II had the lowest FI value of 2.141 and R^2 value of 0.835 and hence was taken as the best prediction model for the below ground carbon content.

The maximum values for determination coefficient were recorded in first five models in the case of the total carbon prediction equations. All the other three models had higher FI value and lower R^2 value and were not considered as good models. Among the first five models, the model I with low value for the Furnival index (3.242) and higher value of R^2 (0.866) made it the best fit prediction equation for total carbon content.

6.3.3 Nondestructive predictors of carbon storage by 15 year teak

The determination coefficient and the Furnival index used to compare the wood carbon prediction equations revealed that all the models produced reasonable performance with sufficiently high R^2 values and small FI values in the case of 15 year old teak (table 6.3). The least value for FI (1.276) was recorded in the model VI of linear family and therefore it was selected as the most precise regression model for predicting the bole carbon content at this age.

The regression equations constructed for predicting the bark carbon showed that model VI had maximum value (0.900) for R^2. It was found that the model VI had lowest FI value (0.387) also. Therefore the model VI was taken as the best fit regression model for predicting the bark carbon content.

For estimating the branch carbon content, various models were constructed but the coefficient of determination were all very low; that is between 0.339 to 0.417 only. When tested the model validation, the f value was also very low and it was not significant. None of the prediction models were found suitable to predict the branch carbon content.

The results of analysis showed that all the models significantly explained the variation in the above ground carbon content and correlated well with the dbh and height in the fifteen year old teak tree. However the power model with dbh as explanatory variable predicted better as it had the lowest FI value (2.161) and higher R^2 value (0.963), hence model III was considered as the best.

All the models tried for predicting the below ground carbon content performed well as regards the R^2 value; the models could predict the root carbon variability with more than 90 % of accuracy. Out of these models the FI value was slightly lower (0.679) in the quadratic model and hence was selected as the best fit prediction model for below ground carbon content.

Table 6.3. Regression models for predicting carbon sequestered in 15 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.948	2.397	203.327	0.282	2.979		2.397
	II	$Y = a + b D + c D^2$	0.978	1.557	248.331	49.668	-3.213	0.186	1.497
	III	$\ln Y = a + b D$	0.963	0.040	289.146	2.898	0.060		2.128
	IV	$\ln Y = a + b \ln D$	0.938	0.052	166.892	1.231	0.952		2.607
	V	$\sqrt{Y} = a + b D$	0.958	0.152	250.255	3.530	0.210		2.092
	VI	$Y = a + b D^2H$	0.985	1.276	743.342	29.471	0.006		1.276
	VII	$\ln Y = a + b D^2H$	0.979	0.030	512.432	3.485	0.000		1.505
	VIII	$\sqrt{Y} = a + b D^2H$	0.984	0.094	677.381	5.594	0.000		1.309
Bark	I	$Y = a + b D$	0.866	0.447	72.192	1.155	0.331		0.447
	II	$Y = a + b D + c D^2$	0.851	0.472	32.490	1.270	3.170	0.000	0.471
	III	$\ln Y = a + b D$	0.845	0.075	60.879	1.032	0.051		0.497
	IV	$\ln Y = a + b \ln D$	0.851	0.074	63.620	-0.431	0.828		0.454
	V	$\sqrt{Y} = a + b D$	0.857	0.091	66.868	1.493	0.065		0.453
	VI	$Y = a + b D^2H$	0.900	0.387	99.774	4.402	0.001		0.387
	VII	$\ln Y = a + b D^2H$	0.861	0.071	69.116	1.535	9.674E		0.454
	VIII	$\sqrt{Y} = a + b D^2H$	0.882	0.083	82.939	2.130	0.000		0.424
Branch	I	$Y = a + b D$	0.417	2.106	8.854	5.539	0.546		2.106
	II	$Y = a + b D + c D^2$	0.411	2.116	4.840	-11.141	2.637	-0.063	2.116
	III	$\ln Y = a + b D$	0.392	0.162	8.081	1.999	0.040		2.279
	IV	$\ln Y = a + b \ln D$	0.417	0.158	8.865	0.810	0.665		2.234
	V	$\sqrt{Y} = a + b D$	0.406	0.290	8.518	2.583	0.074		2.179
	VI	$Y = a + b D^2H$	0.371	2.187	7.489	11.107	0.001		2.187
	VII	$\ln Y = a + b D^2H$	0.339	0.169	6.625	2.410	7.112E		2.143
	VIII	$\sqrt{Y} = a + b D^2H$	0.356	0.301	7.090	3.336	0.000		2.268
Above ground	I	$Y = a + b D$	0.955	2.898	233.146	6.976	3.856		2.898
	II	$Y = a + b D + c D^2$	0.959	2.754	130.155	39.797	-0.258	0.124	2.754
	III	$\ln Y = a + b D$	0.963	0.037	289.226	3.341	0.054		2.161
	IV	$\ln Y = a + b \ln D$	0.951	0.042	214.921	1.800	0.877		3.056
	V	$\sqrt{Y} = a + b D$	0.960	0.161	266.356	4.594	0.229		2.666
	VI	$Y = a + b D^2H$	0.973	2.240	396.837	44.980	0.007		2.240
	VII	$\ln Y = a + b D^2H$	0.961	0.038	268.667	3.881	0.000		2.161
	VIII	$\sqrt{Y} = a + b D^2H$	0.968	0.144	333.061	6.854	0.000		2.396
Below ground	I	$Y = a + b D$	0.957	0.708	245.614	-0.502	0.968		0.709
	II	$Y = a + b D + c D^2$	0.960	0.679	134.640	7.214	0.000	0.029	0.679
	III	$\ln Y = a + b D$	0.943	0.053	183.546	1.676	0.063		0.813
	IV	$\ln Y = a + b \ln D$	0.933	0.058	154.917	-0.109	1.015		0.813
	V	$\sqrt{Y} = a + b D$	0.953	0.095	222.720	1.879	0.123		0.731
	VI	$Y = a + b D^2H$	0.945	0.799	191.153	9.121	0.002		0.799
	VII	$\ln Y = a + b D^2H$	0.907	0.068	108.216	2.307	0.000		1.050
	VIII	$\sqrt{Y} = a + b D^2H$	0.929	0.116	143.861	3.108	0.000		0.912
Total	I	$Y = a + b D$	0.967	3.071	324.854	6.475	4.824		3.071
	II	$Y = a + b D + c D^2$	0.973	2.795	197.646	47.011	-0.258	0.153	2.795
	III	$\ln Y = a + b D$	0.977	0.030	468.914	3.515	0.056		2.631
	IV	$\ln Y = a + b \ln D$	0.965	0.037	304.609	1.932	0.900		2.631
	V	$\sqrt{Y} = a + b D$	0.973	0.148	401.454	4.961	0.259		2.706
	VI	$Y = a + b D^2H$	0.979	2.427	526.012	54.101	0.009		2.427
	VII	$\ln Y = a + b D^2H$	0.968	0.035	330.061	4.070	0.000		2.631
	VIII	$\sqrt{Y} = a + b D^2H$	0.975	0.144	424.912	7.527	0.000		2.644

All the models attempted gave high values for coefficient of determination (R^2 > 0.965) when the total carbon sequestration was taken into account. In the model VI, the calculated value of Furnival index was 2.427 which was the lowest value among all the seven models and therefore it was preferred as the best fit model. This model explained the variation of total carbon content of teak with a coefficient of determination of 97.9 percent.

6.3.4 Nondestructive predictors of carbon storage by 20 year teak

As the model is selected by comparing the goodness of fit as measured by maximum value of R^2 and lowest value of the Furnival index, model-VI was the preferred model for predicting bole carbon in twenty year old teak tree (table 6.4). The coefficient of determination for all models had a value more than 0.91.

In the case of bark compartment all the models gave higher values for determination coefficient (R^2 > 0.925). While comparing the Furnival index values it was found that the model V had comparatively the lowest FI value (0.387) and hence this model could be the best one for the prediction of bark carbon at this age.

The branch carbon content prediction models yielded lower values for the coefficient of determination but the models were statistically valid as the f value was significant in all models. Among the various models, the equation using exponential family showed a lowest value for Furnival index (3.194) and high R^2 value (0.686) and therefore this model IV was preferred as a comparatively better prediction model.

Table 6.4. Regression models for predicting carbon sequestered in 20 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.941	4.725	176.192	-18.652	4.189		4.725
	II	$Y = a + b D + c D^2$	0.944	4.609	93.339	20.849	0.117	0.100	4.609
	III	$\ln Y = a + b D$	0.944	0.071	187.645	2.843	0.065		4.285
	IV	$\ln Y = a + b \ln D$	0.942	0.072	179.439	0.358	1.271		4.285
	V	$\sqrt{Y} = a + b D$	0.947	0.275	198.319	2.818	0.258		4.264
	VI	$Y = a + b D^2H$	0.964	3.685	296.063	30.304	0.006		3.685
	VII	$\ln Y = a + b D^2H$	0.917	0.086	122.717	3.610	8.57E		5.070
	VIII	$\sqrt{Y} = a + b D^2H$	0.945	0.280	190.039	5.862	0.000		4.376
Bark	I	$Y = a + b D$	0.963	0.419	286.602	-1.501	0.474		0.418
	II	$Y = a + b D + c D^2$	0.965	0.407	152.329	2.064	0.106	0.009	0.407
	III	$\ln Y = a + b D$	0.964	0.052	292.281	0.849	0.060		0.410
	IV	$\ln Y = a + b \ln D$	0.960	0.055	267.005	-1.443	1.172		0.410
	V	$\sqrt{Y} = a + b D$	0.967	0.070	320.658	1.127	0.084		0.387
	VI	$Y = a + b D^2H$	0.967	0.396	321.978	4.067	0.001		0.396
	VII	$\ln Y = a + b D^2H$	0.925	0.075	136.958	1.559	7.871E		0.580
	VIII	$\sqrt{Y} = a + b D^2H$	0.949	0.087	205.726	2.116	0.000		0.458
Branch	I	$Y = a + b D$	0.680	3.503	24.421	-7.099	1.156		3.503
	II	$Y = a + b D + c D^2$	0.652	3.658	11.284	3.466	0.067	0.027	3.658
	III	$\ln Y = a + b D$	0.679	0.223	24.255	1.236	0.073		3.226
	IV	$\ln Y = a + b \ln D$	0.686	0.221	24.988	-1.611	1.452		3.194
	V	$\sqrt{Y} = a + b D$	0.690	0.426	25.533	1.059	0.144		3.232
	VI	$Y = a + b D^2H$	0.704	3.371	27.170	6.378	0.002		3.371
	VII	$\ln Y = a + b D^2H$	0.648	0.233	21.274	2.110	9.675E		3.353
	VIII	$\sqrt{Y} = a + b D^2H$	0.685	0.429	24.949	2.755	0.000		3.259
Above ground	I	$Y = a + b D$	0.926	7.409	138.252	-27.253	5.818		7.409
	II	$Y = a + b D + c D^2$	0.926	7.378	70.264	26.379	0.290	0.136	7.378
	III	$\ln Y = a + b D$	0.932	0.080	150.754	3.133	0.066		6.408
	IV	$\ln Y = a + b \ln D$	0.931	0.080	150.413	0.601	1.294		6.408
	V	$\sqrt{Y} = a + b D$	0.934	0.366	157.480	3.198	0.307		6.659
	VI	$Y = a + b D^2H$	0.959	6.161	204.387	40.748	0.008		6.161
	VII	$\ln Y = a + b D^2H$	0.901	0.096	101.365	3.913	8.7064E		7.848
	VIII	$\sqrt{Y} = a + b D^2H$	0.930	0.378	147.647	6.817	0.000		6.879
Below ground	I	$Y = a + b D$	0.932	1.544	151.471	-5.030	1.269		1.544
	II	$Y = a + b D + c D^2$	0.940	1.446	87.559	10.601	-0.342	0.040	1.446
	III	$\ln Y = a + b D$	0.933	0.075	154.603	1.730	0.062		1.472
	IV	$\ln Y = a + b \ln D$	0.926	0.079	139.088	-0.655	1.221		1.472
	V	$\sqrt{Y} = a + b D$	0.937	0.162	165.610	1.675	0.140		1.406
	VI	$Y = a + b D^2H$	0.958	1.213	251.630	9.786	0.002		1.213
	VII	$\ln Y = a + b D^2H$	0.910	0.087	111.786	2.467	8.27E		1.699
	VIII	$\sqrt{Y} = a + b D^2H$	0.939	0.161	169.348	3.317	0.000		1.406
Total	I	$Y = a + b D$	0.933	8.577	153.101	-32.283	7.087		8.577
	II	$Y = a + b D + c D^2$	0.935	8.413	80.256	36.980	-0.052	0.175	8.413
	III	$\ln Y = a + b D$	0.938	0.075	167.433	3.352	0.065		7.882
	IV	$\ln Y = a + b \ln D$	0.937	0.076	163.857	0.848	1.280		7.882
	V	$\sqrt{Y} = a + b D$	0.941	0.381	175.867	3.608	0.337		7.682
	VI	$Y = a + b D^2H$	0.956	6.916	240.822	50.534	0.010		6.916
	VII	$\ln Y = a + b D^2H$	0.908	0.091	110.133	4.125	8.624E		9.101
	VIII	$\sqrt{Y} = a + b D^2H$	0.938	0.391	166.093	7.581	0.000		7.891

The models tried for predicting the above ground carbon content had higher R^2 values in almost all the eight models but the FI value was the lowest in prediction model VI. So the model using Spurr's combined variable with FI value (6.161) and a larger value for determination coefficient (0.959) was listed as the best fit regression equation for predicting above ground carbon content in a 20 year old teak tree.

The best model for below ground carbon prediction in 20 year old teak was also the linear model with combined variable (model VI) which showed a higher value of coefficient of determination (0.958) and the lowest Furnival index value (1.213). All other prediction models had higher R^2 but they had also comparatively higher Furnival index and hence was not considered as best regression models.

It was observed that for the total carbon prediction in 20 year old teak, all the regression models tried were having higher values of coefficient of determination and minimum value for Furnival index. However, the model VI having the lowest Furnival index (6.916) and highest R^2 (0.956) was taken as the most suitable prediction model for total carbon content in this age group.

6.3.5 Nondestructive predictors of carbon storage by 30 year teak

All the models tried for predicting the bole carbon content in 30 year old teak were good performers while considering the coefficient of determination (table 6.5). All the models could predict the bole carbon variability with more than 80% accuracy. Out of these models the FI value was slightly lower (13.624) in the linear model with combined variable and hence model VI was selected as the best fit prediction model for bole carbon content.

Table 6.5. Regression models for predicting carbon sequestered in 30 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.868	15.706	73.208	-63.664	6.437		15.706
	II	$Y = a + b D + c D^2$	0.895	13.974	48.057	108.451	-6.882	0.245	13.974
	III	$\ln Y = a + b D$	0.836	0.167	56.879	2.995	0.060		35.106
	IV	$\ln Y = a + b \ln D$	0.816	0.177	49.898	-0.511	1.571		17.277
	V	$\sqrt{Y} = a + b D$	0.858	0.782	67.714	1.979	0.308		15.486
	VI	$Y = a + b D^2H$	0.901	13.624	100.591	39.969	0.006		13.624
	VII	$\ln Y = a + b D^2H$	0.841	0.164	59.324	3.975	5.194E		16.124
	VIII	$\sqrt{Y} = a + b D^2H$	0.879	0.724	80.542	6.960	0.000		14.355
Bark	I	$Y = a + b D$	0.838	1.519	57.946	-4.466	0.554		1.519
	II	$Y = a + b D + c D^2$	0.845	1.488	30.891	6.983	-0.332	0.016	1.488
	III	$\ln Y = a + b D$	0.784	0.181	40.971	0.785	0.056		1.720
	IV	$\ln Y = a + b \ln D$	0.774	0.186	38.577	-2.459	1.450		1.746
	V	$\sqrt{Y} = a + b D$	0.817	0.256	49.969	0.844	0.087		1.581
	VI	$Y = a + b D^2H$	0.861	1.408	69.025	4.477	0.000		1.409
	VII	$\ln Y = a + b D^2H$	0.782	0.182	40.344	1.689	4.754E		1.720
	VIII	$\sqrt{Y} = a + b D^2H$	0.827	0.249	53.572	2.251	7.481E		1.532
Branch	I	$Y = a + b D$	0.442	5.470	9.703	-3.836	0.816		5.470
	II	$Y = a + b D + c D^2$	0.383	5.752	4.411	4.132	0.200	0.011	5.752
	III	$\ln Y = a + b D$	0.490	0.274	11.573	1.624	0.045		4.509
	IV	$\ln Y = a + b \ln D$	0.494	0.273	11.755	-1.022	1.178		4.509
	V	$\sqrt{Y} = a + b D$	0.469	0.602	10.701	1.641	0.094		4.890
	VI	$Y = a + b D^2H$	0.403	5.656	8.432	9.740	0.001		5.656
	VII	$\ln Y = a + b D^2H$	0.435	0.289	9.476	2.372	3.648E		4.744
	VIII	$\sqrt{Y} = a + b D^2H$	0.422	0.628	9.039	3.216	7.756E		5.101
Above ground	I	$Y = a + b D$	0.872	18.680	76.131	-71.966	7.807		18.680
	II	$Y = a + b D + c D^2$	0.894	17.033	47.300	119.566	-7.014	0.272	17.033
	III	$\ln Y = a + b D$	0.840	0.159	58.570	3.292	0.058		19.704
	IV	$\ln Y = a + b \ln D$	0.825	0.166	52.797	-0.098	1.517		20.853
	V	$\sqrt{Y} = a + b D$	0.863	0.829	70.436	2.582	0.333		18.505
	VI	$Y = a + b D^2H$	0.894	17.051	93.377	54.186	0.007		17.051
	VII	$\ln Y = a + b D^2H$	0.835	0.161	56.755	4.240	4.977E		20.094
	VIII	$\sqrt{Y} = a + b D^2H$	0.872	0.801	76.190	7.988	0.000		17.889
Below ground	I	$Y = a + b D$	0.845	5.435	60.833	-22.023	2.031		5.435
	II	$Y = a + b D + c D^2$	0.889	4.599	44.962	44.208	-3.095	0.094	4.599
	III	$\ln Y = a + b D$	0.768	0.212	37.364	1.723	0.062		6.115
	IV	$\ln Y = a + b \ln D$	0.729	0.230	30.520	-1.819	1.596		6.636
	V	$\sqrt{Y} = a + b D$	0.815	0.521	49.603	0.857	0.176		5.600
	VI	$Y = a + b D^2H$	0.895	4.475	94.501	10.476	0.002		4.475
	VII	$\ln Y = a + b D^2H$	0.809	0.192	47.639	2.720	5.456E		5.545
	VIII	$\sqrt{Y} = a + b D^2H$	0.861	0.452	69.264	3.673	0.000		4.850
Total	I	$Y = a + b D$	0.875	23.231	78.163	-93.989	9.838		23.231
	II	$Y = a + b D + c D^2$	0.902	20.563	51.759	163.774	-10.109	0.367	20.563
	III	$\ln Y = a + b D$	0.846	0.157	61.282	3.484	0.059		24.299
	IV	$\ln Y = a + b \ln D$	0.826	0.167	53.106	0.070	1.530		25.716
	V	$\sqrt{Y} = a + b D$	0.867	0.921	72.777	2.707	0.376		22.832
	VI	$Y = a + b D^2H$	0.903	20.503	103.184	64.662	0.009		20.503
	VII	$\ln Y = a + b D^2H$	0.850	0.155	63.478	4.440	5.057E		23.808
	VIII	$\sqrt{Y} = a + b D^2H$	0.884	0.861	84.724	8.798	0.000		20.950

All the models with the functions of both dbh and height showed very good response in predicting the bark carbon content with the coefficient of determination values greater than 0.78 and almost similar Furnival index. The model VI, as in the case of bole carbon prediction, resulted in a calculated FI value of 1.409 which was the lowest and therefore it was listed this model as the best fit one.

The statistics used to construct the branch carbon prediction equations revealed that all the equations were having very low R^2 values and the f-statistic used for testing the validity of the model showed that the models were non-significant and were not able to predict the branch carbon content from its height and dbh or its various functions. The computation of Furnival index was also not relevant in this situation.

In the case of above ground carbon prediction, it was found that all the models using functions of height and dbh as independent variable gave higher R^2 values ($R^2 > 0.835$) and lower value for Furnival index. Out of these models, the R^2 value was 0.894 in the quadratic model which was slightly higher than others and FI value of 17.03 was also the lowest. So for the prediction of above ground carbon content in 30 year old teak tree, the quadratic model could be the best fit model.

The R^2 value was higher (0.895) in the model VI and the Furnival index value was slightly lower (4.475) compared to other regression models. So this linear model was taken as the best prediction model for below ground carbon content.

The maximum value for determination coefficient (R^2 -0.903) was recorded in model VI in the case of the total carbon prediction equations. The Furnival index value was also lower (20.503) in the same model which made it good fit for carbon prediction.

6.3.6 Nondestructive predictors of carbon storage by 40 year teak

The coefficient of determination for all the models had a value more than 0.949 in forty year old teak tree. The model VIII using square root of carbon content as the dependent variable gave comparatively lower value (7.507) for Furnival index and hence was regarded as the best suitable prediction model of bole carbon of forty year teak tree (table 6.6).

The models tried for predicting the bark carbon content showed that the maximum R^2 value was recorded in model-VI, VII and VIII having both dbh and height as the independent variable and the FI value for these were comparatively lower than the other five models. Out of these three, model VI had the least FI value (0.385) and highest determination coefficient (0.980) and hence it was listed as the best fit regression equation for predicting bark carbon content.

For estimating the branch carbon content, various models were constructed but the coefficients of determination were all very low; that is between 0.071 to 0.353 only. While testing the model validation, the f value was also very low and it was not significant. Therefore all the prediction models considered were not enough to predict the branch carbon content with reasonable accuracy.

The models tried for predicting the above ground carbon content showed that the maximum R^2 value was recorded in power models having logarithmic transformation in the independent variable that is the model-III and the FI value for these were also comparatively low. But the model-V showed the lowest FI value (14.020) with a higher value for determination coefficient (0.930) and hence was listed as the best fit regression equation for predicting above ground carbon content.

Table 6.6. Regression models for predicting carbon sequestered in 40 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.949	10.253	206.583	-124.669	8.779		10.253
	II	$Y = a + b D + c D^2$	0.960	9.047	134.577	211.548	-9.723	0.250	9.047
	III	$\ln Y = a + b D$	0.965	0.043	302.106	3.646	0.044		9.001
	IV	$\ln Y = a + b \ln D$	0.957	0.047	245.867	-0.503	1.604		9.001
	V	$\sqrt{Y} = a + b D$	0.959	0.323	258.722	2.599	0.310		9.194
	VI	$Y = a + b D^2H$	0.972	7.628	381.340	47.862	0.006		7.628
	VII	$\ln Y = a + b D^2H$	0.969	0.040	348.676	4.518	2.861E		9.001
	VIII	$\sqrt{Y} = a + b D^2H$	0.973	0.264	392.247	8.713	0.000		7.507
Bark	I	$Y = a + b D$	0.891	0.903	74.834	-9.342	0.690		0.903
	II	$Y = a + b D + c D^2$	0.877	0.960	33.148	-20.873	1.295	-0.008	0.960
	III	$\ln Y = a + b D$	0.907	0.049	88.798	1.265	0.041		0.823
	IV	$\ln Y = a + b \ln D$	0.913	0.047	95.632	-2.861	1.562		0.823
	V	$\sqrt{Y} = a + b D$	0.900	0.104	82.408	0.916	0.084		0.900
	VI	$Y = a + b D^2H$	0.980	0.385	447.504	4.259	0.000		0.385
	VII	$\ln Y = a + b D^2H$	0.972	0.027	318.746	2.076	0.000		0.582
	VIII	$\sqrt{Y} = a + b D^2H$	0.978	0.049	394.796	2.573	0.000		0.384
Branch	I	$Y = a + b D$	0.154	9.167	2.997	2.814	0.945		9.167
	II	$Y = a + b D + c D^2$	0.071	9.6.3	1.422	-58.229	4.305	-0.045	9.603
	III	$\ln Y = a + b D$	0.160	0.235	3.097	2.690	0.025		8.742
	IV	$\ln Y = a + b \ln D$	0.160	0.235	3.098	0.357	0.901		8.742
	V	$\sqrt{Y} = a + b D$	0.158	0.728	3.070	3.289	0.076		9.138
	VI	$Y = a + b D^2H$	0.077	9.575	1.914	24.361	0.001		9.575
	VII	$\ln Y = a + b D^2H$	0.088	0.245	2.065	3.245	1.359E		9.131
	VIII	$\sqrt{Y} = a + b D^2H$	0.084	0.760	2.002	5.010	4.152E		9.275
Above ground	I	$Y = a + b D$	0.924	14.575	135.197	-117.923	10.096		14.575
	II	$Y = a + b D + c D^2$	0.927	14.297	70.949	201.902	-7.505	0.238	14.297
	III	$\ln Y = a + b D$	0.934	0.053	156.499	4.056	0.040		14.092
	IV	$\ln Y = a + b \ln D$	0.925	0.057	136.041	0.326	1.443		14.092
	V	$\sqrt{Y} = a + b D$	0.930	0.437	146.992	4.232	0.316		14.020
	VI	$Y = a + b D^2H$	0.916	15.348	120.924	83.137	0.007		15.348
	VII	$\ln Y = a + b D^2H$	0.915	0.060	119.782	4.850	2.547E		16.272
	VIII	$\sqrt{Y} = a + b D^2H$	0.916	0.477	121.559	10.532	0.000		15.318
Below ground	I	$Y = a + b D$	0.809	5.319	47.530	-32.211	2.185		5.319
	II	$Y = a + b D + c D^2$	0.820	5.160	26.068	92.538	-4.681	0.093	5.160
	III	$\ln Y = a + b D$	0.805	0.111	46.316	2.193	0.045		5.332
	IV	$\ln Y = a + b \ln D$	0.787	0.116	41.667	-2.000	1.626		5.549
	V	$\sqrt{Y} = a + b D$	0.809	0.379	47.643	1.149	0.156		5.295
	VI	$Y = a + b D^2H$	0.869	4.406	73.846	9.872	0.001		4.406
	VII	$\ln Y = a + b D^2H$	0.846	0.098	61.545	3.067	2.977E		4.867
	VIII	$\sqrt{Y} = a + b D^2H$	0.860	0.325	68.507	4.169	0.000		4.543
Total	I	$Y = a + b D$	0.932	16.723	151.946	-150.134	12.280		16.723
	II	$Y = a + b D + c D^2$	0.939	15.799	86.217	294.440	-12.185	0.331	15.799
	III	$\ln Y = a + b D$	0.945	0.049	188.751	4.201	0.040		13.694
	IV	$\ln Y = a + b \ln D$	0.934	0.054	155.604	0.401	1.471		16.772
	V	$\sqrt{Y} = a + b D$	0.939	0.451	170.952	4.348	0.352		15.807
	VI	$Y = a + b D^2H$	0.937	16.085	165.037	93.009	0.008		16.085
	VII	$\ln Y = a + b D^2H$	0.938	0.052	166.170	5.006	2.613E		16.772
	VIII	$\sqrt{Y} = a + b D^2H$	0.938	0.455	167.802	11.326	0.000		15.923

In the below ground carbon prediction models a similar trend was seen as in the case of the bole regression models, that is the maximum R^2 values were recorded in models having Spurr's combined variable as the independent variable such as model-VI, VII and VIII. The maximum value for determination coefficient (R^2 -0.869) was recorded in model VI and it also had a lower Furnival index value (4.406) and hence this model could be the best one for the prediction of below ground carbon.

It was observed that all the regression models tried were having higher values for coefficient of determination and minimum value for Furnival index when total carbon was considered. However the model III having the lowest value for Furnival index (13.694) and higher value of R^2 (0.945) was taken as the most suitable prediction model for total carbon content in this.

6.3.7 Nondestructive predictors of carbon storage by 50 year teak

It was observed that all the regression models tried were having higher values of coefficient of determination and minimum value for Furnival index when 50 year old teak was considered (table 6.7). However the model I having the lowest Furnival index (19.404) was taken as the most suitable prediction model for total carbon content in this age group. The coefficient of determination for this model also had the highest value (R^2 -0.973) as compared to other models.

In the case of bark compartment, the model-VI having combined form of height and dbh as the independent variable had the maximum R^2 value (0.982). All other models also gave higher R^2 values and comparatively lower values for Furnival index. However, it was found that the model-VI had the lowest FI value (1.224) and hence this model could be the best one for the prediction of bark carbon at this age.

Table 6.7. Regression models for predicting carbon sequestered in 50 year teak

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
Bole	I	$Y = a + b D$	0.973	19.401	403.534	-252.497	12.779		19.401
	II	$Y = a + b D + c D^2$	0.971	20.396	182.585	-204.939	10.745	0.021	20.396
	III	$\ln Y = a + b D$	0.954	0.074	230.405	4.067	0.037		22.260
	IV	$\ln Y = a + b \ln D$	0.968	0.062	330.718	-0.935	1.757		19.910
	V	$\sqrt{Y} = a + b D$	0.969	0.558	345.893	2.408	0.340		19.789
	VI	$Y = a + b D^2H$	0.956	24.871	241.625	61.816	0.005		24.871
	VII	$\ln Y = a + b D^2H$	0.924	0.095	135.185	4.977	1.553E		29.865
	VIII	$\sqrt{Y} = a + b D^2H$	0.945	0.745	189.365	10.800	0.000		26.436
Bark	I	$Y = a + b D$	0.977	1.385	478.234	-18.909	0.993		1.385
	II	$Y = a + b D + c D^2$	0.976	1.433	223.317	-10.124	0.617	0.004	1.433
	III	$\ln Y = a + b D$	0.953	0.073	223.858	1.585	0.036		1.782
	IV	$\ln Y = a + b \ln D$	0.967	0.061	324.052	-3.290	1.712		1.594
	V	$\sqrt{Y} = a + b D$	0.972	0.145	385.570	0.800	0.094		1.455
	VI	$Y = a + b D^2H$	0.982	1.224	614.547	5.292	0.000		1.224
	VII	$\ln Y = a + b D^2H$	0.938	0.084	167.263	2.466	1.524E		2.109
	VIII	$\sqrt{Y} = a + b D^2H$	0.966	0.160	314.578	3.091	3.996E		1.619
Branch	I	$Y = a + b D$	0.119	13.015	2.484	37.819	0.673		13.015
	II	$Y = a + b D + c D^2$	0.094	13.195	1.573	-81.979	5.798	-0.053	13.195
	III	$\ln Y = a + b D$	0.114	0.176	2.418	3.801	0.009		11.882
	IV	$\ln Y = a + b \ln D$	0.128	0.175	2.608	2.541	0.439		11.689
	V	$\sqrt{Y} = a + b D$	0.117	0.754	2.461	6.473	0.039		12.383
	VI	$Y = a + b D^2H$	0.154	12.752	3.004	53.134	0.000		12.752
	VII	$\ln Y = a + b D^2H$	0.154	0.172	3.006	4.003	4.186E		11.689
	VIII	$\sqrt{Y} = a + b D^2H$	0.155	0.737	3.018	7.351	1.799		12.118
Above ground	I	$Y = a + b D$	0.965	25.397	300.847	-233.586	14.445		25.397
	II	$Y = a + b D + c D^2$	0.961	26.697	-297.042	17.160	-0.028		26.697
	III	$\ln Y = a + b D$	0.953	0.066	22.533	4.532	0.032		25.923
	IV	$\ln Y = a + b \ln D$	0.967	0.056	319.714	0.125	1.547		22.450
	V	$\sqrt{Y} = a + b D$	0.963	0.615	283.885	4.890	0.340		24.927
	VI	$Y = a + b D^2H$	0.958	27.812	249.207	120.242	0.006		27.812
	VII	$\ln Y = a + b D^2H$	0.931	0.080	150.133	5.330	1.373E		31.749
	VIII	$\sqrt{Y} = a + b D^2H$	0.948	0.727	200.743	13.245	0.000		29.422
Below ground	I	$Y = a + b D$	0.928	6.378	141.821	-34.032	2.491		6.378
	II	$Y = a + b D + c D^2$	0.939	5.871	85.082	-138.530	6.961	-0.046	5.871
	III	$\ln Y = a + b D$	0.903	0.092	102.925	2.947	0.030		6.883
	IV	$\ln Y = a + b \ln D$	0.929	0.078	145.920	-1.236	1.466		5.960
	V	$\sqrt{Y} = a + b D$	0.920	0.371	126.880	2.583	0.137		6.517
	VI	$Y = a + b D^2H$	0.843	9.402	59.877	29.052	0.001		9.402
	VII	$\ln Y = a + b D^2H$	0.829	0.121	54.407	3.716	1.2257E		9.424
	VIII	$\sqrt{Y} = a + b D^2H$	0.840	0.523	58.793	6.046	5.635E		9.183
Total	I	$Y = a + b D$	0.968	28.351	331.851	-267.618	16.936		28.351
	II	$Y = a + b D + c D^2$	0.965	29.418	154.260	-435.572	24.121	-0.074	29.418
	III	$\ln Y = a + b D$	0.952	0.066	219.930	4.717	0.032		30.798
	IV	$\ln Y = a + b \ln D$	0.968	0.054	335.160	0.344	1.535		26.672
	V	$\sqrt{Y} = a + b D$	0.964	0.652	293.897	5.508	0.367		28.772
	VI	$Y = a + b D^2H$	0.949	35.832	204.017	149.293	0.007		35.832
	VII	$\ln Y = a + b D^2H$	0.923	0.084	132.276	5.511	1.356E		40.743
	VIII	$\sqrt{Y} = a + b D^2H$	0.939	0.847	170.165	14.555	0.000		37.371

The branch carbon content prediction models yielded a lower value for the coefficient of determination and the models were statistically invalid as the f values were insignificant in all the models. Therefore none of the prediction models considered was found suitable to predict the branch carbon content.

It could be found that the maximum R^2 value (0.967) was recorded in the exponential model VI with logarithmic transformation of both the dependent and independent variables. The Furnival index value was also the lowest (22.450) in this model and hence it had the advantage of getting selected as the best model for predicting the above ground carbon content in a fifty year old teak tree.

The best model for below ground carbon prediction in fifty year old teak was the quadratic model II with a higher value of coefficient of determination (0.939) and the lowest Furnival index value (5.871). The prediction models I,IV and V had higher values for the R^2 but their FI values were also higher and hence they were not considered as best regression models.

The prediction models tried for total carbon content showed that all models gave reasonable performance with sufficiently high coefficient of determination. Out of these good models, the R^2 value was maximum in the model-IV (0.968) and the Furnival index of this prediction model was comparatively the lowest (26.672) and hence it was considered the best fit regression model for predicting the total carbon content in fifty year old teak tree.

6.3.8 Allometric models using the pooled data of all age groups of teak

The pooled data from all plantations of different ages (5–50years) were used to formulate regression equations for carbon sequestration assessment in various compartments such as bole, branch, bark, above ground, below ground and total carbon sequestration by teak trees. All equations developed for estimating carbon sequestration by five to fifty year old plantations were highly significant ($p < 0.01$).

In the case of bole carbon prediction, all the eight selected models were highly significant ($p < 0.01$). Though models II and VI had slightly higher R^2 values (0.987) than model V (0.981) the comparatively lower FI value made model V the most appropriate to predict bole carbon (table 6.8).

Table 6.8. Allometric models for bole using pooled data

Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
I	$Y = a + b D$	0.909	35.371	828.694	-75.802	8.081		35.371
II	$Y = a + b D + c D^2$	0.987	13.551	3061.895	16.038	-0.575	0.151	13.551
III	$\ln Y = a + b D$	0.966	0.179	2332.760	2.708	0.067		13.145
IV	$\ln Y = a + b \ln D$	0.932	0.248	1132.917	0.175	1.389		18.589
V	$\sqrt{Y} = a + b D$	0.981	0.663	4263.225	1.502	0.344		11.463
VI	$Y = a + b D^2H$	0.987	13.404	6259.345	28.878	0.006		13.404
VII	$\ln Y = a + b D^2H$	0.763	0.462	268.153	3.688	4.345E		34.536
VIII	$\sqrt{Y} = a + b D^2H$	0.918	1.378	925.365	6.218	0.000		23.807

Scatter plots of bole carbon data with the best fit regression line is provided below in support of the table described above

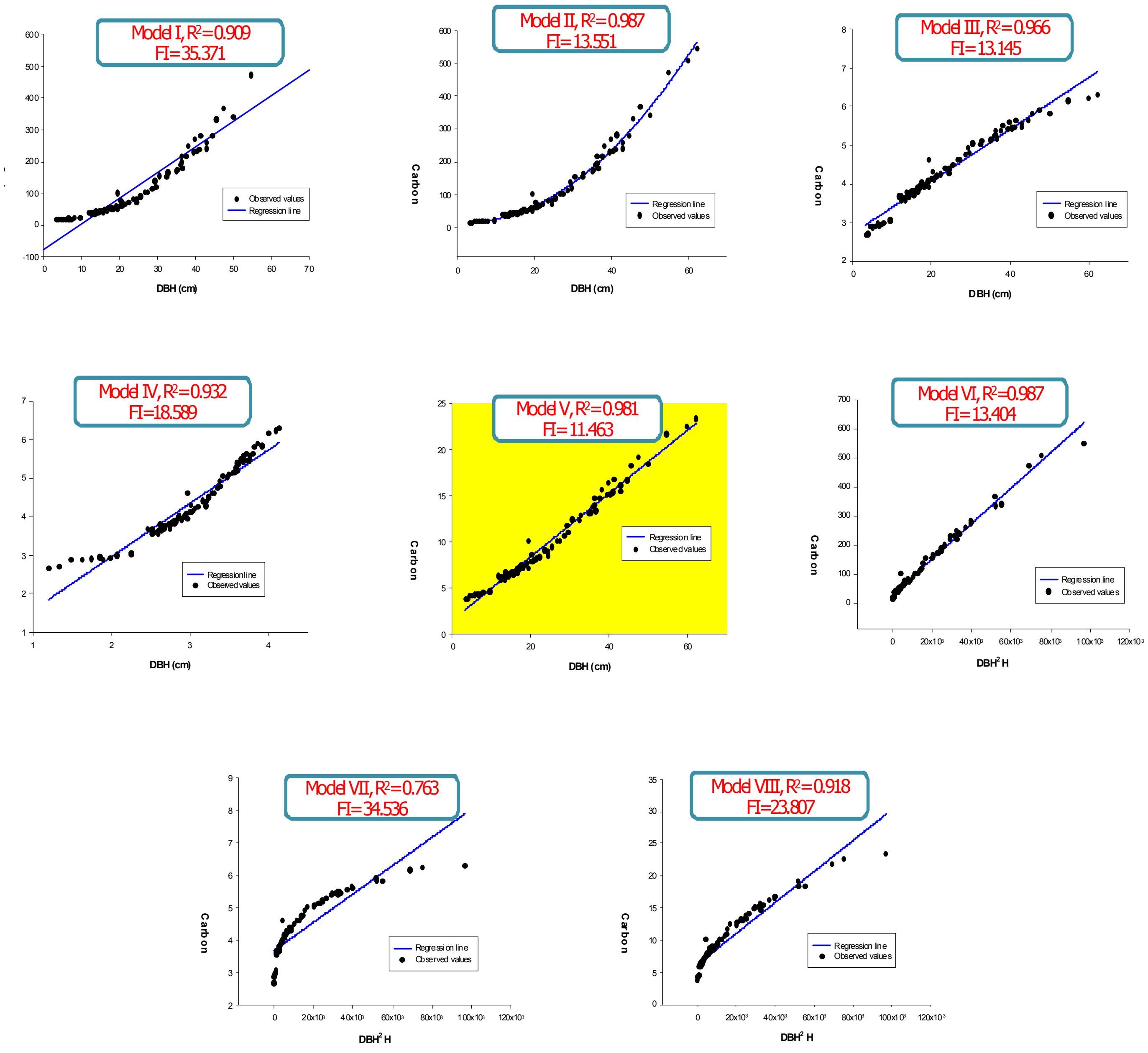

Figure 6.1. Scatter plots of allometric models for bole carbon with observed values and fitted regression line

Among the eight models tried for predicting bark carbon sequestration, the model II had the greatest value of determination coefficient (table 6.9). But the model V gave the least value for Furnival index (1.203) and a higher value of determination coefficient (0.969) and hence was selected as the most suitable prediction model for bark carbon content (figure 6.2). In other models even though they were having higher values for determination coefficient, the residuals departed from the linearity in these models resulting in comparatively higher Furnival index values for these models. Therefore they were not considered prediction models as good.

Table 6.9. Allometric models for bark using pooled data

Model No.	**Regression Equation**	**R^2**	**SEE**	**F**	**a**	**b**	**c**	**FI**
I	$Y = a + b D$	0.913	2.550	872.299	-3.123	0.598		2.550
II	$Y = a + b D + c D^2$	0.973	1.415	1508.139	2.848	0.035	0.010	1.415
III	$\ln Y = a + b D$	0.958	0.143	1915.289	0.970	0.050		1.248
IV	$\ln Y = a + b \ln D$	0.915	0.205	897.478	-0.883	1.019		1.765
V	$\sqrt{Y} = a + b D$	0.969	0.204	2590.815	1.163	0.082		1.203
VI	$Y = a + b D^2H$	0.971	1.465	2817.080	4.683	0.000		1.463
VII	$\ln Y = a + b D^2H$	0.780	0.330	295.206	1.686	3.252E		2.844
VIII	$\sqrt{Y} = a + b D^2H$	0.905	0.357	794.030	2.295	5.768E		2.092

Scatter plots of bark carbon data with the best fit regression line is provided below in support of the table described above

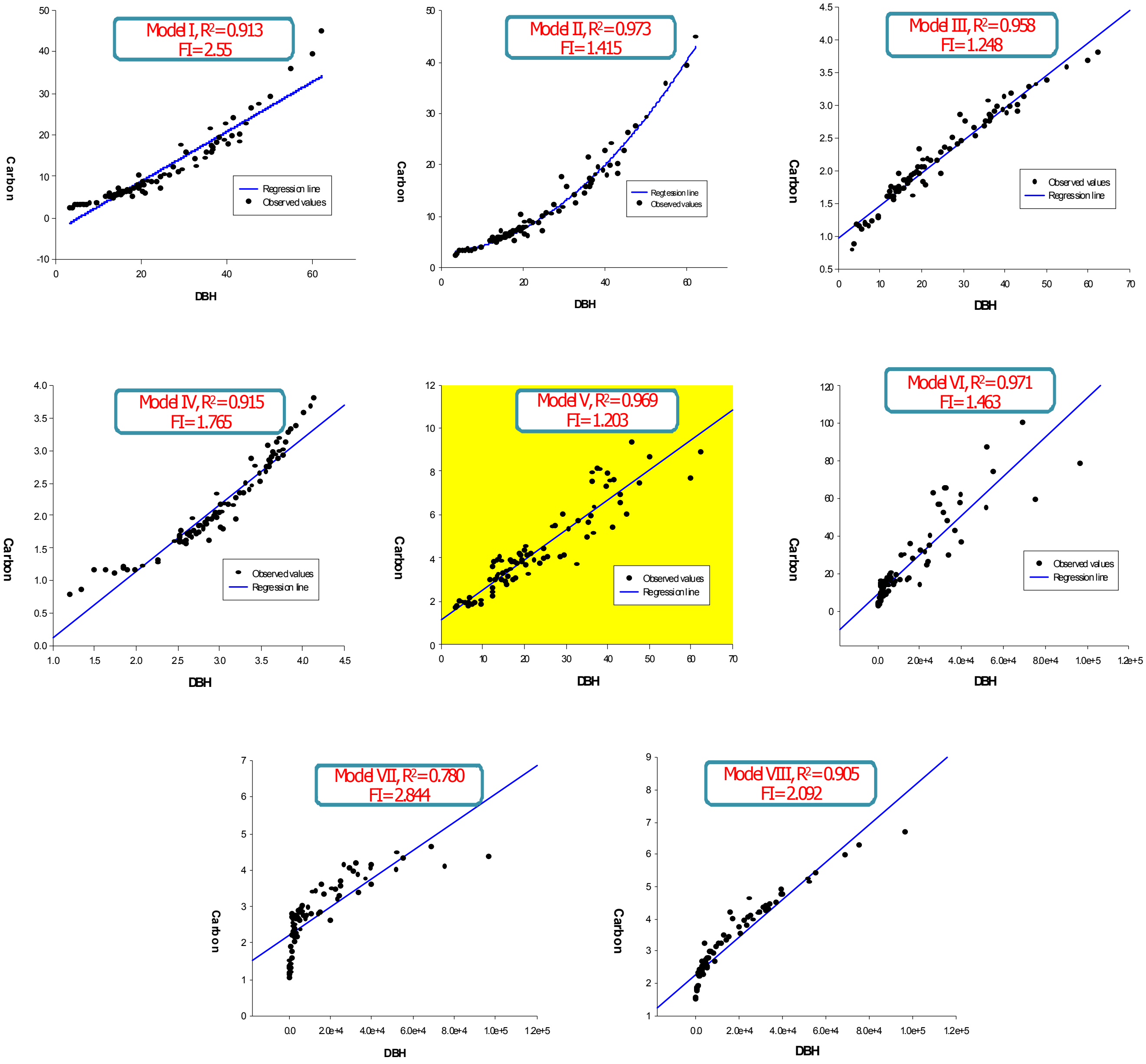

Figure 6.2. Scatter plots of allometric models for bark carbon with observed values and fitted regression line

The statistics used to construct the branch carbon prediction equations revealed that all the equations were having comparatively low R^2 values than in other teak compartments while the F-statistic used for testing the validity of the model showed that the models were significant at 0.05 level (table 6.10). The computation of Furnival index was also done for selecting the best fit model and it was found that model IV in exponential family had the lowest value (5.355) with comparatively higher R^2 value and hence this model was selected as the best fit tree allometric model for branch carbon prediction (figure 6.3).

Table 6.10. Allometric models for branch using pooled data

Model No.	**Regression Equation**	**R^2**	**SEE**	**F**	**a**	**b**	**c**	**FI**
I	$Y = a + b D$	0.799	9.914	331.147	-9.998	1.432		9.914
II	$Y = a + b D + c D^2$	0.811	9.628	178.534	-2.718	0.746	0.012	9.628
III	$\ln Y = a + b D$	0.839	0.371	434.423	1.323	0.061		5.977
IV	$\ln Y = a + b \ln D$	0.871	0.332	562.209	-1.116	1.308		5.355
V	$\sqrt{Y} = a + b D$	0.864	0.760	526.766	1.165	0.138		6.110
VI	$Y = a + b D^2H$	0.813	9.565	361.871	9.040	0.001		9.565
VII	$\ln Y = a + b D^2H$	0.633	0.560	144.004	2.227	3.859E		9.048
VIII	$\sqrt{Y} = a + b D^2H$	0.768	0.991	276.114	3.099	9.45E		6.637

Scatter plots of branch carbon data with the best fit regression line is provided below in support of the table described above

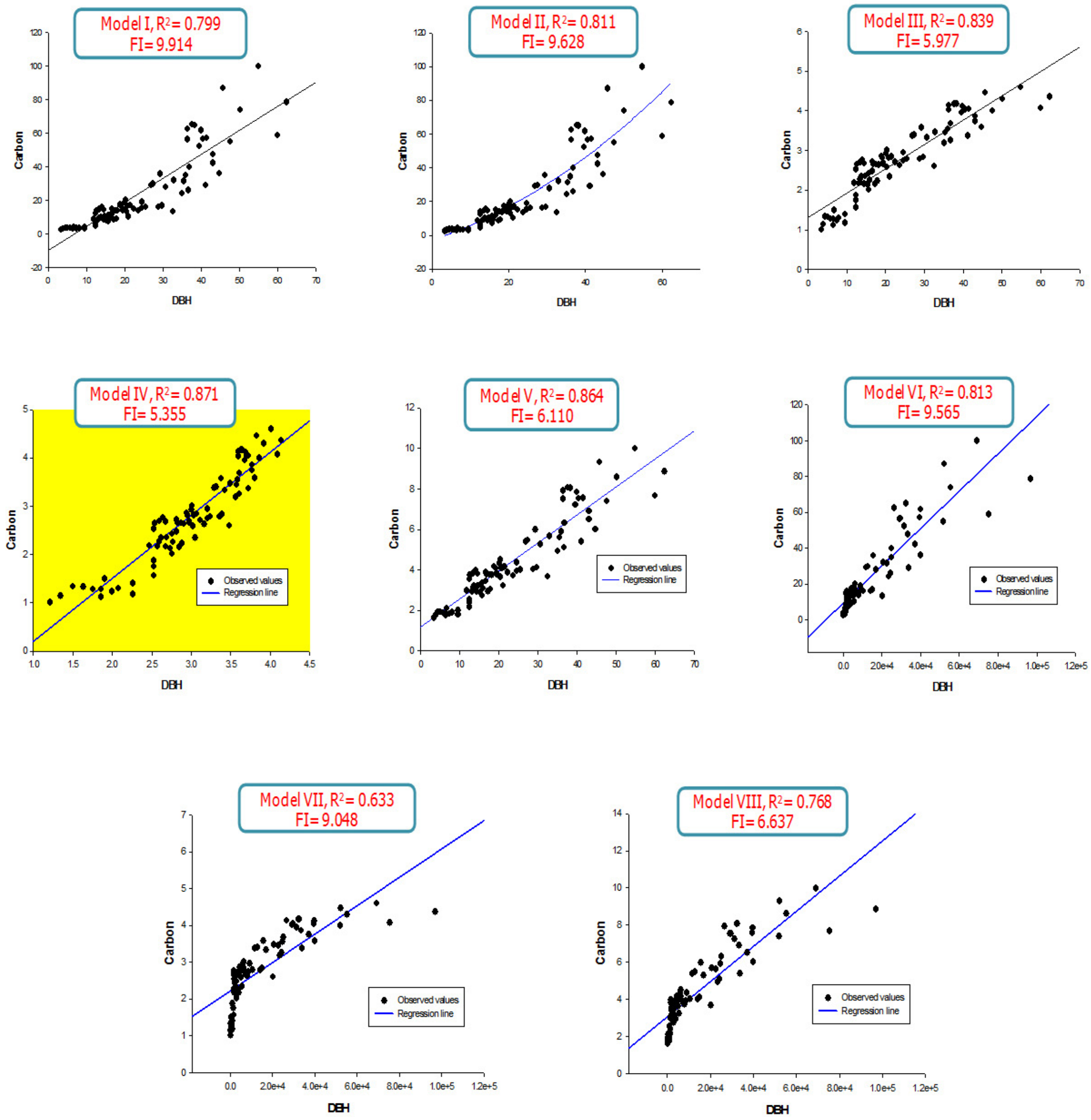

Figure 6.3. Scatter plots of allometric models for branch carbon with observed values and fitted regression line

In the case of above ground carbon prediction, it was found that models II, V and VI had maximum R^2 values (table 6.11). The other five models, even though exhibited higher R^2 values, had higher Furnival index values also. The model V with R^2 value of 0.978 and FI value of 15.631 was preferred as the most suitable model for above ground carbon prediction (figure 6.4).

Table 6.11. Allometric models for above ground carbon using pooled data

Model No.	**Regression Equation**	**R^2**	**SEE**	**F**	**a**	**b**	**c**	**FI**
I	$Y = a + b D$	0.913	43.034	876.344	-88.924	10.111		43.034
II	$Y = a + b D + c D^2$	0.979	21.373	1902.106	16.167	0.173	0.206	21.373
III	$\ln Y = a + b D$	0.959	0.185	1958.768	3.062	0.065		18.493
IV	$\ln Y = a + b \ln D$	0.935	0.234	1189.755	0.603	1.344		23.521
V	$\sqrt{Y} = a + b D$	0.978	0.781	3742.862	2.113	0.379		15.631
VI	$Y = a + b D^2H$	0.982	19.804	4442.982	42.601	0.008		19.804
VII	$\ln Y = a + b D^2H$	0.755	0.454	256.813	4.007	4.177E		45.521
VIII	$\sqrt{Y} = a + b D^2H$	0.909	1.598	830.116	7.326	0.000		32.016

Scatter plots of above ground carbon data with the best fit regression line is provided below in support of the table described above

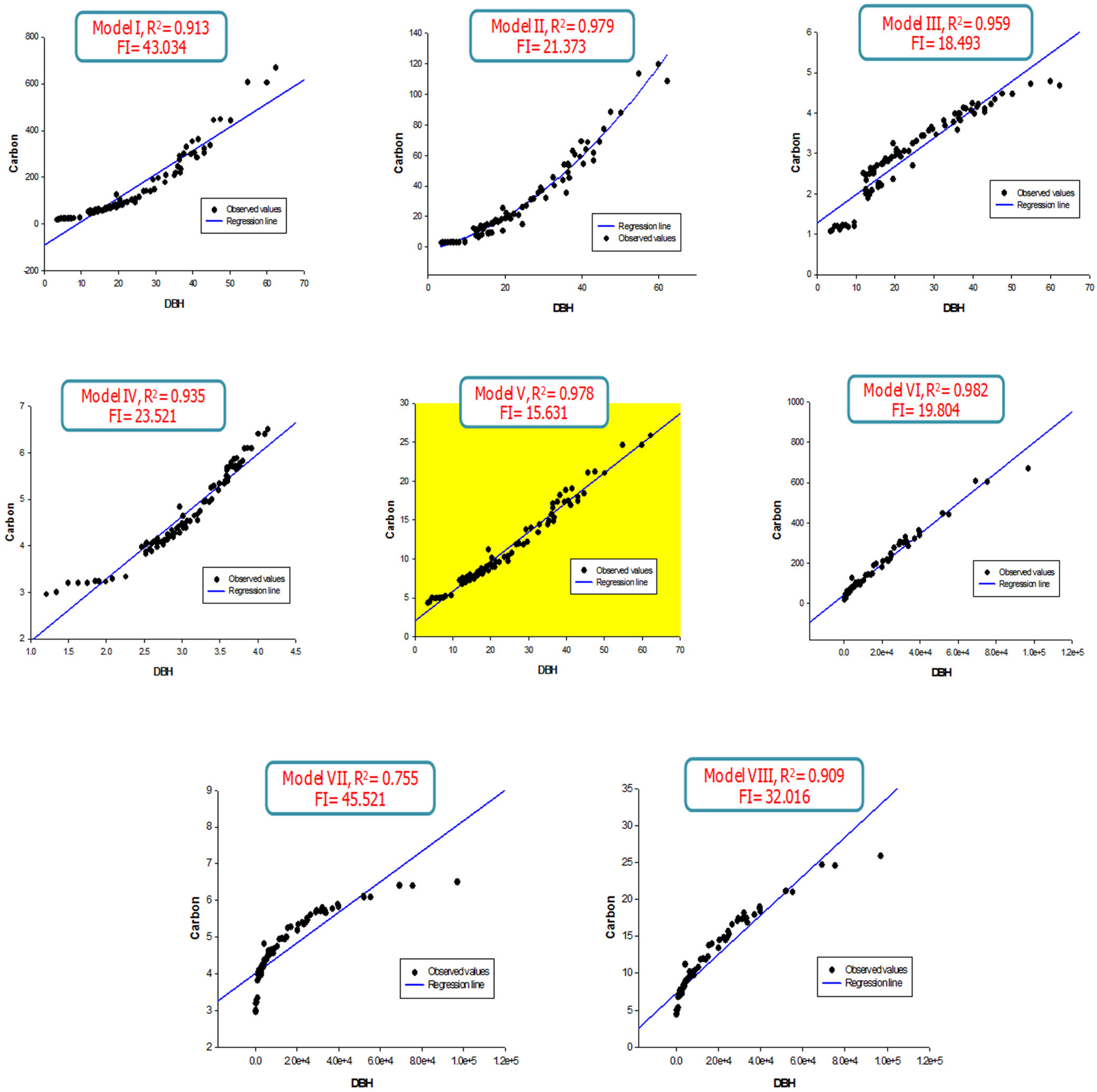

Figure 6.4. Scatter plots of allometric models for above ground carbon with observed values and fitted regression line

The R^2 values were maximum in the models II and V while the FI values were slightly lower compared to other regression models for the prediction of below ground carbon sequestration in teak (table 6.12). The power model had the lowest FI value of 3.630 and high R^2 value of 0.969 and thus was taken as the best prediction model for below ground carbon content (figure 6.5).

Table 6.12. Allometric models for below ground carbon using pooled data

Model No.	Regression Equation	R^2	SEE	F	a	b	c	FI
I	$Y = a + b D$	0.936	6.963	1224.984	-16.248	1.934		6.963
II	$Y = a + b D + c D^2$	0.970	4.799	1335.210	-2.003	0.592	0.023	4.799
III	$\ln Y = a + b D$	0.892	0.338	684.763	1.267	0.070		6.357
IV	$\ln Y = a + b \ln D$	0.938	0.255	1264.900	-1.553	1.506		4.800
V	$\sqrt{Y} = a + b D$	0.969	0.418	2638.586	0.858	0.170		3.630
VI	$Y = a + b D^2H$	0.947	6.390	1469.752	9.536	0.001		6.390
VII	$\ln Y = a + b D^2H$	0.645	0.611	152.038	2.313	4.325E		11.498
VIII	$\sqrt{Y} = a + b D^2H$	0.842	0.950	444.426	3.257	0.000		8.242

Scatter plots of below ground carbon data with the best fit regression line is provided below in support of the table described above

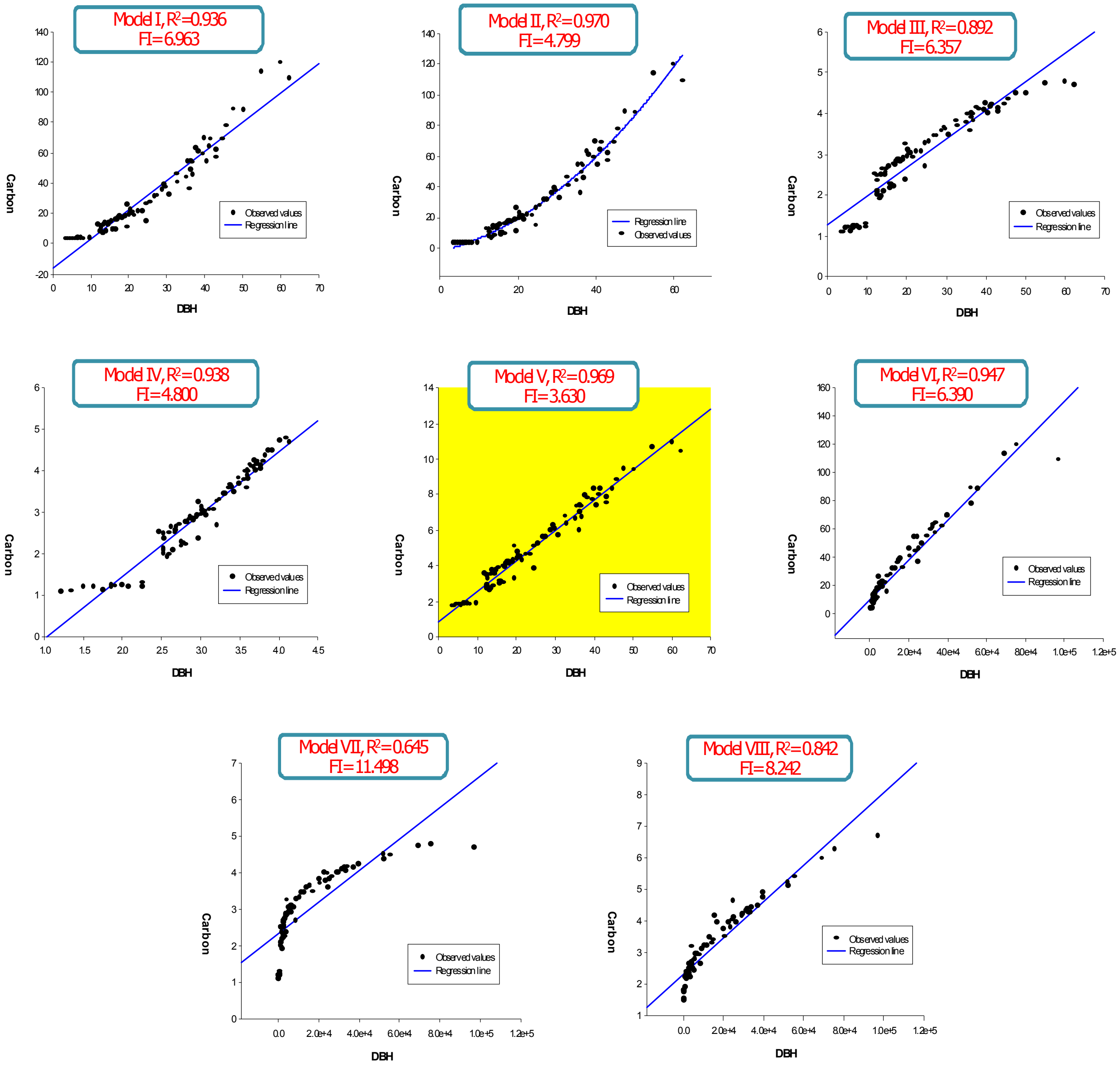

Figure 6.5. Scatter plots of allometric models for below ground carbon with observed values and fitted regression line

The maximum values for determination coefficient were recorded in first six models in the case of total carbon prediction equations (table 6.13). The other two models had higher FI value and lower R^2 value and were hence not considered as good models. Among the six models, the model V with the lowest Furnival index (17.490) and highest R^2 (0.981) made it the best fit prediction equation for total carbon content (figure 6.6).

Table 6.13. Allometric models for total carbon using pooled data

Model No.	**Regression Equation**	**R^2**	**SEE**	**F**	**a**	**b**	**c**	**FI**
I	$Y = a + b D$	0.920	48.963	960.745	-105.172	12.045		48.963
II	$Y = a + b D + c D^2$	0.980	24.465	2047.845	14.164	0.798	0.196	24.465
III	$\ln Y = a + b D$	0.953	0.201	1689.786	3.221	0.066		24.195
IV	$\ln Y = a + b \ln D$	0.941	0.226	1320.432	0.410	1.367		26.985
V	$\sqrt{Y} = a + b D$	0.981	0.800	4281.881	2.289	0.415		17.490
VI	$Y = a + b D^2H$	0.980	24.787	3986.644	52.137	0.009		24.787
VII	$\ln Y = a + b D^2H$	0.740	0.474	237.225	4.180	4.193E		56.680
VIII	$\sqrt{Y} = a + b D^2H$	0.902	1.819	761.884	8.025	0.000		39.763

Scatter plots of total carbon data with the best fit regression line is provided below in support of the table described above

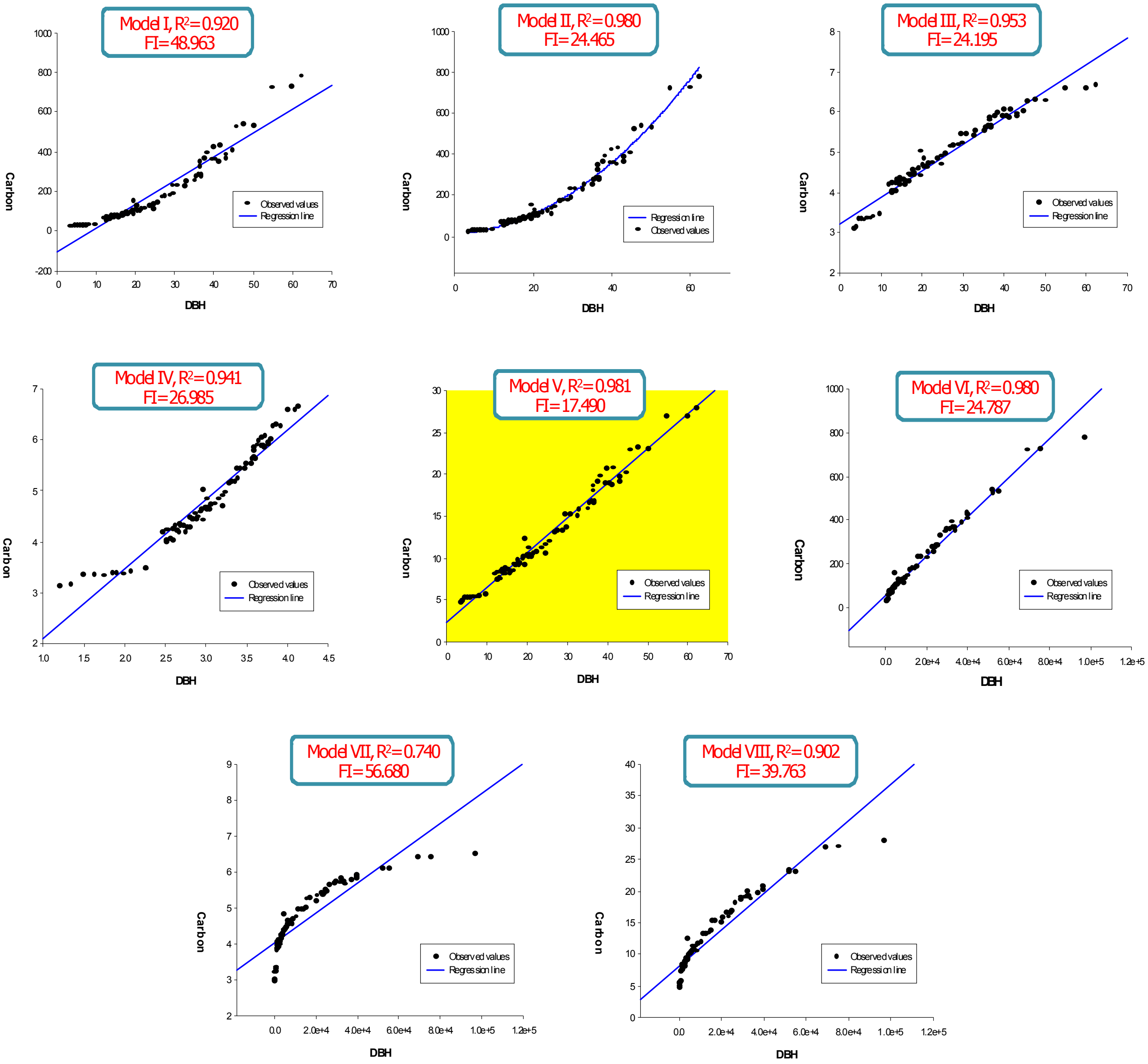

Figure 6.6. Scatter plots of allometric models for total carbon with observed values and fitted regression line

Table 6.14. Allometric models for various compartments using pooled data

Compartment	Model No.	Regression Equation	R^2	SEE	F	a	b	FI
Bole	V	$\sqrt{Y} = a + b D$	0.981	0.663	4263.225	1.502	0.344	11.463
Bark	V	$\sqrt{Y} = a + b D$	0.969	0.204	2590.815	1.163	0.082	1.203
Branch	IV	$\ln Y = a + b \ln D$	0.871	0.332	562.209	-1.116	1.308	5.355
Above ground	V	$\sqrt{Y} = a + b D$	0.978	0.781	3742.862	2.113	0.379	15.631
Below ground	V	$\sqrt{Y} = a + b D$	0.969	0.418	2638.586	0.858	0.170	3.630
Total	V	$\sqrt{Y} = a + b D$	0.981	0.800	4281.881	2.289	0.415	17.490

Table 6.14 sums up the findings of pooled data of 5-50 year old teak. It can be seen that model V with the allometric equation $\sqrt{Y} = a + b D$ was the best fit model in all compartments except branch component. This particular model may be utilized to predict carbon sequestration in teak with reasonable accuracy.

6.4 Discussion

Allometric equations are widely accepted as an effective tool for estimating carbon sequestration by tropical forests (Brown, 1997). Among different models developed, the pantropical models proposed by Chave *et al.* (2005) are considered to be the best for sites that have no local accurate equations available (Clark, 2007). He had developed and evaluated pantropical models for estimating the above ground biomass of tropical trees from their diameter, height and density. Separate models were developed for dry, moist and wet regimes. For each regime he had developed exponential models with and without height; Chave type I included density, diameter and height while Chave type II considered density and diameter only. But the predictive power of their global model differs among sites; for some regions, the relative error could be low, while for others, it could be high (Chave *et al.*, 2005). Simple models using dbh alone are the most practical models for above ground biomass assessment at local level (Litton and Kauffman, 2008; Basuki *et al.*, 2009). The accuracy of estimation can be improved by including wood density (Brown *et al.,* 1989; Baker *et al.*, 2004) and tree height (Brown, 1997; Wang *et al.*, 2006; Nogueira *et al.*, 2008) in the models. However, measuring height and wood density is difficult and consume much time and money.

DBH along with height have been reported to provide better performance (Negi *et al.*, 1995; Segura and Kanninen, 2005) though dbh alone is enough to predict carbon sequestration of several species (Chaturvedi and Singh, 1982; Nelson *et al.*, 1999; Kuyah *et al.*, 2013; Chaturvedi and Raghubanshi, 2013). Logarithmic transformations are also found to increase the predictability (Dudley and Fowns, 1992; Thauitsa,1990; Karmacharya and Singh, 1992; Christine,1992). Diameter, height and density were reported to improve the efficacy of allometric models further (Brown *et al.*, 1989; (Chambers *et al.*, 2001; Baker *et al.*, 2004; Chave *et al.*, 2005; Basuki *et al.*, 2009) which were applicable at regional and global scales.

Allometric regression employing logarithmic transformation is generally considered a better option (Grundy, 1995; Voit and Sands, 1996; Rietz and Smith, 2004; Feldpausch *et al.*, 2011;) though simple linear regression models also provide biomass prediction with good precision (Dash *et al.*, 1991 and Ghan *et al.*, 1993; Wang *et al.,* 1995). The statistical precision in prediction by such model is decided by R^2 values as well as the Furnival index (Kushalappa, 1991).

In the present study, the carbon sequestration of 84 trees were determined through destructive sampling and related by regression analysis to easily measurable parameters such as dbh or a combination of dbh and height. Eight models were compared and the best fit model was selected from among them. Out of the eight models, five were having single independent variables and three were having two independent variables. These linear models have given higher values of coefficient of determination which can be used to predict carbon sequestration with more than 90% accuracy.

Many workers reported that standard error and coefficient of determination are the major criteria for selection of the best regression model (Pande *et al.* 1988; Gupta *et al.*1990; Da Silva, 1993; Deans *et al.* 1996). However, in allometric regressions, these parameters may not always be suitable for comparing different models because the dependent variables differ from one model to another due to transformation of data. But it is possible to compare different models by an index developed by Furnival (1961). Table 6.1 indicated that model II was most suitable for predicting carbon sequestration in various compartments of 5 year teak because of its lowest Furnival index values when compared to 7 other models. Similarly the best allometric models in different compartments of various aged teak were selected based on the lowest value of Furnival index.

Andre *et al.* (2005) reported that models were considerably improved by the introduction of age in the equations. Allometry was different for above ground compartments and below ground compartments, suggesting that stand age could have a significant effect on the relationship between biomass and tree dimensions (Williams *et al.*, 2003; Bond-Lamberty *et al.*, 2002). In the present study also, model parameters were found to vary clearly with stand age. In the case of 5 year teak, the quadratic model with dbh alone as independent variable was found to be the best regression model for predicting carbon sequestered in all the compartments except in branch where R^2 values were very low indicating a large unexplained variation. From 10th year onwards the best regression models for predicting the carbon storage in various compartments differed and no single model was found enough to predict all the variations in carbon sequestration with accuracy. It was reported that allometry of trees vary with age of plantation and hence a single model alone is insufficient to predict carbon sequestered in different compartments of teak (Phillips *et al.* 2002; Chave *et al.* 2004).

The various models used for predicting carbon sequestration in teak considering the pooled data of 84 teak trees showed that out of 8 models, square root transformed model V ($\sqrt{Y} = a + b\ D$) with dbh alone as independent variable gave comparatively higher coefficient of determination and smaller Furnival index values for various compartments such as bole, bark, above ground, below ground and total carbon prediction. The logarithmically transformed model IV was found to be a more suitable model for branch carbon prediction. Whittaker and Marks (1975) reported that even though coefficient of determination values in different models are highly significant, models with height as an additional variable did not represent much improvement over those obtained with dbh alone. Regression equation using dbh alone is more practical for estimating biomass and carbon (Chaturvedi and Singh, 1982; Thakur and Kaushal, 1992; Rana *et al.* 1993; Singh *et al.* 1993; Chaturvedi *et al.*, 2011). In the current study also, incorporation of height as an additional variable have not contributed much to prediction accuracy of carbon sequestration in various teak compartments. Diameter alone was enough to predict carbon storage of teak with accuracy. This can be due to the fact that teak raised on plantation scale with standardized prescriptions of management developed over rotations results in predictable variations in growth parameters.

6.5 Summary

Regression models to predict carbon sequestration with height and dbh as independent variable were tested for best fit based on R^2 value and Furnival index. It was seen that the best regression model for predicting the carbon sequestered in the bole compartment of teak regardless of its age was $\sqrt{Y} = 1.502 + 0.344\ D$, that for bark $\sqrt{Y} = 1.163 + 0.082\ D$, for branch $\ln Y = 1.308 \ln D - 1.116$, for root $\sqrt{Y} = 0.858 + 0.170\ D$, for above ground compartment $\sqrt{Y}$

$= 2.113 + 0.379$ D and for predicting the total carbon sequestered in the teak in all its vegetative parts is $\sqrt{Y} = 2.289 + 0.415$ D. These models were found to be the best ones as they have low value for Furnival index and high value for R^2. The value of R^2 in all the models were nearly 0.97 which indicates that dbh value could predict the carbon sequestration potential with 97% accuracy.

Chapter 7

Carbon Sequestration Potential of Teak Plantations of Kerala

7. Carbon Sequestration Potential of Teak Plantations of Kerala

7.1 Introduction

Clean Development Mechanism (CDM) envisages the reduction of greenhouse gas emissions. It awards credits for such reductions and alternatively for projects that sequester greenhouse gases from the atmosphere including emission reductions by the developing countries (Annex-1) through carbon sequestration in biomass (Robert *et al.*, 2008). Afforestation/ Reforestation and Reduced Emission from Forest Degradation are activities that are eligible for claiming emission reduction. India has developed considerable institutional capacity to support CDM projects and many projects are receiving funds under the program (Narain, 2007). Ministry of Environment, Forests and Climate Change (MoEFCC) in India is the National CDM Authority (NCDMA) to supervise and manage CDM projects.

By 2012 itself 1 billion CERs had been issued by the CDM Executive Board 60% of which emerged from China. India's contribution in this respect was only 15% while the Republic of Korea had 9% and Brazil 7% representation (Swartz, 2013). The carbon market has been increasing steadily from 11 billion USD in 2005 to 30 billion USD in 2006 and 64 billion in 2007. As on August 2015, there are 192 parties that accepted the Kyoto protocol of which only the non-annex countries are eligible to host CDM projects. The countries such as China, India, Republic of Korea and Brazil together account for 90 percent of the registered project. India has adopted numerous measures as part of CDM initiative by reducing emissions of greenhouse gases from various sectors like coal, oil and gas sectors, renewable energy, transport, power industry and residential sectors (Table

7.2). Afforestation and reforestation projects are also being undertaken indifferent States (Table 7.1). The biocarbon reforestation project of Himachal Pradesh is one such project with people participation. People have been encouraged to plant forest trees on degraded land spread across forest, community and private land in the villages which will be locked for a period of 20 years. The benefits accrued are to be shared with the people also. The project is expected to sequester about 500000 Mg CO_2 equivalent of GHG in 20 years. Hariyana has adopted another afforestation project in Sirsa district under the CDM where the participants (beneficiaries) are 227 private land owners from 8 villages covering about 370 hectare of private land. There is provision for the people to walk out of the project without any liabilities. The CER value in Hariyana has been agreed upon as US $130per hectare annually.

Table 7.1. Approved CDM projects in India

Name of State/Country	No of Projects	CER upto 2012
Andhra Pradesh	218	86,823,972
Arunachal Pradesh	1	156,393
Assam	15	852,579
Bhutan	1	529,914
Bihar	9	750,896
Chandigarh	106	27,368,203
Delhi	17	3,823,996
Goa	4	1,186,500
Gujarat	372	127,021,481
Haryana	37	4,512,243
Himachal Pradesh	101	17,273,314
Jammu & Kashmir	4	9814710

Jharkhand	32	24,046,731
Karnataka	255	69,702,116
Kerala	19	642,032
Madhya Pradesh	74	8,787,799
Maharashtra	388	61,620,089
Meghalaya	4	1,598,429
Multi State	103	25,330,436
Orissa	81	22,794,520
Puducherry	3	154006
Punjab	74	12,157,425
Rajasthan	237	63,178,620
Sikkim	10	9,973,169
Tamil Nadu	371	51,950,734
Tripura	1	4,427,526
Uttar Pradesh	173	37,799,292
Uttarakhand	50	20484873
West Bengal	80	26,799,892
Total	**2939**	**722,951,725**

(Source- National CDM Authority, www.cdmindia.gov.in)

Jindal *et al.* (2012) evaluated a forestry based PES program implemented in the Chicale *regulado,* Nhambita region of Mozambique. This program established seven year contracts with participating households to adopt agro-forestry systems such as intercropping with nitrogen fixing tree acacia (*Faidher biaalbida*), planting native hardwood pangapanga (*Millettia stuhlmannii*) on cropping plot boundaries, and planting fruit trees. In return, these households received revenues from the sale of carbon offsets to international buyers at a price of US$ 4.5 t-1 CO_2. In 2007-2008, each participating household received about US$ 80 from C payments.

Table 7.2. Sector wise approved CDM projects in India

Name of Sector	No of Projects	CER up to 2012
Afforestation and Reforestation	28	10,860,666
Agriculture	3	74,393
Chemical Industries	18	11,793,853
Energy Demand	224	27,109,485
Energy Distribution	9	657,149
Energy industries(Renewable/Non-renewable sources)	2309	487,466,079
Fugitive emissions from fuel(Solid, Oil and gas)	4	165,438
Fugitive emissions from production and consumption of halocarbons and sulphur	6	82,095,771
Manufacturing Industries	243	64,405,361
Metal Production	5	5,425,126
Mining/Mineral Production	4	19,053,935
Solvent use	1	103,579
Transport	13	1,238,906
Waste handling and disposal	71	12,498,337
Total (No. of Projects)	**2938**	**722,948,079**

(Source- National CDM Authority, www.cdmindia.gov.in)

It will take a while before the benefits of such projects can be assessed completely but still afforestation/reforestation and reducing emissions from deforestation and forest degradation will definitely enhance the quality of the environment along with bringing financial benefits through CDM. Kerala has plantations of different forest species, teak being the major one. The State has approximately 75000 hectare of teak plantations in various stages of growth. Considering an average yield of $60m^3$ per hectare fetching a price of $Rs.25000m^{-3}$ the State earns revenue of Rs.1500 millions an year. The mean annual increment has been worked out to be $2.423\ m^3\ ha^{-1}$ at 60 years of age which is much below the potential MAI of $4.9688\ m^3\ ha^{-1}$ at the same age indicating scope for better management.

A tropical forest plantation is expected to sequester carbon through its biomass of approximately $20\ Mg\ ha^{-1}yr^{-1}$ yielding $10\ Mg\ ha^{-1}$ of carbon per year. 1000 hectare of teak plantation can assimilate 100000 tons of carbon from the atmosphere in 10 years and thus contribute to GHG reduction. Teak has an added advantage due to its high quality of wood produced for furniture and other interior utilities and thus capable of storing the carbon in the biomass for longer periods even after harvest (Prabhu, 2003).

7.2 Methodology

Teak is planted by the Kerala forest department at 2 x 2 m spacing initially, giving a stand of 2500 trees per hectare. Periodic thinning is carried out to reduce competition between trees as they grow up. The felled trees are considered as the carbon sink as they store carbon in the biomass for longer periods. Trees felled at prescribed felling cycles at Nilambur have been sampled for estimation of carbon sequestration potential in different compartments of the tree. Multi-regional data was beyond the scope of this study; destructive sampling of biomass at each felling cycle itself was carried out with difficulty. Results obtained from teak plantations of Nilambur in various felling cycles was extrapolated using the secondary data of Forest

Working Plans regarding the age and area under teak plantations in Kerala assuming that standard prescriptions are followed at specified felling cycles. Caution is warranted in applying the calculated potential due to uncertainties in the field such as delay in operations due to mismatch of fund allotments for operations and the actual expenditure that has gone up substantially. Another major point to be considered is that the study is restricted to Nilambur region only due to practical considerations and the results on biomass and carbon content of trees at Nilambur is extrapolated to the whole of Kerala. Carbon sequestration potential of teak plantations of Kerala has been calculated for the year 2014 based on the data from our study and the secondary data, assuming that felling is carried out as per prescriptions at specified felling stages.

The carbon sequestered by teak in different ages was obtained during the destructive sampling study as explained in chapter 4. Thus the data of carbon sequestered in 5, 10, 15, 20, 30, 40 and 50 year old teak trees were obtained. The secondary data of the Kerala Forest Department working plans were used to get the standard thinning practices in teak plantations of Kerala. The Forest Department follows the thinning operations as described in Growth and Yield Statistics of Common Indian Timbers (FRI, 1970)

7.3 Results

The data generated from the study in Nilambur teak plantations were extrapolated to entire Kerala by using the secondary data from the Kerala Forest Department and the carbon sequestered by teak plantations in Kerala was calculated. It was found that the total area under teak plantation was 75000 ha in Kerala. The standard thinning operations that the forest department follow were found to be mechanical thinning with removal of every alternate row and column in the 5th year and selective silvicultural thinning in the following 10, 15, 20, 30 and 40 years of age preferentially removing weaker defective trees and considering proper canopy openings to aid adequate sunlight for photosynthesis. The plantations are final felled at the 50th year of age. Replanting normally follows final felling and the process repeats. The area of teak plantation to be felled in the year 2014 was taken from KFD data for estimating the carbon sequestration potential of teak plantations in Kerala at a specified time.

Table 7.3. Carbon sequestration at prescribed felling stages of teak

Age	Trees removed	Carbon sequestered per hectare (Mg ha^{-1})					
		Bole	Branch	Bark	Above ground	Below ground	Total
5	1250	22.78	4.48	3.92	31.18	4.11	35.29
10	448	17.95	4.58	2.52	25.05	3.79	28.84
15	264	12.83	3.8	1.72	18.35	4.01	22.36
20	190	12	2.94	1.47	16.41	3.75	20.17
30	103	10.91	1.82	1.04	13.77	3.24	17.02
40	85	17.51	3.27	1.52	22.3	4.26	26.55
50	160	53.26	10.98	4.25	68.49	12.81	81.3

The carbon sequestered by teak plantations was calculated based on the number of trees removed at each thinning stage and working out the corresponding area at these stages. The year 2014 was taken for calculating the carbon sequestration by teak plantations all over Kerala. The area prescribed to undergo thinning/felling at each stage in this particular year was taken into account and the carbon sequestration worked out accordingly. The carbon dioxide equivalents were further calculated and Certified Emission Reduction obtained based on it.

7.3.1 Carbon sequestration potential of teak plantations in Kerala in the year 2014

The total carbon that can be sequestered in 5 year old plantations during the period 2014 was calculated to be 2912.36 Mg from the thinned area of 82.53 ha (table 7.4). The compartment wise carbon accumulation was estimated as 1880.05 Mg in bole, 369.32 Mg in branch, 323.67 Mg in bark and 339.40 Mg in below ground compartment. The above ground portion sequestered an amount of 2573.05 Mg of carbon during this period.

Table 7.4. CER potential of teak plantations in 2014

Age	Area ha.	Total Carbon sequestered	Equivalent No. of CERs	Price (Million Rupees)
5	82.53	2912.35991	10677.59	8.23
10	478.74	13805.62	50615.54	39.03
15	136.55	3053.22	11194.01	8.63
20	381.76	7700.98	28234.09	21.77
30	466.14	7934.53	29090.38	22.43
40	1529.83	40619.26	148922.38	114.83
50	1784.43	145078.01	531899.52	410.12
Total	4859.98	221103.97	810633.50	625.03

It can be seen from the table that an area of 478.74 ha of 10 year old teak plantations were thinned during the year 2014 in Kerala by the forest department. The total carbon sequestered from these thinning activities was estimated as 13805.62 Mg in this age group, out of which the bole compartment store 8593.33 Mg of carbon. The respective figure for branch was 2190.87 Mg and for bark was 1208.03 Mg contributing to above ground carbon sequestration of 11992.03 Mg and the below ground portion accumulated 1813.22 Mg of carbon.

The total area felled in 15 year plantation during the year 2014 was 136.55 ha which resulted in total carbon accumulation figure of 3053.22 Mg. The carbon stored in various compartments were 2505.63Mg in the above ground portion out of which 1751.36 Mg were contributed by bole, 519.02 Mg by branch, 235.34 Mg by bark respectively and the below ground compartments sequestered 547.50 Mg of carbon.

The thinning activity in 20 year old teak plantations in 2014 conducted in 381.76 hectare could sequester 4582.67 Mg in bole compartment, 1123.32 in branch compartment and 562.14 Mg in bark compartment. The above ground regime accumulated 6268.12 Mg of carbon and the below ground component stored 1433.22 Mg which together accounts for a total carbon sequestration of 7700.98 mega grams.

The thinning activities conducted in an area of 466.76 hectare of 30 year old teak plantations in 2014 resulted in total sequestration of 7934.53 Mg of carbon. The bole component stored 5087.88 Mg of carbon while the respective figures for branch, bark and below ground compartments were 848.58 Mgs, 486.28 Mg and 1511.87 Mg of carbon. The carbon sequestered in above ground portion was found to be 6422.62 Mg by 30 year teak

It was observed that a total figure of 40619.26 Mg of carbon was sequestered in 40 year old teak trees from an area of 1529.83 ha thinned in the year 2014. The contribution from the above ground compartments was 34109.27 Mg and that from below ground portion was 6509.98 Mg to the total accumulation.

The teak plantation final felled during the year 2014 was 1784.43 ha and the carbon accumulated in the various vegetative compartments were 95039.66 Mg in bole, 19595.07 Mg in branch and 7585.60 Mg in bark. The total carbon sequestered was found to be 145078.01Mg of which 122220.35 Mg was from above ground compartments and 22857.66 Mg was from below ground portions.

Thus it was found that an area of 4859.98 ha of teak plantations of various ages were thinned or final felled during the year 2014 sequestering 221103.97 Mg of carbon. The carbon stored in the above ground components was 186091.07 Mg of which 143720.32 Mg was from bole, 29642.36 Mg from branch and 12728.76 Mg was from bark. The below ground compartments sequestered 35012.86 Mg of carbon during this period.

The Certified Emission Reduction units (CER) were calculated to give a total figure of 810633.50 number of CER units in 2014 from various teak plantations of Kerala. Five year old plantations accounted for 10677.59 units while the respective figures for the 10, 15, 20, 30, 40 and 50 year old plantations were found to be 50615.54 units, 11194.01 units, 28234.09, 29090.38, 148922.38, 531899.52 units respectively. The potential value of the CER generated from these teak plantations was 625.03 million Indian rupees of which 8.23, 39.03, 8.63, 21.77, 22.43 114.83 and 410.12 million Indian rupees were from 5, 10, 15, 20, 30, 40 and 50 year old teak plantations respectively.

The total carbon sequestration potential of teak plantation in Kerala was worked out based on the forest statistics and the present study. It was found that there are about 75000 hectares of area under teak in Kerala. The total carbon sequestered in a hectare of teak plantation was calculated as 322.20 Mg taking into account the standard felling schedule. Vegetative compartments contributed 155.90 Mg while the contribution by the soil was 166.30 Mg of carbon. Thus total carbon sequestration potential of the teak plantations in Kerala was estimated as 24165017.14 Mg. The carbon dioxide equivalents in these sequestered carbon was 88596202.35 Mg. The Certified Emission Reduction potential value of the teak plantations of Kerala was calculated based on the CER price and the current transaction rate of Indian rupees and it found that the teak plantations of Kerala has a worth of 67191 million Indian rupees in carbon in addition to to its timber value.

7.4 Discussion

Deforestation and forest degradation in the tropics, especially the developing countries, account for one-fifth of the GHG emissions (Gullison *et al.*, 2007, IPCC, 2007). India's share in CO_2 emission is relatively very small amounting to 3% during the 1980 to 2003 period. India's per capita carbon emissions have been 1/20th of that of the United States of America and 1/10th of Western Europe and Japan (Sathaye *et al.,* 2007). Energy sector contribute 743.8 Tera gram CO_2 equivalent emissions (61%), agriculture sector 344 Tg (28%), industrial processes 102.7 Tg (8%), waste disposal 23 Tg (2%) and LULUCF sector contributes 14 Tg (1%) carbon dioxide emissions.

Forest plantations of fast growing species store carbon, mitigating the effects of deforestation. Thus forest plantations are important in carbon sequestration (Kraenzel *et al.*, 2003). An estimate by Sedjo, 1989 revealed that planting of 400 million hectares of fast growing plantations can sequester 1.8 Pg of atmospheric carbon every year. However, during harvest or natural death, part of the sequestered carbon may return to the atmosphere (Harmon *et al.,* 1990). Forest tree plantations have only a small contribution to the total balance of terrestrial carbon (3.8% or 140 million ha of the world's total forest area; FAO 2006) but their potential to absorb and store carbon has been recognized to play a more important role in the mitigation of climate change (Canadell *et al.,* 2007).

Countries with significant forest resources have the advantage of receiving financial incentives through REDD$^+$ to retain their forests. The developing world stands to gain from REDD$^+$ because most of the forests are in the developing world while most of the emissions are from the developed world; funds can flow from the developed to the developing world. The Cancun agreement at the COP 16 at Mexico in 2010 further supported the activities of REDD+ in carbon sequestration (Angelsen, 2008; Kanninen *et al.*, 2010).

Many of the developing countries (Annex-1) have already claimed CERs under the CDM projects, China leading all others with 60% of total claims. India also is in the list with 14.7% while other leading countries are Republic of Korea with 9.1%, Brazil with 7.2% etc., (Swartz, 2013). Many states in India have running prospective projects. Some projects are Mid-Himalayan Watershed Development Project (MHWDP), Adani's Mundra coal power project in Gujarat, Wind Power Project in Tamil Nadu, etc.

A total of 7659 projects have been registered under CDM till August 2015 in the world of which 1545 were Indian projects (UNFCCC, 2015). The Indian CDM projects have cumulatively received 200.57 million CERs by January 2015. Forest Survey of India reports 76.86 million hectare under forest and tree cover (FSI, 2009) which is equivalent to 23.4% of the geographical area of India. The national forest policy that is conservation oriented further helps in protecting this cover and supports carbon sequestration initiatives.

Kerala State often referred as God’s own country primarily due to its greenery couldn’t capitalize on its potential in carbon sequestration, though there are a few projects in other fields that have already got into the bandwagon. Some of them are Iruttukanam Small Hydro Electric Project in Idukki, Veegaland Small Hydro Electric Project in Ernakulam, Perunthenaruvi small hydro electric project in Kollam etc. Teak plantations with absolute statistics and standard prescriptions of management developed over many years of experience has great potential to claim CERs under the CDM projects. Teak is an excellent species especially in the context of carbon sequestration and useful in claiming CERs through the CDM channel (Prabhu, 2003).

Teak plantations cover an area of approximately 75000 ha in Kerala. Carbon sequestration potential of these plantations can be calculated by taking in to account the felling prescribed at any time of reference. In 2014, 4859.98 ha of teak plantations were prescribed for felling and the carbon sequestration potential of these plantations were calculated assuming that the prescription were effectively implemented. The figure thus calculated was 221103.97 Mg of carbon contributing a total of 810633.50 number of CER units with a potential value of 625.03 million Indian rupees.

Data on the carbon sequestration by teak is essential to support CER claim. The present investigation was a footstep in this direction. Scope of the investigation was limited to Nilambur, the premier teak plantation area in Kerala. Such investigation need to be extended to other prominent regions of Kerala also to arrive at better estimates.

7.5 Summary

Carbon sequestration at successive felling stages of teak has been estimated to be 35.29, 28.84, 22.36, 20.17, 17.02, 26.55 and 81.30 tons per hectare at

5, 10, 15, 20, 30, 40 and 50 years respectively. The area prescribed to be felled in 2014 was utilized to calculate the carbon sequestration potential of teak plantations in Kerala based on the above figures. The total figure expected was thus calculated to be 221103.97 tons of carbon. Certified Emission Reduction (CER) potential based on the above estimate was found to be 810633.49 which is equivalent to 61.48 crores of rupees at current exchange rates.

Conclusions

- Teak raised as plantation in Nilambur were found to attain a height of 6.93 m at five year of mechanical thinning which increased steadily to 22.83 at fiftieth year of final felling. Diameter at breast height increased from 6.36 cm to 45.81 cm at the respective stages.

- The above ground biomass of 57.42 kg tree^{-1} at 5th year increased to 898.39 kg tree^{-1} at the 50th year. Below ground biomass at these stages were 7.97 kg tree^{-1} and 182.28 kg tree^{-1} respectively contributing to a total biomass of 65.38 kg tree^{-1} at 5th year and 1080.70 kg tree^{-1} at the final felling stage.

- Carbon sequestration by teak at 5 year growth was 28.23 kg tree^{-1} of which the above ground contributed 24.94 kg and below ground 3.29 kg of carbon per tree. It was found to increase with age to 508.14 kg tree^{-1}, the above ground contributed 428.08 kg and the below ground contributed 80.06kg tree^{-1} respectively at the 50th year of felling.

- Soil carbon was more in the surface which decreased steadily down the profile. Soil up to 100 cm depth was found to sequester 134.40 ton C ha^{-1} to 197.48 ton C ha^{-1} in successive stages of growth of plantation.

- The various fractions of soil carbon were also found to increase with maturity of plantation. The active carbon pool increased from 0.30% to 0.66%, the slow carbon 0.16% to 0.66% and the passive fraction 0.67 to 1.56% during growth. The three fractions were in dynamic equilibrium and exhibited wide variations though the overall shift from labile to recalcitrant pool was evident with growth of teak.

- Regression models to predict carbon sequestration by above ground compartment as $\sqrt{Y} = 2.113 + 0.379\ D$ and for below ground compartment was $\sqrt{Y} = 0.858 + 0.170\ D$; compartment wise equations were $\sqrt{Y} = 1.502 + 0.344\ D$ for bole, $\sqrt{Y} = 1.163 + 0.082\ D$ for bark and $\ln Y = 1.308 \ln D - 1.116$ for bark. All the models could predict carbon sequestration in teak with 97% accuracy.

- The carbon sequestration potential of teak plantations in Kerala was estimated based on 2014 figures to be 0.22 million tons of carbon. The corresponding Certified Emission Reduction being 0.81 million units equivalent to 61.48 crores of rupees.

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List of Publications

- Sandeep, S., Sivaram, M., Sreejesh, K.K. and Thomas, T.P. 2015. Evaluating Generic Pantropical Allometric Models for the Estimation of Above-Ground Biomass in the Teak Plantations of Southern Western Ghats, India. *Journal of Tropical Forestry and Environment,* 5(01): 1-8.

- Sreejesh K.K., Thomas T.P., Rugmini P., Prasanth K.M. and Kripa P.K. 2013. Carbon Sequestration Potential of Teak (*Tectona grandis*) Plantations in Kerala. *Research Journal of Recent Science*, 2: 167-170.

- Sreejesh,K.K., Thomas, T.P., Prasanth,K.M., Kripa,P.K. Seema Joseph M. and Suthesh. V. K. 2011. Tree legume rotation in Teak silviculture: Suitability of Acacia species. *Indian Journal of Ecology*, 38: 76-79.

Appendices

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Feature Article

Evaluating Generic Pantropical Allometric Models for the Estimation of Above-Ground Biomass in the Teak Plantations of Southern Western Ghats, India

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Abstract

The use of suitable tree biomass allometric equations is crucial for making precise and non-destructive estimation of carbon storage and biomass energy values. The aim of this research was to evaluate the accuracy of the most commonly used pantropical allometric models and site-specific models to estimate the above-ground biomass (AGB) in different aged teak plantations of Southern Western Ghats of India. For this purpose, the AGB data measured for 70 trees with diameter $\geq$10 cm from different aged teak plantations in Kerala part of Southern Western Ghats following destructive procedure was used. The results show that site specific models based on a single predictor variable diameter at breast height (dbh), though simple, may grossly increase the uncertainty across sites. Hence, a generic model encompassing dbh, height and wood specific gravity with sufficient calibration taking into account different forest types is advised for the tropical forest systems. The study also suggests that the commonly used pantropical models should be evaluated for different ecosystems prior to their application at national or regional scales.

Keywords: allometric models, above ground biomass, Western Ghats

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1. Introduction

Estimation of volume, biomass and carbon stocks supports several applications from the commercial exploitation of timber to the global carbon cycle. Especially, in the latter context, the estimation of tree biomass with sufficient accuracy is essential to determine annual changes of carbon stored in particular ecosystems. Such estimations are the core of carbon sequestration projects (sink projects) dealing with the accumulation and long-term storage of atmospheric carbon in vegetation and soil organic matter. These projects give a better understanding of nature’s carbon sinks, and the valuable information and evidence generated therein will help addressing the physical, natural, social and economic aspects of climate change in a more factual way.

Tropical forests, which constitute 60% of world forests and 43% of terrestrial net primary productivity (Dixon et al., 1994), dominate the role of forests in the global carbon flux and stocks, and hence demand great attention with respect to carbon policies and estimations. In spite of their

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importance to the carbon cycle, there is little information on the carbon budgets of tropical forest systems in South Asia. Efficient and accurate national systems for measurement, reporting and verification (MRV) systems are required in the region to properly assess carbon stocks and support international climate change efforts**.** The use of suitable allometric equations is a crucial step in such endeavours, making precise and non-destructive estimation of above and below ground biomass and carbon storage in the region.

Allometry, generally relates some non-easy to measure tree characteristics (i.e., volume, biomass) from easily collected data such as dbh (diameter at breast height, also denoted as D), total height, or tree age and provides relatively accurate estimates. Despite their apparent simplicity, these models have to be built carefully, using the latest regression techniques. Tree growth parameters vary considerably with species, site quality, location, climatic regimes, altitude etc. and therefore becomes necessary to obtain accurate and precise tree allometric estimates in order to improve understanding of the role of these carbon sinks in global carbon cycle. An unsuitable application of allometric equation may lead to considerable bias in carbon stocks estimations (Henry, 2013). Although, large number of allometric equations for estimating above-ground biomass (AGB) have been published in South Asia during the last decades (Sandeep et al., 2014), the pantropical models developed by Chave et al. (2005) are widely considered to be the best current approximation for sites for which local equations are not available (Clark, 2007). However, the predictive power of these global models differs among sites (Chave et al., 2005). For this reason, the evaluation of the accuracy of these models with new data and in different geographic locations is needed.

Due to the uncertainties in the generic pantropical models, a simplest and most practical approach is based only upon tree diameter at breast height (Basuki et al., 2009; Alvarez et al., 2012). However, scaling of dbh alone based models to a regional or global scale may have greater uncertainties than more complex models (West et al., 1999; Zianis, 2008). Inclusion of wood density and tree height has proved to improve biomass estimations considerably (Brown et al., 1989; Chave et al., 2006; ter Steege et al., 2006; Wang et al., 2006; Patiño et al., 2009). The present work aims to evaluate the accuracy of the most commonly employed pantropical allometric models and simple dbh alone based site specific models to estimate AGB in different aged teak plantations of Southern Western Ghats.

2. Materials and Methods

2.1 Tree harvesting and biomass estimation

Teak plantations in different thinning regimes and at final felling were surveyed in Nilambur Forest Division of Kerala state, India and seven sites corresponding to the prescribed felling schedule were selected for the study. Presently the thinning operations are performed in teak plantations at the ages of 5, 10, 15, 20, 30, and 40 years and the plantations are clear felled at 50 years. Each site represents a specific age. Ten randomly selected trees were felled at each of these sites and were used for biomass estimations. Before felling, dbh was measured at 1.37 m or above buttresses.

The total heights (H) of the trees were measured on the ground using a measuring tape from the base towards the apex of the crown. Felled trees were separated into their components (trunk, branches and foliage) and were directly weighed in the field to assess the fresh weight. Root systems of the selected trees in each site were excavated manually by starting at the stump and following the roots to possible limits and weighed. Sufficient samples of wood, branches and roots were taken from each tree to determine their moisture contents. Biomass of various compartments were worked out by estimating dry matter of samples by oven drying to constant weight and extrapolation to the whole biomass, which are referred to as measured biomass in this article.

2.2 Evaluation of existing allometric models

The accuracy of the pantropical allometric models developed by Brown et al. (1989), Chave et al. (2005), and Zianis (2008) (Table 1) were evaluated by calculating the relative error in the predicted biomass to measured biomass for each site. The relative error (RE) for above-ground biomass (AGB) was calculated using equation 1.

Table1: Evaluated pantropical models for estimating the above-ground biomass (dry mass) of tropical trees from their diameter (cm), height (m), and wood density (g cm^{-3}).

Model code	Allometric models	Source
Chave Type I	$\exp(-2.187 + 0.916 \ln(\rho D^2 H)) = 0.112 (\rho D^2 H)^{0.916}$	Chave et al. (2005)
Chave Type II	$\exp(-2.977 + 0.916 - \ln(\rho D^2 H)) = 0.0509 (\rho D^2 H)$	Chave et al. (2005)
Chave Type III	$\exp(-2.557 + 0.940 \ln(\rho D^2 H))) = 0.0776 (\rho D^2 H))^{0.940}$	Chave et al. (2005)
Brown	$\exp(-2.4090 + 0.9522 \ln(\rho D^2 H))$	Brown et al. (1989)
Zianis	$0.1424 D^{2.3679}$	Zianis (2008)

$$RE = (AGB_{predicted} - AGB_{measured}) \Big/ AGB_{measured} \qquad (1)$$

Following Chave et al. (2005), the overall biases were evaluated by examining the mean relative error (%), and the accuracy was evaluated by examining the standard deviation of relative error (%) across sites, which represented the overall predictive power of the regression (Chave et al., 2005).

At a local scale, the simplest models for assessing AGB are based upon tree dbh (Sierra et al., 2007; Litton and Kauffman, 2008; Basuki et al., 2009). Five teak specific allometric models (models 1-7 in Table 2) based only upon dbh, developed in Kerala, were evaluated for their accuracy and predictive capacities. However, a simple geometrical argument suggests that the total AGB of a tree with diameter D should be proportional to the product of wood specific gravity (oven-dry wood over green volume, denoted by ρ), times trunk basal area (BA=π D^2/4), times total tree height (H). Hence, the relationship should hold across forests as in equation 2:

$$GB = F \times \rho \times (\pi \times D^2/4) \times H \qquad (2)$$

Table 2: Tree biomass models for predicting above-ground biomass (y) of teak plantations in Kerala part of Southern Western Ghats.

Models	Allometric models
Model-1	$\log(y) = 1.606 + 0.197 \log(D)$
Model-2	$\log(y) = 0.636 + 1.265 \log(D)$
Model-3	$\log(y) = 0.567 + 1.367 \log(D)$
Model-4	$\log(y) = 0.479 + 1.374 \log(D)$
Model-5	$\log(y) = -0.150 + 1.809 \log(D)$
Model-6	$\log(y) = 1.736 \log(D)$
Model-7	$\log(y)) = 0.685 + 1.376 \log(D)$
Model-8	$y = F \times \rho \times (\pi D^2/4) \times H$

Model 8 tries to capture this argument and hence evaluates the efficacy of equations with wood density and height factors rather than dbh alone. The multiplicative coefficient *F* depends on tree taper and was taken as 0.06 as predicted by Cannell (1984) for broad leaved species (Chave, 2005).

3. Results and Discussion

The results show that there was a linear increase in dbh of tress with age (Figure 1) and there was about 8 cm decadal increases in dbh of teak trees with age. On an average, teak plants yielded 1052.2 kg/tree (AGB+roots) of which 60.4% was contributed by wood, 5.6% by bark, 17.4% by branches and 16.5% by roots (data not shown). As percent of AGB, root contribution was 20%. Though root biomass is as important as shoot in carbon stock estimations, there were very few documents on root growth parameters (Sandeep et al., 2014). As a proportion of AGB, roots were found to contribute 14%-27% to the total biomass of teak. The decline in ratio of root:AGB in teak indicates accumulation of carbon in above-ground portions alone after 30 years.

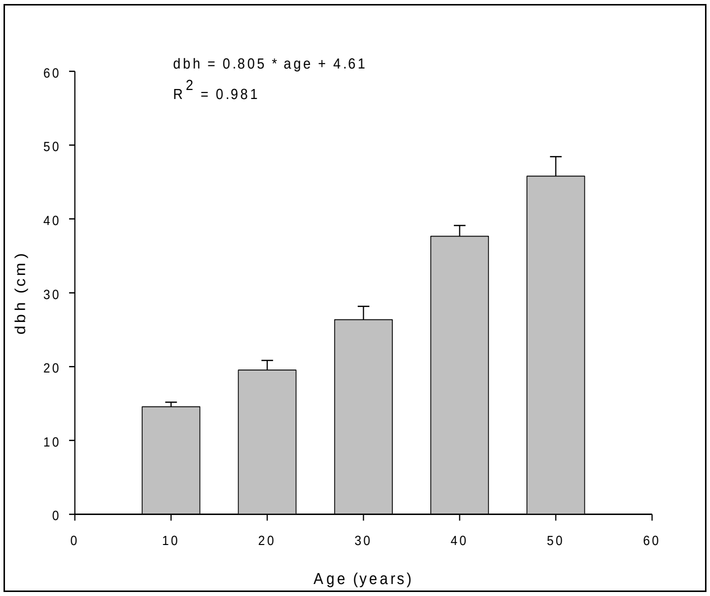

Figure 1: Trends in mean dbh of trees with age in teak plantations of Kerala part of Southern Western Ghats.

Overall, the Chave type of Table 1 (2005; hereafter Chave I) model had the lowest bias for estimating the total average AGB in different sites (-1.5%) (Table 3). However, this model was quite unstable at the site scale (22.5%). The Type II model of Chave et al. (2005; hereafter Chave II) at the site scale underestimated the average AGB of the forests within acceptable limits (-5.0%). The model of Brown et al. (1989; hereafter Brown) had a similar but positive bias in magnitude at the site scale (9.1%) when compared with Chave I and II but highest uncertainty (26.9%) among the tested models.

Zianis model (2008; hereafter Zianis) though underestimated AGB than Brown and Chave (I and II) models at the site scale, had the lowest uncertainty. The Type III model of Chave et al. (2005; hereafter Chave III), tended to strikingly underestimate the AGB across sites with respect to Chave I and II and Brown models and had very low stability. The allometric model developed by Zianis included only dbh as an explanatory variable. Earlier West et al. (1999) and later Chambers et al. (2001) showed that AGB does not follow a simple power law scaling relation with stem diameter. The instability in models with H, ρ and forest types may be due to some fundamental differences in the way ρ was assessed and included in the study. In the present analyses, inferred ρ values were used from the literature which have several disadvantages in comparison to field measurement data because they add an additional amount of uncertainty to the models (Chave et al., 2005).

Table 3: Variation in root biomass to AGB ratio in teak plantations in Kerala part of Southern Western Ghats.

Age	dbh (cm)		AGB (kg/tree)	Root to AGB ratio
	Min	Max		
10	12.2	19.43	133.31	0.16
20	13.69	27.39	189.21	0.26
30	20.38	36.62	320.97	0.27
40	32.80	44.59	621.04	0.21
50	36.31	59.87	878.47	0.20
	Mean		340.99	0.21

The inferred ρ data assumed a unique value across the age and dbh classes. In addition to the concerns related to ρ measurement, the changes in the H:D relationship observed in the data set determined by the site variation were not detected by Brown and Chave model, further restricting their accuracy. All the pantropical models evaluated gave a gross underestimation for dbh values <20 cm and overestimation >40 cm. From the preliminary analysis neither of the evaluated pantropical models could be recommended for application at national or regional scales.

The species-specific models used in this study also had higher biases, but were more stable (except models 1, 7 and 8). Of the species-specific models at the individual scale, model 3 that used the dbh ranges 10-25 cm was statistically the best of all of the models evaluated (Table 5). The study could not conclusively establish that using a single predictor ‘dbh’ in allometric models is an accurate AGB estimation method across different sites, though simple and practical.

Table 4: Relative percent error of pantropical equations in evaluating above-ground biomass in different age teak plantations in Kerala part of Southern Western Ghats.

Age (Years)	Chave Type I	Chave Type II	ChaveType III	Brown	Zianis
5	-38.9	-52.8	-50.7	-38.3	-49.9
10	-44.3	-53.9	-54.2	-42.1	-39.1
15	-46.7	-53.8	-55.6	-43.5	-52.2
20	0.4	-9.3	-15.4	8.3	-14.3
30	6.6	2.1	-8.6	18.0	1.1
40	49.7	56.7	31.6	72.1	23.1
50	62.5	75.8	44.2	89.5	39.0
Mean (%)	-1.5	-5.0	-15.5	9.1	-13.2
SD (%)	22.5	25.8	20.3	26.9	15.0

Model 8 that included dbh, wood density and height showed good performance at the individual site scale at all the evaluated dbh ranges but had very high instability, hence further refinement suggested. The form factor F in model 8 was assumed to be equal to 0.6 for this study, close to the predictions of Dawkins (1961) and Gray (1966) for broadleaf tree species. However, engineering arguments (McMahon and Kronauer, 1976) suggest that the form factor is not a constant but trees taper as a powerlaw along the main stem.

Table 5: Relative percent error of site specific equations in evaluating above-ground biomass in teak plantations in Kerala part of Southern Western Ghats.

Models	Relative Error (%)	Standard Deviation
Model - 1	-68.76	20.2
Model - 2	-19.42	16.3
Model - 3	-5.69	16.2
Model - 4	-21.30	13.4
Model - 5	-26.82	13.2
Model - 6	-18.20	13.2
Model - 7	27.30	21.6
Model - 8	-6.15	55.7

The assumption of a constant *F* will grossly reduce the stability of model 8 across dbh and height classes. Wood specific gravity is another important predictive variable used in model 8. Baker et al. (2004) have reported that ignoring variations in wood density would result in poor overall prediction of allometric models. Several workers (Brown et al. 1989; Nelson et al. 1999; Chave et al. 2003; Baker et al. 2004) have recommended using a species-level average or a stand-level average of wood density as direct tree density measurements are seldom available. Thus a model encompassing D, H and ρ with sufficient calibration for different forest types is advised for the tropical forest systems.

4. Conclusion

AGB quantifications have major implications in assessing ecosystems capacity to sequester carbon. Chave I model had the lowest bias for estimating the total average AGB in different sites, but was quite unstable at the site scale. Zianis model though underestimated AGB than Brown and Chave (I and II) models at the site scale, had the lowest uncertainty. All the pantropical models evaluated gave a gross underestimation for dbh values <20 cm and overestimation >40 cm. From the present study, neither of the evaluated pantropical models could be recommended for indiscriminate application at national or regional scales. Of the species specific models at the individual scale, model 8 that included dbh, wood density and height showed good performance at the individual site scale at all the evaluated dbh ranges but had high instability. The study concludes that a model encompassing D, H and ρ is advised for the tropical forest systems. The model can be made more stable by proper substitution of ρ and form factors considering the age structure and forest types. In this regard, further work is needed to evaluate other available allometric equations besides finding out suitable ρ and form factors.

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Carbon Sequestration Potential of Teak (*Tectona grandis*) Plantations in Kerala

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Abstract

Teak (Tectona grandis) is the most important forest plantation species and it occupies the major area under forest plantations in Kerala. In addition to its value as an ideal timber, it also plays an important role in storing carbon. The silviculture of teak necessitates felling at regular intervals of 5, 10, 20, 30, 40 and 50 years of age. The present study was carried out to estimate the carbon storage in different compartments of teak in each of these felling periods to arrive at an estimate of its carbon sequestration potential. Carbon content of teak biomass was estimated using CHNS analyser. There was slight variation in carbon content between age groups and considerable difference between various parts of the tree. The wood contained around 46%, bark around 32%, branches around 40% and the roots around 45% of carbon. Regression equations were developed to predict the total tree carbon storage from tree measurements. It was found that around 181 ton carbon per hectare is stored by a teak plantation in Kerala during its life time of 50 years by yielding biomass at different stages of thinning operations and at final felling stage.

Key words: Teak, carbon sequestration, Kerala.

Introduction

Teak (*Tectona grandis* Linn. F) is a valuable timber yielding species in the tropics especially India, Indonesia, Malaysia, Myanmar, northern Thailand, and northwestern Laos. The first teak plantation in the world was raised in Nilambur, Kerala, India in the year 1840. The Kerala Forest Department now has about 56510 ha under teak, out of which approximately 64 per cent is in the first rotation and the remaining 36 percent in the second and third rotation stages and about 1000 ha is being felled and replanted every year[1,2].

Global warming due to increased concentration of green house gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and sulphur hexa fluoride (SF6) in the earth's atmosphere is one of the most important concerns of mankind today[3]. United Nations Framework Convention on Climate Change (UNFCCC) created during the Rio Earth Summit in 1992 to stabilize GHG concentration in the atmosphere came into force in March 1994. The 3rd conference of parties (CoP 3) which met in Japan in 1997 decided on certain protocols which came to be known as Kyoto protocol. The Kyoto protocol legally binds 39 developed countries to reduce their GHG emissions by an average of 5.2% relative to 1990 levels by the period 2008-2012, referred as the first commitment period. The Kyoto protocol permits the developed countries to reach their targets through several mechanisms. They are emission trading, joint implementation and clean development mechanism (CDM). CDM allows developed nations to achieve reduction obligation through projects in developing countries that reduce emissions or sequester CO_2 from the atmosphere[4,5]. The CoP 7 of UNFCCC that met in Bonn (Germany) in July 2001 decided to include Afforestation and Reforestation (A/R) as an effective way to reduce atmospheric carbon by building up terrestrial carbon stocks and to produce Certified Emission Reductions (CERs).

It has been suggested that improved land management could result in sequestration of substantial amount of soil carbon and can be an option to reduce atmospheric CO_2 concentration [6,7,8]. Forest management such as rotation length is seen as an activity that countries may apply under the Kyoto Protocol to help them meet the commitments for reduction of green house gas emissions[9]. However, the benefits can get reversed through disturbances and harmful practices during harvest which would release the carbon back to the atmosphere. Individual trees and stands of trees sequester carbon within their main stem wood, bark, branches, foliage and roots. Carbon sequestered by the main stem wood results in longer sequestration while other components sequester and release carbon on shorter intervals due to natural pruning and decomposition[10].

Carbon sequestration potential of tree species becomes relevant in this respect. It varies with species, climate, soil and management. Forest plantations have significant impact as a global carbon sink[11,12]. Young plantations can sequester relatively larger quantities of carbon while a mature plantation can act as a reservoir. Long rotation species such as teak (*Tectona grandis*) has long carbon locking period compared to short duration species and has the added advantage that most of the teak wood is used indoors extending the locking period further.

Material and Methods

Teak plantations in different thinning regimes and at final felling were surveyed in Nilambur forest division, Kerala and seven sites corresponding to the prescribed felling schedule and on comparable site quality selected for the study. Measurements of fifty standing trees as regards height and GBH were taken while the ten felled trees were measured as logs. Fifty trees closest to transects taken at right angles to each other were considered for the purpose of height and GBH measurements. Samples of wood from ten felled trees in each of the sites were collected by slicing thin discs from the cut portions of logs. Samples of wood were also collected from different branches of each felled tree. Root systems of the selected ten trees in each site were excavated manually by starting at the stump and following the roots to possible limits. The stump along with the exposed roots were pulled out with the help of tractor. Estimation of fine roots was done by taking pits around each tree from which all soil was removed to isolate fine roots to possible extent. They were weighed in the field itself and samples collected from different parts of the root system to estimate dry mass.

The schedule of felling operations presently followed by the Kerala Forest Department in teak plantations is the first mechanical thinning at the age of 5 years by removing every alternate row to facilitate space for growth which is followed by selective silvicultural thinnings at 10, 15, 20, 30, and 40 years when 1739, 318, 126, 103, 40 and 19 trees respectively are removed from a hectare. The plantations are clear felled at 50 years when hardly 155 trees remain.

Carbon storage was worked out at two levels *viz*., tree level and plantation level. Above ground and below ground biomass of teak was estimated by destructive sampling. Biomass of trees that are removed from the site through felling at each stage including the final felling stage was only considered for estimating carbon sequestration.

Various regression equations were fitted for each age class using DBH as an independent variable and total tree carbon storage (wood + branches + root + bark) as dependent variables using data from 10 trees/age class. Data were transformed to log to the base 10 as is commonly done to linearize data of this type. The statistical analyses were conducted using SPSS soft ware package.

Results and Discussion

Biomass of teak trees of different ages: Data on biomass of teak at different felling cycles is given compartment wise as wood, bark, branches and root (table 1). Above ground biomass represent mean of 50 trees and below ground biomass represent 10 trees. It can be seen that at the 5th year mechanical thinning wood biomass amounted to 50.56 kg/tree on an average, bark constituted 8.92kg/tree while the contribution of root was 8.33kg/tree. Wood constituted 75%, bark 13% and root 12% of the total biomass. At the age of 10 year the wood biomass was estimated to be around 91.5kg, the bark around 14.89kg, branches 26.91kg and root around 21.28kg per tree. Wood constituted 59%, bark 10%, branches 17% and root 14% of the total biomass.

At the second silvicultural thinning of fifteenth year, wood constituted 121.5kg, bark 16.76kg, branches 27kg and root 38.67kg per tree. The contribution of wood was found to be 50%, bark 8%, branches 25% and root 17% of the total biomass. At the age of 20 years the respective figures were 142.28kg of wood, 19.4kg of bark, 27.53kg of branches and 48.51kg of roots per tree. Wood constituted 60%, bark 8%, branches 12% and root 20% of the total biomass.

At the 30th year of fourth silvicultural thinning, wood was found to yield 254.34kg, while the bark constituted around 28.26kg per tree. The contribution of branches was 38.38kg and that of root 87.60kg per tree towards the tree biomass. Wood constituted 62%, bark 7%, branches 9% and root 21% of the total biomass. The wood biomass at the 5th silvicultural thinning at the age of 40 years was found to be around 480.48kg, bark biomass around 44.63kg while the branches were found to weigh about 95.93kg per tree and the root portion contributed 131.28kg of biomass. Wood constituted 64%, bark 6%, branches 13% and root 17 percent of the total biomass. Biomass partitioning at the age of 50 years was found to be in the order of 635.85kg wood, 59.07kg bark, 183.55kg branches and 173.73kg of roots per tree. Wood constituted 66%, bark 6% and branches and root 17% each of the total biomass.

Table-1
Biomass distribution in various compartments at different thinning stages

	Mean biomass (kg/tree) ± SD						
Compartments	5 year	10 year	15 year	20 year	30 year	40 year	50 year
Wood	50.56 ±3.00	91.50 ±8.55	112.15 ±18.47	142.28 ±54.00	254.34 ±94.50	480.48 ±67.55	635.85 ±155.45
Bark	8.92 ± 0.06	14.89 ±2.03	16.76 ±4.56	19.40 ±4.37	28.26 ±9.24	44.63 ±10.30	59.07 ±12.50
Branches	-	26.91 ±11.53	27.00 ±18.62	27.53 ±22.14	38.38 ±25.34	95.93 ±23.65	183.55 ±64.53
Root	8.33 ±0.50	21.28 ±3.24	38.67 ±4.32	48.51 ±15.00	87.60 ±20.40	131.28 ±25.00	173.73 ±46.53
Total	67.81	154.59	223.14	237.72	408.57	752.32	1052.20

SD - Standard Deviation

Table-2
Mean carbon content in different compartments at various stages of growth

Compartments	**Mean carbon content (kg/tree) ± SD**						
	5 year	**10 year**	**15 year**	**20 year**	**30 year**	**40 year**	**50 year**
Wood	23.26 ±1.50	42.09 ±4.21	51.59 ±7.70	65.45 ±24.25	116.99 ±24.40	221.02 ±21.24	292.49 ±102.50
Bark	2.86 ±0.30	4.77 ±0.45	5.36 ±1.20	6.21 ±2.06	9.04 ±3.22	14.28 ±2.36	18.90 ±6.04
Branches	-	11.30 ±3.23	11.42 ±5.24	11.56 ±7.24	16.12 ±11.76	40.29 ±12.30	77.09 ±20.20
Root	3.33 ±0.15	8.94 ± 1.65	16.63 ±2.22	20.86 ±6.00	38.55 ±9.35	57.76 ±8.54	76.44 ±18.36

SD - standard deviation

Table-3
Regression equations for predicting per tree total carbon content

Plantation	**Regression**	**Adjusted R^2**	**t-value for slope coefficient**
5 Year	Log (Y) = 1.301 + 0.197 log (DBH)	0.875	7.992**
10 Year	Log (Y) = 0.429 +1.201 log (DBH)	0.909	9.542**
15 Year	Log (Y) = 0.381 +1.293 log (DBH)	0.840	6.957**
20 Year	Log (Y) = 0.261 +1.344 log (DBH)	0.944	12.395**
30 Year	Log (Y) = -0.412 +1.818 log (DBH)	0.981	21.509**
40 Year	Log (Y) = -0.282 +1.743 log (DBH)	0.953	13.507**
50 Year	Log (Y) = 0.268 +1.461 log (DBH)	0.883	8.292**

** significant at p = 0.01

Carbon content of teak trees of different ages: Carbon content of teak partitioned in the wood, bark, branches and root is given in Table 2. It can be seen that at the age of 5 years, the wood portion of the tree contained 23.26 kg carbon, the bark 2.86 kg and the root 3.33 kg carbon per tree. At the first silvicultural thinning of 10th year, carbon content in wood was found to be 42.09 kg, that in bark around 4.77kg, branches around 11.3kg and the roots contained around 8.94kg carbon per tree. At 15 year of age, wood portion of the tree on an average was found to contain 51.59kg carbon while the bark contained 5.36kg, the branches 11.42kg and the roots 16.63kg carbon.

Carbon content of wood was found to be 65.45kg, that of bark 6.21kg, branches 11.56kg and the root 20.86kg on an average per tree at the time of third silvicultural thinning at 20 years of age. At thirty year age when the fourth silvicultural thinning is carried out the average carbon content per tree was found to be 116.99kg in wood portion, 9.04kg in bark, 16.12kg in branches and 38.55kg in the roots. At the fifth silvicultural thinning at the 40th year carbon content in wood was about 221.02kg, that in bark around 14.28kg, while the branches contained about 40.29kg and the root 57.76kg per tree. Carbon content of wood portion was found to be around 292.49kg, bark around 18.99kg, branches around 77.09kg while the roots contained 76.44kg carbon per tree at the age of 50 years.

Carbon content in compartments of different aged teak trees is shown in Fig 1. It can be seen that most of the carbon was stored in the wood portion which was followed by root, branches and bark, the trend becoming more pronounced in the latter years.

Development of prediction equations of carbon storage: Various regression equations were fitted for each component of carbon storage to develop non destructive predictors and are given in table 3. The 't' values of regression coefficients of the equations were also highly significant in all cases.

Linear regression equations of log DBH versus per tree total carbon content show that these relationships are strong yielding coefficients of determination (R^2) of 0.840 to 0.981 in various thinning regimes which means that the variation in total carbon content could be well explained by DBH of trees in all the plantations.

Estimation of carbon storage potential of teak plantations in Kerala: Carbon storage potential of teak plantations in Kerala was calculated based on the number of trees removed at each felling cycle and is given in table 4. The carbon storage potential was found to be 51.20 t/ha at the first mechanical thinning of 5 year growth, followed by 21.34, 12.21, 10.72, 7.23 and 6.33 t/ha during the first, second, third, fourth and fifth silvicultural thinning at 10, 15, 20, 30 and 40 years of age respectively and 72.1t/ha at the time of final felling.

Table-4
Plantation level carbon sequestration (Tons per hectare)

Felling regime	No. of trees removed	Carbon (t/ha)
5	1739	51.2
10	318	21.34
15	126	12.21
20	103	10.72
30	40	7.23
40	19	6.33
50	155	72.1
Total	2500	181.13

Conclusion

It can be concluded within the limitations of the present study that 181.13 ton carbon per hectare could be stored by a teak plantation in Kerala during its life time of 50 years by yielding biomass at different stages of thinning operations and at final felling stage.

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Tree Legume Rotation in Teak Silviculture: Suitability of *Acacia* species

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Abstract: The paper describes interim results of soil improvement due to planting of *Acacia* species in degraded teak plantation sites. *Acacia auriculiformis* and *Acacia mangium* were raised along with *Tectona grandis* in clear felled teak plantation sites at Nilambur and Thrissur by the Forest Department. Soil amelioration due to legume tree rotation was assessed in these five year old plots by studying the improvement in soil physical, chemical and biological properties. Litter dynamics of the two species of *Acacia* was also compared with that of the prime species of teak. Soil structure and its water stability were found to be influenced by the species. Both the *Acacia* species were found to be capable of retaining more soil moisture than teak which can be attributed to its canopy characteristics and the slow decomposing litter accumulation combined with the deciduous nature of teak. No significant difference between species could be recorded in soil pH and organic carbon though a slightly higher value of calcium was observed in teak soil. Root nodulation was found to be more in *A. mangium* as compared to *A. auriculiformis.* Litter fall, litter decomposition and nutrient release from the fallen litter were studied. Preliminary results indicate that litter fall was highest in *A. mangium* followed by *A. auriculiformis* and *T. grandis*. Litter decomposition on the contrary was faster in the case of *T. grandis,* which was followed by *A. auriculiformis* and *A. mangium*. All the litter of *T. grandis* got decomposed in 9 months time, while 93 per cent of *A. auriculiformis* and 83 per cent of *A. mangium* litter decomposed in an year's time. Nutrient release was found to follow the pattern of litter decomposition.

Key Words*:* Short rotation tree legumes, Soil amelioration, Litter dynamics, *Acacia auriculiformis, Acacia mangium, Tectona grandis*

Teak is one of the most favoured timber all over the world, since it has been used for many centuries for a range of products and services. Kerala has 74872 ha of teak plantations and on an average 1000 ha. is being felled and replanted every year (Prabhu, 2003). But continuous cropping of the same species over such long gestation period make huge demand on the site and soil especially on sloping terrain. Jose and Koshy (1972) reported soil compaction and fertility decline in teak, Alexander *et al.* (1980) observed site quality deterioration in second and third rotation teak while Balagopalan and Jose (1982) and Balagopalan and Chacko (2001) reported decrease in soil organic carbon and nitrogen in second rotation plantation. Thomas *et al.* (1997) quantified soil erosion from young teak plantation to the extent of 4-15 metric tons/ha.

Forestry, being low input as against agriculture, soil and nutrient enrichment by way of high inputs are not feasible. Rotation with tree legumes, though not attempted till now, has been considered an ideal choice to ameliorate the harm done through continuous monoculture. Kerala Forest Department has raised experimental plots of *Acacia auriculiformis, Acacia mangium* and *Tectona grandis* in clear felled teak plantation sites at Nilambur and Thrissur. *A. mangium* and *A. auriculiformis* are fast-growing legume trees belonging to the sub-family Mimosoidae. They are tropical rainforest species, which originated from Australia. Rhizobium spontaneously infect the acacia root system and form root nodules that have the capacity of directly fixing atmospheric nitrogen like most legumes, thus allowing these species to grow on N deficient soils (Brockwell *et al*., 2005). *Acacia* has also been reported to improve soil (Swamy, 1989). They are also widely grown multipurpose trees in the tropics suitable for firewood, charcoal and paper pulp production and light construction wood. Rotation with tree legumes can improve the soil and reverse deterioration to a certain extent. Yang *et al.* (2009) reported that *A. auriculiformis* and *A. mangium* has the ability to fix nitrogen and *A. mangium* has greater facilitating effects due to greater temperature buffering and nutrient amelioration. Sankaran *et al.* (1993) reported 9.3-12 t ha^{-1} annual litter production in *A. auriculiformis* plantation in Kerala, which is considered higher than those reported for other major plantation species. He had also found VAM and rhizhobial association with the roots of the species. Balasundaram *et al.* (2000) had observed that root nodulation in *A. auriculiformis* was affected by soil properties; less fertile soil inducing more nodulation. The present study was carried out in the experimental plots laid out to understand the influence of *A. auriculiformis* and *A. mangium* in site improvement of teak at Cheppilakkode, Thrissur.

MATERIAL AND METHODS

The study was carried out in the established research plots of Kerala Forest Department at Chepppilakode, Thrissur (10°30'N and 76°20' E). Plots of 20x20m of *Tectona grandis, Acacia auriculiformis* and *Acacia mangium* had been established in 2005 with a spacement of 2x2m and with 4 replications. The site received a rainfall of 2885 mm and temperature varied from 14 to 37°C. The soils in general are well drained reddish-yellow oxisols.

Soil samples were collected from the surface upto a depth of 20cm. Three soil samples were taken from each of the 12 plots. Core samples were collected separately for bulk density and big clods for aggregate stability estimation. Soil samples were air dried, passed through 2 mm sieve and subjected to analyses following procedures given in ASA Monograph (1965) and Jackson (1973). Sand, silt and clay (0.02-2, 0.002-.02 and < 0.002mm) were determined by hydrometer and particle density (PD) by using standard flask. Water stable aggregates were quantified using a Yoder type wet sieving apparatus; pH in 20:40 soil: water suspension and organic carbon (OC) by potassium dichromate-sulphuric acid wet digestion. Exchange acidity (EA) was determined by 0.5 N barium acetate and exchangeable bases by 0.1 N hydrochloric acid. Nitrogen (N) and Phosphorus (P) were estimated by autoanalyser, potassium (K) by colorimeter and calcium (Ca) and magnesium (Mg) by atomic absorption spectrometry. Mean Weight Diameter (MWD) was calculated using the formula MWD = $\Sigma x_i w_i$; where xi is the mean diameter of a particular size class and wi is the weight in that range as a fraction of the total sample weight.

In each plot, 5 litter traps of 1m diameter bamboo baskets were kept and litter samples collected at monthly interval and quantified. Litter bag technique (Swift and Anderson, 1989) was used to study the pattern and rate of litter decomposition and nutrient release of the three species. Fifty grams of oven-dried leaf litter of *T. grandis, A. auriculiformis* and *A. mangium* were kept in 0.5 cm mesh litter bag of size 35 cm × 35 cm and laid in the respective plots. Thirty six litter bags were laid randomly in each plot so that 3 bags could be retrieved every month. The bags were carefully taken to the laboratory, the contents emptied and extraneous materials such as soil, visible animals and fine roots were removed. The sample was oven-dried at 70 °C to constant weight and analysed for N, P, K, Ca and Mg contents.The exponential model of Olson (1963), $X/X_0 = e^{-kt}$ was used to estimate the annual decomposition rate of litter, where ‘X’ is the weight of litter remaining after time‘t’, ‘X_0’ is the initial weight of litter, ‘e’ is the base of natural logarithm and ‘k’ is the decomposition rate constant. This model was also used to calculate the half life of litter decomposition. Statistical analysis of data was carried out by SPSS package.

RESULTS AND DISCUSSION

Data gathered on litter fall and litter decomposition and consequent nutrient release are given in Table 1. The influence of acacia species on soil properties was both positive and negative. Aggregate stability analysis has brought out some positive influence of acacias. Bigger aggregates were formed in acacia plots compared to teak plots. Among the species, *A. auriculiformis* was found to exert greater influence. Mean weight diameter, the index of aggregate stability was higher in acacia plots. This might be due to higher amounts of finer roots that press the particles on the one hand, the differential pressure exerted by these roots during moisture absorption and their contribution towards humus on senescence. Bulk density (g cc^{-1}) was slightly less and porosity slightly more in acacia plots compared to teak. Proportionately higher contents of bigger aggregates would have helped in reducing the bulk density though the effect was not significant. Thus, it can be seen that both *A. auriculiformis* and *A. mangium* were instrumental in improving the soil structure and its stability. Soil acidity was found to be increased by acacia species as was seen in the pH values of 5.25 and 5.3 compared to 5.8 in teak plots and this difference was significant. Similar results were reported by Sankaran *et al.* (1993). Organic carbon contents were significantly higher in acacia plots with values 16.8 g kg^{-1} in *A. auriculiformis* and 14.2 g kg^{-1} in *A. mangium* as compared to lower accumulation of 12.6 g kg^{-1} in *T. grandis* plots. Exchange acidity was more in acacia plots (64 cmol kg^{-1} in the case of *A. auriculiformis* and 66 cmol kg^{-1} in the case of *A. mangium*) as compared to 62 cmol kg^{-1} in *T. grandis,* while exchangeable bases were more in *T. grandis* (54 cmol kg^{-1}) compared to *A. auriculiformis* (46 cmol kg^{-1}) and *A.mangium* (48 cmol kg^{-1})

Table 1. Litter fall (kg ha^{-1})

Species	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Tectona grandis	357±19	337±28	224±21	220±19	240±35	280±19	264±31	310±27	250±30	237±31	342±25	420±19
Acacia auriculiformis	700±40	524±38	206±31	154±32	162±32	237±33	240±29	230±21	251±28	247±25	416±17	815±20
Acacia mangium	574±32	552±30	240±34	235 ±29	210±31	355±22	346±30	284±31	242±21	250±29	376±22	634±15

plots. Higher litter fall (Table. 2) might have compensated for the lower decomposition rate cumulatively over the years.

Table 2. Decomposition rate constant k and half life T $^{1/2}$ decomposition of dry matter litter

Species	*Acacia auriculiformis*	*Acacia mangium*	*Tectona grandis*
k	0.02	0.05	1.2
T(0.5)	270	250	200

There was significant influence of *Acacia* species in improving the nitrogen status of soil. Nitrogen contents were found to be 124 mg kg^{-1} in *T. grandis* while that in *A. auriculiformis* and *A. mangium* were 140 and 138 mg kg^{-1} respectively. Phosphorus was low with around 4-5 mg kg^{-1} and the values did not differ between species. Potassium also was not much influenced by the species; the mean values were around 130 mg kg^{-1}. *T. grandis* exerted significant effect in the calcium content of soil with 325 mg kg^{-1} as compared to 214 mg kg^{-1} in the case of *A. auriculiformis* and 207 mg kg^{-1} in the case of *A. mangium*. Magnesium content on the contrary was greater in acacia plots (240 mg kg^{-1} in *A. auriculiformis* and 237 mg kg^{-1} in *A. mangium*) compared to *T. grandis* with 215 mg kg^{-1} of magnesium.

Litter Fall and Decomposition

Litter fall pattern varied between species and months of the year. Maximum amount of litter fell during December and January months (Table 3). It decreased gradually from February to May and registered slightly higher values from June to November. Total litter in the study year was highest in *A. mangium* plots with 4298 kg ha^{-1} followed by *A. auriculiformis* with 4182 kg ha^{-1} and *T. grandis* contributing 3481 kg ha^{-1} litter. Litter of *A. auriculiformis* consisted of 67 per cent leaf, 6 per cent inflorescence, 14 per cent twig and 13 per cent pod while the respective percentages in *A. mangium* was 70, 5,13 and 12 per cent and in the case of *T. grandis* 90 per cent of litter mass was contributed by leaf and 10 per cent by twigs. Decomposition of litter was found to be more during the wet months starting July and least during the dry summer months of February to May. In an year's time all the litter of *T. grandis* got decomposed while 93 per cent of *A. auriculiformis* and 83 per cent of *A. mangium* got decomposed during the same period. Release of nitrogen through decomposition of litters of *T. grandis* was seen to be 100 per cent in 11 months' time while it was 96% in the case of *A. auriculiformis* and 90 per cent in the case of *A.mangium* in 12 months' time. Decomposition rate constant (k) was lowest in the case of *A. auriculiformis* (0.02), slightly higher in the case of *A. mangium* (0.05) and much greater in *T. grandis* (1.2). Time required for half the litter to decompose, T (0.5) was found to be 270 days for *A. auriculiformis,* 250 days for *A.mangium* and 200 days for *T. grandis.* Plants are capable of taking up maximum nutrients during the wet months and utilizing them for biomass production. As the soil starts drying up, the trees start shedding its foliage to balance the transpiration demand as also reduces the evaporation losses from both foliage and the soil surface. Low rate of decomposition of acacia litter was reported by others also (Swamy, 1989 and Byju, 1989). Teak being an indigenous species has co-evolved with the local climate and the soil organisms and thus its litter is easily decomposible. *Acacia* species that are exotics may not have this advantage. Litters with greater nitrogen content are known to decompose rapidly (Singh and Gupta, 1977; Meentemeyer, 1978). Though *Acacia* litter has this advantage, the decay rate remained low. This can be attributed to the high content of crude fibres in the phyllodes and the presence of thick cuticle (Widjaja, 1980 and Byju, 1989). The lignin content of acacia leaf litter is also more than that of teak (Kumar and Deepu, 1992). It is also reported that decomposition of lignin of nitrogen rich litters is significantly lower than those with poor nitrogen content (Berg *et al.,* 1992).

Table 3. Litter decomposition pattern (%)

Species	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Tectona grandis	10	19	21	25	29	35	51	68	82	93	98	100
Acacia auriculiformis	10	18	20	24	27	32	45	56	63	68	78	93
Acacia mangium	18	28	34	38	39	41	49	56	58	64	75	83

Table 4. Nutrient release (%)

Species	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Tectona grandis	21	28	33	41	48	56	66	73	88	99	100	
Acacia auriculiformis	16	30	34	39	48	53	63	65	71	74	88	96
Acacia mangium	16	27	33	40	46	51	54	60	65	70	88	90

Nutrient release pattern (Table. 4) calculated based on litter decomposition revealed that 100 per cent release could occur in 11 months time in the case of teak, while release from *A. auriculiformis* was 96 per cent and that from *A. mangium* 90 per cent in an year's time. Decomposition rate constant, k, which gives an indication of the decomposability of litter ranges from 4 for climax tropical African forest to 0.25 for pine forest of south eastern United States to still lower values of 0.0625 for Minnesota pine down to 0.0094 for lodge pole pine at 3000 m altitude (Jenny *et al.*,1949) . The values of 0.02 for *A. auriculiformis* and 0.05 for *A. mangium* can thus be seen to be in the lower range of pine forests with low decomposition rate while k value of 1.2 in the case of teak is definitely indicative of faster decomposition (Table 2).Thus, it can be concluded from the limited period observation of the present study that both the species of acacia, namely *A. auriculiformis* and *A. mangium* has both positive and negative influence on soil and its properties. It has a positive effect in soil aggregation and nitrogen enrichment while the negative influence results from the acidifying nature and the slow rate of decomposition. Litter fall was highest in *A. mangium* followed by *A. auriculiformis* and *T. grandis* while litter decomposition was faster in *T.grandis* followed by *A. auriculiformis* and *A. mangium*.

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