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(Final report of the project KFRI 538/07)

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CONTENTS

PROJECT PROPOSAL

1. Project code : KFRI 538/07

2. Title of the project : Carbon storage potential of different age teak plantations in Kerala

3. Objectives : To quantify the carbon stored in various parts of teak as well as in the soil
To develop non destructive predictors of carbon storage
To estimate the potential of teak plantations in storing carbon

4. Date of commencement : September 2007

5. Duration : 3 years + 1 year extension

6. Funding agency : Kerala Forest Department

7. Investigators : M. Balagopalan (upto March 2009)
Thomas P. Thomas (from March 2009)
P. Rugmini

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ABSTRACT

Carbon sequestration potential of teak trees was estimated by quantifying the above ground and below ground carbon contents of teak at various thinning regimes of 5, 10,15,20,30,40 and 50 years of age. It was seen that on an average the wood component contained maximum carbon (292.49 kg) per tree followed by branch (77.09 kg) root (76.44 kg) and bark (18.99 kg) at the age of 50 years. Soil component contained 121.65 ton carbon per hectare in the final felling plantation when the 0-60 cm depth was taken into account. Simple linear regressions of log DBH versus above ground biomass on a plantation scale showed that these relationships were strong yielding coefficients of determination (R^2) of 0.810 to even 0.971 in various thinning regimes. DBH versus carbon content also gave high R^2 values of 0.840 to even 0.981 in various thinning regimes which means that 84.0 to 98.1 percent of the variation in total carbon content on plantation scale could be explained by DBH of trees. It was estimated that the carbon storage potential of teak plantations in Nilambur was around 179.61 tons per hectare considering a final felling regime of 50 years. Carbon stored in the soil upto 60cm depth in the teak plantations of Nilambur, Kerala at this stage had been worked out to be 121.65 tons per hectare. Considering all the compartments together it can be seen that 301.26 tons per hectare of carbon could be stored by the teak plantations of Kerala.

INTRODUCTION

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 (SF_6) in the earth's atmosphere is one of the most important concern of mankind today. Since1890, the global temperature has gone up by 1^oC, and if the emissions are not cut, it may warm up the atmosphere by as much as 3.5- 4.0^oC within a century which may lead to melting of polar ice and glaciers and consequent increase in sea level. Nations of the world have been meeting year after year since 1980s to find ways to mitigate the problem. The International Panel on Climate Change (IPCC) established in 1988 by the United Nations Environment Programme (UNEP) and the World Metrological Organization (WMO) recommended a reduction of CO_2 level in the atmosphere to 350 ppm by 2050 in order to bring the temperature rise to within 2^oC and that industrialized countries must cut their emissions by 25-40 percent of their present rates by the year 2020. The fourth assessment report (AR 4) of the IPCC released in 2007 states that carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas and that the carbon dioxide equivalent emissions has increased at alarming rates during the recent past. It was 0.43 giga ton (gt) CO_2 equivalent per year during the period 1970-1994 but the rate increased to 0.92gt CO_2 equivalent per year during 1995-2004 period. The global atmospheric CO_2 concentration has increased from a pre-industrial value of 280 ppm in 2005 to 379 ppm in 2005 (IPCC, 2007) and 390 ppm in 2010 (Pieter Tans, 2010).

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 Kyoto, Japan in 1997 decided on certain protocols to be followed by the countries which was named the 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 (trading of emission allowances between developed nations), joint implementation (transferring emission allowances between developed countries) 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. The CoP7 of UNFCCC that met in Bonn (Germany) in July 2011 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 (Pastian *et al*., 2000; Metting *et al*., 1999, Post *et al*., 1990). 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.

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 (Montagnini and Porras, 1998). 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. The soil in teak plantations continue to accumulate carbon and thus act as a sink always. Globally, soils contain approximately 1500 Pg of carbon, making it the largest terrestrial carbon pool (Post *et al*., 1990; Eswaran *et al*., 1993; Davidson *et al.*, 2000; Lal, 2004).

Teak (*Tectona grandis*) is the most important forest plantation species of Kerala in every respect. The first teak plantation in the world was raised in Nilambur in the year 1840 and some of the plantations are in the third rotation. Silviculture of this species has thus been standardised long back and has undergone modifications. The present schedule of felling operation is with a mechanical thinnings at the age of 5 years which is followed by selective silvicultural thinning at 10, 15, 20, 30, 40 and 50 years of age. The present study was taken up to assess the carbon storage potential of teak plantations at the respective felling schedules in selected plantations at Nilambur.

The specific objectives were:

1. To quantify the carbon stored in various parts of teak as well as in the soil
2. To develop non destructive predictors of carbon storage
3. To estimate the potential of teak plantations in storing carbon

MATERIALS AND METHODS

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 (Table 1). 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. Bark was estimated from measurements over and under bark of these discs. 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. They were weighed in the field itself and samples collected from different parts of the root system for dry matter estimation. 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. Carbon content was estimated by dry combustion of powdered samples in a muffle furnace and calculated using the following formula

$$\text{Carbon\%} = 100 - [\text{Ash weight} + \text{molecular Weight of } O_2\ (53.3) \text{ in } C_6H_{12}O_6]$$

Soil pits were dug to a depth of 60 cm and samples collected from 0-20cm, 20-40cm and 40-60cm sections. The collected soil samples were sieved through 0.2mm sieve and analysed for organic carbon content following Snyder and Trofymow (1984) method. One gm soil sieved through 1mm sieve was taken and 3ml 2N HCl added to remove carbonates. It was then oxidized with $K_2Cr_2O_7$ in the presence of 25 ml of H_2SO_4+H_3PO_4 (3:2) by heating on a digestion block for 2 hours. The evolved CO_2 was trapped in 2N NaOH and amount of CO_2 entrapped measured by back titration with 0.5N HCl using phenolphthalein. Total OC was calculated based on the amount of CO_2 evolved. Core samples were taken separately for estimation of bulk density which was used for calculating soil organic carbon stock.

Table 1. Basic characteristics of the plantations

Plantation	Age (yrs)	Trees per ha^{-1}	Height (m)			DBH (cm)		
			Min	Max	Mean	Min	Max	Mean
2003 Chathumpurai	5	2500	4.0	10.5	6.86	4.46	9.55	6.74
1998 Kalkulam	10	761	6.0	12.0	9.86	12.12	19.43	14.91
1993 Mundakadavu	15	443	8.0	14.0	12.52	11.78	22.29	16.87
1987 Elenchery	20	317	11.0	17.0	14.62	13.69	27.39	22.18
1976 Peruvambadam	30	214	12.0	19.0	16.10	20.38	36.62	27.78
1967 Kallenthode	40	174	18.0	20.0	20.40	32.80	44.59	40.05
1957 Pulimunda	50	155	20.0	25.0	22.32	36.31	59.87	46.35

n=50

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 and carbon storage of wood, branches, root, bark and soil were estimated in order to describe the relation of diameter at breast-height (DBH) with biomass and carbon content.

Statistical analysis

Various regression equations were fitted for each age class using DBH as an independent variable, and total tree biomass, total tree carbon storage and biomass as well as carbon content of each component of tree viz., wood, bark, branch and root as dependent variables using data from 10 trees/age class. All these data were transformed to log to the base 10, as is commonly done to linearize data of this type. All the statistical analyses were carried out using SPSS software package.

Fig.1. Above ground biomass measurement

Fig. 2. Wood sampling

Fig.2. Root excavation

Fig.3. Estimation of root biomass

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 2 and figure 4) Above ground biomass represents mean of 50 trees and belowground biomass mean of ten trees.

Table 2. Biomass distribution in various compartments at different thinning stages

Compartments	Mean Biomass (kg/tree)						
	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

* Figures in parantheses indicates standard deviation

It can be seen that at the mechanical thinning at 5 years, wood contributed 50.56 kg (75%), bark 8.92 kg (13%) and root 8.33 kg (12%) towards total tree biomass (Fig.4). Branches were too thin most of which get self pruned on senescence as the tree grows and hence not taken in to account.

At the first silvicultural thinning of 10th year, the wood biomass was estimated to be around 91.5 kg, the bark around 14.89 kg, branches 26.91kg and root around 21.28 kg per tree. Wood constituted 59%, bark 10%, branches 17% and root 14% of the total biomass. As compared to the first stage, the proportion of wood and bark decreased while there was appreciable contribution by branches. Root portion also registered slight increase.

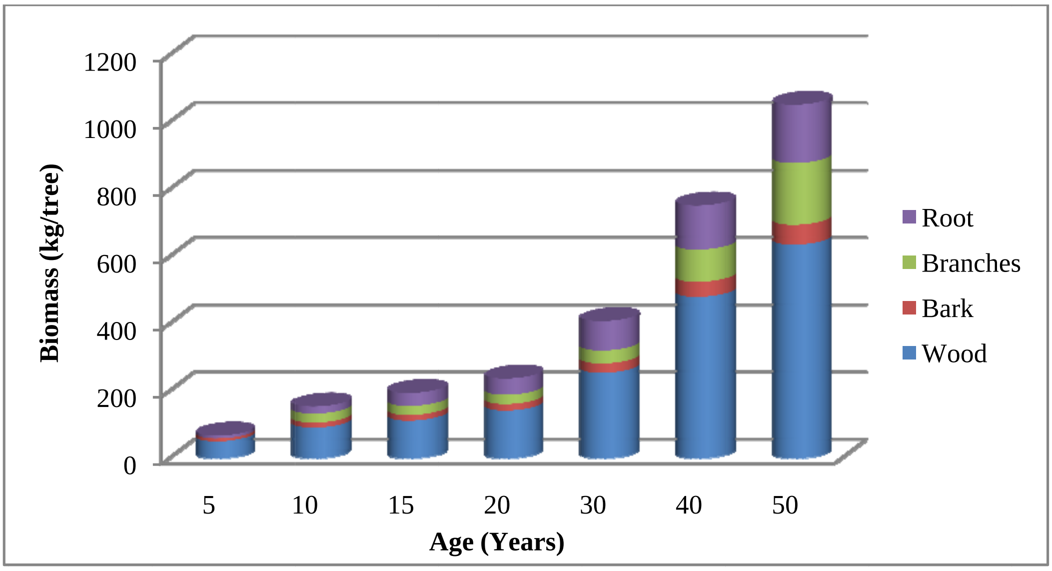

Fig 4. Compartment wise biomass of different aged teak

The contribution of wood at the age of 20 years (3rd silvicultural thinning) was around 142.28 kg, that of bark around 19.4 kg, branches around 27.53 kg while the root portion contributed 48.51 kg per tree. Wood constituted 60%, bark 8%, branches 12% and root 20% of the total biomass. At the third mechanical thinning, it was seen that the wood and root compartments registered appreciable increase while the contribution by bark remain the same and that by branches decreased.

At the 30th year of fourth silvicultural thinning, wood was found to yield about 254.34 kg, while the bark constituted around 28.26 kg per tree. The contribution of branches was 38.38 kg and that of root 87.60 kg per tree towards the tree biomass. Wood constituted 62%, bark 7%, branches 9% and root 21% of the total biomass. The pattern of compartment wise contribution remained similar to the previous stage with wood and root contributing most towards the total biomass.

The wood biomass at the 5th silvicultural thinning at the age of 40 years was found to be around 480.48 kg, bark biomass around 44.63 kg while the branches were found to weigh about 95.93 kg per tree. The root portion contributed 131.28 kg at this age. Wood constituted 64, bark 6, branches 13 and root 17 percent of the total biomass.

Contribution by the different biomass components remained almost similar as was the case in the previous stages with wood and root portions contributing more towards the total biomass.

Biomass partitioning at the age of 50 years was found to be in the order of 635.85 kg wood, 59.07 kg bark, 183.55 kg branches and 173.73 kg of roots per tree. Wood constituted 66%, bark 6, branches 17 and root 17 percent of the total biomass. Contribution of wood towards total biomass was slightly more than the previous stages that by bark and root remained same while there was an increase in the branch component.

Carbon content of teak trees of different ages

Carbon content of teak partitioned in wood, bark, branches and root is given in Table 3 and figure 5. It can be seen that at 5 year age the wood portion of the tree contained 23.26 kg, the bark 2.86 kg and the root 3.33 kg carbon per tree on an average. Branch component was not considered at the first mechanical thinning since they were too thin to be of consideration in biomass estimation.

Table 3. Mean carbon content in different compartments at various stages of teak growth.

	Mean Carbon content (kg/tree)						
Compartments	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 (11.7)	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)

* Figures in parentheses indicate standard deviation

At the first silvicultural thinning of 10th year, carbon content in wood was found to be 42.09 kg, that in bark around 4.77 kg, branches around 11.3 kg and root contained around 8.94 kg carbon per tree. Increase in carbon content per tree was proportional to biomass increase in each of the compartments. Maximum carbon storage was observed in wood compartment and least in the bark with branches and roots contributing more than bark.

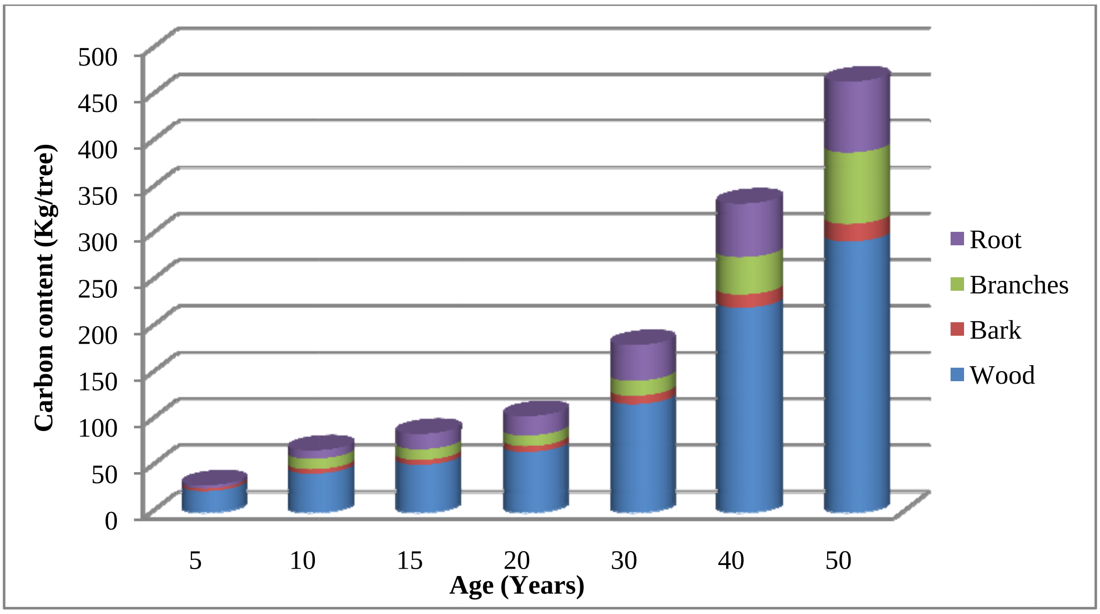

Fig 5. Compartment wise carbon content in different aged teak

Wood portion of the tree on an average was found to contain 51.59 kg carbon while the bark contained 5.36 kg, the branches 11.42 kg and the root 16.63 kg carbon at 15 year of age when the second silvicultural thinning is carried out. Contribution by root towards carbon storage has increased remarkably at this age though wood contained maximum carbon per tree.

Carbon content of wood was found to be 65.45 kg, that of bark 6.21 kg, branches 11.56 kg and the root 20.86 kg on an average per tree at the time of third silvicultural thinning at the age of 20 years. The pattern of contribution by the four compartments remained similar to the previous stage.

At thirty year age when the fourth silvicultural thinning is carried out the average carbon content per tree was found to be 116.99 kg in wood portion, 9.04 kg in bark, 16.12 kg in branches and 38.55 kg in the roots. At this stage wood portion yielded almost double the carbon in the previous stage. Root contribution towards carbon content also increased remarkably.

At the fifth silvicultural thinning of 40th year carbon content in wood was about 221.02 kg, that in bark around 14.28 kg, while the branches contained about 40.29 kg and the root 57.76 kg per tree. Contribution by wood followed the trend of doubling while branches have exhibited greater contribution compared to all the previous stages. Roots were also remarkable in their share towards total carbon content.

Carbon content of wood portion was found to be around 292.49 kg, bark around 18.99 kg, branches around 77.09 kg while the roots contained 76.44 kg carbon per tree at the age of 50 years. It can be seen that the wood portion contributed maximum towards carbon content at this stage also. Contribution by branches was equal to that by roots at this age; root contribution was always higher than that of branches in all the earlier stages.

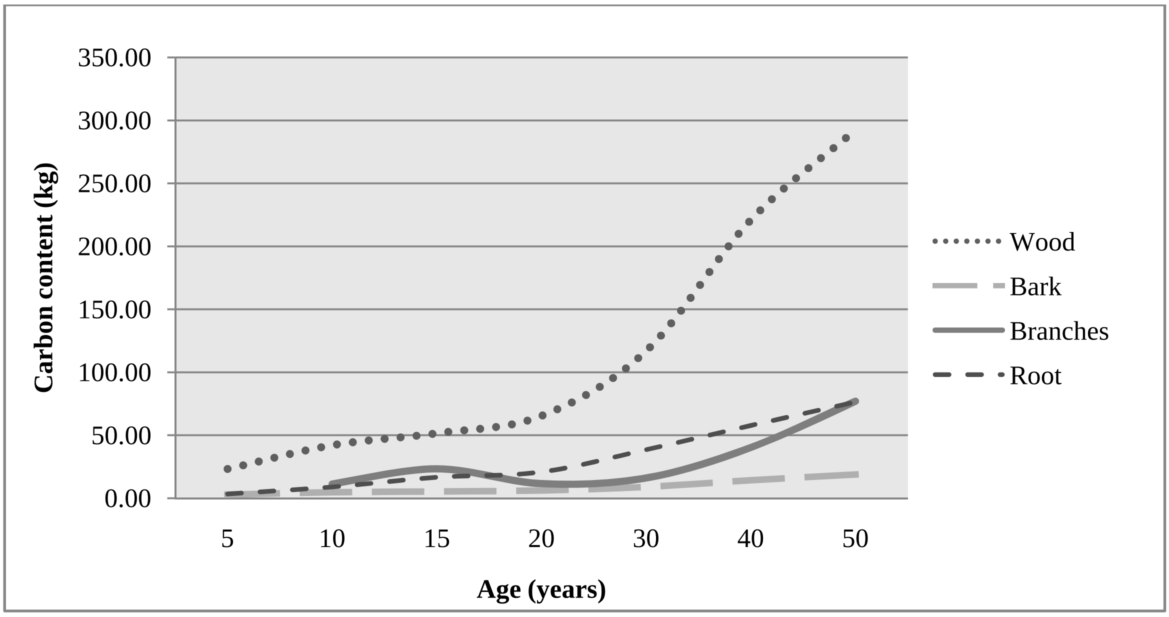

Fig. 6. Compartment-wise carbon content of teak trees of different age

Carbon content in compartments of different aged teak trees is shown in Figure 6. It can be observed from figure 6 that carbon storage in wood portion of an average tree increases gradually with age upto the 20th year after which the climb is steep. Root compartment, on the other hand, demonstrated a gradual but steady increase in carbon storage with increasing age. Contribution by bark though exhibited an increasing trend with age was not remarkable. Branches on the other hand showed an increasing trend upto 15th year after which there was a decline for a short period whereafter its contribution started climbing up progressively.

Development of prediction equations of biomass

Various regression equations were fitted for each component of biomass to develop non destructive predictors which are given in Tables 4 to 9. The‘t’ values of regression coefficients of the equations were also highly significant in most of the cases.

Simple linear regressions of log DBH versus per tree wood biomass (Table 4) show that these relationships are strong, yielding coefficients of determination (R^2) values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in wood biomass could be explained by DBH of trees. Stronger DBH- wood biomass relations existed from 20th year onwards. This is only natural since wood biomass is always proportional to the diameter.

Table 4. Regression equations for predicting per tree wood biomass (Y) for each plantation

Plantation age (year)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 1.535 +0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 1.044 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = 0.823 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = 0.526 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -0.300 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -0.143 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -0.136 +1.788 log (DBH)	0.963	15.419**

** - Significant at $p = 0.01$

Regressions of log DBH versus per tree branch biomass (Table 5) on the other hand show that these relationships are weak at certain stages and somewhat strong in other thinning cycles yielding coefficients of determination (R^2) values of 0.537 to even

0.621 in the initial thinning regimes up to 20 year which means that 53.7 to 62.1 % of the variation in branch biomass alone could be explained by DBH of trees. The 5 year site at Chathumpurai had only thin small branches and hence not taken into account.

From the fourth silivicultural thinning, the relationship between DBH and branch biomass was nonsignificant. This means that the size and mass of branches per tree was highly variable as the tree starts maturing and it had no significant relation with the DBH as such.

Table 5. Regression equations for predicting per tree branch biomass(Y) for each plantation

Plantation age (year)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	No data	-	-
10	Log (Y) = -2.180 + 3.027 log (DBH)	0.621	3.965**
15	Log (Y) = -1.083 + 2.243 log (DBH)	0.526	3.312*
20	Log (Y) = -1.685 +2.343 log (DBH)	0.537	3.382**
30	Log (Y) = -0.637 +1.765 log (DBH)	0.043	1.184^{ns}
40	Log (Y) = 0.294 +1.025 log (DBH)	-0.069	0.649^{ns}
50	Log (Y) = 2.794 +-0.335 log (DBH)	-0.081	-0.569^{ns}

** - significant at p = 0.01; * - significant at p=0.05; ns- nonsignificant

The relationship between DBH and per tree root biomass (Table 6) show that these relationships are strong, yielding R^2 values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in root biomass could be explained by DBH of trees. The ‘t’ values were highly significant at all the stages of sampling. The vegetative growth of a tree is directly dependent on the water and nutrient supply by the roots and hence root biomass always contributes to the diameter increment of a tree.

Table 6. Regression equations for predicting per tree root biomass (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 0.752 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.411 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = 0.361 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = 0.059 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -0.746 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -0.707 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -0.699 +1.788 log (DBH)	0.963	15.419**

** - Significant at p = 0.01

Relationship between DBH and per tree bark biomass (Table 7) showed that these relationships were highly significant yielding R^2 values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in bark biomass could be explained by DBH of trees. As the tree diameter increases the content of bark also increases and hence this strong correlation.

Table 7. Regression equations for predicting per tree bark biomass (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 0.782 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.256 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = -0.002 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = -0.339 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -1.254 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -1.175 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -1.168 +1.788 log (DBH)	0.963	15.419**

** - Significant at p = 0.01

Regressions of log DBH versus per tree above ground biomass (Table 8) showed that these relationships were highly significant with R^2 values of 0.803 to even 0.968 in various thinning regimes which means that 80.3 to 96.8 % of the variation in above ground biomass could be explained by DBH of trees.

Table 8. Regression equations for predicting per tree above ground biomass (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 1.606 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.636 +1.265 log (DBH)	0.889	8.564**
15	Log (Y) = 0.567 +1.367 log (DBH)	0.803	6.147**
20	Log (Y) = 0.479 +1.374 log (DBH)	0.930	10.981**
30	Log (Y) = -0.150 +1.809 log (DBH)	0.968	16.438**
40	Log (Y) = 0.000 +1.736 log (DBH)	0.916	9.975**
50	Log (Y) = 0.685 +1.376 log (DBH)	0.843	7.024**

** - Significant at p = 0.01

Table 9. Regression equations for predicting per tree total biomass(Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 1.663 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.776 +1.201 log (DBH)	0.906	9.364**
15	Log (Y) = 0.730 +1.303 log (DBH)	0.835	6.831**
20	Log (Y) = 0.614 +1.348 log (DBH)	0.943	12.190**
30	Log (Y) = -056 +1.817 log (DBH)	0.979	20.551**
40	Log (Y) = 0.074 +1.742 log (DBH)	0.947	12.673**
50	Log (Y) = 0.651 +1.444 log (DBH)	0.876	8.019**

** - Significant at p = 0.01

Regression equations of log DBH versus per tree total biomass (Table 9) showed that these relationships were also strong yielding coefficients of determination (R^2) values of 0.835 to even 0.979 in various thinning regimes which means that 83.5 to 97.9 % of the variation in total biomass could be explained by DBH of trees.

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 Tables 10 to 15. The 't' values of regression coefficients of the equations were also highly significant in most of the cases.

Table 10. Regression equations for predicting per tree wood carbon content (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 1.198 +0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.707 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = 0.486 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = 0.189 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -0.637 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -0.481 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -0.473 +1.788 log (DBH)	0.963	15.419**

** - Significant at p = 0.01

Regressions of log DBH versus per tree wood carbon content (Table 10) showed that these relationships were significant, yielding R^2 values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in carbon content of wood could be explained by DBH of trees. The 't' values were highly significant at all the stages of sampling. Wood biomass was strongly correlated with DBH which got reflected in the relation between DBH and wood carbon content.

Table 11. Regression equations for predicting per tree branch carbon content (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	No data	-	-
10	Log (Y) = -2.557 + 3.027 log (DBH)	0.621	3.965**
15	Log (Y) = -1.460 + 2.243 log (DBH)	0.526	3.312*
20	Log (Y) = -2.061 +2.343 log (DBH)	0.537	3.382**
30	Log (Y) = -1.013 +1.765 log (DBH)	0.043	1.184^{ns}
40	Log (Y) = -0.083 +1.025 log (DBH)	-0.069	0.649^{ns}
50	Log (Y) = 2.417 +-0.335 log (DBH)	-0.081	-0.569^{ns}

** - Significant at p= 0.01;* - Significant at p = 0.05; ns- non significant

Linear regressions of log DBH versus per tree branch carbon content (Table 11) showed that these relationships are weak to somewhat strong in the different thinning cycles yielding coefficients of determination (R^2) values of 0.526 to even 0.621 in the initial thinning regimes up to 20th year which means that 52.6 to 62.1 % of the variation in branch carbon content alone could be explained by DBH of trees in the initial stages of growth. Relationship between DBH and carbon content in branches were non significant in the latter stages. The 5 year site at Chathumpurai had only thin small branches and hence was not taken into account. From the fourth silivicultural thinning the relationship between DBH and branch carbon content was non significant. This pattern resulted from the high variability of branches and its biomass at most of the thinning stages.

Relationships between DBH and per tree root carbon content (Table 12) showed that these relationships were strong, yielding R^2values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in root carbon content could be explained by DBH of trees. Root growth and its biomass were directly contributing to the overall tree growth that gets reflected in the DBH and hence this pattern of high correlation. The ‘t’ values were also highly significant in all the stages of sampling.

Table 12. Regression equations for predicting per tree root carbon content (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 0.354 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.034 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = -0.006 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = -0.308 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -1.120 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -1.063 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -1.056 +1.788 log (DBH)	0.963	15.419**

** - Significant at p = 0.01

Table 13. Regression equations for predicting per tree bark carbon content (Y) for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 0.287 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = -0.239 +0.781 log (DBH)	0.865	7.645**
15	Log (Y) = -0.497 +0.991 log (DBH)	0.947	12.663**
20	Log (Y) = -0.834 +1.246 log (DBH)	0.965	15.758**
30	Log (Y) = -1.749 +1.843 log (DBH)	0.996	44.944**
40	Log (Y) = -1.670 +1.756 log (DBH)	0.950	13.123**
50	Log (Y) = -1.663 +1.788 log (DBH)	0.963	15.419**

** - Significant at p = 0.01

Regressions of log DBH versus per tree bark carbon content (Table 13) showed that these relationships were highly significant yielding coefficients of determination (R^2) values of 0.865 to even 0.996 in various thinning regimes which means that 86.5 to 99.6 % of the variation in bark carbon content could be explained by DBH of trees. Bark biomass was directly related to diameter of the trees and hence this pattern of its contribution to carbon content.

Relationship between DBH and per tree aboveground carbon content (Table 14) showed that these relationships were strong, yielding coefficients of determination (R^2) values of 0.810 to even 0.971 in various thinning regimes which means that 81 to 97.1 % of the variation in aboveground carbon content could be explained by DBH of trees.

Table 14. Regression equations for predicting per tree above ground carbon content for each plantation

Plantation (years)	Regression equation	Adjusted R^2	t-value for slope coefficient
5	Log (Y) = 1.248 + 0.197 log (DBH)	0.875	7.992**
10	Log (Y) = 0.296 +1.248 log (DBH)	0.894	8.767**
15	Log (Y) = 0.222 +1.354 log (DBH)	0.810	6.271**
20	Log (Y) = 0.131 +1.368 log (DBH)	0.933	11.234**
30	Log (Y) = -0.506 +1.811 log (DBH)	0.971	17.288**
40	Log (Y) = -0.357 +1.738 log (DBH)	0.926	10.697**
50	Log (Y) = 0.296 +1.396 log (DBH)	0.854	7.311**

** - Significant at p = 0.01

Linear regression equations of log DBH versus per tree total carbon content (Table 15) showed that these relationships were strong, yielding coefficients of determination (R^2) values 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. The ‘t’ values were also highly significant at all the stage.

Table 15. Regression equations for predicting per tree total carbon content for each plantation

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

** - Significant at p = 0.01

Plantation level carbon storage

Plantation level carbon storage (total carbon storage, aboveground tree carbon storage and below ground carbon storage) is reported in Table 16.

Teak trees at the age of 5 years on an average was found to store carbon to the tune of 26.12 kg in the above ground biomass and 3.33 kg in the root biomass totaling 29.45 kg of carbon. On a plantation level the above ground carbon content was seen to be 45.4 t/ha while the below ground portion contained 5.79 t/ha of carbon. The total contribution comes to 51.21 t/ha of carbon.

At the age of 10 years, tree carbon storage in the above ground and below ground biomass were 58.16 kg and 8.94 kg respectively yielding a total of 67.1 kg of carbon per tree. On a plantation scale the carbon stored in the above ground portion was 18.49 t/ha and that in the below ground parts was 2.84 t/ha. The total carbon storage on plantation scale at this stage was found to be 21.34 tons per hectare.

Table 16. Plantation level tree carbon storage

Age	No. of trees removed per ha	Per tree carbon storage (kg)			Per plantation carbon storage (t/ha)		
		Above ground	Below ground	Total	Above ground	Below ground	Total
5	1739	26.12 (3.26)*	3.33 (0.44)	29.45 (3.65)	45.42 (5.72)	5.79 (0.72)	51.21 (6.19)
10	318	58.16 (7.50)	8.94 (1.21)	67.10 (8.39)	18.50 (2.25)	2.84 (0.35)	21.34 (2.62)
15	126	68.37 (7.86)	16.63 (2.24)	85.00 (11.05)	8.61 (0.96)	2.10 (0.26)	10.71 (1.33)
20	103	83.22 (9.90)	20.86 (2.70)	104.0 (13.01)	8.60 (1.45)	2.15 (0.28)	10.72 (1.31)
30	40	142.15 (17.06)	38.55 (4.87)	180.70 (22.40)	5.69 (0.65)	1.54 (0.19)	7.23 (0.89)
40	19	275.59 (35.83)	57.76 (7.27)	333.35 (41.00)	5.24 (0.67)	1.10 (0.13)	6.33 (0.77)
50	155	388.48 (50.50)	76.44 (10.70)	464.92 (57.65)	60.21 (7.40)	11.85 (1.48)	72.06 (9.08)
Total					152.24	27.37	**179.61**

* Figures in parentheses indicate standard deviation

At the age of 15 years, tree carbon storage on an average was found to be 68.37 kg above ground and 16.63 kg below ground thus contributing 85.0 kg of carbon per tree. On a plantation scale the carbon stored in the above ground parts was found to be 8.61 t/ha and that in below ground portion 2.09 t/ha. The total carbon storage on plantation scale at this stage was found to be 10.71 tons per hectare.

At the age of 20 years, the average carbon storage per tree was found to be 83.22 kg in the above ground biomass and 20.86 kg in the below ground biomass giving a total of

104.08 kg per tree of carbon storage. When the plantation as a whole was considered, the carbon storage was around 8.57 t/ha in the above ground compartment and 2.15 t/ha in the below ground portion. The total contribution was to the tune of 10.72 tons per hectare on plantation basis.

At 30 years of age, per tree carbon storage was calculated to be 142.15 kg in the above ground portions, 38.55 kg in the below ground and 180.7 kg when both above and below ground parts were considered together. Plantation level carbon storage was about 5.68 t/ha in above ground portion and 1.54 t/ha in the below ground parts making a total contribution of 7.23 tons per hectare.

Carbon storage per tree at the age of 40 years was found to be 275.59 kg in the above ground parts and 57.76 kg in the below ground parts making a total figure of 333.35 kg of carbon per tree. Plantation level carbon storage was found to be 5.24 t/ha in the above ground compartment and 1.10 t/ha in the below ground portion. Total carbon storage at plantation level was 6.33 tons per hectare.

Storage of carbon per tree at the final felling stage of 50 years was observed to be around 388.48 kg in the above ground component and 76.44 kg in the below ground parts; the total per tree carbon storage was 464.92 kg . On a plantation scale the carbon storage in the above ground parts was about 60.21 t/ha while that in below ground portion was 11.85 t/ha giving a total figure of 72.06 tons of carbon per hectare.

On plantation scale the total carbon storage during the 7 thinning stages was estimated to be 152.24 t/ha in the above ground compartment and 27.36 t/ha in the below ground compartments yielding a total figure of 179.61 tons per hectare of carbon sequestration.

Plantation level biomass prediction

Various regression equations were developed for predicting biomass in wood, root, aboveground and total biomass from DBH using data obtained from all the plantations together (Table 17 and Fig .7).

Table 17. Regression equations for predicting per tree biomass using DBH for all plantations

Dependent variable (Y)	Regression equations	Adjusted R^2	t-value for slope
Wood biomass	Log (Y) = 0.417 +1.381 log (DBH)	0.937	32.054**
Root Biomass	Log (Y) = -0.456 +1.617 log (DBH)	0.966	44.236**
Above ground biomass	Log (Y) = 0.504 +1.414 log (DBH)	0.948	35.572**
Total Biomass	Log (Y) = 0.545 +1.445 log (DBH)	0.959	40.063**

** - Significant at $p = 0.01$

It can be seen from the table and figure referred above that all the relationships are strong, yielding high (> 90 %) coefficients of determination (R^2), which means that almost all the variation in wood, root, aboveground and total biomass could be explained by DBH of trees ; the ‘ t’ values were also highly significant in all the cases.

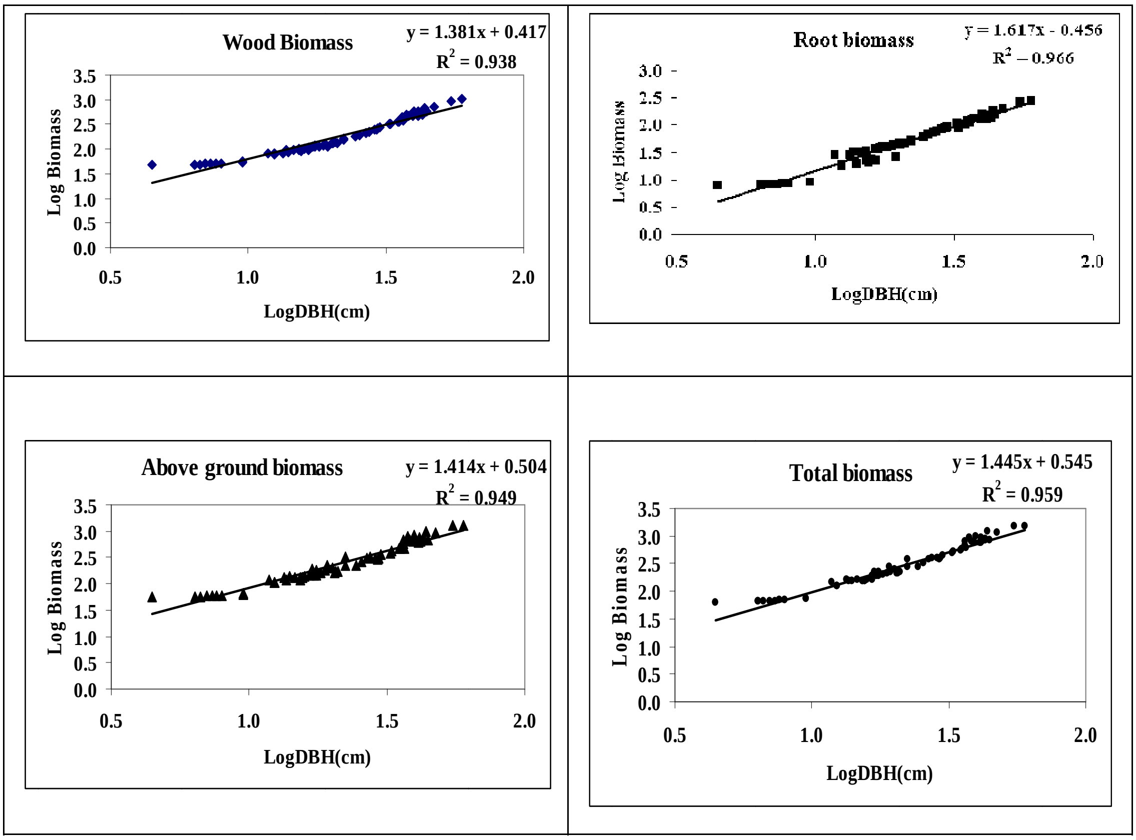

Fig.7. Linear regressions of DBH versus wood, root, aboveground and total biomass

Plantation level carbon prediction

Various regression equations were developed for predicting carbon storage in wood, root, aboveground and total from DBH using data obtained from all the plantations together (Table 18 and Fig . 8).

Table 18. Regression equations for predicting per tree carbon content

Dependent variable (Y)	Regression equations	Adjusted R^2	t-value
Wood carbon	Log (Y) = 0.080 +1.381 log (DBH)	0.937	32.054**
Root carbon	Log (Y) = -0.888 +1.665 log (DBH)	0.965	43.900**
Above ground carbon	Log (Y) = 0.138 +1.421 log (DBH)	0.949	35.800**
Total carbon	Log (Y) = 0.171 +1.457 log (DBH)	0.959	40.370**

** - Significant at p = 0.01

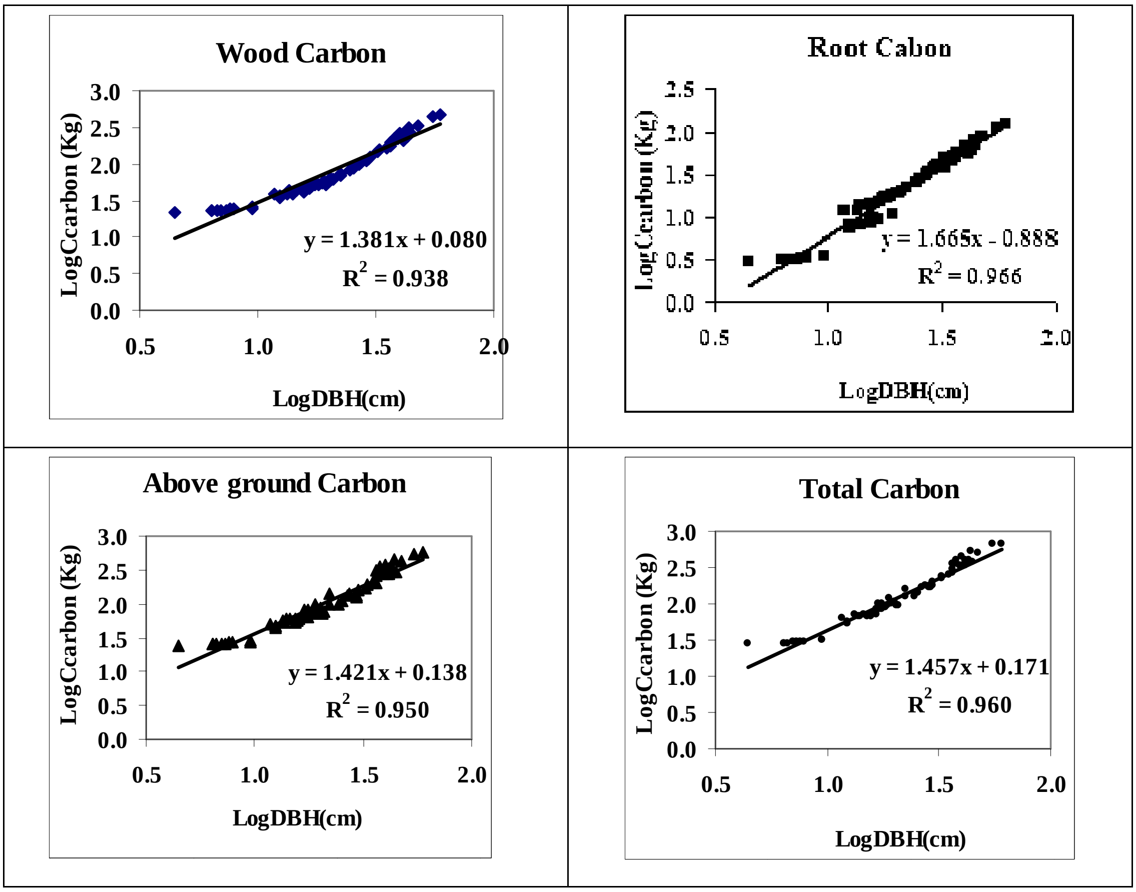

Fig.8. Linear regressions of DBH versus wood, root, aboveground and total carbon storage

It can be seen from the table 18 and figure 8 that all the relationships are strong, yielding high (> 90 %) coefficients of determination (R^2), which means that most of the variation in wood, root, aboveground and total carbon content could be explained by DBH of trees; the ‘t’ values were also highly significant in all the cases.

Carbon sequestration by soil in teak plantations

Total organic carbon in the soil determined following Snyder and Trofymow (1984) revealed gradual decrease in organic carbon content down the soil profile. Soil carbon varied between site, the age of plantation having some influence on the carbon content. It can be seen from table 19 that the 0-20 cm layer of 5 year old teak plantation could sequester 41.04 tons per hectare of carbon, 20-40 cm layer 30.24 t/ha and the 40-60 cm layer 14.30 t/ha of carbon giving a total of 85.58 tons per hectare of soil organic carbon when 0-60 cm depth is considered.

In the ten year old plantation the respective figures were 37.82, 24.38, 10.56 and 72.76 tons per hectare of soil organic carbon. Values of organic carbon in the fifteenth year plantation were 45.47, 41.00 and 11.00 t/ha in the three depths giving a total of 98.17 tons per hectare of soil organic carbon in the 0-60 cm depth.

Surface soil (0-20 cm) in the twentieth year plantation had 49.45 ton carbon while the subsequent depth of 20-40 cm could sequester 43.65 tons per hectare and 40-60 cm could sequester 12.80 tons per hectare of carbon giving a total figure of 105.90 t/ha of organic carbon in the 0-60 cm layer. A teak plantation in its 30th year was found to sequester 54.00 tons of soil organic carbon per hectare in the 0-20 cm layer, 45.72 t/ha in the 20-40 cm layer and 14.26 tons per hectare in the 40-60 cm layer of soil giving a total of 113.98 ton per hectare of carbon in the 0-60 cm depth.

Soil organic carbon sequestration in the 40th year old plantation was found to be 48.3 t/ha, 45.36 t/ha and 11.96 t/ha in the three succeeding depths giving a total value of 105.62 tons per hectare when 60 cm depth was considering. Fifty year old teak plantation was found to contain 57.50 tons per hectare carbon in the 0-20 cm depth, 49.40 t/ha in the 20-40 cm depth and 14.74 tons per hectare in the 40-60 cm depth of soil. Total soil organic carbon in 0-60 cm layer was thus found to be 121.65 tons per hectare.

Table 19. Soil organic carbon status in different age plantations

Age (years)	0-20 cm		20-40 cm		40-60 cm		Total (t/ha)
	%	t/ha	%	t/ha	%	t/ha	
5	1.71 (0.22)*	41.04	1.20 (0.10)	30.24	0.55 (0.10)	14.30	85.58
10	1.55 (0.18)	37.82	0.96 (0.12)	24.38	0.40 (0.05)	10.56	72.76
15	1.96 (0.20)	45.47	1.64 (0.15)	41.00	0.45 (0.07)	11.70	98.17
20	2.15 (0.24)	49.45	1.76 (0.14)	43.65	0.50 (0.10)	12.80	105.90
30	2.25 (0.27)	54.00	1.80 (0.18)	45.72	0.54 (0.10)	14.26	113.98
40	2.10 (0.18)	48.30	1.80 (0.17)	45.36	0.46 (0.13)	11.96	105.62
50	2.30 (0.25)	57.50	1.90 (0.20)	49.40	0.55 (0.12)	14.74	121.65

n=10 *Figures in parentheses indicate standard deviation

Considering that final felling is carried out at the age of 50 years and taking into account the soil organic carbon content at this point as a culmination of soil organic carbon sequestration, it can be concluded that a teak plantation could sequester around 121.65 tons per hectare of soil organic carbon.

Estimate of carbon storage potential of teak plantations in Kerala

An attempt to estimate the carbon storage potential of teak plantations in Kerala revealed that 179.61 tons per hectare of carbon could be stored in various compartments of the teak tree considering the present management schedule of thinning operations and taking 50 years as the final felling stage as is being considered in Nilambur region lately. Caution is warranted to consider the limitations of the present study in the context that only that portion of carbon stored in wood, bark, branches and roots have been taken into account while calculating carbon storage by the trees. The under growth and litter have been excluded after consideration of the high variability between sites and age classes and the impact of disturbances such as fire which is not uncommon in these sites. Also since the soil carbon is being estimated it was assumed that whatever carbon is stored in the undergrowth and litter will eventually get accounted in the soil carbon figures.

Carbon storage in the soil component was also worked out for all the plantations that were sampled and an estimate of carbon storage potential per hectare was calculated. Here also it should be remembered that soil samples were taken up to 60 cm depth only beyond which the content of organic carbon was very negligible. Inorganic forms of carbon are rare in Kerala and hence that part has been left out of the present investigation. Carbon stored in the soil up to 60 cm depth in the teak plantations of Nilambur, Kerala has thus been worked out to be 121.65 tons per hectare at the age of 50 years. Considering all the compartments of the tree and the soil together it can be seen that 301.26 tons per hectare of carbon could be stored in the teak plantations of Kerala.

SUMMARY

Teak plantations of Nilambur at prescribed thinning regimes were sampled for wood, bark, branches, root and the soil to reveal carbon contents and thus understand the carbon sequestration potential of teak both on a tree basis and also on a plantation basis taking one hectare as the unit area. Biomass samples were oven dried, powdered and ashed to get the carbon content while the soil to a depth of 60 cm was analysed for total organic carbon content. It was seen that the wood compartment sequestered maximum carbon (292.49 kg) per tree followed by branch (77.09 kg), root (76.44 kg) and bark (18.90 kg) at the age of 50 years. Soil component contributed 121.65 tons per hectare of carbon. Simple linear regression of log DBH verses biomass revealed high R^2 values of around 0.8 to 0.9 in various thinning regimes. Similar was the case with carbon content. On a plantation scale it was seen that 179.61 tons per hectare of carbon could be sequestered by teak considering the extracted biomass during various felling including the final felling at 50 years of age. Considering the tree and the soil together it was seen that 301.26 tons per hectare of carbon could be sequestered by a teak plantation.

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