"BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION IN AN AGE SERIES OF TEAK PLANTATION IN TROPICAL ENVIRONMENT"

Ph.D. (Forestry) THESIS

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“BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION IN AN AGE SERIES OF TEAK PLANTATION IN TROPICAL ENVIRONMENT”

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CERTIFICATE - I

This is to certify that the thesis entitled **"BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION IN AN AGE SERIES OF TEAK PLANTATION IN TROPICAL ENVIRONMENT"** submitted in partial fulfillment of the requirements for the degree of **"DOCTOR OF PHILOSOPHY IN FORESTRY"** of the Indira Gandhi Krishi Vishwavidyalaya, Raipur is a record of bonafide research work carried out by **Mr. RAJESH ANANDRAO ALONE** under my guidance and supervision. The subject of the thesis has been approved by the Student's Advisory Committee and the Director of Instructions.

No part of the thesis has been submitted for any other degree or diploma (certificate awarded etc.) or has been published / published part has been fully acknowledged. All the assistance and help received during the course of the investigation has been duly acknowledged by him.

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CERTIFICATE - II

This is to certify that the thesis entitled **"BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION IN AN AGE SERIES OF TEAK PLANTATION IN TROPICAL ENVIRONMENT"** submitted by **Mr. RAJESH ANANDRAO ALONE** to the Indira Gandhi Krishi Vishwavidyalaya, Raipur in partial fulfillment of the requirements for the degree of **"DOCTOR OF PHILOSOPHY IN FORESTRY"** in the **DEPARTMENT OF FORESTRY** has been approved by the external examiner and Student's Advisory Committee after oral examination.

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LIST OF ABBREVIATIONS

Abbreviations	Description
%	Per cent
&	And
<	Less than
=	Equal to
>	More than
^0C	Degree centigrade
A	Abundance
A/F	Abundance/Frequency
BA	Basal Area
C.G.	Chhattisgarh
CBH	Circumference at breast height
cm	Centimeter
Cd	Simpson's index
D	Density
DBH	Diameter at breast height
et al	And others/co-workers
Fig.	Figure
GBH	Girth at breast height
GIS	Geographical Information System
ha	hectare
ha^{-1}	Per hectare
$t\ ha^{-1}$	tons per hectare
ht	Height
i.e.	that is
viz.	namely
e.g.	for example
m ha	million hectare
$Kg\ ha^{-1}$	kilogram per hectare
m	meter
g	gram
AGB	Above Ground Biomass
BGB	Below Ground Biomass

Abbreviations	Description
NPP	Net Primary Productivity
H’	Shannon index
C	Carbon
CO_2	Carbon dioxide
Mg	mega gram = 10^6 gram
MoEF	Ministry of Environment and Forest
R.B.A.	Relative Basal Area
R.D.	Relative Density
R.F.	Relative Frequency
IVI	Importance Value Index
FSI	Forest Survey of India
UNEP	United Nation Environment programme
IPCC	Inter-governmental Panel on Climate change
FAO	Food and Agricultural Organization
amsl	above mean sea level
No.	Number
M.P.	Madhya Pradesh
NE	North East
Mt	Metric ton
$g\ m^{-2}$	gram per square meter
AGBD	above ground biomass density
PMDF	primary mixed deciduous forests
SMDF	secondary mixed deciduous forests
BAR	biomass accumulation ratio
TAGB	total above ground dry biomass
GPP	gross primary production
ANPP	above-ground net primary production
APR	aboveground plant respiration
TBCF	total below-ground carbon flux
NEP	net ecosystem production
MAP	mean annual precipitation
$\mu\ g\ g^{-1}$	micro-gram per gram
MAT	mean annual temperature
TDF	tropical dry forests

Abbreviations	Description
S.E.	Standard error
d	species richness
Cd	Concentration of dominance
ha^{-1} yr^{-1}	per hectare per year
BNP	Belowground net production
P	Phosphorus
K	Potassium
N	Nitrogen
m^2	Square meter
CD	Critical differences
SOM	Soil organic matter
GHG	Green House Gases
Pg	Petagram (1Pg = 10^{15} grams)
SOC	Soil organic carbon
Tg	Tera gram (1Tg = 10^{12} grams)
KP	Kyoto Protocol
CDM	Clean Development Mechanism
CER	Certified emission reductions
CSP	Carbon Sequestration Potential
SCS	Soil Carbon Sequestration
MBC	Microbial Biomass carbon

CHAPTER-I

INTRODUCTION

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INTRODUCTION

Tropical forests play crucial roles in the functioning of our planet and the maintenance of life (Myers, 1988). Covering only 7% of the earth's land surface the tropical forests have more than half of the world's species (May & Stump, 2000), serve as regulators of global and regional climate systems, act as carbon sinks, provide valuable ecosystem services and serve as vital resources for human populations (Laurance, 1999).

Tropical forests in India cover 56.60 m ha of total geographical area of the country which comes out to be 81.96 % of the actual forest cover of which nearly one third (33.92%) falls in the tropical moist deciduous type (SFR, 2011). Tropical forests often referred to as one of the most species diverse terrestrial ecosystems (Kumar *et al.,* 2006) and most used and threatened ecosystems, especially in India (Shankar, 2001). However , the structure, composition and functioning of deciduous forests undergo changes with the length of wet period, amount of rainfall, latitude, longitude and altitude (Shankar, 2001) and impacts of human and livestock activities.

Tropical forests harbour the greatest wealth of biological and genetic diversity on the Earth. These biodiversity rich forests have world attention because of the growing awareness of its importance on the one hand and the anticipated massive depletion on the other (Singh, 2002).

Forests are the natural storehouses of biomass and carbon (C). They sequester and store more C than any other terrestrial ecosystem and are an important natural 'brake' on climate change (Gibbs *et al*, 2007)). Forests fix, store and emit C by photosynthesis, respiration, decomposition and disturbances through a series of stages in the life cycle from regeneration to harvest (Fukuda *et al,* 2003). Forest vegetation represents a major pool in the global C cycle and alone contains over 350,000 Tg C (Dixon *et al*, 1994). In the last few years in particular, there has been increasing interest in the quantification of the biomass of forest ecosystems and its potential C fixation (Usuga *et al*, 2010). Live tree biomass pool is an important source of uncertainty in C balance from the tropical regions in part due to scarcity of reliable estimates of tree biomass and its variation across landscapes and forest types(Alves *et al*, 2010). It plays an important role in the global C cycle, accounting for a significant fraction of the total C pool and nutrient stocks.

Carbon fixation through forestry is a function of the amount of biomass in a given area. Therefore, any activity or management practice that changes the amount of biomass in an area has an effect on its capacity to store or sequester carbon. Forest management practices can be used to reduce the accumulation of green house gases in the atmosphere through two different approaches. One is by actively increasing the amount or rate of accumulation of carbon in the area. The second is by preventing or reducing the rate of release of carbon already fixed.

Plantations are a very efficient way of promoting biomass and carbon accumulation, and tend to be easier to manage than multi-species stands or natural forests (Evans, 1992).

India's low per capita forest area of 695 sq. m. results in a large gap between supply and demand for forest products. India has 2.5% of the world's land area and 1.8% of the global forest area, but supports 15.6% of the world's human population and 14% of the livestock population. It has large rural population of nearby 700 million with a high population density of 2.57 persons/ha and 4.26 livestock/ha of forestland. This large population depends on forest for meeting diverse biomass needs and thus secondary forest are very important for the supply of fuel wood raw materials for rural hand crafts and industries, among other products. They are potentially very important also for their environmental functions including soil and water conservation, flood control, and carbon storage.

Deforestation and biomass burning are some of the causes of increasing carbon concentration in atmosphere. In India, 4.3 m.ha of forest was diverted to non-forest use from 1951 to 1980 and total decline was 47,725 ha/year. Forest cover in the country has more or less stabilized since 1980’s,however, as per India state of the forest report (SFR, 2011), forest cover has declined by 367 sq.km compared to the forest cover in preceding SFR in 2009. (Nayak, B.P. *et. al.,* 2011).

Due to rapid human population growth, demand for timber, fuel material, and other forest products is increasing. In many areas of India, native broad-leaved forests have been cleared for the last several decades, and subsequent development has involved the plantation of more productive forest species. Many forestry experts claim that the establishment of plantations will reduce or eliminate the need to exploit natural forest for wood production. In principle this is true because due to the high productivity of plantations less land is needed. Establishment of forest plantation on wastelands, community lands and in agricultural land would not only fulfill the target of covering the forest areas but also mitigate the carbon content from atmosphere.

Teak (*Tectona grandis*) is amongst the principal economic tree species commonly recommended for plantation programmes in dry tropical regions for timber production. The durability and workability of teak were recognized many centuries ago, leading to its relatively widespread distribution and cultivation throughout the tropics. Today, teak ranks among the top five tropical hardwood species in terms of plantation area established worldwide. Teak is relatively easily established in plantations and because of the enduring global demand for products from teak, it has good prospects as a plantation species.

Teak is a tall tree species indigenous to India, Myanmar and Thailand but also growing in seasonal dry tropical areas in Asia (Bunyavejchewin, 1983). It is highly rated among hardwood plantations due to its durability, mellow color, and long straight cylindrical bole. The wood of teak is used for furniture, flooring, joinery, trim, doors, paneling, carving, musical instruments, turnery, vats, boat masts and decks, railway sleepers, mine props, fuel, and fence posts (Nair and Chavan 1985; Tiwari 1992; Bhat 1995; Brennan and Radomiljac 1998; Trockenbrodt and Josue 1998; Priya and Bhat 1999; Bhat 2000; Baillères and Durand 2000; Kokutze *et al.* 2004). The heartwood of teak is golden brown with a distinct grain and has a specific gravity of 0.55 (Longwood 1961).

Although natural teak is distributed in relation to productive soils, derived from e.g. limestone (Tanaka *et al.*, 1998), teak is planted over many tropical countries, such as Nigeria, the Sierra Leone in Africa, and Costa Rica, Panama, Colombia, Trinidad and Tobago and Venezuela in central America, as well as Asian countries (Kashio & White, 1998; Pandey & Brown, 2000). It can grow in a wide variety of soils, tolerate a wide range of climates, and have best growth under the conditions that the minimum monthly temperature is above 13°C and the maximum monthly temperature is below 40°C. Optimal rainfall for teak ranges between 1250 and 3750 mm per year, however, for the production of good-quality timber the species requires a dry season of at least four months with less than 60 mm precipitation (Kaosa-ard, 1981). Teak occurs on a variety of geological formations such as trap, limestone, granite, gneiss, mica schist, sandstone, quartzite, conglomerate, shale and clay (Tiwari, 1992). It usually grows on the soils with a pH range of 6.5 to 7.5. Below pH 6.0 it is absent and beyond pH 8.0 it suffers stress in growth. Altitude plays an important role in the plant growth. Normally teak does not grow at altitude of over 900 m and the plant vigour decreases over 750 m (Takle and Mujumdar, 1956). Similarly aspects of the locality also affect the plant's growth and the plants grow better on the cooler northern and eastern aspects than on the hotter southern and western ones (Seth and Yadav, 1957).

Teak is one of the most extensively planted tree species in the tropics, constituting about 6.0 million ha plantation area worldwide (Bhat and Hwan Ok Ma, 2004). Approximately 94% plantations of this net area are located in Tropical Asia, with 44% in India and 31% in Indonesia. The plantations of other countries in the region contribute significantly with 7% in Thailand, 6% Myanmar, 3.2% Bangladesh and 1.7% Sri Lanka. The area of teak plantations in Tropical Africa is about 4.5% of total area of teak plantations and the rest are in Tropical America, mostly in Costa Rica and Trinidad and Tobago (Pandey, 1998). The plantation forests of 5.3 million ha teak in Asian Pacific region have been managed under 35 to 80-year rotations, yielding 5 to 20 $m^3 \cdot ha^{-1} \cdot year^{-1}$, while 310000 ha plantations in Africa are harvested at 20-year rotations, yielding between 4 and 13 $m^3 \cdot ha^{-1} \cdot year^{-1}$ (Bhat and Hwan Ok Ma, 2004).

By the year 2004, global teak plantation area reached 6 million hectares and is still growing for investment by small landholders in agroforestry management as well as industrial wood supply (ITTO, 2004). However, the expansion of teak plantation has been propounding discussion from environmental perspectives, such as reduced biodiversity by mono-cultural plantations involving the clearing of undergrowth vegetation; soil erosion by fire treatment and litter raking; nutrient losses during harvesting; the spread of pests such as defoliators, the bee hole borer, skeletonizer;

and the effects of water cycling (Niskanen, 1998; Pandey & Brown, 2000; Hallett *et al*., 2011).

Plantation of teak, in India, started during the middle of the 19th century. In the year 1842, Conolly, collector of Malabar initiated plantation of teak in Nilambur (Kerala) with a view to ensuring quick regeneration of teak forests (Dwivedi, 1993). From that year until 1862, more than 1 million teak plants were raised for plantation development. The area planted is now about 980 000 ha.

Current teak plantation management is dominated by the public sector, especially Government Forest Departments or state corporations/enterprises. Private involvement in establishing teak plantations is a recent development and the area under private sector management is expected to increase rapidly as long as teak planting is perceived as a commercially attractive investment. Under clear and favorable tenure conditions, less restrictive policies, and the provision of economic incentives, teak plantings have particularly expanded in small woodlots and homesteads.

Nowadays, one of the incentives for planting teak is to meet the demand in terms of carbon sequestration by indigenous tree species, at least in Indochina, with high economical return (Pibumrung *et al*., 2008; Jayaraman *et al.,* 2010). However, despite several studies on carbon and biomass distribution in teak plantation in many countries, the carbon cycling of teak plantation has rarely been reported (Khanduri *et al.*, 2008; Kraenzel *et al.*, 2003; Viriyabuncha *et al.*, 2002; Pande, 2005). Teak plantation production varies widely among countries and depending on soil conditions (Enters, 2000; Kaosa-ard, 1998). For example, the mean annual increment ranged from 2.0 m^3 ha^{-1} y^{-1} in poor sites in India to 17.6 m^3 ha^{-1} y^{-1} in prime sites in Indonesia with 50 year rotation periods (Pandey & Brown, 2000). Thus, the quantative illustration of carbon cycling in teak plantations is useful for understanding the key carbon sequestration channels, which may serve as the basis for improving forest management.

Although forest tree plantations have only had 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 future mitigation of climate change (Canadell *et al.*, 2007).

Estimation of biomass and productivity are essential for determining the status and flux of biological materials in an ecosystem and for understanding the dynamics of the ecosystem (Anderson, 1970.). However, the biomass and productivity of tree species varies from place to place due to variation in climate, soil, temperature and rainfall. Teller (1968) pointed out that forest floor biomass plays a significant role in the structure and functioning of forest ecosystems by acting as a nutrient reservoir and improves the infiltration rate and water holding capacity of soils. The quantity of tree biomass per unit area of land constitutes the primary data needed to understand the flow of materials and water thorough forest ecosystem (Swank, 1974). Lieth and Whittaker (1975) pointed out that if forest biomass is to be measured and analysed in its proper way as a part of production, this gives an overall picture of ecosystem functioning. According to Lodhiyal and Lodhiyal (1997), the rising demand of energy from renewable sources has generated new ideas and turn attention to woody biomass production system. The increasing trends of plantations of an indigenous tree species are widely gaining popularity due to their higher biomass accumulation per unit area, better nutrient conservation efficiency and suitability in nutrient poor sites.

The estimates of carbon stock are also important for scientific and management issues such as forest productivity, nutrient cycling, and inventories of fuel wood and pulp. In addition, aboveground biomass is a key variable in the annual and long term changes in the global terrestrial carbon cycle and other earth system interactions. It is also important in the modelling of carbon uptake and redistribution within ecosystems. Of most interest is live wood biomass, which is involved in the regulation of atmospheric carbon concentrations. Thus, its dynamics must be understood if annual spatial variations are to be related to spatial weather and climate variables. Other computations, which require an accurate estimate of biomass along with carbon emission and carbon sequestration rates, are defining the carbon status and flux in a given geopolitical unit for the assessment, for example carbon taxes and similar international CO_2 mitigation measures.

Therefore, this study is focused on carbon sequestration, specifically in terms of aboveground biomass and carbon stock.

The objectives of study are :

1. To quantify the biomass pattern in age series of teak plantation,
2. To quantify the carbon storage pattern in age series of teak plantation,
3. To quantify the carbon sequestration in vegetation and soil under an age series of teak plantation, and
4. Estimation of different soil organic carbon components under age series of teak plantation.

CHAPTER-II

REVIEW OF LITERATURE

CHAPTER-II
REVIEW OF LITERATURE

In this chapter an attempt has been made to review the work done on **"Biomass, Carbon Stock and Carbon Sequestration in an Age series of Teak Plantation in Tropical Environment".**

However, due to paucity of literature on few aspects, the similar types of studies carried in other forest ecosystems are also cited. The literature is broadly reviewed under the following major aspects.

2.1 Biomass pattern, litterfall and Net Primary Productivity (NPP),

2.2 Carbon storage pattern and carbon sequestration,

2.3 Soil and nutrient.

2.1 Biomass pattern, litterfall and Net primary Productivity (NPP)

Biomass constitutes a primary data needed for understanding a number of ecological processes like energy flow, water and nutrient cycling in forest ecosystems (Chaturvedi and Singh, 1987; Tiwari, 1994). On the other hand, the estimation of woody biomass is also necessary for determining the storage and flux of biological materials in an ecosystem (Anderson, 1970). The quantity of tree biomass per unit land area forms the primary data needed to understand the flow of materials and water through forest ecosystems (Swank and Schreuder, 1974).

The biomass estimations in forests are conventionally made by the use of species specific allometric equations and component wise viz., stem, branch, foliage and root biomass are estimated in both tree and shrub layer (Misra, 1968; Odum, 1983; Rai, 1984). In this approach, the availability of species-specific local regression equations is essential for precisely estimating the forest biomass.

Ambagahaduwa *et. al.* (2009) estimated the above ground biomass production in a 25 year-old *Pinus caribaea* plantation. Using these site-specific formulae derived from empirical data, the above ground biomass of the 25 year-old *P. caribaea* stand was found to be 194 t/ha. A second estimation of 136 t/ha for the above ground biomass was obtained using standard formulae. Of the live standing crop, the stem represented 60%, the branches 17%, leaves 13%, cones 3% and dead branches 7%. This pine stand had 695 pine trees/ha, a mean diameter at breast height (dbh) of 20.1 cm, a mean height of 20.7 m and mean basal area of 23.6 m^2/ha. The estimated above ground biomass showed that the *P. caribaea* plantation studied is a good sink for sequestered carbon. Based on a metaanalysis of literature data on *P. caribaea* in the tropics, it was found that a *P. caribaea* plantation up to an age of 25 years attains maximum above ground biomass when it reached *ca.* 22 years.

Baisya *et al.* (2009) studied above ground biomass distribution and carbon storage in different DBH and compared the natural semi evergreen forest and Sal plantation in the humid tropics of NE India. They found that the above ground biomass in natural forest was higher in the trees having DBH > 60 cm as compared to plantation forests.

Barbhuiya *et al. (*2012) estimated the fine root dynamics in undisturbed and disturbed stands of a tropical wet evergreen forest in northeast India. In the highly disturbed stand, more than 90% of the fine root biomass was recorded in the surface soil layer, whereas in the moderately disturbed and undisturbed stands the proportion averaged 67%. In the undisturbed stand, higher concentrations of fine roots in the surface soil layer were associated with higher nutrient concentrations and moisture retention in the undisturbed stand. Root turnover also decreased with increasing soil depth, root size and intensity of stand disturbance. In the undisturbed, moderately disturbed and highly disturbed stands. The annual fine-root turnover was 3181, 1701 and 822 kg ha^{-1} yr^{-1}, respectively. The study revealed that growth and accumulation of fine roots varied with species composition, tree density and basal area.

Bargali *et al. (*1992) studied and analysed that biomass of vegetation, forest floor litter mass, tree litter fall and net primary productivity of trees and shrubs increased with the increase in plantation age, whereas herb biomass and NPP significantly decreased with the increase in plantation age. The total plantation biomass increased from 7.7 t ha^{-1} in the 2-year old to 126.7 t ha^{-1} in the 8-year old and NPP from 8.6 t ha^{-1} $year^{-1}$ in the 2-year old to 23.4 t ha^{-1} $year^{-1}$ in the 8-year old plantation. The biomass accumulation ratio ranged from 0.81 to 5.93 in 2 to 8-yearold plantation of *Eucalyptus tereticornis.*

Bijalwan *et. al*. (2010) reported the result of study conducted during 2001-2002 to characterize the land use, biomass and carbon status of dry tropical forest in Raipur district of Chhattisgarh, India using satellite remote sensing data and GIS techniques. The main forest types observed in the area are Teak forest, mixed forest, degraded forest and Sal mixed forest. The aspect and slope of the sites influenced the forest vegetation types, biomass and carbon storage in the different forests. The standing volume, above ground biomass and carbon storage varied from 35.59 to 64.31 $m^3 \cdot ha^{-1}$, 45.94 to 78.31 $Mg \cdot ha^{-1}$, and 22.97 to 33.27 $Mg \cdot ha^{-1}$, respectively among different forest types. The highest volumes, above ground biomass and carbon storage per hectare were found in the mixed forest and lowest in the degraded forest. The total standing carbon present in the entire study area was 78170.72 Mg in mixed forest, 81656.91 Mg in Teak forest, 7833.23 Mg in degraded forest and 7470.45 Mg in Sal mixed forest, respectively. The study shows that dry tropical forests of the study area in Chhattisgarh are in growing stage and have strong potential for carbon sequestration.

Brown *et al.* (1997) examined quantities and distribution of above ground biomass density (AGBD, Mg ha^{-1}) of US eastern hardwood forests and assessed their biological potential for continued biomass accumulation in the future and found that the presence of a large proportion of the AGBD of moist tropical forests in large diameter trees (> 70 cm diameter) which indicate the mature and undisturbed conditions. Biologically these forests have potential to accumulate significant quantities of additional biomass, if left unharvested.

Cairns *et al. (*2003) estimated the aboveground tree biomass of a dry semi-evergreen forest of Mexico's Yucatan Peninsula and stated that a total of 72 species were found in a 0.5 ha stand with a basal area of 31.3 m^2 ha^{-1} constituting about 225 Mg ha^{-1} of total aboveground tree biomass which was dominated (85%) by the biomass of the large trees.

Castellanos *et al. (*1991) studied the root biomass of dry deciduous tropical forest in Mexico and found that the above and below ground biomass of trees, shrubs and lianas was 73.6 t ha^{-l} and 31 t ha^{-l}, respectively. A root: shoot biomass ratio of 0.42 was calculated.

Cordero and Kanninen (2003) studied aboveground biomass of *Tectona grandis* plantations in Costa Rica. This paper reports the distribution of total aboveground biomass *of Tectona grandis* and its relationship with diameter at breast height (dbh), age and stand density in plantations across Costa Rica. Foliage, branch, stem and total aboveground biomass were highly correlated both with dbh ($r > 0.91$) and with age ($r > 0.85$). Foliage dry biomass represented between 1 and 6% of the total tree dry biomass, while 5 to 30% corresponded to branches and 70 to 90% to stem dry weight. Per hectare aboveground biomass tended to increase with increasing age class (young, intermediate and mature). Significant relations between crown diameter and aboveground biomass with dbh, age and stand density, useful for the management of stand competition, are the main results of this study.

Devagiri *et al.* (2013) used the Remote sensing and GIS based approach for estimation of above ground biomass (AGB) and carbon pool at regional scale in south western part of Karnataka. This study integrates field measured biomass with spectral responses of different bands and indices of MODIS 250 m spatial resolution. Based on relative forest area within the MODIS pixel, area weighted biomass was estimated for each site using ground measured plot (0.4 ha) biomass. Field measured AGB ranged between 7.25 to 287.047 t-dry wt ha^{-1} across different vegetation types in the region. The best fit regression equation (Y = 0.053e9.382x) was obtained between area weighted AGB (Y) and NDVI of December month (x) with R^2 value of 0.8074. This equation was further used for spectral modeling to estimate the AGB and vegetation carbon pool and to prepare a map to understand the geospatial distribution in the region. Total AGB on dry weight basis was estimated at 6.43 Mt (mean biomass density of 70 t ha^{-1}) and carbon stock of 3 Mt (mean carbon density of 33 t ha^{-1}) in the entire region. This study revealed that remote sensing technique combined with field sampling provides quick and reliable estimates of above ground biomass and carbon pool and such approach could be used more conveniently for carbon inventories at the State and National level.

Hall and Uhling (1991) estimated the biomass density of forest in South and South East Asia using the volume estimates and biomass comparison factors derived from Brown *et. al.* (1989). Their biomass estimates for India ranged from 116 Mg ha^{-1} for undisturbed forest for 60-80 years and 35, 66 and 84 Mg ha^{-1} for logged, unproductive and managed forests, respectively. However, these estimates were only made from 9 per cent of forest area and no information was given in relation to forest types and species composition.

Joseph *et. al.* (2010) conducted the study to estimate the biomass and carbon stock of major tropical forest types in India, and to identify suitable interpolation techniques for mapping carbon stock. Empirically derived allometric equations and carbon conversion coefficients were used to estimate the aboveground biomass and carbon stock, respectively. The point estimates were interpolated to spatial surface using different interpolation techniques. Two main modelling approaches were implemented: deterministic modelling and stochastic modelling. Deterministic modelling was to interpolate point information using similarities between measured points (inverse distance weighted (IDW) interpolation), and fitting a smoothing curve along the measured points (polynomial interpolation). In stochastic modelling, ordinary kriging (OK) was employed using parameters derived from semivariograms. The results showed that the average carbon stock in the study area was 84 t/ha. The highest carbon stock was in evergreen forest and the lowest in thorny scrub forest. Validation of the model using the mean and RMS errors indicated that ordinary kriging performs better than IDW and polynomial interpolations.

Kaewkrom *et.al*. (2011) carried out the the study to monitor forest types and carbon storage in both biomass and soil within primary mixed deciduous forests (PMDF) and secondary mixed deciduous forests (SMDF). One study plot measuring 50 x 50 m and five 10 x 10 m plots were set up at each study site for trees and shrubs inventory, respectively. The trees and shrubs were counted and identified by species. Organic carbon in biomass was estimated by using allometry equation and soil carbon concentration was analyzed by Walkley-Black method. The results revealed that

PMDF had a higher level of carbon storage in biomass than SMDF by approximately two times, while soil carbon stock in PMDF was also quite higher than SMDF. The dominant species having a high carbon concentration included *Canarium subulatum*, *Pterocarpus macrocarpus*, *Dalbergia cultrate*, *Lagerstroemia tomentosa* and *Xylia xylocarpa* var kerrii. These species were found in intermediate succession, thus indicating that some may be suitable for replanting in future restoration processes in order to accelerate natural succession and storage carbon. This may be one method to reduce the CO_2 in the atmosphere by making the SMDF act as a carbon sink.

Konopka (2009) studied the differences in fine root traits between Norway spruce (*Picea abies* [L.] Karst.) and European beech (*Fagus sylvatica* L.) Sequential soil coring was repeatedly implemented in April, June, July, September and October including the soil layers of 0–5, 5–15, 15–25 and 25–35 cm. Spruce had a lower standing stock of fine roots than beech and fine roots of spruce were more superficially distributed than those of beech. Furthermore, he estimated higher seasonal dynamics and also higher turnover of fine roots in spruce than in beech. The production to mortality ratio was higher in beech than in spruce, which was hypothetically explained as the effect of drought episodes that occurred in July and August. The results suggested that the beech root system could resist a physiological stress better than that of spruce. This conclusion was supported by different vertical distributions of fine roots in spruce and beech stands.

Koppad and Rao (2013) conducted an experiment at Mundgod in hill zone of Karnataka, India, during the year 2001-2002. Teak (*Tectona grandis*) plantations raised with high input management practices *viz.*, application of fertilizers (organic and chemical), irrigation, weed management and intercultural operations for 2 years after planting were selected as better managed plantations. Plantations raised without any management practices were selected as poorly managed plantations. Observations *viz.,* plant height, diameter at breast height and wood density were recorded in five year and ten year old plantations. Results indicated that plantations raised with high input management practices recorded 19.471 and 59.552 tonnes wood biomass per hectare in five and ten year teak plantations as compared to only 8.866 and 31.517 tonnes in poorly managed plantations respectively. Carbon sequestration in five and ten-year-old plantations due to management practices was 4.879 and 12.896 tonnes higher per hectare respectively when compared to poorly managed teak plantations. On an average 0.976 and 2.579 tonnes of excess carbon has been sequestered per hectare per year in better managed plantations over conventional grown (poorly managed) five and ten year old teak plantations respectively. The results indicated that high input management practices followed at initial years (2-3years) had increased the carbon sequestration in five and ten year old teak plantations.

Kumar *et al.* (2011) studied the biomass and net primary productivity of different age group (5, 10 and 15 year old) of *Butea monosperma* forest ecosystems in western India, Rajasthan. The vegetation biomass, forest floor, litter fall and net primary productivity (NPP) of trees and shrubs were estimated and it was found that the tree biomass and net primary productivity increased with increasing age of the forest stand, whereas the herb biomass and net primary productivity decreased significantly ($P < 0.01$) with increase in the forest age. The biomass of trees increased with age from 183.7 to 298.3 t ha^{-1} while shrub biomass ranged from 4.9 to 6.3 t ha^{-1} and the herb biomass fluctuated from 1.7 to 2.1. The tree layer NPP varied from 17.2 to 29.3 t ha^{-1} yr^{-1} where the NPP of the shrub layer was 0.88 to 1.6 t ha^{-1} yr^{-1}. The productivity of the herb layer ranged from 2.3 to 3.1 t ha^{-1} yr^{-1}. The all values of biomass and NPP of trees, shrubs and herbs were low in 5 year old, moderate in 10 year old and high in 15 year old forest stands. The total forest biomass increased from 190.7 t ha^{-1} in the 5 year old to 306.3 t ha^{-1} in 15 year old forest and net primary productivity from 21.1 t ha^{-1} yr^{-1} in the 5 year old to 33.2 t ha^{-1} yr^{-1} in the 15 year old forest.

Kumar *et al.* (2009) studied the quantification of nutrient content in the aboveground biomass of teak plantation in a tropical dry deciduous forest of Udaipur, India. The nutrient contents in the total biomass of teak in the plantation were 165.47 kg/ha N, 20.96 kg/ha P, 35.06 kg/ha K, 49.29 kg/ha Ca, 31.52 kg/ha Mg, 4.27 kg/ha Na, 4.06 kg/ha S and 3.21 kg/ha Cl. Of the total, 42.93% of the dry matter accounted for crown biomass (leaves, branches, twigs and reproductive parts), which in turn accounts for 60.93% N, 58.63% P, 54.30% K, 51.40% Ca, 62.5% Mg, 53.62% Na, 59.85% S and 60.74% Cl of the aboveground biomass, whereas 57.07% of the dry matter account for trunk biomass (bole bark and bole wood), which in turn accounts for 39.07% N, 41.37% P, 45.70% K, 48.6% Ca, 37.5% Mg, 46.38% Na, 40.15% S and 39.26% Cl.

Lieth and Whittaker (1975) pointed out that if forest biomass is measured and analysed in its proper context as part of production an overall picture of ecosystem functioning can be gained. The biomass and productivity of tree species varies from place to place due to variation in climate, soil, temperature and rainfall.

Lodhiyal *et al.* (1995) studied the dry matter dynamics of an age series of poplar plantations in Central Himalaya. The biomass of plantation, forest floor litter mass, tree litter fall and net primary productivity (NPP) of trees and shrubs increased with increase in plantation age, whereas herb biomass and NPP significantly ($P < 0.01$) decreased with increasing plantation age. The total plantation biomass increased from 84.0 t ha^{-1} in the 5-year-old to 170.0 t ha^{-1} in the 8-year-old plantation and NPP from 16.8 t ha^{-1} yr^{-1} in the 5 and 6-year-old to 21.8 t ha^{-1} yr^{-1} in the 8-year-old plantation. The biomass accumulation ratio (biomass: net production, BAR) for different tree components increased with the increased age of plantation.

Lodhiyal *et al.* (2000) studied the biomass and net primary productivity of 5 to 15 year old Shisham forests in Central Himalaya. The biomass (dry matter), forest floor biomass (standing crop litter), tree litter fall and NPP of trees and shrubs increased with increasing age of the forest stand, whereas the dry matter and herb net primary productivity decreased significantly with increasing age of the forest.

Lone and Pandit (2007) evaluated impact of grazing on species composition and plant biomass for the herbaceous community in Langate forest division of Kashmir and observed that protected areas registered higher values for biomass as compared to the grazed ones. The plant biomass for protected areas was maximum in summer (1221.56 g/m^2) and minimum in winter (290.62 g/m^2) as against the grazed area bearing maximum value of 590.81 g/m^2 in autumn and 183.75 g/m^2 in winter.

Mbaekwe and Mackenzie (2008) studied the use of a best-fit allometric model to estimate aboveground biomass accumulation and distribution in an age series of teak (*Tectona grandis* L.f.) plantations at Gambari Forest Reserve, Oyo State, Nigeria. Biomass accumulation and distribution in four selected plots of an age series (5, 8, 11 and 14 years) of teak plantations were studied. Ten trees per plot (50 m × 50 m) were randomly selected and destructively sampled for the fresh and oven-dry weights of their tree components. The dry weights of the tree components were regressed with their trunk diameters at breast height. The log allometric model was used to estimate the biomass. The trends in the biomass accumulation and distribution, as well as those of the mean annual increase in biomass, percentage contribution of the leaf biomass to the overall tree biomass and the undergrowth and litter were discussed.

Because of its rapid rate of biomass accumulation compared to species of natural and other timber plantations, the use of teak as an alternative source of timber is justified.

Murali *et al.* (2005) derived biomass estimation equation for tropical deciduous and evergreen forests and developed linear and non–linear regression equations for estimation of biomass of tropical forests along with estimates of goodness of fit and percentage of errors. Basal area and height of trees were found to give high goodness of fit and low percentage of errors for deciduous forests. They found that generally the coefficient of determination (R2) was low for evergreen forests. The coefficient of determination was high and estimate of error was low for deciduous forests. They concluded that the biomass estimation equations for deciduous forests were precise and therefore useful for field applications.

Nascimento and Laurance (2002) studied the total above ground biomass in central Amazonian rain forests and quantified total above ground dry biomass (TAGB) within 201 ha plots in undisturbed site. TAGB values were very high averaging 397.7 + 30.0 t ha^{-1}. The most important component of above ground biomass were large trees (< or > 10 cm dbh) which comprised 81.9% of TAGB followed by downed wood debris (7.0%), small trees, saplings and seedlings (< 10 cm dbh; 5.3%), lianas (2.1%), litter (1.9%), snags (1.5%), and stemless palms (0.3%). Among large trees above ground biomass was greatest in intermediate sized (20-50 cm DBH) stems (46.7% of TAGB), with very large (< or > 60 cm DBH) trees also containing substantial biomass (13.4% of TAGB). They also found that there were no significant correlations between large tree biomass and that of any other live or dead biomass components.

Oliveria *et al.* (2003) tested the hypothesis, that there are significant impacts in above ground alive standing biomass among areas under fragmentation and evaluated the standards of biomass distribution among four areas around the highways BR 364 and BR 364 (Acre, Brazil) through allometric equations and found that the dynamics of biomass in primary forests are related to the process of forest fragmentation. They found the smallest values for the variable basal area (20.3 m^2 ha^{-1}) and biomass (384 tons ha^{-1}) in the smallest forest fragments. The effect of selective logging was evident and showed a drastic reduction in biomass for the logged species.

Pande *et al.* (1986) studied the biomass production and distribution of nutrients in moist deciduous forests in Goa and found that the dominant species were *Terminalia tomentosa* in the upper storey and *Careya arborea* and *Lannea grandis* in the under storey and reported that as much as 92% of the total biomass was contributed by *Terminalia tomentosa* with only 8% by the other two species.

Pande and Patra (2010) estimated the biomass and productivity of Sal forest (SF) and miscellaneous forest (MF) of Satpura (Madhya Pradesh) India. These forest types were divided into four sites namely open miscellaneous (OMF Site-I), closed miscellaneous (CMF Site-II), open Sal (OSF Site-III) and closed sal (CSF Site-IV). OSF Site-III and CSF Site-IV was most and least disturbed site among the four and stated that the closed canopy forests produced higher above ground tree biomass, root biomass and total NPP as compare to open site. The ranges for above ground, below ground and total biomass (t ha^{-1}) were 154.9-345.6; 35.60-62.16 and 190.53- 406.27 respectively. Disturbances in open forests not only reduce the stand biomass of tree species, dominant species in particular but also declined the forest productivity.

Prasad *et al.* (2002) studied the biomass burning and related trace gas emission from tropical dry deciduous forests of India. The dominant vegetation type of the study area is tropical dry deciduous along with moist mixed evergreen. Two ground based experiments were carried out to quantify the emission burning practices. Using the DMSP-OLS derived aerial estimates of active fires; the trace gas emissions released from the biomass burning were quantified. The results suggested the emission of 8.2x1010 g CO_2, 1.8x108 g CO, 6.0x106 g N_2O, 3.0x106 g NOx and 1.2x108 g CH_4 during March 1987. The emissions increased to 1.0x1011 g CO_2, 2.3x108 g CO, 7.8x106 g N_2O, 3.9x107 g NOx and 1.6x108 g CH_4 over a period of 10 years. The results of the analysis suggest the possible use of monitoring biomass burning events from DMSP-OLS night-time data.

Raizada *et al.* (2007) estimated the biomass production and prediction models for *Acacia nilotica* in salt affected vertisols in Karnataka and they observed that although the plantation is even-aged, there were wide variations in diameter (3.1 to 16 cm) in the entire block and 9.3 to 15.4 cm in the sampled trees. Tree height also varies from 3.5 to 5.1 m, which in turn has influenced above ground biomass. Utilizable biomass (bole + bark + leaf) for firewood ranged from 18.3 to 72.64 kg/tree and total above ground biomass ranged from 26.50 to 100.74 kg/ tree.

Read and Lawrence (2008) stated that the above ground biomass of Calakmul tropical forest ecosystem was 136.42 Mg ha^{-1} in their study recovery of biomass following shifting cultivation in dry tropical forests of the Yucatan, Mexico.

Rizvi *et al.* (2006) developed prediction models for timber boimass of *Populus deltoides* planted on farmlands in Haryana. He estimated the fresh green timber of poplar tree, and evaluated growth process based non-linear models for fresh timber boimass The models viz.; W=1.398 D1.608 and W=9.975 exp (1+7.768 exp (-1.299 (D2H)-0.217)); where W – fresh timber boimass, D - diameter at breast height and H - height of the tree, was found to be good fit. The mean errors in prediction of timber weight by these models were 10.4 and 7.0 kg, respectively.

Roy and Ravan (1996) estimated the biomass in tropical dry deciduous forest of Madhav National Park of Madhya Pradesh using two approaches viz. Homogeneous vegetation stratification (HVS) and spectral response model. The biomass estimated for the entire national park through stratified and spectral response modeling approached was compared and it showed only a small difference of 4.69 per cent between two approaches. Total biomass of the different community type of dry tropical forests ranged from 7.42 to 52.41 t ha^{-1}. Haripriya (2000) estimated the forest biomass from volume inventories of forests. The above ground biomass for tropical forests ranged from 14 to 210 Mg ha^{-1}, with a mean of 67.4 Mg ha^{-1}.

Sharma *et al.* (2002) studied the biomass, net primary productivity, energetics and energy efficiencies in an age series of *Alnus*-cardamom plantations in the eastern Sikkim Himalaya. The impact of stand age (5, 10, 15, 20, 30 and 40 years) on the performance of mixtures of N_2-fixing (*Alnus nepalensis*) and non-N_2-fixing (large cardamom) plants was studied. Large cardamom (*Amomum subulatum*) is the most important perennial cash crop in the region and is cultivated predominantly under *Alnus* trees. Net primary productivity was lowest (7 t ha^{-1} per year) in the 40-year-old stand and was more than three times higher (22 t ha^{-1} per year) in the 15-year-old stand. Agronomic yield of large cardamom peaked between 15 and 20 years of age. Cardamom productivity doubled from the 5 to the 15-year-old stand, and then decreased with plantation age to reach a minimum in the 40-year-old stand. Annual net energy fixation was highest (444 x 106 kJ ha^{-1} per year) in the 15-year-old stand, being 1.4 times that of the 5-year-old stand and 2.9-times that of the 40-year-old stand. Inverse relationships of production efficiency, energy conversion efficiency and energy utilized in N2-fixation against stand age and a positive relationship between production efficiency and energy conversion efficiency suggest that the younger plantations are more productive.

Sharma *et.al*. (2010) studied the four forest stands each of twenty major forest types in sub-tropical to temperate zones (350m asl–3100m asl) of Garhwal Himalaya. The aim of the study was to assess the stem density, tree diversity, biomass and carbon stocks in these forests and make recommendations for forest management based on priorities for biodiversity protection and carbon sequestration. Stem density ranged between 295 and 850 Nha^{-1}, while total biomass ranged from 129 to 533 Mg ha^{-1}. Total carbon storage ranged between 59 and 245 Mg ha^{-1}. The range of Shannon–Wiener diversity index was between 0.28 and 1.75. Most of the conifer-dominated forest types had higher carbon storage than broadleaf-dominated forest types. Protecting conifer-dominated stands, especially those dominated by *Abies pindrow* and *Cedrus deodara*, would have the largest impact, per unit area, on reducing carbon emissions from deforestation.

Shrestha *et al.* (2000) analyzed the vegetation of natural and degraded forests in Chitrepani in Siwalik region of Central Nepal and stated that the natural and regenerating forest sites had much higher tree density than the degraded forest site as it had lost more than 70% species, 90.9% plant density, 80.0% basal area and 80.1% tree biomass. The above ground live biomass of trees was highest in natural site (807 t ha^{-1}) while degraded site had the lowest value (160 t ha^{-1}).

Singh and Singh (1991) studied the species structure, dry matter dynamics and carbon flux of Dry Tropical forests of Vindhyan region. They found that the average standing biomass of vegetation was 66.98 t ha^{-1} with 46.70 t ha-l in tree layer, 13.97 t ha^{-1} in the shrub layer, 0.35 t ha^{-1} in the herb layer, 2.83 t ha^{-1} in litter layer and 3.13 t ha^{-1} in fine roots. Total annual inputs of litter ranged between 4.88-6.71 t ha^{-1} of which

65- 72 per cent was leaf litter fall and 28-35 per cent wood litter fall. Net primary production ranged between 11.3 and 19.2 t $ha^{-1}yr^{-1}$, to which the contribution of trees, shrubs and herbs averaged 72, 22 and 6%, respectively. Contribution of roots to NPP was substantial and ranged from 2.9-5.3 t ha^{-1} yr^{-1}.

Singh and Singh (1993) concluded that the short live components in a dry tropical forest ecosystem in India (tree foliage, fine root and herbaceous plants) are shown to be important for biomass production and nutrient cycling. Almost they contribute 62% to the dry matter production, while long lived components (tree boles, branches and coarse roots) make up only 38%. The contribution of short-lived components to the total uptake of different nutrients was also high 18-30% of tree foliage, 26-34% for fine roots and 6-19% for herbs. The results indicated that the short lived components play a significant role in the functioning of dry tropical forests.

Singh *et al.* (2009) studied the impact of land use changes on species structure, biomass and carbon storage in tropical deciduous forest and converted forest. They found that the total biomass recorded among the different forest plots was 192.933 Mg ha^{-1} in natural forest followed by 95.64 Mg ha^{-1} in 32 years old converted forest, 85.78 Mg ha^{-1} in 23 years old converted forest and 92.05 Mg ha^{-1} in 15 years old converted forest. The total above ground biomass in different forest plots ranged from 71.94 to 162.91 Mg ha^{-1} with highest in natural forest and lowest in 23 years old converted forest. The below ground biomass varied from 13.97 to 30.02 Mg ha^{-1} with the highest in natural forest and lowest in 23 years old converted forest. Carbon storage was also maximum in natural forest (96.44 Mg ha^{-1}) followed by 32 years old converted forest (47.801 Mg ha^{-1}), 15 years old converted forest (46.25 Mg ha^{-1}) and 23 years old converted forest (42.88 Mg ha^{-1}).

Singh *et al.* (2004) studied biomass and productivity of an age series of three cottonwood clones (*Populus deltoides*) in central Himalayan tarai region, India. Estimates of biomass and net primary productivity of three clones of *Populus deltoides,* namely, IC, D-121 and G-3. Each of the three clones had one young (four years old), one middle age (six years old) and one mature (8 to 10 years) stand. Highest basal area (22.8-24.1 m2ha^{-1}) was attained by mature stands. Total tree biomass in investigated clones increased from young (32-42 t ha^{-1}) to mature stands (120-170 t ha^{-1}), the lowest and highest biomass being in IC and G-3 clones, respectively. Net primary productivity also revealed similar pattern. At maturity, net productivity was in the order: D-121 (23 t ha^{-1} year^{-1}) > G-3 (21 t ha^{-1} year^{-1}) > IC (14 t ha^{-1} year^{-1}). The ratio of stem to leaf production generally decreased with age from around 2.0 in young stands (D-121 and G-3 clones) to less than 1.0 mature stands. The relationship between biomass and net primary production was very weak.

Swamy and Puri (2005) conducted the study to determine biomass production, C-sequestration and nitrogen allocation in *Gmelina arborea* planted as sole and agrisilviculture system on abandoned agricultural land. At 5 years, total stand biomass in agrisilviculture system was 14.1 Mg ha^{-1}. Plantations had 35% higher biomass than agrisilviculture system. At 5 years, leaves, stem, branches and roots contributed 4.1, 65.2, 10.0 and 20.7%, respectively to total standing biomass (17.9 Mg ha^{-1}). Over the 5 years of study, trees had 3.5 Mg ha^{-1} more C and 36 kg ha^{-1} more N in plantation than agrisilviculture system. Biomass and C storage followed differential allocation. Relatively more C was allocated in above ground components in plantations compared to agrisilviculture system. C:N ratios for tree components were higher in stem wood (135–142) followed by roots (134–139), branches (123–128) and leaves (20–21). In agrisilviculture system crops recommended are: soybean and cowpea in rainy season; wheat and mustard in winter season. After 5 years, soil organic C increased by 51.2 and 15.1% and N by 38.4 and 9.3% in plantation and agrisilviculture system, respectively. Total C storage in abandoned agricultural land before planting was 26.3 Mg ha^{-1}, which increased to 33.7 and 45.8 Mg ha^{-1} after 5 years in plantation and agrisilviculture system, respectively. Net C storage (soil + tree) was 7.4 Mg ha^{-1} in agrisilviculture system compared to 19.5 Mg ha^{-1} in *G. arborea* monoculture stands. The studies suggest that competitive interactions played a significant role in agrisilviculture system. Plantations were more efficient in accreting C than agrisilviculture system on abandoned agricultural land.

Swamy *et al.* (2010) studied the biomass, litterfall and net primary productivity (NPP) of tropical evergreen forests of Western Ghats, India and concluded that total stand biomass averaged from 440 to 571 Mg ha^{-1}, of which trees contributed 90.2-92.2 % and remaining 8.8-9.8 % contributed by shrubs and herbs. The standing litter ranged from 3.5 to 4.2 Mg ha^{-1} and litter production from 4.0 to 5.7 Mg ha^{-1} yr^{-1}.The average NPP was 23.7 Mg ha^{-1} yr^{-1}, of which 64.7% was contributed by trees, 13.6% by shrubs, 2.7% herbs and 19.1% by litter, Turnover rate and turnover time ranged from 0.93 to 0.95 yr^{-1} and 1.05 to 1.08 yrs, respectively.

Swe *et al.* (2012) conducted the study with the main objective of assessing the carbon storage in fine root (<2 mm in diameter) biomass of 20-yr and 30-yr old Teak (*Tectona grandis*) plantations. The amount of live fine roots in terms of dry weight in every stand was estimated from soil cores taken to a depth of 50 cm where most of the root fragments were distributed. Tree species, diameter (1.3m above ground level) and tree height were measured for all trees within the plot with a breast height diameter greater than 4.5 cm. This allowed accurate determination of individual tree volumes and basal areas, as well as respective stand level characteristics. The average carbon accumulation in the soils of 20-yr and 30-yr old Teak plantations were 95 ton ha^{-1} and 161 ton ha^{-1}, respectively. Fine root biomass for each stand was 2050 and 3800 kg ha^{-1}, and the respective C amounts to 1215 and 2110 kg C ha^{-1} in15-yr and 30-yr old Teak plantations, respectively. The carbon accumulation in soils is increasing with increasing stand age. However, there is no relationship between fine root biomass and the amount of carbon stored in the soils. Commonly used variables describing the stand structure also did not show any notable correlation with the fine root biomass at the stand level. Swe recommondet the continuous studies at ecosystem level for understanding and predicting the below-ground responses to global change.

Thakur and Khare (2008) investigated the changing status of forest vegetation of Patharia hills at Sagar in India and mentioned that the topography, soil properties and extent of human disturbances are attributed as the major factor influencing the vegetation structure and biomass.

Thakur and Swamy (2012) carried out the study to characterize the land use, vegetation structure, diversity, biomass production, C and nutrient storage of a dry tropical forest ecosystem in Barnawpara Sanctuary, Raipur district of Chhattisgarh through satellite remote sensing techniques and GIS. Results revealed that density of different forest types varied from 324 to 733 trees ha^{-1}, basal area from 8.13 to 28.87 m^{2} ha^{-1} and number of species from 9 to 26. Similarly, the diversity ranged from 1.36 to 2.98, concentration of dominance from 0.07 to 0.49, species richness from 3.88 to 6.86 and beta diversity from 1.29 to 2.21. Sal mixed forest type recorded highest basal area and diversity was highest in Dense mixed forest, while Teak forest recorded maximum density. It was poor in Degraded mixed forests. Results revealed that the highest biomass was found in Dense mixed forest (321464.28 Mg), while net production was highest in Teak forests. Both were lowest in Degraded mixed forests

(42996.08 Mg) in different forest types. The total storage of nutrients in vegetation (OS+US+GS) varied from 105.1 to 560.69 kg ha^{-1} N, 4.09 kg ha^{-1} to 49.59 kg ha^{-1} P, 24.59 kg ha^{-1} to 255.58 kg $ha^{-1}$for K and 7310 to 4836 kg ha^{-1} for C in different forest types. They were highest in dense mixed forest and lowest in degraded mixed forest. The study also showed that NDVI and carbon storage was strongly correlated to Shannon Index and species richness thus it indicates that the diversity of forest type play a vital role in carbon accumulation. The study also developed reliable regression model for the estimation of LAI, biomass, NPP, C & N storage in dry tropical forests by using NDVI and different vegetation indices, which can be derived from fine resolution satellite data. Both quantitative and qualitative information derived in the study helped in evolving key strategies for maintaining existing C pools and also improving the C sequestration in different forest types. The study explores the scope and potential of dry tropical forests of Chhattisgarh for improving C sequestration and mitigating the global warming and climatic change.

Thapa *et al.* (1999) conducted biomass study of *Acacia auriculiformis*, *A. catechu*, *Dalbergia sissoo*, *Eucalyptus camaldulensis* and *E. tereticornis* on a five and half-year-old 'Fuelwood Species Trial under Short Rotation' through destructive sampling at Tarahara, Sunsari District of Nepal. The lowest Furnival Index (FI) was the main criteria for selecting a model. Among the six models tested, a transformed model from a power equation was selected. Selected prediction models of tree components and aboveground wood (green as well as oven dry), and their coefficient of determination (R2) values, regression constant and coefficient, correction factor, precision and bias per cent of five species are presented. With the exclusion of branchwood models, R2 is higher in a range of 88.7% for oven dry stemwood of *A. catechu* to 99.3% for aboveground wood model of *D. sissoo*. However, R2 is less than

80% in branchwood (green and oven dry) of *A. auriculiformis, E. camaldulensis* and *E. tereticornis* showing moderate relationship between branchwood and diameter at breast height. In the case of *E. tereticornis*, precision is more than 49% which leads to low reliability in biomass estimation resulting in true biomass deviation in a range of approximately 49.51 to 56.74%, so biomass models could not be used for estimation of tree components and aboveground wood. Despite it, generally, precision per cent of the selected models has been found less than 15%. Bias per cent was found quite large for allometric branchwood model comparatively to stemwood and aboveground wood models. *D. sissoo* had less than 10% bias. Bias per cent was the highest (23.11%) for green branchwood *of A. auriculiformis*. Others had in a range of 0.5% for green aboveground wood model of D. sissoo to 18.4% for green and oven dry branchwood models of *E. tereticornis.*

Tyagi *et al.* (2009) studied the biomass and productivity in 3, 6 and 9 years old plantation of *Dalbergia sissoo* in sodic lands of Sultanpur district in eastern Utter Pradesh, India. A set of regression equations for biomass production per unit area was also developed. All the standing trees, in the study area, were measured for their diameter at breast height (DBH) and the entire DBH range was highest in leaves, followed by bark and bole. Major portion of above ground biomass was allocated to bole and the remaining was allocated in leaves, twigs, branches and bark. The contribution of leaves, bark and bole to the above ground biomass increased with the increase in age, while twigs and branches showed a reverse trend. Biomass production was positively correlated with age, DBH and height of the trees and the total biomass increased from 388.52 kg/ha in 3 years to 5, 0927.13 kg/ha in 9 years old plantation. In order to predict biomass of the stand on a regional basis, a set of regression equations was derived between easily measurable parameters (DBH and height) and dry weight of different sample tree components (leaves, twigs, branches, bole bark total above ground biomass, root and total biomass).

Ugalde Arias *et al*. (2002) developed Preliminary models for the estimation of biomass of ten species native to the Atlantic zone of Costa Rica. For their study they selected ten species from a series of three species trails for the development of biomass prediction models. Selection criteria were growth rate, economic value and farmers' preference, nodulation (in the case of leguminous species), impact on soil fertility, and plant availability. The species were *Calophyllum brasiliense*, *Vochysia guatemalensis, Jacaranda copaia, Virola koshnyi, Dipteryx panamensis, Terminalia amazonia, Genipa americana, Vochysia ferruginea, Hyeronima alchorneoides* and *Pithecellobium elegans.*

Upadhyay *et al.* (2009) analyzed that effect of disturbance on standing biomass in a sal mixed forest of Eastern U.P. Three sites selected on the basis of disturbance gradient showed sequential differences in standing biomass. The total biomass of the three forest sites differs significantly from severely disturbed site I to relatively undisturbed site III of which 83% was allocated to above ground parts and 17% to below ground. The understorey contributed about 32% (172 t ha^{-1}) and overstorey layer constituted about 68% (372 t ha^{-1}) to the total biomass.

Wilsey and Potvin (2000) reported that total and belowground biomass increased with increasing levels of species evenness. Studies on biodiversity in relation to ecosystem functioning have revealed that species diversity enhances the productivity and stability of ecosystems (Naeem et al., 1994; Tilman et al., 1996). Mishra *et al.* (1998) studied the biomass status of two biotically disturbed site (BD) and an undisturbed site (UD) of mixed dry deciduous forest of Shiwalik hill in Haryana. The total basal area was 7.9 m^2 ha^{-1} in BD and 9.7 m^2 ha^{-1} in UD. Three important tree species *Anogeissus latifolia*, *Acacia catechu*, and *Terminalia tomentosa* accounted for 88% of total tree density in BD and 66% in UD. Total above ground tree biomass was 22.05 t ha^{-1} in BD and 31.19 t ha^{-1} in UD, indicating a significant difference.

Zhang *et al*. (2004) derived prediction models of foliage and branch biomass based on the foliage distribution within the crown and the pipe model theory. Resulting models were fitted for data collected from intensively managed loblolly pine (*Pinus taeda* L.) plantations in the Lower Coastal Plain and Piedmont of Georgia. They found that diameter outside bark at the base of the live crown, crown height, and crown length are key predictors of foliage biomass. Together they produce reliable predictions of foliage and branch biomass for stands managed under a wide array of silvicultural treatments. The model indicates that an annual fertilization treatment significantly increased foliage and branch biomass in the Lower Coastal Plain. However, in the Piedmont, complete control of competing vegetation significantly increased foliage and branch biomass. It was found that a significant fertilization-age interaction for foliage and branch biomass was also in Piedmont stands.

Litterfall, the organic debris shed by forest vegetation upon the surface of the soil, has long engaged the attention of ecologists (Bray and Gorhams, 1964). Litterfall represents an essential link in organic production decomposition cycle and this is a fundamental ecosystem process (Meentemeyer *et al.* 1982). Litterfall is the major pathway for the return of the dead organic matter and nutrients held in it from the aerial parts of the plant communities to the surface of the soil. Studies on litter production and nutrient release through litter decomposition in forest ecosystem are of great importance to understand nutrient cycling, energy flow, primary production etc.

Adhikari *et al.* (1995) observed that total biomass was 505 t ha^{-1} in horse chestnut, 566 t ha^{-1} in silver fir and 593 t ha^{-1} in Kharsu oak forests of Central Himalaya, where maximum contribution was by tree layer followed by shrub, herb, sapling and seedling layers. The forest floor biomass was 2.1, 4.7 and 4.2 t ha^{-1} in horse chestnut, silver fir and Kharsu oak forests, respectively. The total litter fall was 7.3, 6.7 and 9.4 t ha^{-1}, of which leaf litter contributed 48, 39 and 64% of horse chestnut, silver fir and Kharsu oak forest, respectively.

Carlisle *et al.* (1966) opined that 60 percent of the intersystem nutrient input to the forest floor was accounted by the litterfall. Lutz and chandler (1955) reported that leaf fall exerts an important influence on physical, chemical and biological characters of soil and ultimately balances the nutrients of the forest soil.

Herbohn and Congdon (1993) reported the rates of litterfall over 3year at one undisturbed site and two disturbed site by selective harvesting for a tropical rain forest area in North Queensland, Australia. No significant differences were observed in annual litterfall between the sites, with annual litterfall rates ranged from 5.0 to 6.0 t ha-1 yr^{-1}. Litter fall was found to be strongly seasonal at all the sites with the maximum falls occurring from the end of the dry season to the end of wet season. The average percentages of leaves, wood and reproductive materials in litterfall were similar at each site. Leaves were the dominant component of litterfall with the average proportion of the total litterfall ranging from 72% to 76% over the study period at each of the four sites. At certain times, however, the fall of wood and reproductive materials was quite significant, comprising as much as 71% and 34% of litterfall, respectively. A strong negative correlation was found between the fall of leaves and wood of all the sites.

Kumar (2008) studied the litter production in two age groups of *Acacia auriculiformis.* Periodic collection and quantification of different litter components of 3 years old and 6 years old monoculture plantations of *Acacia auriculiformis* for two consecutive years were done. The litter production was 5.27 to 6.80 t ha^{-1} yr^{-1} in three year old plantations and 9.56 to 11.78 t ha^{-1} yr^{-1} in six years old plantation.

Pathak *et al.* (2010) have studied the leaf fall of some forest tree species in tropical dry deciduous mixed forest of Naoradehi wildlife sanctuary Sagar (M.P.) and observed that leaf fall phenomenon amongst 35 tree species indicate that 50% species showed leaf fall during winter months and remaining during summer months. Leaf fall may be effected by different microclimate factors and different environmental conditions.

Pragasan and Parthasarathy (2005) have investigated the quantity and seasonal patterns in fine litter production and standing crop of litter in two tropical dry evergreen forest sites namely Kuzhanthai Kuppam (KK) and Oorani (OR) on the coromondel coast of south India, following a stone block lined denuded quadrant technique. Fine litter production amounted to 13.51 and 13.27 t ha^{-1} at KK and OR respectively, while the standing crop of total forest floor litter was 4.11 t ha^{-1} at KK and 4.86 t ha^{-1} at OR. Leaves formed 71.4% at (KK) and 67.9 % at (OR) of the total litter production peaked during summer on both the sites. Leaf production by the two life forms ,trees and lianas respectively ,was 71 and 29% at KK and 61 and 39% at OR. The three physiognomy groups, viz. evergreen, brevi-deciduous and deciduous species respectively contributed 42.3, 30.4 and 34.4% at OR.

Prasad and Mishra (1984) studied litter production in a natural dry deciduous teak forest of Sagar (M.P.). It was observed that *Tectona grandis* alone produced one third of the total production of the stand. The other species, which dominated the litter output in stand, were *Terminalia tomentosa, Diospyros melanoxylon, Butea monosperma* and *Miliusa tomentosa*. Leaf fragments of other minor species accounted for about one third of total production. Tree species like *Anogeissus latifolia* and *Lagertroemia parviflora* contributed only a fraction of total litter production. The total leaf litter production in these forests was found to be 4.96 t ha^{-1}.

Rawat *et al*. (2009) studied the litter production pattern and nutrient discharge from decomposing litter in a Himalayan alpine ecosystem. The amount of standing litter biomass varied both in the protected and unprotected sites and was maximum in the protected area.

Singh (1995) studied the seasonal variations in biomass and nutrient content of the forest floor in a dry tropical forest in India and found that range of variation in standing crop of fresh leaf litter, partly decayed litter and wood litter during different season were 30.8-220.9, 36.1-115.6 and 76.4-151.6 g m^{-2}, respectively. The mass of herbaceous live shoots and dead shoots varied 1.4-62.9 and 3.3-22.9 g m^{-2}, respectively.

Vituosek and Sanford (1986) have reported that total litterfall in tropical moist forest ranged from 3.6 to 12.4 t ha^{-1}yr^{-1}. Murphy and Lugo (1986) observed that the total litterfall in dry and wet tropical forests was between 3-10 t ha^{-1}yr-1 and 5.0-14.0 t ha^{-1}yr^{-1}, respectively. Litter production of rain forest in Karnataka, India was in between 3.4 and 4.2 t ha^{-1}yr^{-1} (Rai and Proctor, 1986).

NPP is defined as the net flux of carbon between the atmosphere and terrestrial vegetation, which can be estimated on annual basis in terms of net biomass accumulation or net primary production. To understand the carbon and nutrient budgets of any ecosystem, an estimate of vegetation net primary productivity (NPP) is necessary as the vegetation play an important role in flow of nutrients in the ecosystem (Goward et al., 1994). NPP is thus, considered an important indicator for determining the ecological status and relative significance of an ecosystem. Net primary productivity of an ecosystem is estimated by different methods ranging from simple biomass increments measurements to complex eco-physiological models.

Glumphabuter and Kaitpraneet (2007) studied the aboveground biomass and net primary production in natural evergreen forest in eastern region of Thailand and reported that the net primary productivity (NPP) of three forests sites were varied from 13.24 t $ha^{-1}yr^{-1}$ for moist-evergreen forests, 28.91 t $ha^{-1}yr^{-1}$ for dry evergreen forests and 7.46 t $ha^{-1}yr^{-1}$ for hill evergreen forests.

Katayama *et al.* (2013) examined the gross primary production (GPP) and C allocation, i.e., above-ground net primary production (ANPP), aboveground plant respiration (APR), and total below-ground carbon flux (TBCF) for the Bornean tropical rainforest and compared with those from Amazonian tropical rainforests with dry seasons. The objective of the study was to clarify characteristics of carbon (C) allocation in a Bornean tropical rainforest without dry seasons. GPP (30.61 Mg C ha^{-1} $year^{-1}$, eddy covariance measurements; 34.40 MgC ha^{-1} $year^{-1}$, biometric measurements) was comparable to those for Amazonian rainforests. ANPP (6.76 Mg C ha^{-1} $year^{-1}$) was comparable to, and APR (8.01 Mg C ha^{-1} $year^{-1}$) was slightly lower than, their respective values for Amazonian rainforests, even though aboveground biomass was greater at Bornean site. TBCF (19.63 Mg C ha^{-1} $year^{-1}$) was higher than those for Amazonian forests. The comparable ANPP and higher TBCF were unexpected, since higher water availability would suggest less fine root competition for water, giving higher ANPP and lower TBCF to GPP. Low nutrient availability may explain the comparable ANPP and higher TBCF. These data show that there are variations in C allocation patterns among mature tropical rainforests, and the variations cannot be explained solely by differences in soil water availability.

Li *et al.* (2003) assessed the temporal variations in net primary production (NPP) and net ecosystem production (NEP) in West Central Canadian forests over 1920-1995 and their responses to natural and anthropogenic disturbances were simulated using the Carbon Budget Model of the Canadian Forest Sector (CBMCFS2). The results show that forest NPP in the region was 215.0 g C m^{-2} yr^{-1} in 1920, varied between 105.0 and 317.0 g C m^{-2} yr^{-1} depending on ecoclimatic province, but gradually increased to 330.0 (158.0 to 395.0) g C m^{-2} yr^{-1} in early 1980s before declining to 290.0 (1480 to 395.0) g C m^{-2} yr^{-1} by 1995. Forest NEP was estimated to be 53 (-13 to 88) g C $m^{-2}yr^{-1}$ in 1920-1924, increased to 75.0 (5.0 to 98.0) g C $m^{-2}yr^{-1}$ in1960 and then decline to 26.0(-14.0 to 53.0) g C m^{-2}yr-1 in 1991-1995.

Paoli and Curran (2007) studied to improve models of terrestrial productivity to understand the function of tropical forests in global carbon cycles require a mechanistic understanding of spatial variation in aboveground net primary productivity (ANPP) across tropical landscapes. To help derive such an understanding for Borneo, they monitored aboveground ANPP (their sum) in mature forest over 29 months. In 300 (0.07 ha) plots stratified throughout the watershed (340.0 ha, 8-190 m.a.s.l.), they measured productivity. ANPP across the study area was among the highest reported for mature lowland tropical forests. The ANPP, sum of these parameters, ranged from 11.10 to 32.30 Mg $ha^{-1}yr^{-1}$.

According to Schuur (2003) the response of tropical forest carbon balance to global change is highly dependent on the factors limiting net primary productivity (NPP) in this biome. Current empirical global NPP-climate relationships predict that the response of NPP to climate diminishes at higher levels of mean annual precipitation (MAP) and mean annual temperature (MAT), but data have been relatively scarce in warm and wet tropical ecosystems. By integrating data from a new comprehensive global survey of NPP from tropical forests and a climate gradient from Maui, Hawaii, along with data previously used to develop NPP-climate relationships, there was a strong negative relationship between MAP and NPP in humid ecosystems. The relationships derived here clearly demonstrate that NPP in wet tropical forests is sensitive to climate and that future forest growth may be limited by increased precipitation forecast by global climate models for the wet tropics.

Singh *et al.* (2011) studied the biomass and net primary productivity (NPP) of rehabilitated subtropical forest in India and estimated that the net production of rehabilitated forest was 25 Mg ha^{-l} yr^{-1}.

As per the measurement of Zhuang *et al.* (2009) Chinese forest and woodland ecosystems have total NPP of 1325.0±1020 and 1258.0±186.0 Tg C yr^{-1}in 1.57 million km2 forests with a regression method and a kriging method, respectively. These estimates are higher than the satellite-based estimate of 1034.0 Tg C yr^{-1} and almost double the estimate of 778.0 Tg C yr^{-1} using a process based terrestrial ecosystem model.

2.2 Carbon storage pattern

Albrecht and Kandji (2003) conducted the study with an objective to analyse C storage data in some tropical agroforestry systems and to discuss the role they can play in reducing the concentration of CO_2 in the atmosphere. The C sequestration potential of agroforestry systems is estimated between 12 and 228Mg ha^{-1} with a median value of 95Mg ha^{-1}. Therefore, based on the earth's area that is suitable for the practice (585–1215 × 106 ha), 1.1–2.2 Pg C could be stored in the terrestrial ecosystems over the next 50 years. Long rotation systems such as agroforests, homegardens and boundary plantings can sequester sizeable quantities of C in plant biomass and in long-lasting wood products. Soil C sequestration constitutes another realistic option achievable in many agroforestry systems. In conclusion, the potential of agroforestry for CO_2 mitigation is well recognised. However, there are a number of shortcomings that need to be emphasised. These include the uncertainties related to future shifts in global climate, land-use and land cover, the poor performance of trees and crops on substandard soils and dry environments, pests and diseases such as nematodes. In addition, more efforts are needed to improve methods for estimating C stocks and trace gas balances such as nitrous oxide (N_2O) and methane (CH_4) to determine net benefits of agroforestry on the atmosphere.

Chaturvedi *et. al.* (2011) studied the carbon density and accumulation in trees at five sites in a tropical dry forests (TDF) to address the questations how is the structure in the terms of tree and carbon density in differenet DBH classes? What are the levels of carbon density and accumulation in the woody species of TDF? Is the vegetation carbon density evenly distributed across the fortests? Does carbon stored in the soil reflect the pattern of aboveground vegetation carbon density? Which species in the forest have a high potential for carbon accumulation? The WSG among species ranged from 0.39 to 0.78 cm^{-3}. The study indicated that most of the carbon resides in the old-growth high DBH trees; 88-97% carbon occurred in individuals above 19.1cm DBH, and therefore extra care is required to protect such trees in the dry forest. *Acacia catechu, Buchanania lanzan, Hardwickia binata, Shorea robusta* and *Terminalia tomentosa* accounted for more than 10 t ha^{-1} carbon density, warranting extra efforts for their protection. Species also differed in their capacity to accumulate carbon indicating variable suitability for afforastation. Annually, the forest accumulated 5.3 t C ha^{-1} yr^{-1} on the most productive, wetted Hathinala site to 0.05 t C ha^{-1}yr^{-1} on the least productive, driest Kotwa site. This study indicated the marked Patchy distribution of carbon density (151 t C ha^{-1} on Hathinala site to 15.1 t C ha^{-1} on the Kotwa site); the maximum value was more than nine times the minimum value. These findings suggests that there is a substantial scope to increase the carbon density and accumulation in this forest through management strategies focused on the protection, from deforestation and fire, of the high carbon density sites and the old-growth trees, and increasing the stock density of the forest by planting spcies with high potential of carbon accumulation.

Chen *et.al.* (2005) studied how the forest conversion affects ecosystem carbon storage by comparing 33 year-old plantations of two coniferous trees, Chinese fir (*Cunninghamia lanceolata,* CF) and *Fokienia hodginsii* (FH) and two broadleaved trees, *Ormosia xylocarpa* (OX) and *Castanopsis kawakamii* (CK), with an adjacent relict natural forest of *Castanopsis kawakamii* (NF, ~ 150 year old) in Sanming, Fujian, China. Overall estimates of total ecosystem carbon pools ranged from a maximum of 399.1 Mg ha^{-1} in the NF to a minimum of 210.6 Mg ha^{-1} in the FH. The combined tree carbon pool was at a maximum in the NF where it contributed 64% of the total ecosystem pool, while the OX had the lowest contribution by trees at only 49%. Differences were also observed for the carbon pools of undergrowth, forest floor and standing dead wood, but that these pools together represent at the most 5% of the ecosystem C stock. Total C storage in the surface 100 cm soils ranged from 123.9 Mg ha^{-1} in the NF to 102.3 Mg ha^{-1} in the FH. Significant differences ($P < 0.01$) in SOC concentrations and storage between native forest and the plantations were limited to the surface soils (0–10 cm and 10–20 cm), while no significant difference was found among the plantations at any soil depth ($P > 0.05$). Annual aboveground litterfall C ranged from 4.51 Mg ha^{-1} in the CK to 2.15 Mg ha^{-1} in the CF, and annual belowground litterfall (root mortality) C ranged from 4.35 Mg ha^{-1} in the NF to 1.25 Mg ha^{-1} in the CF. When the NF was converted into tree plantations, the vegetation C pool (tree plus undergrowth) was reduced by 27–59%, and the detritus C pool (forest floor, standing dead wood, and soils) reduced by 20–25%, respectively. These differences between the NF and the plantations may be attributed to a combination of factors including more diverse species communities, more C store types, higher quantity and better quality of above- and belowground litter materials under the NF than under the plantations and site disturbance during the establishment of plantations.

De Ridder *et.al*. (2010) conducted the study with an objective to evaluate the potential of these long-rotation plantations as production forests (timber) and carbon sinks. Five different plantations, between 50 and 58 years old, were sampled. Over a sample surface of more than 73 ha, the diameter above buttresses of 2680 trees, bole height of 265 trees and tree height of 128 trees was measured. To estimate the commercial volume, a nonlinear power law regression was used (R^2 = 0.95). A power law variance function was applied to counter heteroscedasticity of the residual plot. Estimates of commercial tree and stand volume at 50 to 58 yr were 5.6 ± 4.1 m^3 and 183.9 ± 135.0 m^3 ha^{-1}. Stand volumes appear low but are explained by a large decrease in tree density. However, the mean volume increment of 3.2–3.7 m^3 $ha^{-1}yr^{-1}$ corresponds well with teak plantations of a similar age. For limba, aboveground biomass and carbon estimates of this study (resp. 108.4 and 54.2 Mg ha^{-1}) differ significantly from those of existing aboveground biomass models (resp. 135.7–143.9 Mg ha^{-1} biomass and 67.9–72.0 Mg ha^{-1} C). All aboveground biomass and carbon estimates for *T. superba* stands were lower than for the estimates of young fast-growing plantations like *Tectona grandis* L. f., *Eucalyptus* spp. and *Acacia* spp. (≤ 30 y).

Derwisch *et al.* (2009) studied the estimation and economic evaluation of aboveground carbon storage of *Tectona grandis* plantations in Western Panama. The objectives of study were to measure the carbon (C) storage potential of 1, 2 and 10-years old *Tectona grandis* plantations in the province of Chiriquí, Western Panama and to calculate the monetary value of aboveground C storage if sold as Certified Emission Reduction (CER) carbon credits. The average aboveground C storage ranged from 2.9 Mg C ha^{-1} in the 1-year-old plantations to 40.7 Mg C ha-1 in the 10-year-old plantations. They estimated the potential aboveground C storage of the teak plantation over a 20 year rotation period, using regression analysis . The CO_2-storage over this period amounted to 191.1 Mg CO_2 ha^{-1}. The discounted revenues that could be obtained by issuance of carbon credits during a 20 year rotation period were about US $ 460 for temporary CER and US $ 560 for long-term CER, and thus, contribute to a minor extent (1%) to overall revenues, only.

Egbe and Tabot (2011) assessed the carbon sequestration potentials of 8 woody species on an ecosystem level, using the CO2FIXV.2 model, for two scenarios. Net carbon sequestration potentials ranged from 246.23 to 306.22 Mg C ha^{-1} with complete rotation every 40 years, and 292 to 359.3 Mg C ha^{-1} with partial cut. *Ricinodendron heudelotii* had the highest net carbon sequestration potential (306.22 and 359.3 Mg C ha^{-1} for the complete and partial cuts respectively), while *Cola lepidota* had the least under both scenarios. There were higher carbon stocks in plant biomass than soil for all agroforests under both management regimes. Fine litter had the highest soil carbon fraction and soluble compounds had the least in all the agroforests. Under complete rotation, the agroforests had potential carbon credit values ranging from US$2756 to $3264/ha/rotation, and $ 3114 to $3678/ha/rotation with partial cut. Partial cuts allowed for higher rates of carbon accumulation, and the farmer always has a standing crop. Economic prioritization showed that *Irvingia wombulu* was the best (US$6.67/Kg), followed by *Ricinodendron heudelotii* and *Afrostyrax lepidophyllus* ($5.55/Kg) and the least was *Trycocypha abut* ($0.33/Kg).

Fonseca *et al.* (2011) studied the carbon accumulation in aboveground and belowground biomass and soil of different age native forest plantations in the humid tropical lowlands of Costa Rica. Carbon fraction in the biomass, mean (± standard deviation), for the different pools varied between 38.5 and 49.7%. Accumulated carbon in the biomass increased with the plantation age, with mean annual increments of 7.1 and 5.3 Mg ha^{-1} $year^{-1}$ for forest plantations of *V. guatemalensis* and *H. alchorneoides*, respectively. At all ages, 66.3% of total biomass was found within the aboveground tree components, while 18.6% was found in structural roots. The soil (0–30 cm) contained 62.2 and 71.5% of the total carbon (biomass plus soil) under *V. guatemalensis* and *H. alchorneoides*, respectively. Mean annual increment for carbon in the soil was 1.7 and 1.3 Mg ha^{-1} $year^{-1}$ in *V. guatemalensis* and *H. alchorneoides*. Allometric equations were constructed to estimate total biomass and carbon in the biomass which had an *R*2aj (adjusted R square) greater than 94.5%.

Haripriya (2003) quantified the role of Indian forests as source or sink of carbon. The net carbon balance calculated as the net source or sink of the forest sector was assessed for the year 1993-94. For the available data and the underlying assumptions, the results of the carbon budget model indicated that Indian forest sector acted as a source of 12.8 Tg C (including accumulation of carbon in the dead biomass) for the year 1994.

Huifeng and Wang (2008) estimated the changes in forest biomass carbon storage in the South Carolina (SC) Piedmont between 1936 and 2005. They observed that since 1936, the SC Piedmont forests have accumulated 81.84 Tg C due to forest expansion and regrowth, increasing from 57.36 Tg C in 1936 to 139.20 Tg C in 2005. They found that the hardwood and softwood forests accounted for 74% (60.45 Tg C) of carbon accumulations during this period, respectively. It was found that the above ground forest biomass carbon pool represented 80% or 65.17 Tg C of the total carbon accumulation while the below ground fine and coarse roots only accounted for 20% or 16.67 Tg C . It was found that from 1936 through 2005 , forest carbon accumulated at a rate of 1.19 Tg C yr^{-1} , offsetting 5.7 % of CO_2 emission (20.94 Tg C in 2003) of the entire state of South Carolina.

Jain and Ansari (2013) described a standardized method for estimating carbon stock in teak (*Tectona grandis* Linn. F.). As the non-destructive methods for quantification of carbon sequestration in tropical trees are inadequately developed, they developed a linear allometric equations using girth at breast height (GBH), height and age to quantify above ground biomass (AGB). They used AGB to estimate carbon stock for teak trees of different age groups (1.5, 3.5, 7.5, 13.5, 18.5 and 23.5 years). The regression equation with GBH, $y = 3.174x - 21.27$, $r^2=0.898$ ($p < 0.01$), was found precise and convenient due to the difficulty in determination of height and age in dense natural forests of teak. The equation was evaluated in teak agroforestry systems that included *Triticum aestivum* (wheat), *Cicer arietinum* (gram), *Withania somnifera* (ashwagandha), *Avena fatua* (wild oat) and *Hordeum vulgare* (barley) as agricultural crops established at Tropical Forest Research Institute, Jabalpur, M.P. (India). The annual carbon stock gain in teak in different agroforestry systems was in the order: teak-barley (60.47%) > teak-wheat (56.92%) > teak-wild oat (54.94%) > teak-gram (37.15%) > teak-ashwagandha (11.86%). The results from GBH-based regression equations provided satisfactory estimates of carbon stock in tropical trees.

Jangra *et al.* (2010) estimated carbon sequestration, and soil carbon stability in a 25 year old plantation of *Grevillea robusta*, at the Central Soil Salinity Research Institute, Karnal. The soil organic carbon varied from 0.96-0.12% in 0-100 cm soil depths. The organic matter input to the soil in litterfall was 3.458 Mg C ha^{-1} . The fine root biomass varied from 2.279 to 8.732 Mg ha^{-1} in different seasons. The biomass accumulation in different tree components (Mg ha^{-1}) was: 216.943 bole > 41.380 branches > 7.590 foliage. Root biomass accounted for 14.59% of total tree biomass. Total aboveground net production was 17.389 Mg ha^{-1} yr^{-1}. The carbon flux through total net primary productivity was 11.322 Mg C ha^{-1} yr^{-1}. The organic and inorganic carbon stock up to 1-m soil depth was 48.058 Mg C ha^{-1} and 28.698Mg IC ha^{-1}, respectively. The soil microbial biomass, being an active pool of carbon, formed 1.91% of soil organic carbon up to 30 cm soil depth (0.571 Mg C ha^{-1}). The microaggregates (250 μm, 53 μm and <53 μm) formed a large fraction of soil aggregates and protected most of soil organic carbon in the soil. Montmorillonite, chlorite, illite, kaolinite and vermiculite were found to be the main clay minerals. The plantations of Grevillea, by increasing plant biomass production and soil carbon pool, can play an important role in carbon sequestration on marginal lands. The soil microbial biomass was found to be a good indicator of improved soil conditions.

Kaul *et al.* (2010) reported the C storage and sequestration potential of carbon of selected tree species in India. The results indicate that long-term total carbon storage ranges from 101 to 156 Mg C ha^{-1}, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg C ha^{-1}). The net annual carbon sequestration rates were achieved for fast growing short rotation poplar (8 Mg C ha^{-1}yr^{-1}) and Eucalyptus (6 Mg C ha^{-1}yr^{-1}) plantations followed by moderate growing teak forests (2 Mg C ha^{-1}yr^{-1}) and slow growing long rotation sal forests (1 Mg C

$ha^{-1}yr^{-1}$). The carbon stock in soil and products was less sensitive than carbon stock of trees to the change in rotation length. Extending rotation length from the recommended 120 to 150 years increased the average carbon stock of forest ecosystem (trees + soil) by 12%. The net primary productivity was highest (3.7 Mg $ha^{-1}yr^{-1}$) when a 60-year rotation length was applied but decreased with increasing rotation length (e.g., 1.7 Mg $ha^{-1}yr^{-1}$) at 150 years.

Kirby and Potvin (2007) examined the implications of a relationship for forestry and agriculture-based climate change mitigation activities. They worked with a community in Eastern Panama to determine the average above- and below-ground C stocks of three land-use types in their territory: managed forest, agroforests and pasture. They examined evidence for a functional relationship between tree-species diversity and C storage in each land-use type, and also explored how the use of particular tree species by community members could affect C storage. They found that managed forests in this landscape stored an average of 335 Mg C ha^{-1}, traditional agroforests an average of 145 Mg C ha^{-1}, and pastures an average of 46 Mg C ha^{-1} including all vegetation-based C stocks and soil C to 40 cm depth. They did not detect a relationship between diversity and C storage; however, the relative contributions of species to C storage per hectare in forests and agroforests were highly skewed and often were not proportional to species' relative abundances. They conclude that protecting forests from conversion to pasture would have the greatest positive impact on C stocks, even though the forests are managed by community members for timber and non-timber forest products. However, because several of the tree species that contribute the most to C storage in forests were identified by community members as preferred timber species, They suggest that species-level management will be important to avoiding C-impoverishment through selective logging in these forests.

The data also indicate that expanding agroforests into areas currently under pasture could sequester significant amounts of carbon while providing biodiversity and livelihood benefits that the most common reforestation systems in the region i.e. monoculture teak plantations, do not provide.

Kraenzel *et al.* (2003) measured above and belowground biomass and tissue carbon content of 20-year-old teak trees in four Panamanian plantations to estimate carbon storage potential-level of tree carbon storage, which averaged 102 t ha^{-1}. Litter, underground and soil compartment were estimated to accumulation. The estimate of carbon storage in Panamanian harvest-age teak plantations to be 351 t C ha^{-1}. They concluded that teak plantations have appreciable mean carbon storage capacity, much greater than that of the abandoned pasture they were planted on. The compartment of the plantation with the greatest potential for carbon sequestration and carbon storage is the wood biomass (120 t C ha^{-1}).

Melkania (2009) conducted studies indicating that the Indian forests store 1083.81 Mt C (wood only) in the year 1994 to 3907.87 Mt C (above and below ground material) in the year 1993. In forest soil, total C storage is estimated 9815.95 Mt as per 1994 forest stands under 19 ligneous species. Site-specific C estimates depend on stand composition, age, site quality and management. Estimated rate of C flux in selected Indian planted forests reveals that : (i) planted forests of short-rotation tree species with regular leaf shading patterns have more capacity for C sequestering in litter which decomposes more rapidly than those with annual or bimodal leaf shading patterns, and (ii) mixed planted forests of exotic and native species could be more efficient in sequestering C than the monocultures. This contribution reviews C sequestration in Indian forests at national level and site-specific situations, and elaborates some possible opportunities for sustainable C forestry.

Miegroet *et al.* (2007) reported that the forest contained on average 403 Mg C ha^{-1} almost half of which stored belowground for a high-elevation red spruce-Fraser fir forest [Picea rubens Sarg./Abies fraseri (Pursh.) poir] in the great smoky Mountains National Parks. Live trees, predominantly spruce, represented a large but highly variable C pool (mean 126 Mg C ha^{-1}, CV = 39%), while dead wood (61 Mg C ha^{-1}), mostly fir, accounted for as much as 15 % of the total ecosystem C. The 10-year mean C sequestration in the living trees was 2700 kg C ha^{-1} $year^{-1}$, but increased from 2180 kg C ha^{-1} $year^{-1}$ in 1993 – 1998 to 3110 kg C ha^{-1} $year^{-1}$ in 1998 – 2003, especially at higher elevations. Dead wood also increased during that period, releasing on average 1600 kg C ha^{-1} $year^{-1}$. Estimated net soil C efflux ranged between 1000 and 1450 kg C ha^{-1} $year^{-1}$ depending on the calculation of total belowground C allocation. Based on current flux estimated, they concluded that this old-growth system was close to C neutral.

Mini and Rao (2011) evaluated the soil carbon sequestration in Teak (*Tectona grandis*) and Eucalypt plantations. Soil organic carbon in plantations of teak was found to initially decrease and then increase with age of the plantation. On the other hand in plantations of eucalypt, it decreased with rotation. When plantations under teak and eucalypts for similar period of time were compared, it was observed that teak lost 35 per cent of organic carbon while eucalypt lost 24 per cent in 20-30 year period. After 30-40 year period, the loss from teak was 47 per cent and in eucalypts, it was 46 per cent. The loss from replanted eucalypts during the same period was only 27 per cent. However, soils under teak for more than 40 years show a dramatic increase in organic carbon content with a loss of about 10 per cent. Among third rotation eucalypt plantations, replanted plantations were richer in organic carbon than the corresponding coppiced one. Hence changes in the chemical composition of organic matter also affect the carbon sequestration rate. Over a 60 year rotation period, soils under teak stores considerable amount of organic carbon. However, if the rotation period of teak plantation is reduced, a corresponding decrease in carbon storage is to be expected. Eucalypt, being a short rotation crop, is less effective in sequestering carbon. However, the higher efficiency of replanted eucalypt plantation in storing carbon illustrates the importance of appropriate management practices to improve the carbon storage potential of plantations.

Nair *et. al.* (2009) stated that the available estimates of C-sequestration potential of agroforestry systems are derived by combining information on the aboveground, time-averaged C stocks and the soil C values; but they are generally not rigorous. Methodological difficulties in estimating C stock of biomass and the extent of soil C storage under varying conditions are compounded by the lack of reliable estimates of area under agroforestry. It is estimated that the area currently under agroforestry worldwide is 1,023 million ha. Additionally, substantial extent of areas of unproductive crop, grass, and forest lands as well as degraded lands could be brought under agroforestry. The extent of C sequestered in any agroforestry system will depend on a number of site-specific biological, climatic, soil, and management factors. Furthermore, the profitability of C-sequestration projects will depend on the price of C in the international market, additional income from the sale of products such as timber, and the cost related to C monitoring. Our knowledge on these issues is unfortunately rudimentary. Until such difficulties are surmounted, the low-cost environmental benefit of agroforestry will continue to be underappreciated and underexploited.

Petsri *et al.* (2007) estimated the aboveground carbon content in mixed deciduous forest and teak plantations. The aboveground carbon content was likely to increase according to age. That is to say, the aboveground carbon content found in the teak plantation trees aged 6, 10, 15, and 23 and 24 years old and in the mixed deciduous forest was 39.51, 40.82, 33.87, 55.23, 41.13 and 71.60 t ha^{-1}, respectively. Furthermore, the density of stands was positively related to the aboveground carbon content. Namely, the greater the density of tree stands, the greater the aboveground carbon content.

Potvin *et al.* (2004) estimated a case study of carbon pools under three different land-uses in PANAMA. Analysed soil profiles in a grazed pasture and an adjacent 5-year-old teak (*Tectona grandis*) plantation. There were small differences in soil C mass in the top 10 cm of the pasture and the plantation, though analysis of paired profiles suggested larger differences at greater depth. Analysis of the δ13C signatures in the pasture soils and litter showed that 90% to 95% of the organic matter in the surface 5 cm was derived from C_4 pasture plants, over the 45 years since the pasture was converted from forest. Comparison of the δ13C signatures in the pasture and teak plantation profiles indicated substantial replacement of C_4 derived organic matter with the dominantly C_3 derived plantation tissues. Organic matter turnover times in the upper 10 cm of the soils ranged from 8 to 34 years and from 11 to 58 years in the upper 30 cm, depending on topographic location. The two ecosystems studied are estimated to be small CO_2 sinks, 92 g C m^{-2} yr^{-1} for the pasture, and 57 g C m^{-2} yr^{-1} for native species plantation in the first year after establishment. The pasture's response to seasonal change was more pronounced, both in term of CO_2 fluxes and in term of herbaceous productivity, than the plantation's response.

Raizada *et al.* (2003) estimated the C flux through litter fall (total and leaf litter fall alone) in forest plantations occurring in four major forest groups in India. Using published studies covering 82 stands and 24 species raised in plantations the annual C flux rates were computed. The C flux rates from leaf litter alone were highest (3.03 Mt C per year) in the montane sub-tropical forests. Results indicate that plantations of short rotation tree species with regular leaf shedding patterns have more C sequestering capacity than species with unimodal or bimodal leaf shedding patterns. Such species could be raised in wastelands for twin purposes biomass production and carbon sequestering.

Ramachandran *et al.* (2007) studied the carbon sequestration: estimation of carbon stock in natural forests using geospatial technology in the Eastern Ghats of Tamil Nadu, India. The total biomass, both above and below ground, was calculated and the total carbon stock was estimated. Likewise, the sequestered soil carbon was also estimated. The biomass carbon was 2.74 Tg and the soil carbon was 3.48 Tg. The lesser soil organic carbon indicates that the forest area is severely affected by degradation due to various need-based forestry practices and anthropogenic disturbances. The need for a carbon databank was addressed in the context of mitigating climatic changes. They suggested that a national-level carbon databank should be envisaged for all types of forest in India so as to study the temporal change and carbon sequestration potential for better management of forests in future.

Ramachandran *et al.* (2007) studied the carbon management in forest floor-an agenda of 21st century in Indian forestry scenario. Degradation of forests is very common in Indian scenario since 1901 to to-date. The reasons are removal of large scale timber species for railway sleepers, ship building charcoal for all kinds of transports, Kumri cultivation in the forest woodlands reforestation of softwoods and miscellaneous species, cattle grazing and human induced fire . The aforementioned problem of degradation led to loss of carbon stock in the standing biomass as well as in soil carbon pool. Such kind of huge loss of carbon pool both in standing biomass and soil had a breakdown in carbon cycle leading to climatic imbalance.

Specht and West (2003) measured tree stem diameters in a stratified random sample fashion of plots in each of 19 forest plantation estates in Northern New South Wales. With the stratified random sample data, the allometric relationships were used to predict the total amount of carbon sequestrated in tree biomass and its 95% confidence limit across each estate. It was concluded that using sampling intensities of around 2-4% of the estate area, the total carbon sequestrated by an individual small plantation estate in the region could generally be estimated satisfactorily with a 95% confidence limit of about 30-40% of the estimate or better with a minimum of about 10%.

Sreejesh *et. al.* (2013) carried out the study to estimate the carbon storage in different compartments of teak (*Tectona grandis*) in each of the following felling periods of 5, 10, 20, 30, 40 and 50 years of age 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 content of carbon in wood, bark, branches and roots were 46, 32, 40 and 45%, respectively. 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.

Srivastava and Singh (2007) studied the carbon sequestration and mitigation through conservation approach and they found that the recognition that reforestation and forestation, as well as combating deforestation can not only make a contribution to the local socioeconomic physical conditions and the climate, but the intrinsic part to take along with the preservation of biodiversity which also serves the purpose of acting as a carbon store.

Tangsinmankong *et al.* (2007) studied the carbon stocks in soil of mixed deciduous forest and teak plantation. Results revealed that soil organic carbon from all sites decreased generally with the increasing depth, from the surface soil down to the level of 100 cm. The highest carbon stocks in soil were recorded in the 6-year-old teak plantation followed by the 24 and 15-year-old teak plantations and mixed deciduous forest as 157.03, 105.67, 78.78 and 70.96 t C ha^{-1}, respectively. The dissimilarity in soil organic carbon may be due to forest fire, forest management and topography.

Terakunpisut *et al.* (2007) studied the carbon sequestration potential in aboveground biomass of Thong Pha Phum National Forest, Thailand. Tropical rain forest (Ton Mai Yak station) had higher carbon stock than dry evergreen forest (KP 27 station) and mixed deciduous forest (Pong Phu Ron station) as 137.73 ± 48.07, 70.29 ± 7.38 and 48.14 ±16.72 tonne C ha^{-1}, respectively. Habitat variability caused differences of biomass accumulation, species composition and the allometric relationships of forests. In the study area, all forest had a similar pattern of tree size class, with a dominant size class at 4.5-20 cm. The 4.5-20 cm trees potentially provided a greater carbon sequestration in tropical rain forest and dry evergreen forest while the size of > 20- 40 cm gave potentially high carbon sequestration in mixed deciduous forest. Due to the trees have the lowest carbon sequestration but they considerably grow up to the further size classes. Apparently, they will be able to increase more biomass accumulation and store more carbon. They concluded that the greatest carbon sequestration potential is in mixed deciduous forest and followed by tropical rain forest and dry evergreen forest in Thong Pha Phum National Forest. Finally, the appropriate forest ecosystem management can be an alternative solution for carbon dioxide reduction in terms of carbon sink role.

Thomas (2005) analysed the carbon sequestration potential of four different types of forest stands in Costa Rica by estimating carbon stocks and rates of carbon accumulation. The analysed stands comprised an undisturbed primary forest, a slightly logged primary forest, a secondary forest and four 11-year old plantations of *Tectona grandis* (teak), *Bombacopsis quinata, Terminalia amazonia* and *Swietenia macrophylla* (mahogany), respectively. He found that the total carbon stock of the undisturbed primary forest was 356.1 t C ha^{-1}. The slightly logged primary forest stores 308.6 t C ha^{-1}, while the value for the secondary forest is 260.1 t C ha^{-1} and values in plantations lay between 172.6 and 264.7 t C ha^{-1}. The largest component is soil carbon followed in case of the forests by the carbon in above ground biomass and in case of the plantations by the carbon stored in products. Accumulation rates in the plantations are 2.9 to 15.5 t C ha^{-1} yr^{-1}, while values for forests are between -1.3 and + 1.7 t C ha^{-1} yr^{-1}. Management objectives and site qualities have a strong impact on the performance of the *T. grandis* plantations.

2.3 Soil and nutrient

Boley *et al.* (2009) analyzed the soil samples taken from the O/A and B horizons of undisturbed forest, active pasture, and 8- to 12-year-old teak (*Tectona grandis*) and mixed native plantations. Samples were analyzed for K, Ca, Mg, soil organic carbon, pH, exchangeable acidity, bulk density, and compared with a fertility equation. Bulk density was significantly lower in the undisturbed forest than other land uses, suggesting that after approximately 10 years of growth neither plantation lowered bulk density significantly from that of the active pasture. Teak plantations had significantly higher Mg and K (B horizon) and Ca (O/A horizon) concentrations than the undisturbed forest. This trend suggests that exchangeable base concentrations increase when land use changes from undisturbed forest to pasture, then pasture to plantation, with the most pronounced effect of this in teak plantations exhibiting more high fertility plots than other land uses. Soil organic carbon concentration was similar for all land uses except for a significantly lower concentration in teak plantations than in active pasture (O/A horizons). These results suggest that teak plantations may be advantageous for increasing soil fertility but, with respect to restoration of undisturbed forest conditions, present significant deviations in soil chemistry.

Chhabra *et al.* (2003) attempted to estimate soil organic carbon pool in Indian forests. In this study, a database of published measurements (with depth) of soil organic carbon (C) containing information on location , soil type, texture, estimated bulk density, and forest type in Indian forests was prepared. It was used for estimating soil organic C densities for various forest types for two depth classes (0-50 and 50-100 cm). The mean soil organic C density estimates for top 50 cm based on 175 observations ranged from 37.5t / ha^{-1} in tropical dry deciduous to 92.1 t / ha^{-1} in littoral swamp forest. The mean soil organic C density estimates based on 136 observations ranged from 70 t / ha^{-1} in tropical dry deciduous forest to 162 t / ha^{-1} in montane temperate forest for top 1m soil depth. The estimated soil organic C densities were combined with remote sensing based recent forest area inventory (64.20 Mha) by Forest Survey of India to arrive at estimates of soil organic C pool by major forest types of India. The total organic C pools in Indian forests have been estimated as 4.13 Pg C in top 50 cm and 6.81 Pg C in top 1 m soil depth. These estimates may be taken valid for 1980-1982 period on which the remote sensing based forest area assessment was made by FSI. The historic loss in forest soil organic C pool (1880-1981) in top 1 m soil depth has been estimated as 4.13 PgC. The estimated soil organic C densities by forest types can form input in models for estimating net C release from forests by deforestation as well as in estimation of historic loss in soil organic C pool in Indian forests.

Dinakaran and Krishnayya (2010) carried out the study showing a variation in soil organic carbon (SOC) and litter decomposition across different vegetal covers. Tropical vegetal covers occupied by teak, bamboos and mixed species were used for the study. SOC was analyzed in the soil up to a depth of 1.25 m at different intervals. Physical fractionation was done in the collected soil samples. Respiration was measured in the soils of three types in summer, monsoon and winter. Litter-bag experiment was carried out to understand the process of decomposition in three types of litter at three depths, viz. top, 25cm and 50 cm. SOC values from the three different types of vegetal cover showed significant differences. The annual fall of leaf-litter was maximum in mixed vegetal cover followed by teak and bamboo. Litter-bag experiment showed that the litter got decomposed within a year on storage. Higher soil respiration in all the three vegetal covers supports faster rates of decomposition. The decomposition was faster in bags kept at the top layers of the soil compared to the ones in the deeper layers. There was an increase in SOC of samples from the litter-bag study, indicating that tropical soils can absorb additional carbon. Physical fractionation of SOC showed uniformity in the proportions of mobile and recalcitrant pools across soil profiles of the three vegetal covers. A proton NMR study carried out to understand the chemical nature of SOC revealed complete absence of carboxyl group, whose presence is generally reported in the SOC of temperate soils. The groups observed were alkyl, *0*-alkyl and aromatic. Fluctuations were seen in the proportion of alkyl groups. Uniformity seen in the chemical composition of SOC from the proton NMR study revealed that barring initial steps, decomposition of organic matter would follow more or less the same path in tropical soils, irrespective of differences in plant litter.

Karia and Kiran (2004) studied the physicochemical properties of soil under different forest classes i.e. closed teak forest, closed mixed forest, open mixed forests, degraded forest, scrub and scrub with coppice forests of Sajwa, Kalarani and borial surrounds of Chhotaudepur forest division, Vadodara district, Gujarat. This was done to have the primary information on the status of the forest soils. The physical properties of soils such as colour, texture, field capacity, pH, EC and Chemical properties such as a on micronutrients like N, P and K and some of the micronutrients such as Z, Fe, Mn and Cu were determined for forest classes. Soils had a higher nutrient status in their topsoil. Some exceptions have been observed where the concentration of micronutrients like Mn, Fe and Cu and macronutrients like N, P and K increased in sub-surface soils. Fe and N in closed mixed forest and degraded forest, Cu and Fe in degraded and scrub forest and P and K in open mixed forest increase in sub-surface soils. The concentration of macro and micronutrients were also in good amount. Thus it shows that the soils of the forests at present are in good shape.

Kumar *et al.* (2010) studied the tree species diversity and soil nutrient status in three sites of tropical dry deciduous forest of western India. The tree stand density varied from 458-728 individuals ha^{-1} with the average basal area ranging from 5.96 - 19.31 m^2 ha^{-1}. Shannon-Weiner Index (H') ranged from 0.67 - 0.79. The Simpson Index of dominance varied from 0.08 - 0.16, the Margalef’s Species Richness Index varied from 21.41 - 23.71, Equitability or evenness index varied from 0.02 - 0.05, the species heterogeneity index varied from 2.53 - 3.61 and β diversity varied from 2.05 - 4.87. Organic carbon ranged from 2.23 - 2.81 %, while concentration of nitrogen fluctuated from 0.16 - 0.21 %, and that of phosphorus varied from 0.021- 0.033 % in all three sites. The C: N ratio ranged from 10.61 - 20.06, whereas C: P ratio fluctuated between 97.9 and 106.2, and N: P ratio ranged from 4.8 -10.0.

Masamichi *et al.* (2012) carried out the study in Thailand to determine the carbon balance in the soils of tropical seasonal forests, especially for teak, which is widely planted over the country. Soil respiration rate at a natural forests (mixed deciduous forest type) were usually higher than a young 6-year old teak (*Tectona grandis*). In both stands soil respiration rates showed clear seasonal pattern, that is high rates occurred in the wet season from April to November and low in the dry season from December to March. The rates were closely correlated with soil moisture conditions. The amounts of total carbon released by the soil respiration annually were estimated to be 19 Mg C ha^{-1} for the natural forest and 13 Mg C ha^{-1} for the teak plantation. A small amount of carbon input through leaf and root litter in the teak plantation was assumed to result in lower carbon sequestration in the soil. Indeed, the storage of soil carbon in natural forest was larger than that in the teak plantation. Study concluded that a young teak plantation could not contribute to the accumulation of carbon in the soil.

Studies conducted by Paoli *et al.* (2008) on the relationship between soil fertility and aboveground biomass in lowland tropical forests have yielded conflicting results, reporting positive, negative and no effect of soil nutrients on aboveground biomass. He quantified the impact of soil variation on the stand structure of mature Bornean forest throughout the lowland watershed (8–196 m a.s.l.) with uniform climate and heterogeneous soils. Categorical and bivariate methods were used to quantify the effects of (1) parent material varying in nutrient content (alluvium > sedimentary > granite) and (2) 27 soil parameters on tree density, size distribution, basal area and aboveground biomass. Trees >=10 cm (diameter at breast height, dbh) were enumerated in 30 (0.16 ha) plots (sample area = 4.8 ha). Six soil samples (0–20 cm) per plot were analyzed for physiochemical properties. Aboveground biomass was estimated using allometric equations. Across all plots, stem density averaged 521 $\pm$ 13 stems ha^{-1}, basal area 39.6 $\pm$ 1.4 m^2 ha^{-1} and aboveground biomass 518 $\pm$ 28 Mg ha^{-1} (mean $\pm$ SE). Adjusted forest-wide aboveground biomass to account for apparent overestimation of large tree density (based on 69 0.3-ha transects; sample area = 20.7 ha) was 430 $\pm$ 25 Mg $ha^{-1.}$ Stand structure did not vary significantly among substrates, but it did show a clear trend toward larger stature on nutrient-rich alluvium, with a higher density and larger maximum size of emergent trees. Across all plots, surface soil phosphorus (P), potassium, magnesium and percentage sand content were significantly related to stem density and/or aboveground biomass (R_{Pearson} = 0.368–0.416). In multiple linear regression, extractable P and percentage sand combined explained 31% of the aboveground biomass variance. Regression analyses on size classes showed that the abundance of emergent trees >120 cm dbh was positively related to soil P and exchangeable bases, whereas trees 60–90 cm dbh were negatively related to these factors. Soil fertility thus had a significant effect on both total aboveground biomass and its distribution among size classes.

Singh and Singh (2002) studied the changes in soil properties and foliage nutrient composition in different age classes of *Eucalyptus camaldulensis* plantation. Height and diameter at breast height (dbh) of the stand ranged from 9.2 to 25.7 m and 9.4 to 21.5 cm respectively, depending on the age of the stand. Foliage nutrients were in order Ca>N>K> Mg > P and differed considerably between different ages. Foliage N and P increased until Y12 and decreased afterwards. Soil organic matter and nitrogen (NH_4-N + NO_3-N) were significantly higher in the 0-15 cm layer compared with the 15-30 cm layer. Soil nutrients were significantly higher in the plantation area compared with the non-planted control plot. Soil pH, PO_4-P, Ca, Mg and K concentrations decreased with stand age whereas SOM, NH_4-N, NO3-N, Cu, Zn and Mn increased. The study thus suggested that plantations require fertiliser application and/or thinning after 12 years to manage the problem of nutrient depletion.

Singh and Kashyap (2007) studied the variations in soil N-mineralization and nitrification in seasonally dry tropical forest and savanna ecosystems in Vindhyan region, India.The annual N-mineralization and nitrification rates were highest at Hathinala moist forest site having maximum moisture content, organic- C, N and water holding capacity of soil than other study sites. N-mineralization and nitrification rates differ significantly across the sites and seasons. These rates were significantly correlated with soil moisture and mineral-N contents. The result suggested that variations in rates of N-mineralization and nitrification in the dry tropical ecosystems are related to differences in soil moisture content, nutrient status and vegetational cover in combination with other environmental factors.

Singh *et al.* (2011) studied the carbon sequestration potential of Indo-Gangetic agroecosystem soils. The soil texture was loam in the upper soil layers but changed to silt loam as the depth increased. Bulk density increased with soil depth, and had a negative relationship with soil organic C. A significant positive correlation between SOC and clay content was observed. About 69 % of soil carbon in the profile was confined to the upper 40 cm soil layer where C stock ranged from 8.5 to 15.2 t C ha^{-1}. They estimated that the agricultural soils of Indo-Gangetic Plains may contain 12.4 to 22.6 t ha^{-1} of organic C in the top 1 m soil depth. Since agricultural soils contain significantly lower C content than the soils of natural forest ecosystem in the same climate zone, management practices such as residue placement and reduced or no tillage are required to enhance C sequestration.

Tangsinmankong *et al.* (2007) studied the carbon stocks in soil of mixed deciduous forest and teak plantation. Results revealed that soil organic carbon from all sites decreased generally with the increasing depth from the surface soil down to the level of 100 cm. The highest carbon stocks in soil were measured at the 6-year-old teak plantation followed by the 24 and 15-year-old teak plantations and mixed deciduous forest as 157.03, 105.67, 78.78 and 70.96 t C ha^{-1}, respectively. The dissimilarity of soil organic carbon may be due to forest fire, forest management and topography.

Takahashi *et al.* (2009) studied the soil respiration in different ages of teak plantations in Thailand. Total soil respiration rate was significantly correlated with soil water content in the 0–30 cm layer. The annual amount of CO_2 efflux from the forest floor was estimated to be 1,062–1,154 g C m^{-2} y^{-1} in the teak plantations in 1997. In 1998, annual CO_2 efflux declined to 80% of that in 1997 in the T-Y plot, probably due to low rainfall. They concluded that carbon dynamics in the soil under teak plantations in western Thailand were determined by the soil moisture regime, which is controlled by seasonal rainfall pattern and annual rainfall. Soil respiration in teak plantations had no clear difference between different stand ages.

Watanabe *et al.* (2009) conducted the study to assess the growth and carbon storage of Teak (*Tectona grandis*) and to evaluate the influence of chemical properties and soil moisture on teak growth in Afransu Brohuma forest reserve Ghana. Teak growth was classified as good (1), medium (2) and poor growth (3) and aboveground biomass and carbon storage were estimated. The mean and top height of 14-year old teak in the respective sites ranged from 13.3 to 18.6 m and 15.0 to 24.3, respectively. Aboveground biomass ranged from 91.0 to 239.0 kg tree^{-1}, while the total aboveground biomass ranged from 30.6 to 145.1 Mg ha^{-1} and total aboveground carbon storage was between 15.6 and 72.0 Mg C ha-1. Total C and N, available P and exchangeable Ca at 0 to 20 cm soil depth were significantly higher than that of the 30-40 and 50-55 siol depth ($P < 0.05$). However, the mean pH (H_2O), pH (KCl), exchangeable Mg, exchangeable K and exchangeable Na were not significantly different in soil depths. They reported that pH, total N and exch.Ca and K in soils were positively correlated with teak height and basal area. They concluded that the teak growth was probably affected by some chemical properties and moisture status of soils in the present study sites and suggested to preserve the teak plantations on long term to achieve efficient carbon storage in a plantations for carbon projects.

Yao *et al.* (2010) studied the effects of land use types on soil organic carbon and nitrogen dynamics in Mid-West Côte d'Ivoire. Results showed that total soil organic carbon content decreased significantly (p=0.007) from natural forest to mixed crop systems. The average values were around 2.58 % in natural forest, 1.99 % in multispecies tree plantations, 1.69 %, in teak to 1.48 % in cocoa plantations and 1.29 % in mixed-crop fields. Significantly lower soil pH was observed in cocoa plantations, mixed-crop fields and mixed-tree plantations as 5.98, 6.9 and 6.7, respectively, as compared to natural forest and teak plantations (7.3), ($p<0.0001$). Total soil N, organic C and C: N ratios were significantly influenced by land use (p=0.0012; 0.007 and 0.0136, respectively). Higher mineralizable C and N levels were observed in natural forest, mixed-tree and teak plantations, with significant differences between main land use types (CMIN, p=0.0084; NMIN, <0.0001). The study also shows a highly significant and positive correlation between clay and soil organic C, as well as total N contents (r^2=0.637; p<0.0001). Land use impact on soil organic C and total N were also significant across the different land use types.

Zhang *et al.* (2007) studied the soil organic carbon in pure rubber and tea-rubber plantations in South-western China. Effects of rubber plantation (RP) and tea-rubber intercropping (TRI) systems on soil organic carbon pools were evaluated by recording changes in soil organic carbon in an age sequence of 12, 20, 26 and 40-year old plantations. Labile organic carbon (LOC) increased in surface soils (0-10 cm) with aging of rubber plantation and tea-rubber intercropping stands. Total organic carbon (TOC) in the soils did not change between stand ages of 12 and 20 years, however it decreased at the 26-year old stand. The TOC increased remarkably in tea-rubber intercropping tea-row soils but remained low in the rubber plantations and tea-rubber intercropping rubber-row soils at the 40-year stand. The study suggests that tea-rubber intercropping tends to sequestrate higher atmospheric carbon in soils than rubber monoculture alone through increased organic carbon pools in the tea-row soils and reduced organic carbon turnover rates in the rubber-row soils.

CHAPTER-III

MATERIALS AND METHODS

CHAPTER-III

MATERIALS AND METHODS

A study on **"Biomass, Carbon Stock and Carbon Sequestration in an Age series of Teak Plantation in Tropical Environment"** was carried out at Barnawapara Wildlife Sanctuary, North Raipur Forest Division of Raipur district (Chhattisgarh) during the year 2010-2013. The details of the study site, climate, geology, soils, forest flora, fauna and other features of area along with the methodologies used are described below:

3.1 Study site

The study was conducted in Barnawapara Wildlife Sanctuary (North Raipur Division) situated in North corner of Raipur district. The geographical location and physiographic features of study area are detailed below.

3.1.1 Geographical location and physiography

The study area is located between 21° 20' 0" to 21° 25'47" North latitudes and 82° 21' 17" to 82° 26' 27" East longitudes. It is situated about 27 km away from Patewa on Raipur-Sambalpur NH No. 6 just on the border of Chhattisgarh. The location of study area is shown in Fig. 3.1 and 3.2.

The general topography of area is undulating due to formation of rockout crop. The area adjoining Nawapara forest village has a number of hillocks scattered all over the area. The slopes of hillocks are moderate to steep. Tilsa pathar is the highest with an approximate altitude of 463 m above m.s.l. The streams and nalas flowing in the area have steep bank rich in alluvial soil and sustain a rich variety of vegetation.

Dry deciduous forest, grasslands, agriculture lands and human habitations surrounds the study area. Most of the villages in study area are categorized as forest villages and majorities of them are accessible through kaccha roads, which is

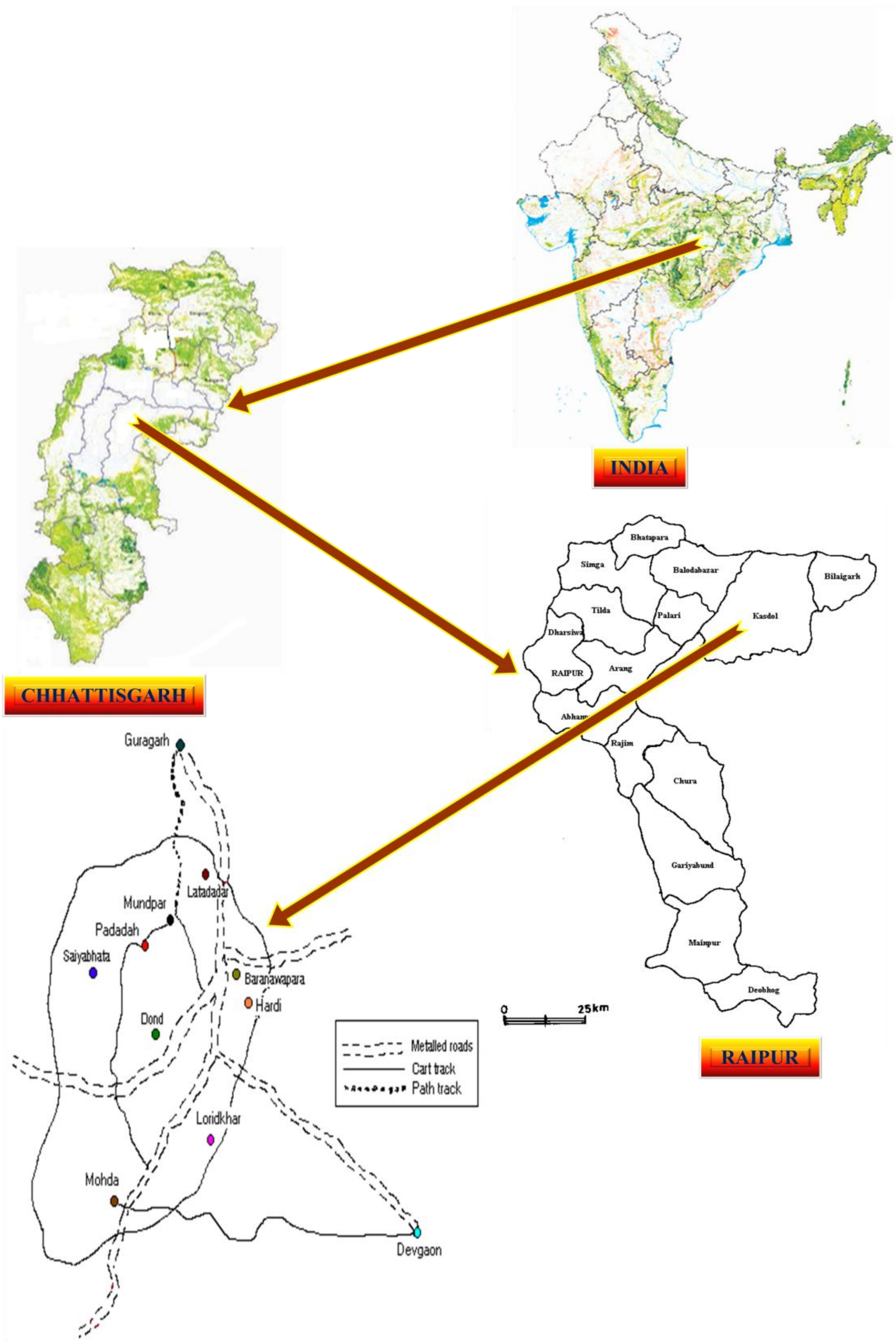

Fig 3.1: Location Map of Barnawapara Wildlife Sanctuary

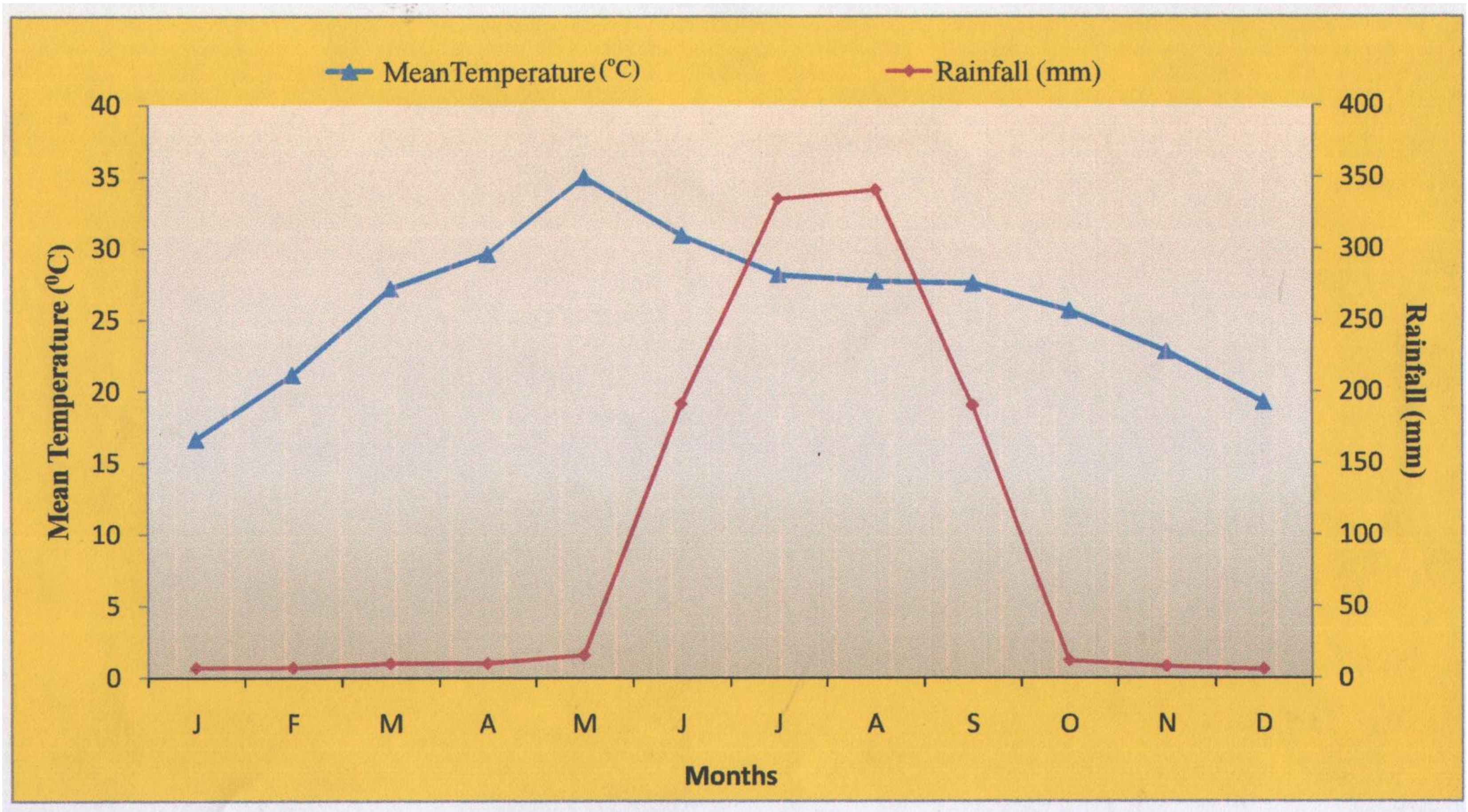

Fig. 3.2 : Ombrothermic diagram for the typical dry deciduous forest based on five year data (2008-2012)

motorable only in dry season. Road network is absent in few hilly tracts, which are inaccessible due to steep slopes and dense forest.

3.1.2 Climate

The climate of study area is dry humid tropical comprised of three seasons viz. rainy, winter and summer. The rainy season commences from the mid-June to October. The winter season, which commences from the beginning of November and last till the end of February. The summer commences from the beginning of March. It is quite prolonged and lasts till monsoon sets in.

3.1.3 Rainfall

The average annual rainfall in the study area ranges from 1200-1350 mm. It gradually decreases from south east direction to North West direction. About 80 percent of the rainfall in the study area is received from south west monsoon during June to September. The highest amount of rainfall occurs in July. Number of rainy days varies from 90-100 days.

3.1.4 Temperature

The mean monthly maximum temperature varies from 27.3° C in January to 41.8° C in May and mean monthly minimum temperature ranges from 12.7° C in December to 27.3° C in May. The mean annual maximum and minimum temperatures of study area are 33.1° C and 20.5° C, respectively.

3.1.5 Humidity

Relative humidity of study area increases with the onset of south-west monsoon and it generally becomes more than 80% in July. In the post monsoon and winter season the relative humidity lies between 50-65% in the morning (6:00 to 12:00 hrs.) and 30-40% in the afternoon (12:00 to 16:00 hrs.). Relative humidity is lowest during summer and drops below 30 percent in the afternoon in April and May.

3.1.6 Geology

The Barnawapara sanctuary area has three distinct geological formations viz., Chhattisgarh super group, Late Precambrian and Early Precambrian. Lithologically, the area is divided into seven groups namely Raipur shale and limestone, Khairagarh sandstone, Gunderdehi shale, Cuddapahas charmur limestone, Chandrapur sand grit, Dharwar rocks, Granite and gneiss.

3.1.7 Soils

Soils of Barnawapara area are grouped into three classes viz., Inceptisols, Alfisols and Vertisols. The Inceptisols are immature soils mostly sandy loam having light texture and shallow to moderate depth. They are low in organic matter and available nutrients, which support mainly grassland and degraded forests, these soils are commonly found in Eastern and Southern aspects. Alfisols occur in midland situation, which are moderately deep and hence have good water holding capacity and bear luxuriant vegetation, on the other hand Vertisols are deep clayey soils having good water holding capacity and are supporting rich vegetation. Some of these lands are utilized for cultivation of agricultural crops.

3.1.8 Forest types and flora

Different types of forest vegetation occur in the study area. Northern and Eastern part are covered with luxuriant forests, whereas teak plantations occupy a major area in southern part. In western part, large area is covered by degraded and mixed forest and also with bamboo brakes occasionally found as patches. According to Champion and Seth (1968), the forest of the study area are classified into four major types viz., (1) Southern Tropical Dry Deciduous Teak Forest ($5A/C_{1b}$), (2) Northern Tropical Dry Deciduous Sal Forest ($5B/C_{1c}$), (3) Northern Tropical Mixed Deciduous Sal Forest ($5B/C_2$), (4) Dry Bamboo Brakes ($5/E_9$).

Plate 3.1 : A view of 19 years old teak plantation

Plate 3.2: A view of 23 years old teak plantation

Photo 3.3: A view of 33 years old teak plantation

3.2 Experimental details:-

3.2.1 Sampling

A study on Biomass, Carbon Stock and Carbon Sequestration in an Age series of Teak Plantation in Tropical Environment was conducted at Barnawapara wildlife sanctuary. Three sites comprising teak plantation were selected at Barnawapara Wildlife Sanctuary i.e. 19 years, 23 years and 33 years old teak plantation site (Plates 3.1-3.3).

3.2.2 Method

On each of the above site one hectare permanent plot was established and within the permanent plot ten quadrats (10m x 10m) were randomly placed.

In the center of each 10 m × 10 m quadrat, 2 m × 2 m quadrat area was marked for enumeration of saplings (individuals > 10 cm - < 30 cm girth) and seedlings (individuals > 10 cm but $\leq$ 30 cm height. Girth of adult individual and sapling was measured at 1.37 m from the ground level, for seedling it was measured at 10 cm from the ground. Thus, all individual were enumerated by species and the girths of the individuals were measured.

3.2.3 Phytosociological analysis

The vegetation data were quantitatively analyzed for frequency, density and basal cover (Curtis and McIntosh, 1950). Frequency, density and basal covers were calculated as given below.

$$\text{Frequency (\%)} = \frac{\text{Number of quadrats in which species occurred}}{\text{Total number of quadrats studied}} \times 100$$

$$\text{Density (tree/ha)} = \frac{\text{Total number of individuals of a species}}{\text{Total number of quadrates studied}} \times 100$$

Basal area (m^2/ha) of trees was calculated as cross sectional area of stem at breast height i.e. at 1.37 m from the ground level. The relative frequency, relative density and relative basal area, were calculated as follows.

$$\text{Relative frequency (RF)} = \frac{\text{Frequency of the individual species}}{\text{Total frequency of all the species}} \times 100$$

$$\text{Relative density (RD)} = \frac{\text{Density of the individual species}}{\text{Total density of all species}} \times 100$$

$$\text{Relative basal area (RBA)} = \frac{\text{Basal area of the individual species}}{\text{Total basal area of all species}} \times 100$$

The Importance Value Index (IVI) was calculated as the sum total of relative frequency, relative density and relative basal area (Phillips, 1959).

Importance Value Index (IVI) = RD + RF + RBA

3.2.4 Species diversity analysis

Species diversity on different sites were calculated following Sagar and Singh (1999). Species diversity parameters were determined using basal cover values. Shannon-Wiener information function (Shannon and Weaver, 1963) was used for the species diversity:

$$\mathbf{H' = - \sum Pi \log_2 Pi}$$

Where, Pi is the proportion of total stand basal cover represented by the i^{th} species. The working formula given by Smith (1974) was used here

$$\mathbf{H' = 3.3219[\log_{10} N - (\sum Ni \log_{10} Ni/ N)]}$$

Where, Ni was the total basal cover of species i and N was the total basal area of all the species. The factor 3.3219 was used to convert the index value to $\log_2$.

Concentration of dominance was measured by Simpson's index (Simpson, 1949):

$$\mathbf{Cd = \sum (Ni/ N)^2}$$

Ni and N were same as described above.

Equitability (e) was calculated as suggested by Pielou (1966).

$$\mathbf{e = H' / InS.}$$

Where, H′ = Shannon index and S = number of species.

Species richness was calculated following Marglef (1958).

$$\mathbf{d = S\text{-}1 / InN.}$$

Where, S = total number of species and N = basal area of all species.

Beta diversity was calculated according to the formula given by Whittaker (1972).

$$\boldsymbol{\beta d = Sc/ \bar{S}}$$

Where, Sc = total number of species on all the sites and $\bar{S}$ = average number of species per site.

3.2.5 Biomass estimation

Tree biomass:

For the measurement of tree biomass, allometric equation relating tree circumference to biomass developed earlier by Singh and Mishra (1979) were used (Appendix- I). Computation protocol as described by Singh and Singh (1991) was used. In brief, the tree individuals in each quadrate were categorized into different girth classes. The mean CBH (circumference at breast height) value for each species for a girth class was used in the regression equation to get an estimate of biomass (by component) for that girth class. Then this value was multiplied by the density of trees in that girth class. The girth class values were summed to obtain the biomass estimate for each of the 10 quadrats on each site. The estimates were averaged across the number of quadrats to obtain mean estimate for each site.

The relationship between girth of a tree and dry weight of a component is given by equation:

$$\mathbf{Log\ Y = a + b\ log\ X}$$

Where,

Y = dry weight (kg) of component (bole, branch, leaf and root)

X = girth (cm) at 1.37 m height

a and b = allometric constants.

3.2.6 Forest floor biomass

Forest floor biomass were measured by using 50 cm × 50 cm randomly placed 10 quadrats (Plate 3.5). Forest floor litter was collected in every month during study period and then categorized into different component viz., fresh leaf, wood and partially decayed litter. The collected litter was brought to the laboratory and oven dry weights were determined.

3.2.7 Litter fall:

The litter input was measured by randomly placing stone-block lined denuded quadrat technique following Pragasan & Parthsarthy (2005) on the forest floor. Litter from each location was collected at monthly intervals, placed in labelled polythene bags, brought to the laboratory and separated into leaf, wood, branches etc. The samples were weighed after oven drying at 60^0C to constant weight.

3.2.8 Estimation of Net Primary Productivity:

The net primary production of the teak plantations was measured using girth increments and biomass data following Singh and Singh (1991). The method is briefly described below.

In March 2011, sufficient numbers of tree individuals of teak and other species observed on the sites were marked and their girth was measured and the girth of the same individuals were remeasured after one year (2012) and subsequent year (2013) for the girth increments. The individuals selected were the representative of all girth class in the biomass estimation. Mean annual girth increment for each girth class was

Plate 3.4: Measurement of trees in study area

Plate 3.5: Quantification of forest floor biomass in study area

Plate 3.6: Quantification of fine root biomass in study area

calculated. Using the allometric equations following Singh and Mishra (1979) the girth class and subsequently stand biomass for bole, branch, foliage and coarse roots were calculated separately from girth measurements. The mean foliage biomass is taken as foliage production for the year. The net biomass accumulation for two annual cycles was calculated. The annual wood and miscellaneous litter fall values were added into the above biomass accumulation values.

In the present study fine root production was estimated by considering peak fine root biomass in the annual cycle assuming < 1 year turnover of fine roots.

3.2.9 Fine root biomass

The belowground plant material (stand fine roots < 5 mm diameter) was sampled from 5 monoliths (15 cm × 15 cm × 15 cm, Plate 3.6) on each site in every month during study period. Monoliths were washed with a fine jet of water using 2 mm and 0.5 mm mesh screens. Proportions of live and dead fine roots were estimated on the basis of visual observations such as color, texture etc. Sample were dried at 80^{o}C to constant weight and weighed. Fine roots were classified into two classes: fine roots < 1 mm diameter and fine roots > 1 - 5 mm diameter. Finally each fine root class was converted into live fine root and dead fine roots using live and dead fine roots proportions.

3.2.10 Estimation of carbon stock and carbon sequestration

Samples of different tree components (bole, branch, foliage, coarse roots) for all species were separately collected from 20-30 trees of all available girth classes on each site. Composite samples of each component of tree were brought to the laboratory and oven dried at 80^{o}C.The oven dried samples were mill ground and stored for chemical analysis.

Carbon concentration was analyzed using CHNOS-Auto Analyzer "Elementar Vario EL". The carbon storage for the vegetation components was computed as the sum of the products obtained by multiplying dry weights of components with their mean carbon concentrations. The values for carbon storage in different components were summed to obtain total carbon storage in the vegetations. The carbon sequestration was determined by multiplying net primary productivity and carbon concentration of respective species.

3.2.11 Estimation of carbon stock in soil:

The 10 soil samples were randomly collected from all the sites at two depths viz. 0-10 cm and 10-20 cm depths. These soil samples of all the sites were brought to the laboratory and oven dried at 80^0C. The oven dried samples were millground and stored for chemical analysis. Carbon concentrations were analyzed using CHNOS-Auto Analyzer "Elementar Vario EL". The amount of carbon in soil (0-10 and 10-20 cm) was determined from bulk density, soil volume and carbon values.

Available phosphorus and available potassium were determined using spectrophotometer and flame photometer, respectively following Jackson, (1958).

3.2.12 Measurement of soil microbial biomass

The soil samples were analyzed for microbial biomass C by chloroform fumigation- extraction method (Brookes *et al.*, 1982, 1985; Vance *et al*., 1987). Biomass C was determined in 0.5 M K_2SO_4 soil extracts of fumigated (24 h) and unfumigated samples, followed by dichromate oxidation in a reflux system and titration with ferrous ammonium sulphate. Biomass C (MB-C) was then calculated from the equation: MB-C = 2.64 Ec, where Ec is the difference between C estimated from fumigated and unfumigated soils (Vance *et al.*, 1987).

3.2.13 Statistical analysis

The data on density, basal area, biomass, litterfall, carbon stock, net primary productivity and carbon sequestration was analyzed in one-way analysis of variance.

The data on physico-chemical properties of soil i.e. bulk density, total soil carbon, total nitrogen, available phosphorus and available potassium was analyzed in three-way analysis of variance. For this, the soil sampling was done following stratified random sampling in 3 stratas viz. age of plantation (i.e. 19, 23 and 33years old teak plantations), years (1^{st} year and 2^{nd} year) and soil depth (0-10 cm and 10-20 cm).

The significant differences between treatment means of all parameters were tested for their significance at 5% or 1% levels following Snedecor and Cochran (1967).

CHAPTER-IV

RESULTS

CHAPTER-IV

RESULTS

The results on "Biomass, Carbon Stock and Carbon Sequestration in an Age series of Teak Plantation in Tropical Environment" are described in this chapter. The findings are presented in four parts to facilitate the interpretation of results in accordance with topics. First part deals with the results on physic-chemical properties of soil and total soil carbon stock, second part deals with quantification of species structure and species diversity (phytosociological analysis), the third part deals with the results on estimation of biomass pattern, the fourth part deals with the results on estimation of carbon storage pattern in an age series of teak plantation and the fifth part deals with estimation of net primary productivity and carbon sequestration in tropical environment at Barnawapara wildlife sanctuary. Results on different aspects in each part are described below:-

4.1 Physico- chemical properties of soil and total soil carbon stock

The soil samples were collected from 0-10 cm and 10-20 cm soil depth in the month of October. The soil samples for estimation of microbial carbon biomass were collected from both the depth in summer season. The physico-chemical properties of soils in different sites viz. 19 years, 23 years and 33 years old teak plantation sites in an age series is given in Table-4.1 and 4.2.

The soil of all the teak plantations in an age series is characterized by sandy loam texture with considerably varying proportions of sand, silt and clay. The soil pH was in the range of 6.12 – 6.44.

In the surface soil (0-10 cm) layer, the values for bulk density (1.31 g cm^{-3}), total nitrogen (0.14 %), total carbon (1.67 %) and available potassium (372.32 kg ha^{-1}) were measured highest on the 23 years old teak plantation site. Whereas, on the 33 years old teak plantation site microbial carbon biomass (522.13 μ gm gm^{-1} soil), available phosphorus (13.47 kg ha^{-1}), C:N ratio (12.48) and soil moisture (9.93 %) were highest. Soil pH (6.12), bulk density (1.24 g cm^{-3}), C:N ratio (11.00), available phosphorus (8.45 kg ha^{-1}), and microbial biomass carbon (228.01 μ gm gm^{-1} soil) were lowest on 19 years old teak plantation in surface layers. The 23 years old teak plantation site recorded the lowest soil moisture (7.05 %). The 33 years old plantation site recorded the lowest values for total nitrogen (0.09 %) and available potassium (288.56 kg ha^{-1}) in the surface soil layer.

In lower soil (10-20 cm) layer total nitrogen (0.09 %), total carbon (1.25 %), C:N ratio (13.93) and available phosphorus (15.26 kg ha^{-1}) were highest for 23 years old teak plantation. Highest bulk density (1.33 g cm^{-3}) and highest available potassium (329.62 kg ha^{-1}) was measured on 19 years teak plantation. The highest value for microbial biomass carbon (318.03 μ gm gm^{-1} soil) was measured on 33 years teak plantation. In lower soil layer, the lowest values of total nitrogen (0.06 %), total carbon (0.74 %), C:N ratio (11.45), microbial biomass carbon (112.75 μ gm gm^{-1} soil), available phosphorus 11.61 (kg ha^{-1}) and soil moisture (7.25 %) were measured in 19 years old teak plantation. The lowest values for bulk density (1.22 g cm^{-3}) and available potassium (255.74 kg ha^{-1}) in the lower soil layer was measured on 33 years old teak plantation site.

The data on total nitrogen, total carbon, available phosphorus and available potassium were analysed through analysis of variance.

The three way Analysis of variance indicates that the variation in total carbon content due to site and soil depths were statistically different ($p<0.05$). In addition, the interaction of site x soil depth was also significant ($p<0.05$). Therefore it is sufficient to compare differences among interactions mean only. (Appendix-II)

The total carbon content of upper soil layer of 19 years old teak plantation site was at par with that of both soil layers of 33 years old teak plantation site, whereas the carbon content of lower soil layer of 19 years old teak plantation site and both layers of 23 years of 23 years old teak plantation site was significantly different from each other.

The variation in total carbon content between two years (1st year and 2nd year observations were statistically non-significant.

The three way Analysis of variance indicates that the variation in total nitrogen content of soil due to site and soil depth was found statistically significant ($p<0.05$). In addition, the interaction of site x soil depth was also significant ($p<0.05$). Therefore it is sufficient to compare differences among interactions mean only. (Appendix-III)

The total nitrogen content of upper soil layer of 33 years old teak plantation site was at par with that of lower soil layer of 23 years old teak plantation site.

The total nitrogen content of upper soil layer of 23 years old teak plantation site, lower soil layer of 33 years old teak plantation site and both layers of 19 years old teak plantation sites were significantly different from each other.

The variation in total nitrogen content between two years (1st year and 2nd year observations was statistically non-significant.

The three way analysis of variance indicates that the variations in available phosphorus due to site and soil depth were statistically significant ($p<0.05$). The interaction of site x soil depth was also significant ($p<0.05$). Therefore it is sufficient to compare differences among interactions mean only. (Appendix-IV)

The available phosphorus content of upper soil layer of 33 years old teak plantation site was at par with that of lower layer of 23 years old teak plantation site.

However, the available phosphorus content of lower soil layer of 23 old teak plantation site was significantly different from that of both soil layers of 19 years old teak plantation site, upper soil layer of 23 years old teak site and lower soil layer of 33 year old teak plantation site.

The variation in available phosphorus content of soil between two years (1^{st} year and 2^{nd} year observations was statistically non-significant.

The three way analysis of variance indicates that the variation in available potassium content of soil due to site and soil depth were statistically significant ($p<0.05$). The interaction of site x soil depth was also significant ($p<0.05$). Therefore it is sufficient to compare differences among interactions mean only. (Appendix-V)

The available potassium content of soil of both layers of 33 years old teak plantation site and lower soil layer of 23 years old teak plantation was at par. The available potassium content of upper soil layer of 19 year old teak plantation site was found at par with that of upper layer of 33 old teak plantation site, but significantly higher than lower soil layers of 33 and 23 years old teak plantation sites.

The variation in available potassium content of both soil layers of 23 years old teak plantation sites was not significant.

The available potassium content of upper soil layer of 23 years old teak plantation site was different from lower soil layer and both layers of 19 years and 33 years old teak plantation sites.

The three way analysis of variance indicates that the variations in C:N ratio due to sites and soil depth were statistically significant ($p<0.05$). In addition, the interaction of site x soil depth was also significant ($p<0.05$). Therefore it is sufficient to compare differences among interactions mean only. (Appendix-VI)

The variation in C:N ratio of both soil layers of 19 years old teak plantation was not significant. Also, the C:N ratio of lower soil layer of 19 years teak plantation was at par with that of upper soil layer of 23 years old teak plantation site. However, the C:N ratio of upper soil layers of 19 years and 23 years old teak plantation were significantly different.

The C:N ratio of upper soil layers of 23 and 33 years old teak plantation sites was at par. However, it is significantly different from that of both soil layers of 19 years old teak plantation site. The C:N ratio of lower soil layers of 33 years old teak plantation site was at par with that of upper soil layer, but it was significantly different from that of upper soil layer of 23 years old teak plantation site.

The C:N ratio of lower soil layer of 23 years old teak plantation site was at par with that of lower soil layer of 33 years old site, but significantly different than that of upper layers of 33 years old teak plantation site.

The three way analysis of variance also indicates that the variation in C:N ratio between two years (1^{st} year and 2^{nd} year observations were also found statistically significant ($p<0.05$).

4.1.1 Physico-chemical properties of soil at 19 years old teak plantation site

The soil of 19 years old teak plantation site was characterized by sandy loam texture. The soil of this site contained 53 % sand, 27 % silt, and 20 % clay. The soil pH under 19 years old teak plantation site was 6.12 and 6.16 in surface soil and lower soil layers, respectively.

In the surface soil (0-10), the bulk density was 1.24 g cm^{-3}. The soil contained 7.72 % moisture in October month. Total soil nitrogen was 0.10 % in surface soil layer. The concentration of available phosphorus and available potassium was 8.45 and 313.9 kg ha^{-1}, respectively. The total carbon in the surface soil layer of 19 years

Table 4.1 : Physical properties of soil on different sites in an age series of teak plantation

Properties	**19 years old teak plantation**		**23 years old teak plantation**		**33 years old teak plantation**	
Soil depth	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**
Texture	Sandy loam		Sandy loam		Sandy loam	
Mechanical composition						
Sand (%)	53±2.5		60±4.3		66±6.1	
Silt (%)	27±4.1		27±3.1		26±2.7	
Clay (%)	20±1.8		13±2.1		8±0.6	
Soil moisture (%)	7.72±0.55	7.25±0.35	7.05±0.18	10.01±0.26	9.93±0.40	10.66±0.14
Bulk density (gm^{-3})	1.24±0.06	1.33±0.06	1.31±0.04	1.26±0.01	1.27±0.03	1.22±0.03

Table 4.2 : Chemical properties of soil on different sites in an age series of teak plantation

Properties	**19 years old teak plantation**		**23 years old teak plantation**		**33 years old teak plantation**	
Soil depth	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**	**0-10 cm**	**10-20 cm**
Soil pH	6.12	6.16	6.23	6.25	6.41	6.44
Total N %	0.10±0.01	0.06±0.02	0.14±0.04	0.09±0.01	0.09±0.03	0.08±0.02
Total C %	1.12±0.05	0.74±0.07	1.67±0.13	1.25±0.07	1.12±0.08	1.07±0.03
C:N Ratio	11.00±0.16	11.45±0.38	11.78±0.30	13.93±0.34	12.48±0.32	13.27±0.32
Microbial biomass C (μ g g^{-1} of soil)	228.01±2.72	112.75±3.82	349.00±3.21	202.18±4.29	522.13±4.95	318.03±2.28
Available P (kg/ha.)	8.45±0.89	11.61±0.79	11.64±0.47	15.26±0.75	13.47±0.67	12.03±0.41
Available K (kg/ha.)	313.9±1.40	329.62±2.05	372.32±3.13	263.09±3.49	288.56±1.98	255.74±2.79

old teak plantation site was 1.12 % which revealed lower value as compare to other site. The C:N ratio was estimated 11.00 for surface layer soil. The microbial biomass carbon was 228.1 µ gm gm^{-1} of soil in surface layer.

In the lower soil (10-20 cm) layer, the bulk density was 1.33 g cm^{-3}. The soil contained 7.25 % moisture in the month of October. Total nitrogen was 0.06 % in lower soil layer soil. The concentrations of available phosphorus and available potassium were 11.61 and 329.62 kg ha^{-1}, respectively. The total carbon content in the lower soil layer of 19 years old teak plantation site was 0.74 % which revealed lower value as compare to other site. The C:N ratio was 11.45 for lower layer soil. The microbial biomass carbon was 112.75 µ gm gm^{-1} of soil in lower layer.

4.1.2 Physico-chemical properties of soil at 23 years old teak plantation site

The soil of 23 years old teak plantation site was characterized by sandy loam texture. The soil of the site comprised of 60 % sand, 27 % silt, and 13 % clay. The soil pH at this site was 6.23 and 6.25 in surface soil and lower soil layers, respectively.

In the upper soil (0-10) layer, the bulk density was 1.31 g cm^{-3}. The soil contained 7.05 % moisture in October month. Total nitrogen was 0.14 % in surface soil layer sample. The quantity of available phosphorus and available potassium was 11.64 and 372.32 kg ha^{-1}, respectively. The total carbon content in the surface layer soil of 23 years old teak plantation site was 1.67 %. The C:N ratio was 11.78 for surface soil. The microbial biomass carbon was 349.00 µ gm gm^{-1} of soil in surface layer.

In the lower soil (10-20 cm) layer, the bulk density was 1.26 g cm^{-3}. The soil contained 10.01 % moisture in October month. Total nitrogen was 0.09 % in lower soil layer sample. The concentration of available phosphorus and available potassium was 15.26 and 263.09 kg ha^{-1}, respectively. The total carbon content in the lower soil layer of 23 years old teak plantation site was 1.25 %. The C:N ratio was estimated 13.93 for lower soil layer. The microbial carbon biomass was estimated 202.18 µ gm gm^{-1} of soil in lower layer.

4.1.3 Physico-chemical properties of soil at 33 years old teak plantation site

The soil at 33 years old teak plantation site was characterized by sandy loam texture. The soil of this site comprised of 66 % sand, 26 % silt, and 8 % clay. The soil pH under 33 years old teak plantation site was 6.41 and 6.44 in surface soil and lower soil layers, respectively.

In the surface soil (0-10) layer, the bulk density was 1.27 g cm^{-3}. The soil contained 9.93 % moisture in the month of October. Total nitrogen was 0.09 % in surface soil layer soil. The quantity of available phosphorus and available potassium was 13.47 and 288.56 kg ha^{-1}, respectively. The total carbon in the surface soil layer of 33 years old teak plantation site was 1.12 %. The C:N ratio was 12.48 for surface soil layer. The microbial biomass carbon was 522.13 µ gm gm^{-1} of soil in surface layer.

In the lower soil (10-20 cm) layer, the bulk density was 1.22 g cm^{-3}. The soil comprised 10.66 % moisture in the month of October. Total soil nitrogen was 0.08 % in lower soil layer sample. The amount of available phosphorus and available potassium was 12.03 and 255.74 kg ha^{-1}, respectively. The total carbon content in the lower soil layer was 1.07 %. The C:N ratio was 13.27 for lower soil layer. The microbial biomass carbon was 318.03 µ gm gm^{-1} of soil in lower layer.

4.1.4 Total carbon stock in soil:

The total soil carbon stock in surface soil (0-10 cm) and lower layer (10-20 cm) at different sites under study viz. 19 years, 23 years and 33 years old teak plantation sites in an age series was calculated from bulk density, soil volume and soil carbon values and given in Table-4.3.

Table 4.3 : Total carbon stock (t ha^{-1}) in the different layers of soils at an age series of teak plantation sites

Soil depth	**Sites**		
	19 year old teak plantation	**23 year old teak plantation**	**33 year old teak plantation**
0-10 cm	13.90$\pm$0.20	21.37$\pm$0.15	14.73$\pm$0.13
10-20 cm	9.85$\pm$0.16	15.28$\pm$0.12	13.52$\pm$0.03
TOTAL	**23.76$\pm$0.32**	**36.65$\pm$0.18**	**28.26$\pm$0.12**

In the surface soil (0-10 cm) layer, the total soil carbon stock was found highest (21.37 t ha^{-1}) in soil at 23 year old teak plantation site followed by the soil of 33 year old teak plantation site (14.73 t ha^{-1}). The lowest value for total soil carbon stock (13.90 t ha^{-1}) was recorded in 19 years old teak plantation site.

In the lower soil (0-10 cm) layer, the total soil carbon stock was found highest (15.28 t ha^{-1}) in soil at 23 year old teak plantation site followed by the soil of 33 year old teak plantation site (13.52 t ha^{-1}). The lowest value for total soil carbon stock (9.85 t ha^{-1}) was measured in 19 years old teak plantation site.

The total carbon stock in 0-20 cm soil layer was found highest (37.65 t ha^{-1}) in 23 years old teak plantation site followed by 33 years old teak plantation site (28.26 t ha^{-1}) and lowest was estimated (23.76 t ha^{-1}) in 19 years old teak plantation site.

4.2 Species structure and diversity in an age series of teak Plantation

4.2.1 Species structure

The species structure in an age series of teak plantation sites (19 years old, 23 years old and 33 years old teak plantations) for tree layer, sapling layer and seedling layers is given in Table 4.4-4.6. Analysis of variance indicated that the variation in densities of trees and seedlings and tree basal area along the age series of plantation were significantly different ($p < 0.05$). (Appendix-VII, IX and X)

The variation in sapling density and sapling basal area along the age series of plantation were non-significant. (Appendix- VIII and XI)

4.2.1.1 Species structure of 19 years old teak plantation

In the 19 years old teak plantation a total of 1100 trees ha^{-1} comprising of 4 species were observed. The total density of tree layer was 1100 stems ha^{-1} followed by 2500 stems ha^{-1} and 13250 stems ha^{-1} for sapling and seedling, respectively (Fig. 4.1).

In tree layer, basal area of individual tree species varied from 0.08 m^2 ha^{-1} to 26.93 m^2 ha^{-1} and the density of individual tree species varied from 10 to 1050 stems ha^{-1}. The total basal area of tree layer in 19 years old teak plantation was 27.52 m^2 ha^{-1} (Table-4.4).

In tree layer, highest tree density was measured for *Tectona grandis* (1050 stems ha^{-1}). Lowest tree density (10 stems ha^{-1}) was measured for *Lagerstroemia parviflora.*

In tree layer, highest basal area 26.93 m^2 ha^{-1} was measured for *Tectona grandis* followed by 0.34 m^2 ha^{-1} for *Diospyros melanoxylon* . Lowest basal area (0.08 m^2 ha^{-1}) was measured for *Lagerstroemia parviflora*.

In sapling layer, basal area of individual tree species varied from 0.02 m^2 ha^{-1} to 0.13 m^2 ha-1 and the density of individual tree species varied from 250 stems ha^{-1} to 750 stems ha^{-1}.

In sapling layer, highest basal area was observed for *Tectona grandis* (0.13 m^2 ha^{-1}) followed by *Lagerstroemia parviflora* (0.08 m^2 ha^{-1}) and *Cleistanthus collinus* (0.05 m^2 ha^{-1}).

In tree layer the IVI of *Tectona grandis* was highest (264.72) followed by *Cleistanthus collinus* (16.74). In sapling layer also (Table-4.5) the IVI of *Tectona grandis* was highest (97.37) followed by *Lagerstroemia parviflora* (62.50) and *Cleistanthus collinus* (54.90). In seedling layer (Table 4.6) IVI was highest for *Diospyros melanoxylon* (72.33) followed by *Pterocarpus marsupium* (36.10) and *Tectona grandis* (36.01).

4.2.1.2 Species structure of 23 years old teak plantation

In 23 years old teak plantation a total of 1440 trees ha^{-1} comprising of 7 species were observed. The total density of tree layer was 1440 stems ha^{-1} followed by 2750 stems ha^{-1} and 8500 stems ha^{-1} for sapling and seedling, respectively (Fig. 4.2).

In tree layer, basal area of individual tree species varied from 0.11 m^2 ha^{-1} to 39.55 m^2 ha^{-1} and the density of individual tree species varied from 10 to 1190 stems ha^{-1}. The total basal area of tree layer on 23 years old teak plantation was 42.65 m^2 ha^{-1}.

In tree layer, highest tree density was measured for *Tectona grandis* (1190 stems ha^{-1}) followed by *Lagerstroemia parviflora* (180 stems ha^{-1}). Lowest tree density (10 stems ha^{-1}) was measured for *Boswellia serrata*, *Buchnania lanzan* and *Madhuca indica* (Table-4.4).

In tree layer, highest basal area was observed for *Tectona grandis* (39.55 m^2 ha^{-1}) followed by *Lagerstroemia parviflora* (2.13) and *Semecarpus anacardium* (0.32). Lowest basal area (0.11 m^2 ha^{-1}) was measured for *Madhuca indica*.

In sapling layer, basal area of individual tree species varied from 0.04 m^2 ha^{-1} to 0.14 m^2 $ha^{-1}$and the density of individual tree species varied from 250 to 1000 stems ha^{-1} (Table-4.5).

In sapling layer, highest basal area was observed for *Lagerstroemia parviflora* (0.14 m^2 ha^{-1}) followed by *Diospyros melanoxylon* (0.13 m^2 ha^{-1}).

The IVI of *Tectona grandis* was highest (213.83) in tree layer followed by *Lagerstroemia parviflora* (52.11) and *Semecarpus anacardium* (9.84). In sapling layer *Lagerstroemia parviflora* showed highest value of IVI (110.72) followed by *Diospyros melanoxylon* (89.94). In seedling layer IVI was highest for *Tectona grandis* (88.75) followed by *Buchnania lanzan* (71.96).

Table 4.4 : Species structure of tree layer at Barnawapara Wildlife Sanctuary

Species	19 years old teak plantation				23 years old teak plantation				33 years old teak plantation			
	F (%)	D (stems ha^{-1})	BA (m^2 ha^{-1})	IVI	F (%)	D (stems ha^{-1})	BA (m^2 ha^{-1})	IVI	F (%)	D (stems ha^{-1})	BA (m^2 ha^{-1})	IVI
Boswellia serrata, Roxb. exColebr.					10.00	10.00	0.14	4.87				
Bridelia retusa Spreng.									10.00	10.00	0.29	4.44
Buchnania lanzan Spreng.					10.00	10.00	0.18	4.97	60.00	60.00	0.86	24.76
Cassia fistula Linn.									10.00	20.00	0.33	5.22
Cleistanthus collinus	20	20	0.17	16.74					20.00	30.00	0.69	9.83
Diospyros melanoxylon Roxb.	10	20	0.34	10.21	20.00	20.00	0.21	9.58	20.00	20.00	0.19	8.05
Emblica officinalis Gaertn.									10.00	10.00	0.50	4.90
Lagerstroemia parviflora Roxb.	10	10	0.08	8.33	90.00	180.00	2.13	52.11	40.00	50.00	0.77	17.63
Lannea coromandelica Houtt.									10.00	10.00	0.15	4.15
Madhuca indica J.F.Gmel.					10.00	10.00	0.11	4.81	20.00	20.00	0.54	8.81
Semecarpus anacardium Linn.					20.00	20.00	0.32	9.84				
Tectona grandis Linn.	100	1050	26.93	264.72	100.00	1190.00	39.55	213.83	100.00	1190.00	41.01	202.78
Terminalia tomentosa Roth.									20.00	30.00	0.51	9.44
TOTAL	140	1100	27.52	300.00	260.00	1440.00	42.65	300.00	320.00	1450.00	45.84	300.00

*F = Frequency, D = Density, BA = Basal Area, IVI = Importance Value Index

Table 4.5 : Species structure of sapling layer at Barnawapara Wildlife Sanctuary

Species	**19 years old teak plantation**				**23 years old teak plantation**				**33 years old teak plantation**			
	F (%)	**D (stems ha^{-1})**	**BA (m^2 ha^{-1})**	**IVI**	**F (%)**	**D (stems ha^{-1})**	**BA (m^2 ha^{-1})**	**IVI**	**F (%)**	**D (stems ha^{-1})**	**BA (m^2 ha^{-1})**	**IVI**
Buchnania lanzan	10	250	0.02	24.47					10.00	250.00	0.058	71.96
Cassia fistula	10	250	0.04	30.06								
Cleistanthus collinus	20	500	0.05	54.90	10	250	0.04	27.63				
Diospyros melanoxylon	10	250	0.04	31.04	30	750	0.13	89.94	10.00	250.00	0.06	71.81
Lagerstroemia parviflora	20	500	0.08	62.50	40	1000	0.14	110.72	10.00	250.00	0.05	67.48
Tectona grandis	30	750	0.13	97.37	30	750	0.06	71.72	10.00	250.00	0.10	88.75
TOTAL	100	2500	0.35	300.35	110	2750	0.37	300.00	40.00	1000.00	0.26	300.00

* F = Frequency, D = Density, BA = Basal Area, IVI = Importance Value Index

Table 4.6 : Species structure of seedling layer at Barnawapara Wildlife Sanctuary

Species	19 years old teak plantation				23 years old teak plantation				33 years old teak plantation			
	F (%)	D (stems ha^{-1})	A	IVI	F (%)	D (stems ha^{-1})	A	IVI	F (%)	D (stems ha^{-1})	A	IVI
Anogeissus latifolia	20	750	1.50	20.82								
Azadirachta indica									20	500	1.00	16.18
Bauhinia racemosa									20	500	1.00	16.18
Boswellia serrata, Roxb.									10	250	1.00	11.07
Buchnania lanzan									20	750	1.50	21.05
Cassia fistula									20	500	1.0	16.18
Cleistanthus collinus	20	750	1.50	20.82	20	1000	2.0	51.04				
Diospyros melanoxylon	80	4500	2.25	72.33	30	1500	2.0	62.48	70	4000	2.29	66.39
Grewia tiliaefolia	30	1000	1.33	24.84					30	750	1.00	21.30
Holarrhena pubescens									20	1000	2.00	25.91
Kydia calycina	20	500	1.00	15.96								
Lagerstroemia parviflora	20	750	1.50	20.82	30	750	1.0	39.57	20	1000	2.00	25.91
Pterocarpus marsupium	40	1750	1.75	36.10								
Schleichera oleosa	10	750	3.00	26.61					10	500	2.00	18.91
Tectona grandis	60	1500	1.00	36.01	100	5250	2.1	146.90	70	3500	2.00	60.91
Terminalia tomentosa	20	1000	2.00	25.68								
TOTAL	320	13250	16.83	300.00	180	8500	7.1	300.00	310	13250	16.79	300.00

* F = Frequency, D = Density, A = Abundance, IVI = Importance Value Index

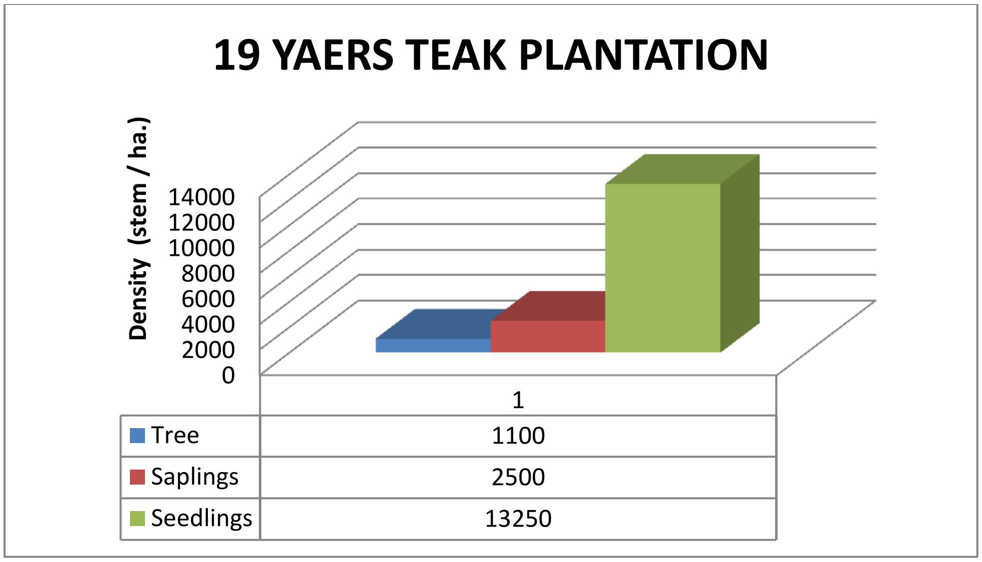

Fig 4.1: Population structures of tree, sapling and seedling layers in 19 years old teak plantation.

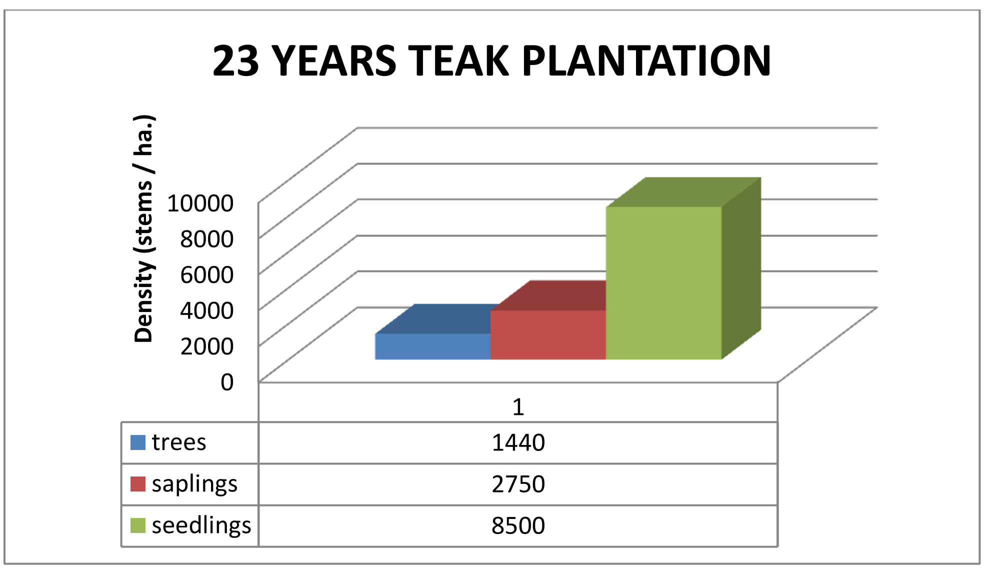

Fig 4.2: Population structures of tree, sapling and seedling layers in 23 years old teak plantation.

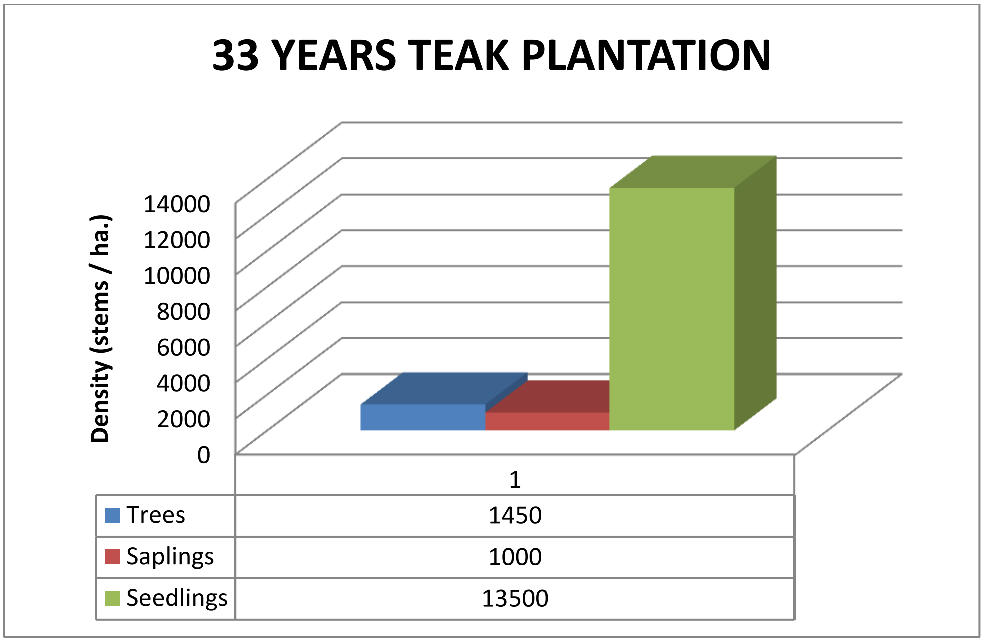

Fig 4.3: Population structures of tree, sapling and seedling layers in 33 years old teak plantation.

4.2.1.3 Species structure of 33 years old teak plantation

In the 33 years old teak plantation 1450 trees ha^{-1} comprising 11 species were observed. The overall density of tree layer was 1450 stems ha^{-1} followed by 1000 stems ha^{-1} and 13250 stems ha^{-1} for sapling and seedling, respectively (Fig.4.3).

In tree layer, basal area of individual tree species varied from 0.19 m^2 ha^{-1} to 41.01 m^2 ha^{-1} and the density of individual tree species varied from 10 to 1190 stems ha^{-1}. The total basal area of tree layer on 33 years old teak plantation was 45.84 m^2 ha^{-1}. (Table-4.4)

In tree layer, highest tree density was observed for *Tectona grandis* (1190 stems ha^{-1}) followed by *Buchnania lanzan* (60 stems ha^{-1}) and *Lagerstroemia parviflora* (50 stems ha^{-1}). Lowest tree density (10 stems ha^{-1}) was recorded for *Bridelia retusa*, *Emblica officinalis* and *Lannea coromandelica.*

In tree layer, highest basal area was observed for *Tectona grandis* (41.01 m^2 ha^{-1}) followed by *Buchnania lanzan* (0.86 m^2 ha^{-1}) and *Lagerstroemia parviflora* (0.77 m^2 ha^{-1}). Lowest basal area (0.15 m^2 ha^{-1}) was recorded for *Lannea coromandelica*.

In sapling layer, basal area of individual tree species varied from 0.05 m^2 ha^{-1} to 0.10 m^2 ha^{-1} and the density of all 4 individual tree species was found to be 250 stems ha^{-1}. (Table-4.5)

In sapling layer, highest basal area was observed for *Tectona grandis* (0.10 m^2 ha^{-1}) followed by *Diospyros melanoxylon* (0.06 m^2 ha^{-1}).

In tree layer *Tectona grandis* showed highest value of IVI (202.78) followed by *Buchnania lanzan* (24.76) and *Lagerstroemia parviflora* (17.63). In sapling layer, *Tectona grandis* (88.75) again showed highest IVI followed by *Buchnania lanzan*

(71.96) and *Diospyros melanoxylon* (71.81). In seedling layer IVI was highest for *Diospyros melanoxylon* (66.39) followed by *Tectona grandis* (60.91).

4.2.2 Density – GBH relationship

Woody species density – GBH distribution followed an exponential model [Y=exp (a – bx)] on all the three sites studied. The teak plantation sites exhibited a small structure as 89 – 94% individuals had $\leq$ 10 cm girth and only 1.5 – 3.7% were in girth classes exceeding 50 cm GBH. When data were pooled across the circle of 19 years, 23 years and 33 years old teak plantation sites, the woody species density was related to GBH according to:

(1) Y= exp [34587-0.82x] for 19 years old teak plantation site

r^2=0.794 p<5%

(2) Y=exp [21765-0.66x] for 23 years old teak plantation site

r^2=0.855 p<5%

(3) Y=exp [17710-0.62x] for 33 years old teak plantation site

r^2=0.868 p<5%

4.2.3 Species diversity

Diversity parameters in different plantation sites are summarized in Table-4.7.

4.2.3.1 Species richness (d)

Species richness for tree layer varies from 0.43 for 19 years old teak plantation to 1.37 for 33 years old teak plantation. In tree layer species richness was highest (1.37) on 33 years old teak plantation followed by 23 years old teak plantation (0.83) and lowest on 19 years old teak plantation (0.43). Species richness for seedling layer was highest (1.05) on 33 years old teak plantation followed by 19 years old teak plantation (0.95) and lowest on 23 years old teak plantation (0.23) (Table-4.7).

Species richness for sapling layer varies from 0.38 for 23 years old teak plantation to 0.64 for 19 years old teak plantation.

4.2.3.2 Shannon index (H′)

In tree layer Shannon index (H′) value was 0.34 on 19 years old teak plantation, 0.92 on 23 years old teak plantation and 1.23 on 33 years old teak plantation. In sapling layer Shannon index (H′) value was 2.4 on 19 years old teak plantation, 1.87 on 23 years old teak plantation and 2.00 on 33 years old teak plantation. In seedling layer Shannon index (H′) value was 2.95 on 19 years old teak plantation, 1.54 on 23 years old teak plantation and 2.88 on 33 years old teak plantation. On all the three sites the species diversity for tree layer was highest on 33 years old teak plantation whereas for sapling layer it was highest on 19 years old teak plantation and in seedling layer it was highest on 33 years old teak plantation.

4.2.3.3 Concentration of dominance (Cd)

In the plantation under study highest Cd value for tree layer was (0.91) on 19 years old teak plantation followed by (0.70) 23 years old teak plantation and (0.68) 33 years old teak plantation. The Cd values for sapling layer were 0.20, 0.29 and 0.25, respectively for 19 years old, 23 years old and 33 years old teak plantation. The Cd values for seedling layer were 0.16, 0.43 and 0.18, respectively for 19 years old, 23 years old and 33 years old teak plantation (Table-4.7). In the seedling layer Cd value was highest on 23 years old teak plantation followed by 33 years old teak plantation and 19 years old teak plantation.

4.2.3.4 Equitability (e)

Equitability (e) for tree layer was 0.24 for 19 years old teak plantation, 0.47 for 23 years old teak plantation and 0.51 for 33 years old teak plantation. In sapling layer it was 1.37 for 19 years old teak plantation, 1.35 for 23 years old teak plantation

Table 4.7 : Diversity parameters on different sites of teak plantations at Barnawapara Wildlife Sanctuaty

	Tree Layer			Sapling Layer			Seedling layer		
Parameters	**19 yrs old teak plantation**	**23 yrs old teak plantation**	**33 yrs old teak plantation**	**19 yrs old teak plantation**	**23 yrs old teak plantation**	**33 yrs old teak plantation**	**19 yrs old teak plantation**	**23 yrs old teak plantation**	**33 t yrs old teak plantation**
Species richness (d)	0.43	0.83	1.37	0.64	0.38	0.43	0.95	0.33	1.05
Shannon index (H')	0.34	0.92	1.23	2.4	1.87	2.00	2.95	1.54	2.88
Concentration of dominance (Cd)	0.91	0.70	0.68	0.20	0.29	0.25	0.16	0.43	0.18
Equitability (e)	0.24	0.47	0.51	1.37	1.35	1.44	1.28	1.11	1.20
Beta diversity (βd)	3.25	1.86	1.18	1	1.5	1.5	1.6	4	1.45

and 1.44 for 33 years old teak plantation; while for seedling layer it was 1.28 for 19 years old teak plantation, 1.11 for 23 years old teak plantation and 1.14 for 33 years old teak plantation (Table-4.7). The equitability (e) values for tree layer were highest on 33 years old teak plantation followed by 23 years old teak plantation and lowest at 19 years old teak plantation. For sapling layer, the equitability (e) values for tree layer were highest on 33 years old teak plantation followed by 19 years old teak plantation and lowest at 23 years old teak plantation. For seedling layer, the values of equitability (e) were highest on 19 years old teak plantation followed by 33 years teak plantation.

4.2.3.5 Beta diversity

Beta diversity for the plantations under study were 3.25, 1.86 and 1.18 (Table-4.7), for tree layer on 19 years old teak plantation, 23 years old teak plantation and 33 years old teak plantation, respectively. For sapling layer, it was 1.00, 1.50 and 1.50 and for seedling layer it was 1.60, 4.00 and 1.45 on 19 years old teak plantation, 23 years old teak plantation and 33 years old teak plantation, respectively. Beta diversity for tree layer was highest on 19 years old teak plantation (3.25) followed by 23 years old teak plantation (1.86) and 33 years old teak plantation (1.18). Beta diversity for sapling layer was highest (1.50) on both 19 years and 23 years old teak plantation. Beta diversity for seedling layers was highest on 23 years old teak plantation.

4.3 Estimation of biomass pattern in an age series of teak plantation

4.3.1 Trees biomass

The total biomass of teak plantation on 19 years, 23 years and 33 years old teak sites is given in Tables-4.8, 4.9 and 4.10. Total biomass in the present study was between 125.76 t $ha^{-1}$and 233.49 t ha^{-1}. It was measured highest on 33 years old teak plantation (233.49 t ha^{-1}) followed by 23 years old teak plantation (195.94 t ha^{-1}) and lowest on 19 years old teak plantation (125.76 t ha^{-1}). The total tree biomass increased with age from 125.76 t ha^{-1} in 19 years old teak plantation to 233.49 t ha^{-1} in 33 years old teak plantation. Total above ground biomass was between 104.27 t ha^{-1} and 196.32 t ha^{-1} and total below ground biomass was between 21.49 t ha^{-1} and 37.17 t ha^{-1}, respectively. Analysis of variance indicated that the variations in above ground biomass, below ground biomass and total biomass among the different age of plantation were significantly different ($p<0.05$). (Appendix-XII, XIII and XIV)

4.3.1.1 Tree biomass of 19 years old teak plantation

The total biomass estimated in 19 years old teak plantation was 125.76 t ha^{-1}, of which 104.27 t ha^{-1} was above ground and 21.49 t ha^{-1} below ground. The distribution of biomass in the different components was as follows; 63.48 t ha^{-1} in bole, 26.92 t ha^{-1} in branch, 13.87 t ha^{-1} in leaf and 21.49 t ha^{-1} in root. The bole, branch, leaf and root biomass contributed 50.47, 21.40, 11.02, and 17.08 %, respectively to the total biomass (Table-4.8).

Tectona grandis was dominant species. The biomass of *Tectona grandis* was 122.48 t ha^{-1} of which 101.56 t ha^{-1} was above ground part and 20.92 t ha^{-1} below ground. The allocation of biomass in bole, branch, leaf and root of *Tectona grandis* were 62.01 t ha^{-1}, 25.84 t ha^{-1}, 13.71 t ha^{-1} and 20.92 t ha^{-1}, respectively. *Tectona grandis* constituted the highest biomass (122.48 t ha^{-1}) followed by *Diospyros melanoxylon* (1.75 t ha^{-1}) and *Cleistanthus collinus* (1.05 t ha^{-1}) which constituted 97.39, 1.39 and 0.83 % of the total biomass. However, lowest biomass was measured for *Lagerstroemia parviflora* (0.48 t ha^{-1}).

4.3.1.2 Tree biomass of 23 years old teak plantation

The total biomass measured in 23 years old teak plantation was 195.94 t ha^{-1} of which 163.91 t ha^{-1} was above ground and 32.03 t ha^{-1} below ground. The allocation of biomass in the different components was 98.14 t ha^{-1} in bole, 44.96 t ha^{-1}

Table 4.8: Biomass (t ha^{-1} $\pm$ 1 SE) of different tree components in 19 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	**Branch**	**Leaf**	**Root**	**Total**
Cleistanthus collinus Roxb.	0.46±0.08 (43.81)	0.36±0.09 (34.29)	0.06±0.02 (5.71)	0.17±0.05 (16.19)	1.05±0.14
Diospyros melanoxylon Roxb.	0.81±0.07 (46.29)	0.56±0.08 (32.00)	0.08±0.01 (4.57)	0.31±0.04 (17.71)	1.75±0.11
Lagerstroemia parviflora Roxb.	0.2±0.04 (41.67)	0.16±0.08 (33.33)	0.03±0.006 (6.25)	0.09±0.02 (18.75)	0.48±0.13
Tectona grandis Linn.	62.01±2.03 (50.63)	25.84±1.38 (21.1)	13.71±0.93 (11.19)	20.92±1.10 (17.08)	122.48±2.84
Total	63.48	26.92	13.87	21.49	**125.76**

Note: The values in parenthesis indicate relative percentage of total tree biomass.

Table 4.9: Biomass (t ha^{-1} $\pm$ 1 SE) of different tree components in 23 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	Branch	Leaf	Root	**Total**
Boswellia serrata, Roxb. exColebr.	0.41±0.06 (41.83)	0.38±0.08 (38.77)	0.05±0.02 (5.10)	0.15±0.04 (15.30)	0.98±0.11
Buchnania lanzan Spreng.	0.35±0.06 (48.61)	0.21±0.08 (29.16)	0.05±0.02 (6.94)	0.11±0.03 (15.27)	0.72±0.10
Diospyros melanoxylon Roxb.	0.44±0.02 (47.83)	0.26±0.02 (28.26)	0.05±0.006 (5.43)	0.18±0.01 (19.57)	0.92±0.03
Lagerstroemia parviflora Roxb.	4.2±0.83 (42.59)	3.38±0.92 (34.28)	0.61±0.28 (6.18)	1.67±0.34 (16.93)	9.86±1.95
Madhuca indica J.F. Gmel.	0.23±0.04 (43.23)	0.18±0.05 (34.61)	0.03±0.01 (5.76)	0.09±0.02 (17.3)	0.52±0.07
Semecarpus anacardium Linn.	0.81±0.04 (41.12)	0.75±0.05 (38.08)	0.09±0.01 (4.56)	0.31±0.02 (15.73)	1.97±0.07
Tectona grandis Linn.	91.7±1.79 (50.67)	39.8±1.28 (21.99)	19.94±0.80 (11.01)	29.54±0.92 (16.32)	180.98±2.51
Total	98.14	44.96	20.81	32.03	**195.94**

Note: The values in parenthesis indicate relative percentage of total tree biomass.

Table 4.10: Biomass (t ha^{-1} $\pm$ 1 SE) of different tree components in 33 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	**Branch**	**Leaf**	**Root**	**Total**
Bridelica retusa Spreng.	0.95±0.12 (37.84)	1.11±0.16 (44.22)	0.1±0.03 (3.98)	0.35±0.07 (13.94)	2.51±0.21
Buchnania lanzan Spreng.	1.98±0.52 (48.05)	1.25±0.64 (30.33)	0.29±0.19 (7.03)	0.61±0.28 (14.8)	4.12±0.88
Cassia fistula Linn.	0.87±0.44 (40.27)	0.86±0.53 (39.81)	0.1±0.09 (4.62)	0.33±0.15 (15.27)	2.16±0.75
Cleistanthus collinus Roxb.	2.00±0.46 (38.98)	2.16±0.61 (42.1)	0.22±0.13 (4.28)	0.75±0.28 (14.61)	5.13±0.82
Diospyros melanoxylon Roxb.	0.44±0.15 (46.82)	0.26±0.15 (28.26)	0.05±0.02 (5.43)	0.18±0.09 (19.56)	0.92±0.24
Emblica officinalis Gaerth.	1.2±0.09 (36.36)	1.58±0.41 (47.87)	0.11±0.02 (3.33)	0.41±0.04 (12.42)	3.30±0.17
Lagerstroemia parviflora Roxb.	1.92±0.46 (40.0)	1.7±0.49 (35.41)	0.26±0.16 (5.41)	0.92±0.35 (19.16)	4.8±0.78
Lannea coromandelica Houtt.	0.41±0.02 (40.84)	0.38±0.02 (38.77)	0.05±0.006 (5.1)	0.15±0.01 (15.3)	0.98±0.03
Madhuca indica J.F. Gmel	1.59±0.23 (38.4)	1.79±0.32 (43.23)	0.17±0.06 (4.1)	0.60±0.14 (14.49)	4.14±0.42
Tectona grandis Linn.	102.29±1.69 (50.67)	45.13±1.18 (22.35)	22.09±0.77 (10.94)	32.36±0.91 (16.03)	201.87±2.37
Terminalia tomentosa Roth.	1.4±0.85 (39.43)	1.47±0.08 (41.4)	0.16±0.02 (4.5)	0.53±0.03 (14.92)	3.55±1.48
Total	115.05	57.67	23.60	37.17	**233.49**

Note: The values in parenthesis indicate relative percentage of total tree biomass.

in branch, 20.81 t ha^{-1} in leaf and 32.03 t ha^{-1} in root. The bole, branch, leaf and root biomass constituted 50.08, 22.94, 10.62 and 16.34 %, respectively of the total biomass (Table-4.9).

Tectona grandis was dominant species on this site. The total biomass of *Tectona grandis* was 180.98 t ha^{-1} of which, 151.44 t ha^{-1} was above ground and 29.54 t ha^{-1} below ground. The allocation of biomass in bole, branch, leaf and root of *Tectona grandis* was 91.70 t ha^{-1}, 39.80 t ha^{-1}, 19.94 t ha^{-1} and 29.54 t ha^{-1}, respectively. *Tectona grandis* constituted the highest biomass (180.98 t ha^{-1}) followed by *Lagerstroemia parviflora* (9.86 t ha^{-1}) and *Semecarpus anacardium* (1.97 t ha^{-1}) which constituted 92.36, 5.03 and 1.00 % of the total biomass. However, lowest biomass was measured for *Madhuca indica* (0.52 t ha^{-1}).

4.3.1.3 Tree biomass of 33 years old teak plantation

The total biomass measured in 33 years old teak plantation was 233.49 t ha^{-1} of which, 196.32 t ha^{-1} was above ground and 37.17 t ha^{-1} below ground. The distribution of biomass in the different components was 115.05 t ha^{-1} in bole, 57.67 t ha^{-1} in branch, 23.60 t ha^{-1} in leaf and 37.17 t ha^{-1} in root. The bole, branch, leaf and root biomass constituted 49.14, 24.63, 10.08, and 16.13 %, respectively of the total biomass (Table-4.10).

The *Tectona grandis* was dominant species on this site. The total biomass of *Tectona grandis* was 201.87 t ha^{-1}, of which 169.51 t ha^{-1} was above ground and 32.36 t ha^{-1} below ground. The biomass of bole, branch, leaf and root in *Tectona grandis* was 102.29 t ha^{-1}, 45.13 t ha^{-1}, 22.09 t ha^{-1} and 32.17 t ha^{-1}, respectively. *Tectona grandis* constituted the highest biomass (201.87 t ha^{-1}) followed by *Cleistanthus collinus* (5.13 t ha^{-1}) and *Lagerstroemia parviflora* (4.80 t ha^{-1}) which constituted 86.49, 2.19 and 2.05 %, respectively of the total biomass. However, lowest biomass was estimated for *Diospyros melanoxylon* (0.92 t ha^{-1}).

4.3.2 Distribution pattern of biomass on different age of plantation sites:

Although the young individuals belonging to seedlings and saplings classes, seedlings dominated the entire three sites in terms of density. The total biomass accumulation was greater in the middle girth class in an age series of teak plantation (Fig 4.4).

In 19 years old teak plantation total biomass accumulation was greater in the middle girth class followed by higher girth class while it was minimum in lower girth classes (Fig 4.5). About 59.80 per cent biomass accumulation was in the girth class ≥ 50-70 cm, 18.74 per cent in girth class ≥ 70-90 cm and 21.45 per cent in girth class ≥ 30-50 cm.

In 23 years old teak plantation total biomass accumulation was greater in the middle girth class followed by higher girth class while it was minimum in lower girth classes (Fig 4.6). About 39.52 per cent biomass accumulation was in the girth class ≥ 50-70 cm, 34.21 per cent in girth class ≥ 70-90 cm, 17.02 per cent in girth class ≥ 30-50 cm and 9.23 per cent in girth class ≥ 90-110 cm.

In 33 years old teak plantation, total biomass accumulation was greater in the middle girth followed by higher girth class while it was minimum in lower girth classes (Fig 4.7). About 39.44 per cent biomass accumulation was in the girth class ≥ 50-70 cm, 35.68 per cent in girth class ≥ 70-90 cm, 10.43 per cent in girth class ≥ 30-50 cm and 3.28 per cent in girth class ≥ 110-130 cm.

4.4 Forest floor biomass

The seasonal standing crop of forest floor biomass in an age series of teak plantations at Barnawaparao Wildlife Sanctuary i.e. 19 years old teak plantation, 23

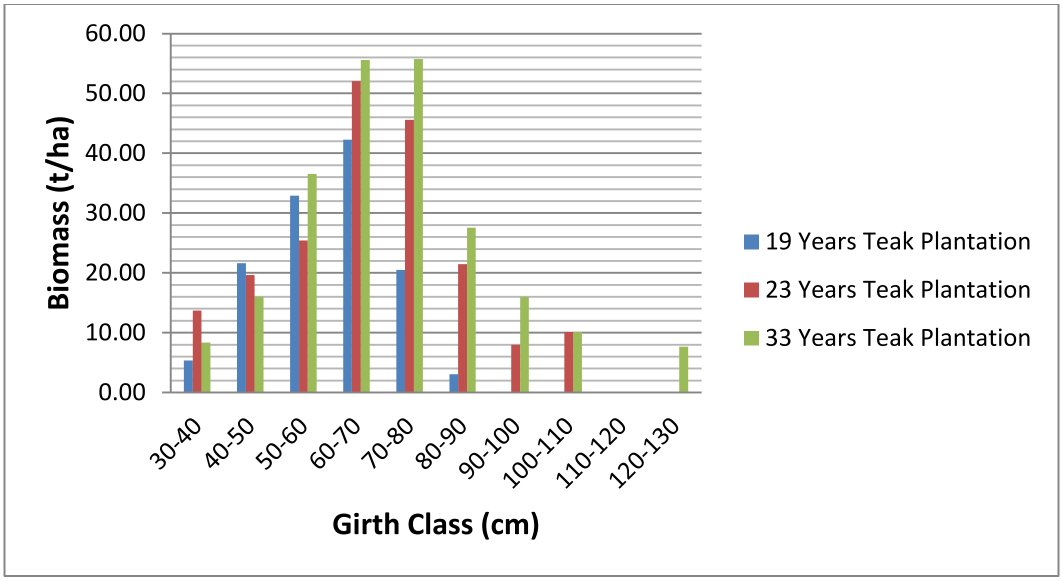

Fig. 4.4: Distribution pattern of biomass along the girth classes in an age series of teak plantation.

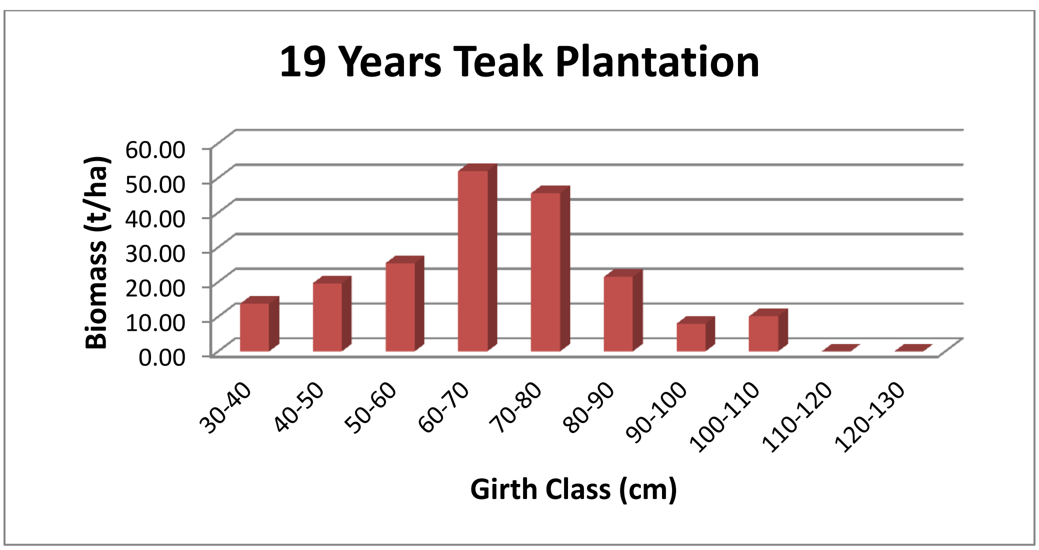

Fig 4.5: Distribution pattern of biomass along the girth classes in 19 years old teak plantation.

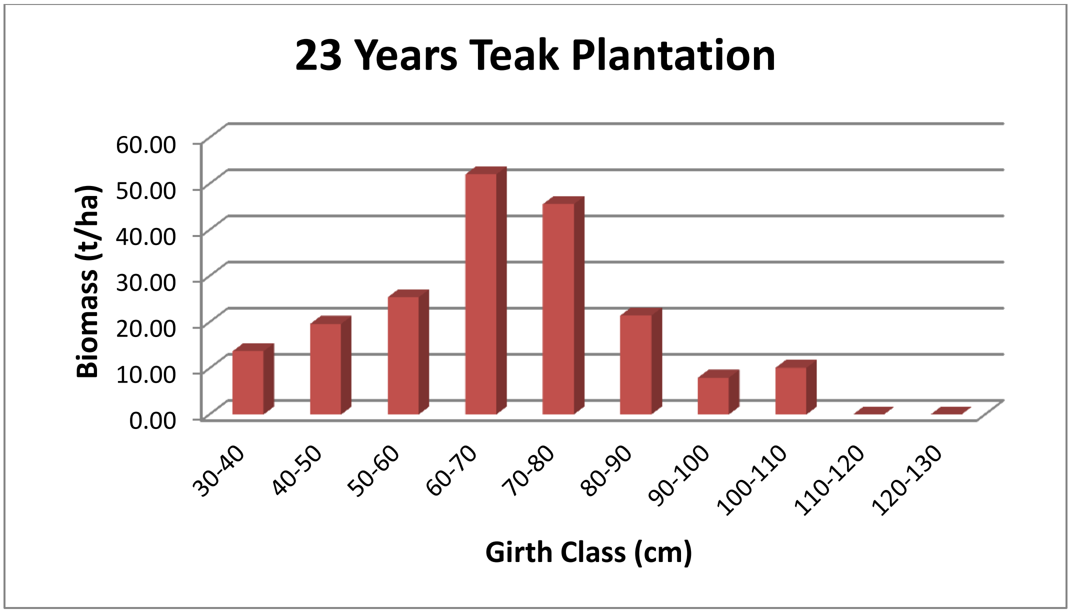

Fig 4.6: Distribution pattern of biomass along the girth classes in 23 years old teak plantation.

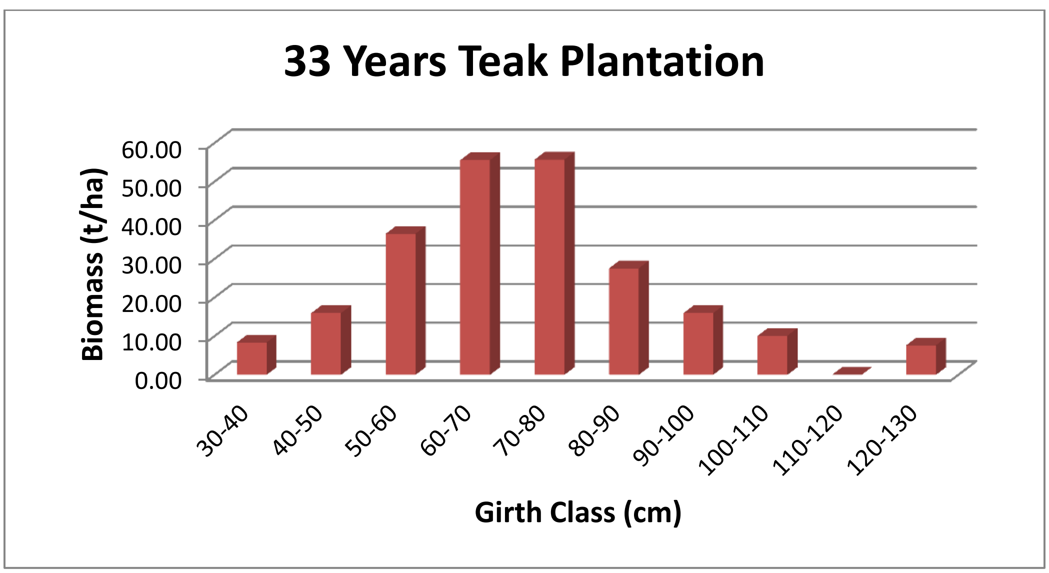

Fig 4.7: Distribution pattern of biomass along the girth classes in 33 years old teak plantation.

years old teak plantation and 33 years old teak plantation sites are given in Table-4.11. Analysis of variance indicated that the variations in fresh litter biomass, partially decayed biomass, wood litter biomass and total forest floor biomass among the different age of plantation were significantly different ($p<0.05$). (Appendix-XV, XVI, XVII and XVIII)

4.4.1 Forest floor biomass at 19 years teak plantation

4.4.1.1 Fresh leaf litter

The seasonal mean mass of fresh leaf litter in 19 years old teak plantation site was 90.35 g m^{-2} in rainy, 323.32 g m^{-2} in winter and 473.64 g m^{-2} in summer season. It was highest during summer season on all the three sites (Table-4.11).

Within an annual cycle, the mean standing crop of fresh leaf litter ranged from 14.66 g m^{-2} in July to 174.28 g m^{-2} in May, at 19 years old teak plantation (Table-4.12) (Fig.4.8 A).

4.4.1.2 Partly decayed litter

The mean standing crop of partly decayed litter in 19 years old teak plantation site was 397.55 g m^{-2}, 324.92 g m^{-2} and 226.81 g m^{-2} in rainy, winter and summer season, respectively. It was maximum during rainy season and minimum during summer season (Table-4.11).

The mean mass of the partly decayed litter was highly variable and ranged between 46.49 g m^{-2} in May to 103.23 g m^{-2} in August. Partly decayed litter peaked in August at 19 years old teak plantation site and thereafter it declined gradually (Table-4.12) (Fig 4.9 A).

4.4.1.3 Wood litter

The mean standing crop of wood litter mass in 19 years old teak plantation site was 290.77 g m^{-2}, 281.23 g m^{-2} and 292.74 g m^{-2} in rainy, winter and summer seasons,

Table 4.11 : Seasonal variation in forest floor biomass (g / m^2 ± S.E.) at different teak plantation sites

Forest Floor Components	19 years old teak plantation			23 years old teak plantation			33 years old teak plantation		
	Rainy	**Winter**	**Summer**	**Rainy**	**Winter**	**Summer**	**Rainy**	**Winter**	**Summer**
Fresh litter	90.35±0.77	323.32±1.92	473.64±1.13	115.94±1.10	362.08±1.49	480.11±1.74	138.04±1.51	510.16±2.44	615.52±4.22
Partly decayed litter	397.55±0.68	324.92±1.98	226.81±1.47	438.36±1.13	357.67±2.34	249.52±1.41	484.47±1.86	400.49±1.46	272.77±1.6
Wood litter	290.77±3.74	281.23±2.17	292.74±3.93	330.27±3.14	309.34±4.15	322.22±2.65	363.33±3.43	340.32±4.31	354.19±3.94
Total	**778.67**	**929.47**	**993.19**	**884.57**	**1029.09**	**1051.85**	**985.84**	**1250.97**	**1242.48**

Table 4.12: Monthly variation in forest floor biomass (g / m2 + S.E.) at an age series of teak plantation.

Sites	Components	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19 years old teak plantation	Fresh leaf litter	90.26±1.35	118±1.93	128.95±1.4	153.66±1.71	174.28±1.53	16.75±0.39	14.66±0.71	14.29±0.98	15.78±0.93	45.62±0.93	46.32±2.22	68.67±0.84
	Partly decayed litter	79.53±2.25	57.51±1.42	50.64±0.78	48.24±0.61	46.49±0.70	81.44±2.18	95.27±1.52	103.23±0.71	101.67±1.29	97.39±1.31	95.27±1.73	92.6±0.65
	Wood litter	70.30±2.7	72.15±3.16	74.12±3.07	75.69±3.47	77.22±6.19	65.71±1.06	65.56±2.0	79.56±5.53	81.72±2.74	63.93±3.31	69.84±1.5	68.94±1.94
	Total	**240.09**	**247.66**	**253.71**	**277.59**	**297.99**	**163.9**	**175.49**	**197.08**	**199.17**	**206.94**	**211.43**	**230.21**
23 years old teak plantation	Fresh leaf litter	102.06±2.42	104.5±2.64	110.42±2.12	168.95±0.94	185.47±1.44	15.28±0.8	13.83±1.12	18.15±0.62	22.78±1.06	61.18±1.27	72.69±0.54	82.83±1.19
	Partly decayed litter	87.72±1.01	65.91±1.55	57.63±1.65	52.41±0.4	49.83±1.6	89.65±1.32	103.22±0.88	115.43±1.03	111.71±0.93	108.0±1.58	103.60±1.67	100.64±3.0
	Wood litter	77.3±4.53	79.37±3.39	81.52±3.52	83.26±3.14	85.19±3.4	72.25±2.57	82.62±1.43	87.5±4.79	89.84±1.42	70.31±2.01	76.84±1.69	75.83±2.99
	Total	**267.08**	**249.78**	**249.57**	**304.62**	**320.49**	**177.18**	**199.67**	**221.08**	**224.33**	**239.49**	**253.13**	**259.3**
33 years old teak plantation	Fresh leaf litter	138.05±1.88	156.38±2.83	180.52±2.34	201.26±2.41	214.6±4.69	19.14±0.38	17.58±0.51	23.39±1.22	24.31±1.62	72.76±1.21	104.77±1.54	110.96±1.21
	Partly decayed litter	98.57±1.06	74.36±1.39	64.34±1.05	58.34±1.54	51.6±2.22	98.49±1.34	112.82±1.7	128.7±0.92	123.52±2.33	119.42±1.15	115.28±1.19	112.29±1.96
	Wood litter	85.1±2.94	87.3±4.82	89.69±4.17	91.58±4.15	93.44±3.07	79.49±2.81	90.87±1.92	96.25±2.51	98.86±0.92	77.34±5.04	84.51±3.14	83.41±2.55
	Total	**321.72**	**318.04**	**334.55**	**351.18**	**359.64**	**197.12**	**221.27**	**248.34**	**246.69**	**269.52**	**304.56**	**306.66**

respectively. The wood litter was maximum during summer season followed by rainy and winter season (Table-4.11).

Due to the variations in the pattern of wood litterfall several peaks and troughs were observed in the standing crop of this component during annual cycle, at 19 years old teak plantation site. (Fig.4.10 A) However, the mean wood litter was maximum in September (81.72 g m^{-2}) and minimum in October (63.93 g m^{-2}) (Table-4.12) (Fig. 4.10 A).

4.4.2 Forest floor biomass at 23 years teak plantation

4.4.2.1 Fresh leaf litter

The seasonal mean mass of fresh leaf litter on 23 years old teak plantation site was 115.94 g m^{-2} in rainy, 362.08 g m^{-2} in winter and 480.11 g m^{-2} in summer season. It was highest during summer season (Table-4.11).

Within an annual cycle, the mean standing crop of fresh leaf litter ranged from 13.83 g m^{-2} in July to 185.47 g m^{-2} in May, at 23 years old teak plantation (Table-4.12) (Fig.4.8 B).

4.4.2.2 Partly decayed litter

The mean standing crop of partly decayed litter in 23 years old teak plantation site was 438.36 g m^{-2}, 357.67 g m^{-2} and 249.52 g m^{-2} in rainy, winter and summer season, respectively. It was maximum during rainy season and minimum during summer season (Table-4.11).

The mean mass of the partly decayed litter was highly variable and ranged between 49.83 g m^{-2} in May to 115.43 g m^{-2} in August. Partly decayed litter peaked in August at 23 years old teak plantation site and thereafter it declined gradually (Table-4.12) (Fig 4.9 B).

4.4.2.3 Wood litter

The mean standing crop of wood litter mass on 23 years old teak plantation site was 330.27 g m^{-2}, 309.34 g m^{-2} and 322.22 g m^{-2} in rainy, winter and summer seasons, respectively. The wood litter was maximum during summer season followed by rainy and winter season (Table-4.11).

Due to the variations in the pattern of wood litterfall several peaks and troughs were observed in the standing crop of this component during annual cycle at 23 years old teak plantation site. (Fig.4.10 B) However, the mean wood litter was maximum in September (89.84 g m^{-2}) and minimum in October (70.31 g m^{-2}) (Table-4.12) (Fig. 4.10 B).

4.4.3 Forest floor biomass at 33 years teak plantation

4.4.3.1 Fresh leaf litter

The mean seasonal mass of fresh leaf litter on 33 years old teak plantation site was 138.04 g m^{-2} in rainy, 510.16 g m^{-2} in winter and 615.52 g m^{-2} in summer season. It was highest during summer season (Table-4.11).

Within an annual cycle, the mean standing crop of fresh leaf litter ranged from 17.58 g m^{-2} in July to 214.6 g m^{-2} in May at 33 years old teak plantation (Table-4.12) (Fig.4.8 C).

4.4.3.2 Partly decayed litter

The mean standing crop of partly decayed litter in 33 years old teak plantation site was 484.47 g m^{-2}, 400.49 g m^{-2} and 272.77 g m^{-2} in rainy, winter and summer season, respectively. It was maximum during rainy season and minimum during summer season (Table-4.11).

The mean mass of the partly decayed litter was highly variable and ranged between 51.6 g m^{-2} in May to 128.7 g m^{-2} in August. Partly decayed litter peaked in

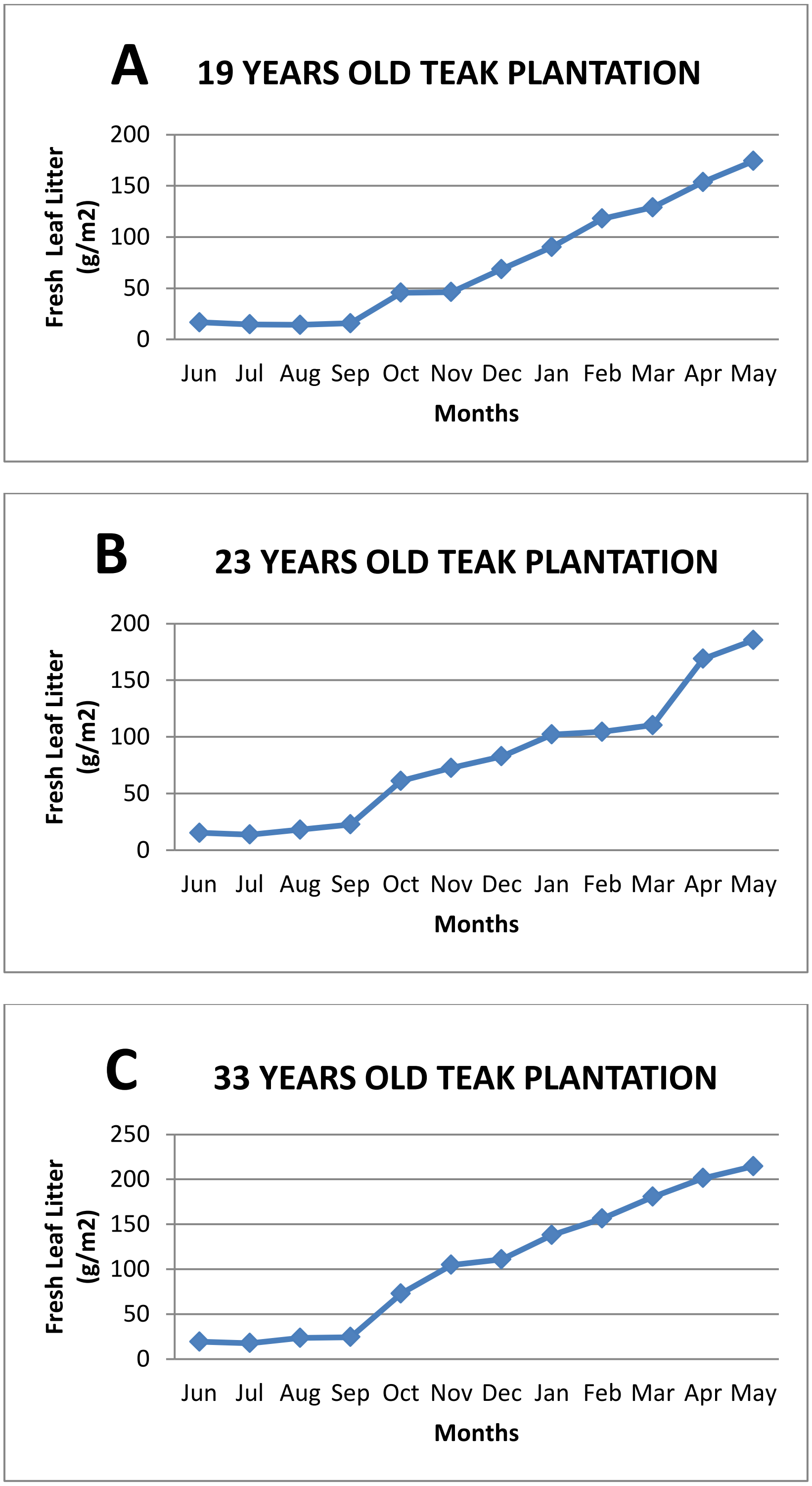

Fig. 4.8 : A, B, C : Monthly variation in the standing crop of fresh leaf litter in an age series of teak plantation

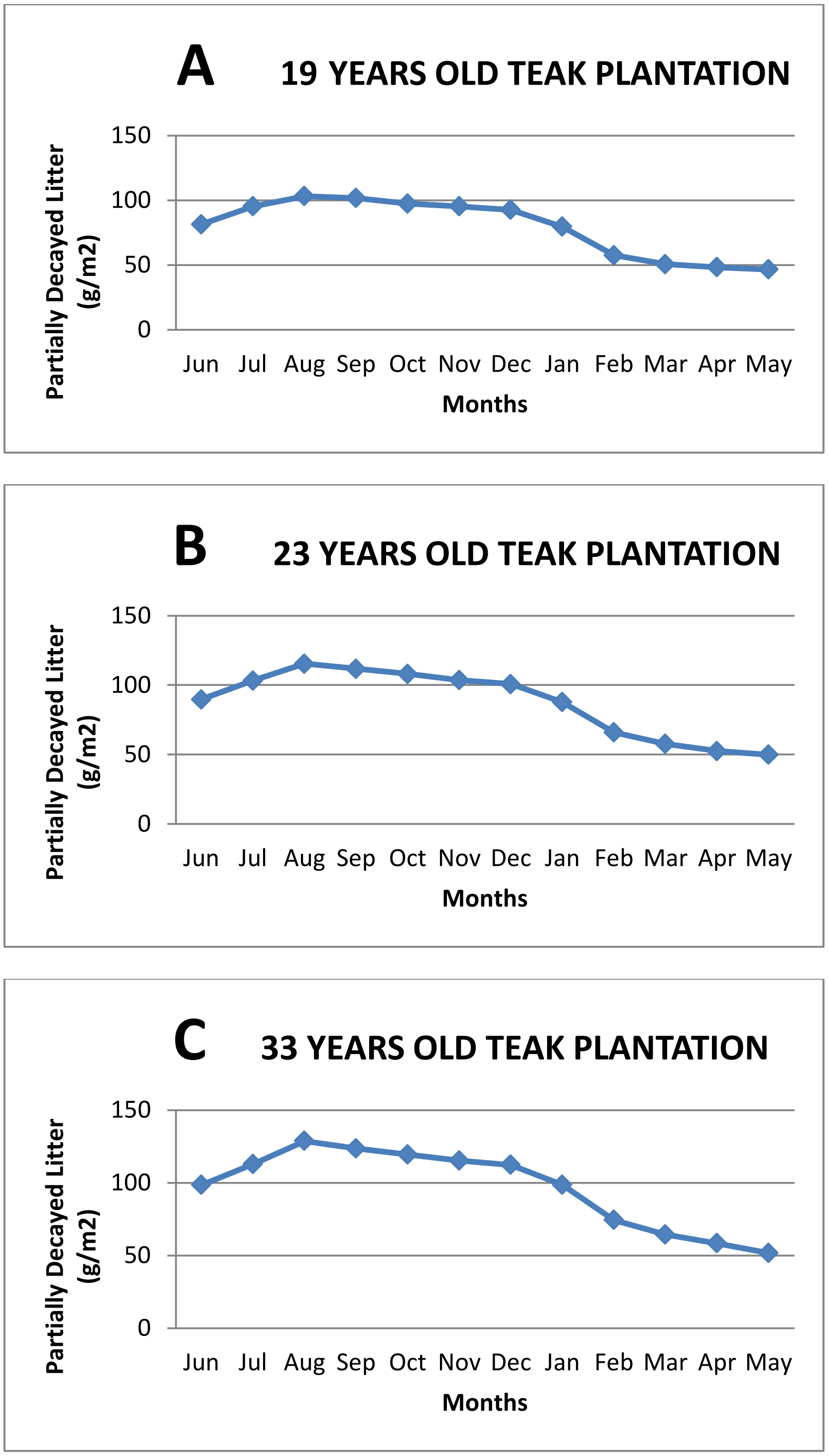

Fig. 4.9 : A, B, C : Monthly variation in the standing crop of partially decayed litter in an age series of teak plantation.

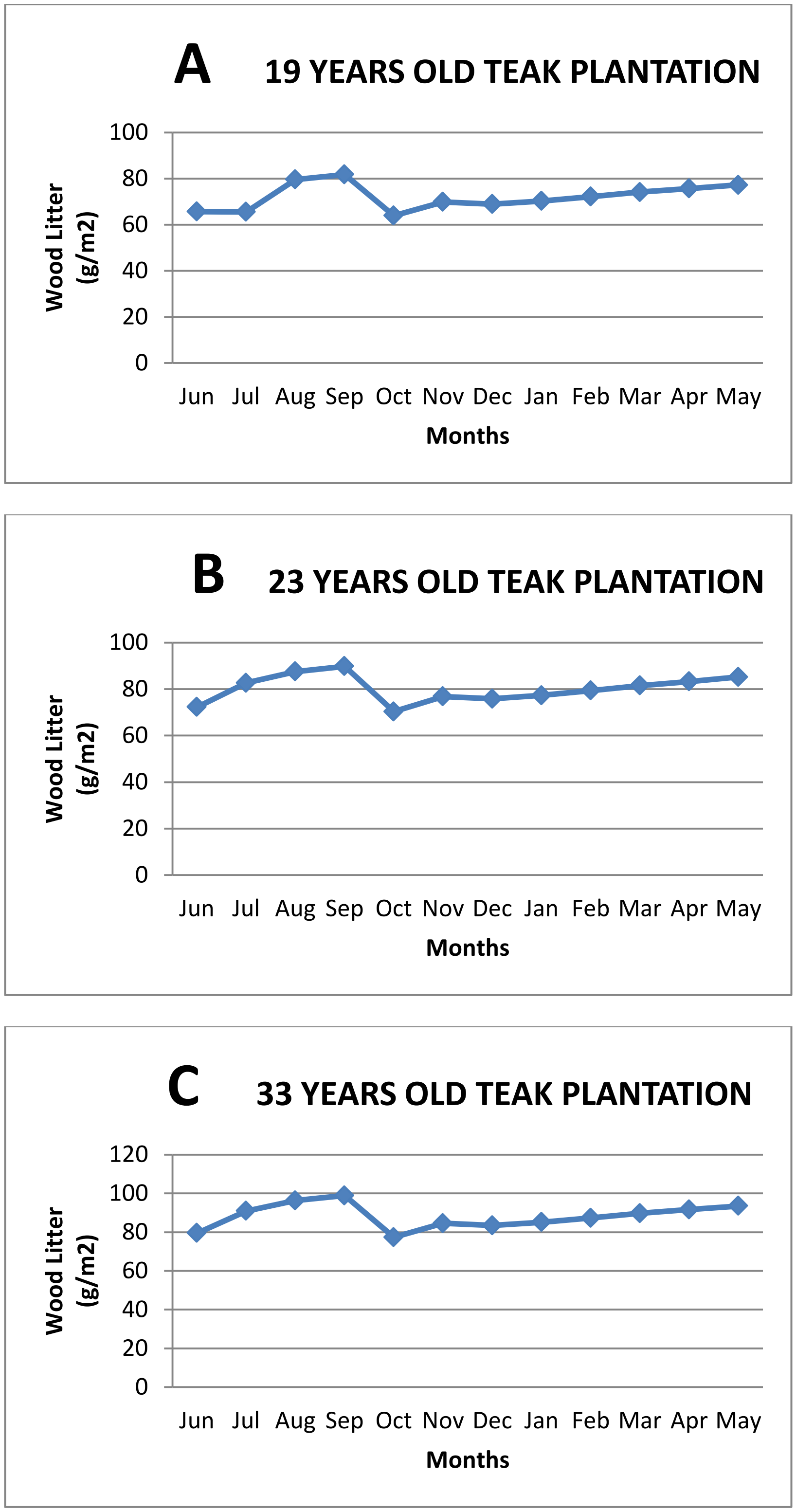

Fig. 4.10 : A, B, C : Monthly variation in the standing crop of wood litter in an age series of teak plantation.

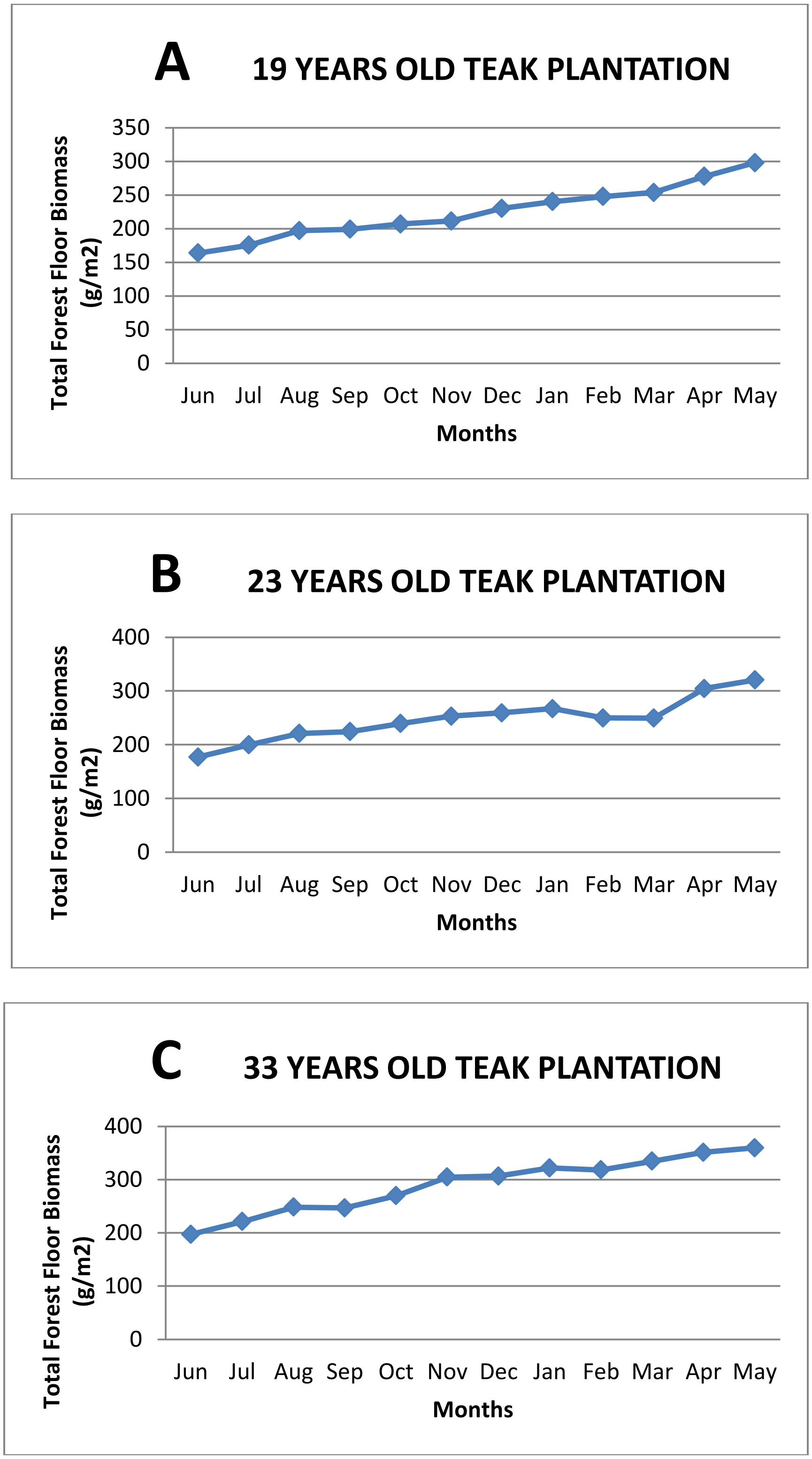

Fig. 4.11 : A, B, C : Monthly variation in the standing crop of total forest floor biomass in an age series of teak plantation.

August at 33 years old teak plantation site and thereafter it declined gradually (Table-4.12) (Fig 4.9 C).

4.4.3.3. Wood litter

The mean standing crop of wood litter on 33 years old teak plantation site was observed 363.33 g m^{-2}, 340.32 g m^{-2} and 354.19 g m^{-2} in rainy, winter and summer seasons, respectively. The wood litter was maximum during summer season followed by rainy and winter season (Table-4.11).

Due to the variations in the pattern of wood litterfall several peaks and troughs were observed in the standing crop of this component during annual cycle, at 33 years old teak plantation site. (Fig.4.10 C) However, the mean wood litter was maximum in September (98.86 g m^{-2}) and minimum in October (77.34 g m^{-2}) (Table-4.12) (Fig. 4.10 C).

4.5 Quantification of fine root biomass

4.5.1 Fine root biomass in 19 years old teak plantation

The fine root biomass measured at monthly interval is given in Table- 4.13. The maximum fine root biomass (503.59 g m^{-2}) was measured in July and minimum (339.46 g m^{-2}) in the month of May. The total fine root biomass, averaged for all sampling intervals, was 4.06 t ha^{-1} (Table-4.14) and ranged seasonally from 3.78 t ha^{-1} in summer to 4.56 t ha^{-1} in rainy season, (Table-4.15).

Bulk of the fine root biomass belonged to <1 mm diameter class (64.07 % of the total). In this diameter class live roots averaged 76.97 % and dead roots 23.03 %. However, in >1 – 5 mm diameter size, live roots accounted for up to 73.16 % and dead roots up to 26.84 % of the biomass. In an annual cycle, proportion of dead fine roots was maximum (43.69 %) in June and minimum (15.83 %) in July.

Table 4.13 : Monthly pattern of fine root biomass (g m^{-2} $\pm$ SE) in an age series of teak plantations

Components	Months											
	June	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**
< 1mm	**19 years old teak plantation**											
Live	193.33±1.71	374.66±1.26	306.66±1.96	335.11±1.52	308.89±1.57	233.78±1.66	232.00±0.35	236.44±0.72	251.11±1.86	215.11±1.77	221.78±0.87	216.89±1.00
Dead	162.32±4.30	74.41±0.47	53.48±0.59	50.63±1.10	59.83±0.60	74.41±0.19	78.38±0.65	72.54±1.14	73.84±1.69	98.27±0.64	76.33±1.28	60.45±1.54
>1-5 mm												
Live	45.04±0.74	49.18±1.16	49.63±0.38	67.26±1.37	48.15±0.92	47.26±1.05	48.59±0.80	49.18±1.06	66.67±2.85	47.26±2.10	49.04±0.98	33.68±1.00
Dead	22.67±4.40	5.33±4.62	14.22±3.22	16.00±4.91	11.11±2.80	24.00±4.60	12.89±2.09	28.00±3.68	14.22±7.54	14.67±4.05	28.89±3.73	28.44±4.37
TOTAL	**423.36**	**503.59**	**424.00**	**469.00**	**427.97**	**379.44**	**371.86**	**386.17**	**405.83**	**375.30**	**376.03**	**339.46**
< 1mm	**23 years old teak plantation**											
Live	130.22±1.28	283.55±1.25	214.66±1.15	205.78±1.62	196.89±0.96	164.00±1.24	161.33±1.42	154.22±1.25	160.44±0.94	149.78±1.36	143.11±0.53	140.89±0.51
Dead	68.27±0.99	55.47±0.97	48.18±1.08	36.62±1.14	45.51±0.79	53.16±0.80	56.00±1.09	54.76±1.28	63.82±0.48	58.84±0.83	57.95±0.93	40.71±0.82
>1-5 mm												
Live	65.48±1.28	38.52±0.66	37.04±0.98	42.81±1.30	38.52±0.62	36.74±0.81	36.74±1.36	35.56±0.69	44.44±0.53	40.74±1.01	44.59±0.77	30.32±0.31
Dead	24.89±4.25	8.89±3.77	17.33±4.33	24.89±4.96	18.22±3.52	18.67±4.49	17.33±3.83	28.44±3.50	16.89±6.95	7.11±3.31	13.78±3.42	21.78±4.37
TOTAL	**288.86**	**386.43**	**317.21**	**310.10**	**299.14**	**272.56**	**271.40**	**272.98**	**285.60**	**256.47**	**259.43**	**233.70**
< 1mm	**33 years old teak plantation**											
Live	94.22±2.27	174.22±2.78	146.67±1.17	140.89±1.04	136.44±0.57	136.89±2.12	136.00±1.77	103.55±1.46	96.89±1.09	104.00±1.11	99.55±1.32	112.44±2.17
Dead	48.89±1.25	39.29±1.70	36.27±1.02	43.02±0.94	31.47±0.61	34.84±0.32	33.96±0.64	32.00±0.50	49.24±1.59	40.36±1.33	44.09±1.26	35.2±1.14
>1-5 mm												
Live	71.85±7.82	29.93±1.05	27.7±0.21	33.78±0.76	28.3±0.35	29.48±0.55	26.81±0.51	25.18±0.74	37.48±1.13	23.26±2.52	29.93±1.09	20.3±0.41
Dead	16.00±3.34	23.56±5.00	17.33±4.30	22.22±5.80	11.11±1.74	16.00±2.29	17.33±3.59	20.44±4.12	12.00±3.34	14.22±5.04	32.44±5.11	12.44±2.94
TOTAL	**230.96**	**266.99**	**227.97**	**239.91**	**207.32**	**217.21**	**214.10**	**181.18**	**195.61**	**181.84**	**206.01**	**180.38**

Table 4.14 : Biomass live and dead fine root (g m^{-2}) in an age series of teak plantations

Categories	19 years old teak plantation	23 years old teak plantation	33 years old teak plantation
< 1mm live	260.48±3.36	175.41±3.12	123.48±2.17
< 1mm dead	77.91±3.20	53.27±1.20	39.05±0.94
>1-5 mm live	50.08±1.22	40.96±1.30	32.00±2.26
>1-5 mm dead	18.37±1.73	18.19±1.42	17.93±1.36
TOTAL	**406.84**	**287.83**	**212.46**

Table 4.15 : Seasonal pattern of fine root biomass (g m^{-2} $\pm$ 1 SE) in age series of teak plantations.

Fine root Categories	19 years old teak plantation			23 years old teak plantation			33 years old teak plantation		
	Rainy	Winter	Summer	Rainy	Winter	Summer	Rainy	Winter	Summer
< 1mm									
Live	331.33±0.97	238.33±0.76	211.78±1.03	225.22±0.89	160.00±1.04	141.00±0.47	149.55±0.86	118.33±0.63	102.55±0.80
Dead	59.59±0.51	74.79±029	99.34±1.45	46.44±0.46	56.93±0.45	56.44±0.25	37.51±0.89	37.51±0.27	42.13±0.50
>1-5 mm									
Live	53.56±0.31	52.93±0.90	43.75±0.52	39.22±0.48	38.37±0.19	45.28±0.50	29.93±1.93	29.74±0.39	36.33±3.22
Dead	11.67±2.69	19.78±2.61	23.67±2.23	17.33±3.20	20.33±3.50	16.89±2.86	18.56±2.85	16.44±2.45	18.78±2.55
TOTAL	**456.14**	**385.82**	**378.54**	**328.22**	**275.63**	**259.61**	**235.55**	**202.03**	**199.80**

The fine root biomass of <1 mm diameter class was measured minimum in month of June. It suddenly increases in July and remains high during August, September and October (rainy season) and then decreases sharply. (Fig.4.12 A). The total fine root biomass (live + dead) follows the same trend (Fig. 4.13 A).

Analysis of variance indicated that the variations in < 1 mm live fine root biomass, < 1 mm dead fine root biomass, > 1-5 mm live fine root biomass and total fine root biomass among the different age of plantation were significantly different ($p<0.05$). (Appendix -XIX, XX, XXI and XIII)

However the variations in > 1-5 mm dead fine root biomass among the different age of plantation was found statistically insignificant. (Appendix- XXII)

4.5.2 Fine root biomass in 23 years old teak plantation

Data on fine root biomass are given in Table-4.13. The maximum fine root biomass (386.43 g m^{-2}) was estimated in July and minimum (233.70 g m^{-2}) in the month of May. The total fine root biomass, averaged for all sampling intervals, was 2.87 t ha^{-1} (Table-4.14) and ranged seasonally from 2.59 t ha^{-1} in summer to 3.28 t ha^{-1} in rainy season, (Table-4.15).

Bulk of the fine root biomass belonged to <1 mm diameter class (60.94 % of the total). In this diameter class live roots averaged 76.7 % and dead roots 23.3 %. However, in >1 – 5 mm diameter size, live roots accounted for up to 69.24 % and dead roots up to 30.76 %. In an annual cycle, proportion of dead fine roots was maximum (32.24 %) in June and minimum (16.65 %) in July.

The fine root biomass of <1 mm diameter class was minimum in the month of June. It suddenly increases in July and remains high during August, September and October months (rainy season) and then decreases sharply. (Fig. 4.12 B). The total fine root biomass (live + dead) follows the same trend (Fig. 4.13 B) as above.

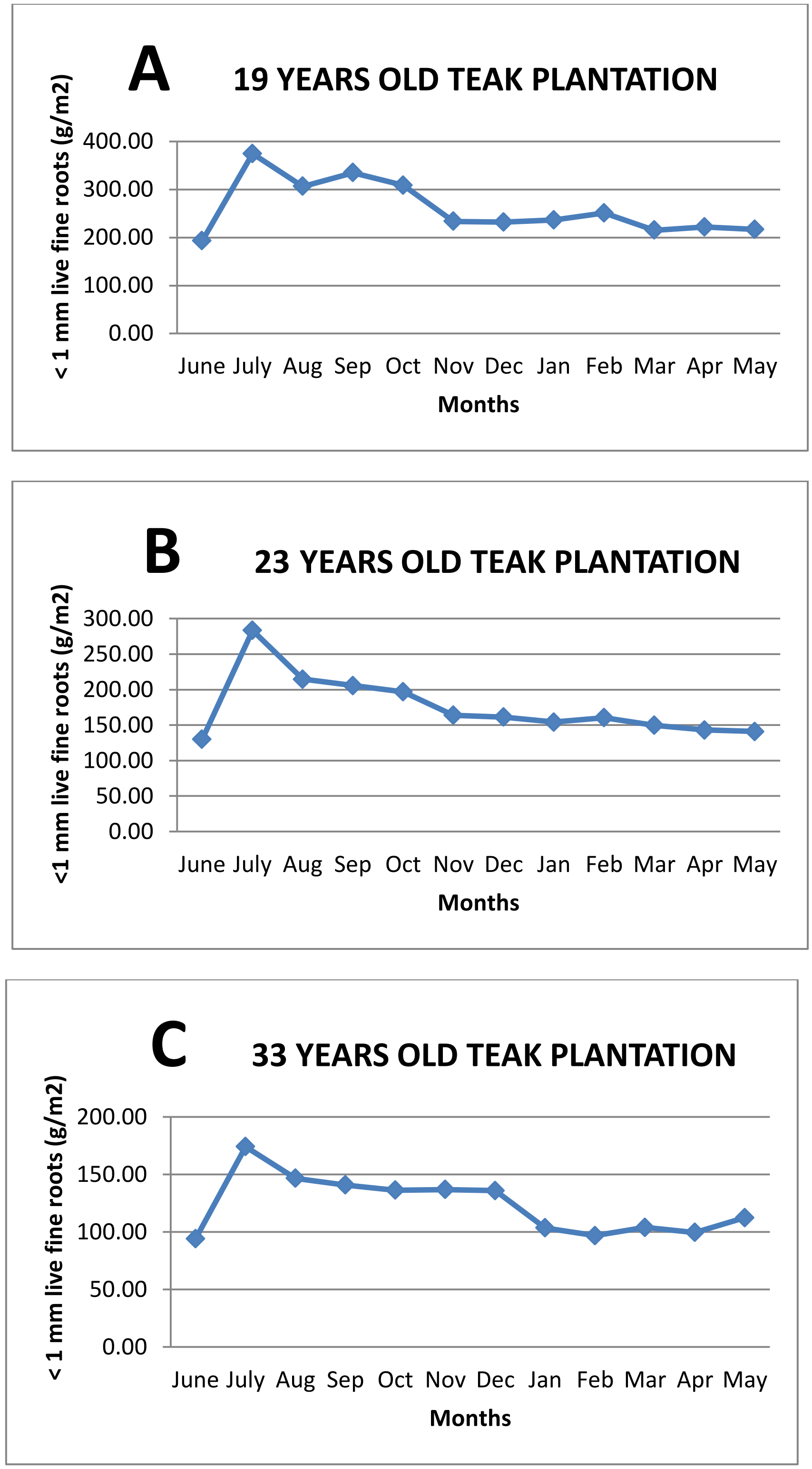

Fig. 4.12 A, B, C: Monthly pattern in < 1 mm live fine root biomass in an age series of teak plantations

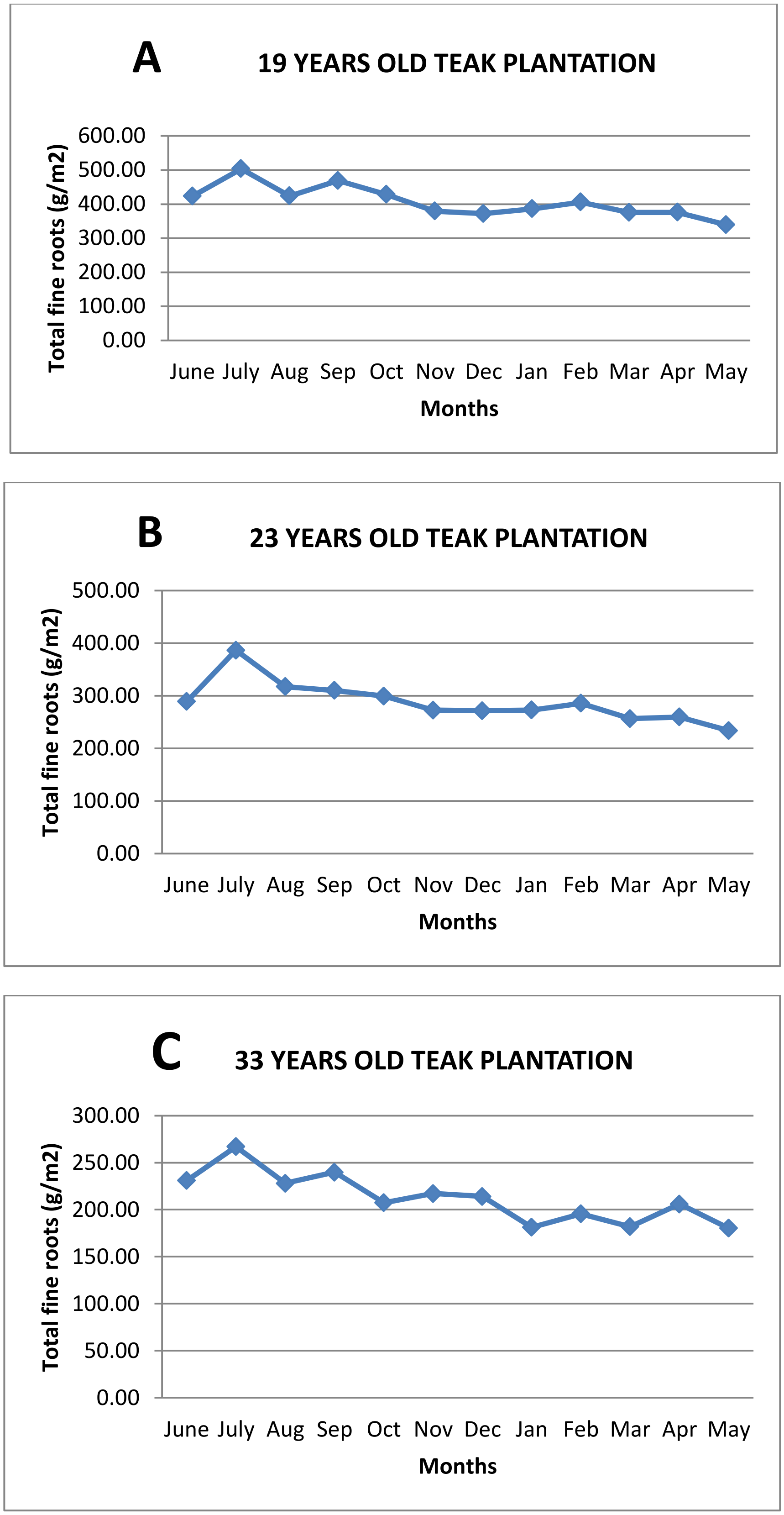

Fig. 4.13 A, B, C: Monthly pattern in total fine root (live and dead) biomass in an age series of teak plantations

4.5.3 Fine root biomass in 33 years old teak plantation

Data on fine root biomass are given in Table-4.13. The maximum fine root biomass (266.99 g m^{-2}) was measured in July (rainy season) and minimum (180.38 g m^{-2}) in the month of May. The total fine root biomass, averaged for all sampling intervals, was 2.12 t ha^{-1} (Table-4.14) and ranged seasonally from 1.99 t ha^{-1} in summer to 2.35 t ha^{-1} in rainy season, (Table-4.15).

Bulk of the fine root biomass belonged to <1 mm diameter class (58.11 % of the total). In this diameter class live roots averaged 75.97 % and dead roots 24.03 %. However, in >1 – 5 mm diameter size, live roots accounted for up to 64.08 % biomass and dead roots up to 35.92 %. In an annual cycle, proportion of dead fine roots was maximum (37.14 %) in the month of April and minimum (20.53 %) in October month.

The fine root biomass of <1 mm diameter class was minimum in the month June. It suddenly increases in July and remains high during the period from August to December and then decreases sharply. (Fig. 4.12 C).

The total fine root biomass (live + dead) also increases suddenly in July and remains high during rainy season, then after it decreases forming several crests and troughs. This is due to variation in the biomass of the dead fine roots (Fig. 4.13 C).

4.6 Litterfall

4.6.1 Annual Litterfall

The total annual litterfall ranged between 1494.91 and 2257.82 g $m^{-2}yr^{-1}$ (Table-4.16). The highest leaf litter values were recorded for 33 years old teak plantation site (1940.99 g $m^{-2}yr^{-1}$) followed by 23 years old teak plantation (1790.35 g $m^{-2}yr^{-1}$) and the lowest at 19 years old teak plantation site (1202.7 g $m^{-2}yr^{-1}$).

Table 4.16: Annual litterfall (g m^{-2} $\pm$ 1 SE) in an age series of teak plantations.

Teak plantation sites	Litterfall (gm^{-2} yr^{-1})		Total
	Leaf litter	Wood litter	
19 years teak plantation	1202.7$\pm$120.15 80.45	292.21$\pm$37.10 19.54	1494.91$\pm$120.01
23 years teak plantation	1790.35$\pm$139.66 85.49	303.72$\pm$34.54 14.5	2094.07$\pm$138.99
33 years teak plantation	1940.99$\pm$142.93 85.96	316.83$\pm$33.85 14.03	2257.82$\pm$141.90

Note: The values in parenthesis indicate relative percentage of the total litterfall.

Wood litter fall along the age series of teak plantations followed the order: 33 year old > 23 year old > 19 year old. The contribution of leaf fall to the total litterfall was 80.45 %, 85.49 % and 85.96 %, respectively on 19 years, 23 years and 33 years old teak plantation sites. The wood litterfall accounted for 19.54 %, 14.5 % and 14.03 % of the total litterfall, respectively, on 19 years, 23 years and 33 years old teak plantation sites. Analysis of variance indicated that the site to site difference were significant ($p< 0.05$) for leaf litter fall, wood litter fall and total litterfall. (Appendix-XXIV, XXV and XXVI)

4.6.2 Monthly pattern of Litterfall

The litterfall data were analysed through analysis of variance. The differences in the quantity of litterfall due to months and category (leaf, wood) were significant ($p < 0.01$) and the interaction of month x category was also significant ($p < 0.05$) indicating a differential temporal pattern of fall of leaf and wood litter.

4.6.2.1 Monthly pattern of litterfall at 19 years old teak plantation site:

The monthly leaf litterfall ranged between 5.89 – 271.46 g m^{-2} (Table-4.17), with the peak leaf fall in December. The leaf shedding was concentrated between October to February and less litterfall were observed during June – September. The leaf litterfall indicated a sigmoid pattern with a hump in October – January, and by the month of May 100 % leaf fall was completed (Fig. 4.14 A).

Wood litter consisted of twigs, branches, bark and fruits and seeds. The fall of wood litter among different months ranged between 5.56 – 45.13 g m^{-2} (Table-4.17). The pattern was irregular with multiple peaks and trough (Fig 4.15 A)**.** Cumulative pattern of wood litterfall resulted in a continuously increasing curve from the September to a maximum in March (Fig. 4.15 A).

The peak total litterfall (leaf + wood) occurred in December (Fig. 4.16 A) and monthly values ranged between 11.45 – 307.48 g m^{-2} (Table-4.17). The shape of

Table 4.17: Monthwise pattern of litterfall (g m^{-2} ± 1 SE) in an age series of teak plantations.

Sites	Components	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19 years old teak plantation	Leaf litter	254.59±1.53	98.87±0.96	72.98±2.47	59.15±1.54	30.59±1.04	5.89±0.27	9.02±1.11	10.57±0.97	12.68±1.27	112.12±2.86	264.78±2.23	271.46±2.72
	Wood litter	42.11±3.35	43.35±1.95	45.13±3.33	19.23±2.11	10.0±2.7	5.56±1.64	6.76±1.26	8.24±2.92	9.12±1.95	33.45±3.36	33.24±2.34	36.02±3.81
	Total	**296.7**	**142.22**	**118.11**	**78.38**	**40.59**	**11.45**	**15.78**	**18.81**	**21.8**	**145.57**	**298.02**	**307.48**
23 years old teak plantation	Leaf litter	357.67±2.41	161.73±1.52	116.52±1.98	97.81±1.11	48.67±0.84	12.52±0.49	15.12±1.23	18.43±1.38	19.38±0.77	166.52±2.62	380.65±3.91	395.33±3.66
	Wood litter	42.32±3.0	43.22±1.77	45.30±6.35	19.80±1.34	10.35±2.16	7.46±2.34	8.64±1.25	10.34±2.51	12.40±1.74	34.13±2.67	33.54±1.9	36.22±2.27
	Total	**399.99**	**204.95**	**161.82**	**117.61**	**59.02**	**19.98**	**23.76**	**28.77**	**31.78**	**200.65**	**414.19**	**431.55**
33 years old teak plantation	Leaf litter	378.32±1.29	171.65±0.47	132.21±1.97	111.81±0.55	57.39±1.14	15.13±0.35	17.1±0.88	20.06±0.34	21.81±0.49	178.82±3.00	414.11±2.13	422.58±1.94
	Wood litter	43.32±1.53	44.34±1.05	47.34±4.16	20.10±2.65	13.4±2.58	8.32±1.42	9.4±1.44	11.05±2.23	13.47±1.03	34.66±1.8	34.1±2.27	37.33±4.04
	Total	**421.64**	**215.99**	**179.55**	**131.91**	**70.79**	**23.45**	**26.5**	**31.11**	**35.28**	**213.48**	**448.21**	**459.91**

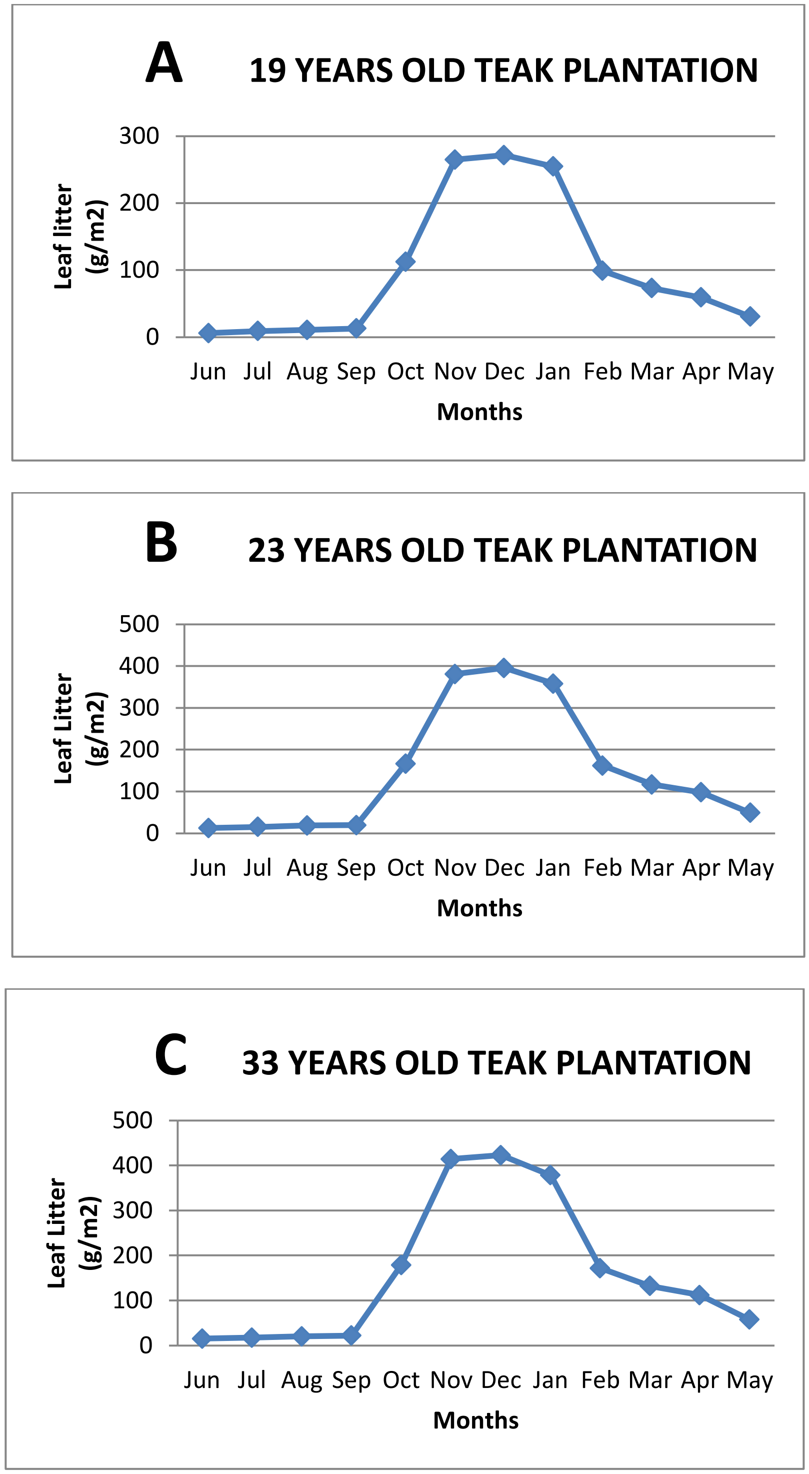

Fig. 4.14 A, B, C: Monthly variation in leaf litterfall in an age series of teak plantations.

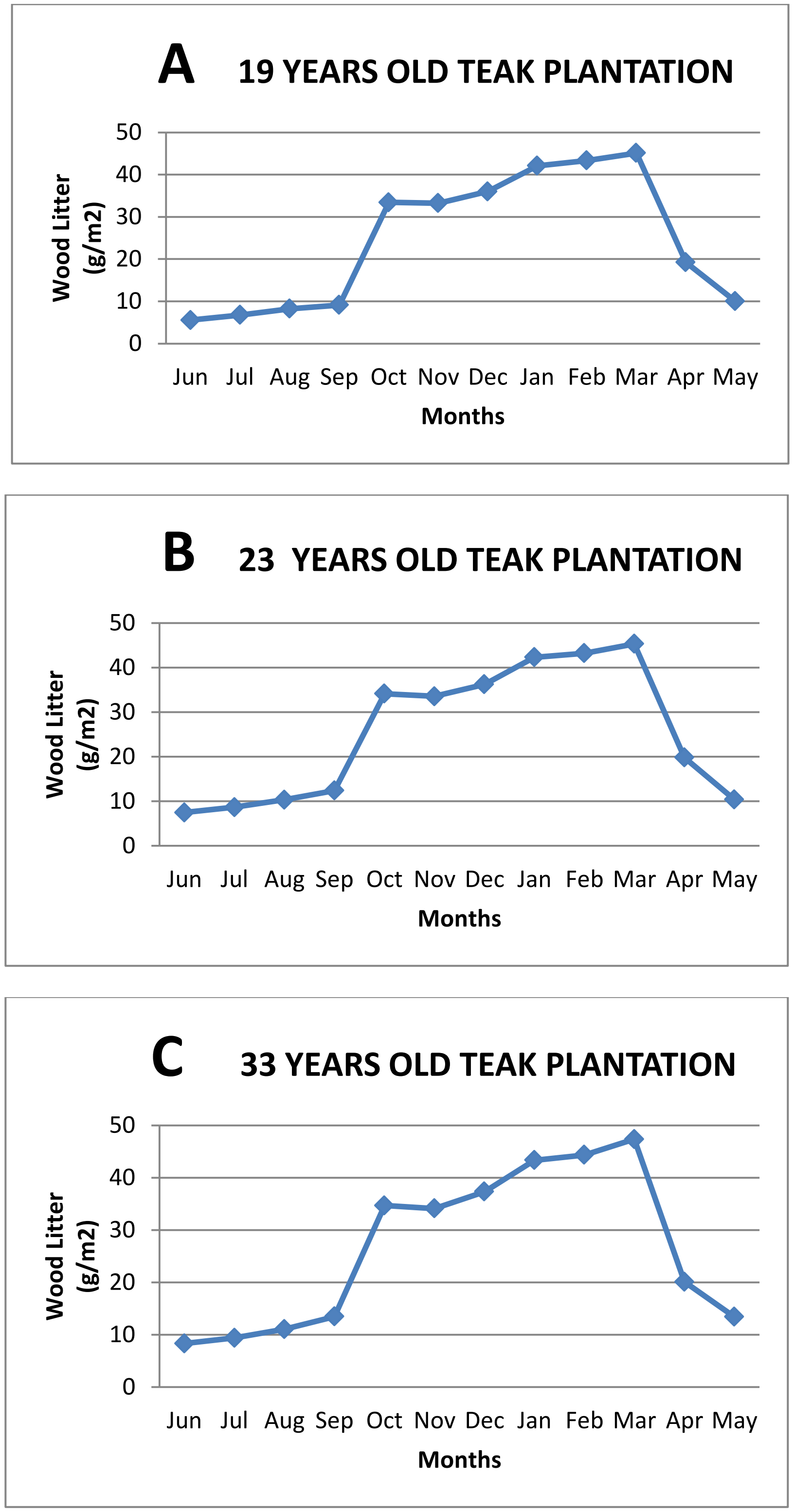

Fig. 4.15 A, B, C: Monthly variation in fall of wood litter in an age series of teak plantations.

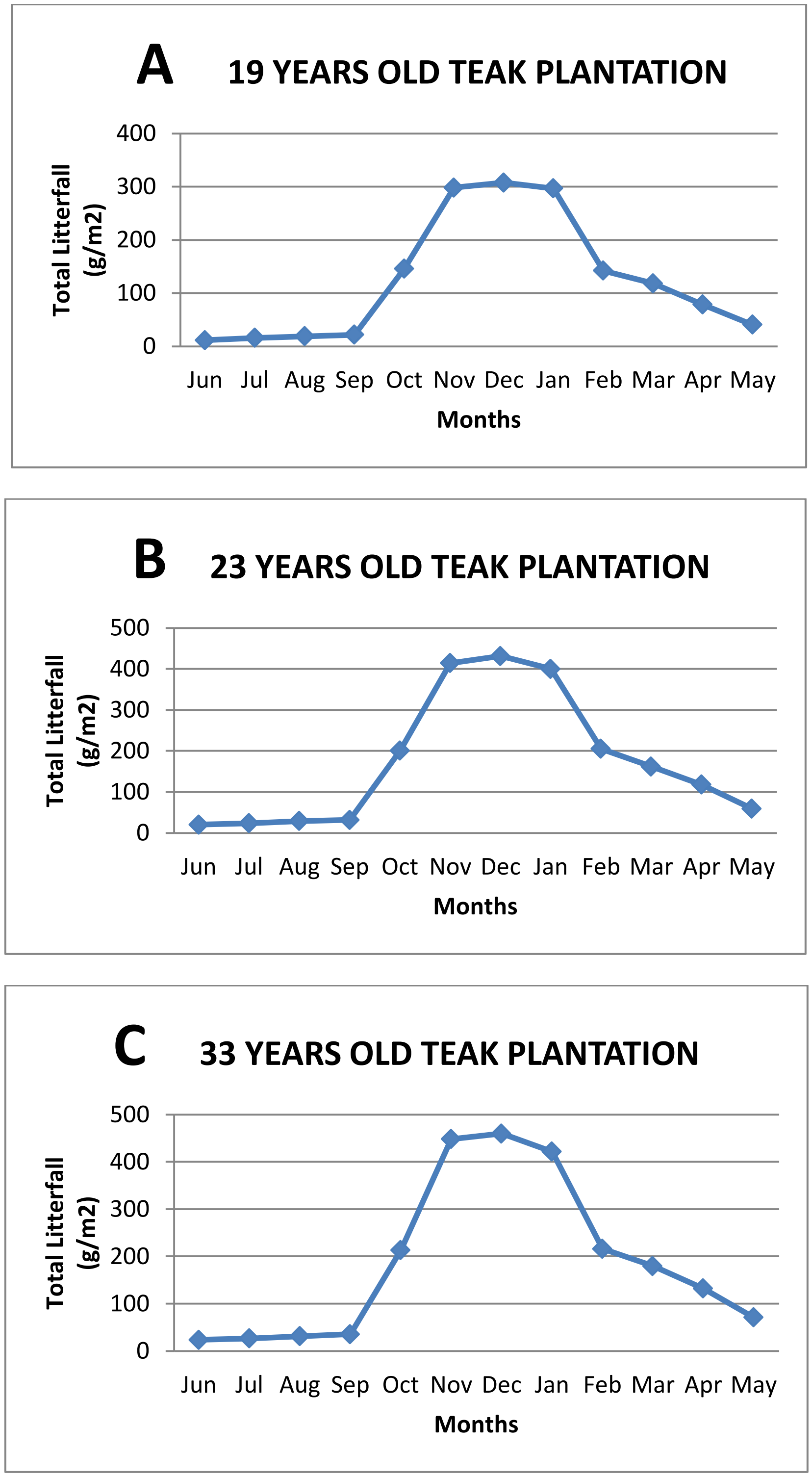

Fig. 4.16 A, B, C: Monthly variation in total litterfall in an age series of teak plantations.

curve for Cumulative total litterfall was sigmoid and by the end of May 100 % total litterfall was completed (Fig. 4.16 A).

4.6.2.2 Monthly pattern of litterfall at 23 years old teak plantation site:

The temporal pattern was similar to that of 19 year old teak plantation site. The peak leaf fall occurred during November to January (Fig 4.14 B). The monthly leaf fall ranged between 12.52 – 395.33 g m^{-2} (Table-4.17). The cumulative leaf fall yielded an annual value of 1790.35 g $m^{-2}yr^{-1}$ (Table-4.16) and the leaf fall was completed by the month of May.

The wood fall among different months ranged between 7.46 – 45.30 g m^{-2}. The wood fall pattern was irregular though there was peak in March. (Fig. 4.15 B). The cumulative wood fall increased till the end of the annual cycle resulting into a total of 303.72 g $m^{-2}yr^{-1}$ (Fig.4.15 B).

The total litterfall ranged between 19.98 – 431.55 g m^{-2} and was highest in December and lowest in June (Table-4.17) (Fig. 4.16 B). The cumulative total litterfall yielded an annual value of 2094.07 g $m^{-2}yr^{-1}$ (Table-4.16).

4.6.2.3 Monthly pattern of litterfall at 33 year old teak plantation site:

The temporal pattern of litterfall is broadly similar to the patterns of 19 and 23 years old teak plantation sites. The peak leaf fall occurred in December. The monthly leaf fall ranged between 15.13 – 422.58 g m^{-2} (Table-4.17). By the month of May 100 % leaf litterfall was completed (Fig.4.14 C).

The fall of wood litter among different months ranged between 8.32 – 47.34 g m^{-2} (Table-4.17). The pattern of wood litterfall was irregular and cumulative wood litter deposition resulted into an annual value of 316.83 g $m^{-2}yr^{-1}$ (Fig. 4.15 C).

The total litterfall followed the similar pattern as leaf litterfall and ranged between 23.45 – 459.91 g m^{-2} (Table-4.17). The cumulative total litterfall yielded an annual value of 2257.82 g $m^{-2}yr^{-1}$ (Table-4.16) (Fig. 4.16 C).

Table 4.18 : Seasonal pattern of litterfall (g m^{-2} $\pm$ 1 SE) at age series of teak plantations.

Components	19 years teak plantation			23 years teak plantation			33 years teak plantation		
	Rainy	**Winter**	**Summer**	**Rainy**	**Winter**	**Summer**	**Rainy**	**Winter**	**Summer**
Leaf litter	144.38±2.38	889.7±1.97	168.61±2.11	219.44±2.59	1295.38±2.76	275.51±1.66	237.79±2.62	1386.67±2.03	316.55±1.16
Wood litter	57.57±3.30	154.72±3.51	79.93±2.74	65.5±2.46	155.31±1.98	82.91±4.90	68.58±2.10	159.58±2.10	89.16±2.79
Total	**201.95**	**1044.42**	**248.54**	**284.94**	**1450.69**	**358.42**	**306.37**	**1545.77**	**405.71**

4.6.3 Seasonal pattern of litterfall:

The seasonal pattern of litterfall is illustrated in Table-4.18. The seasonal pattern of leaf litterfall on the 19 year old teak plantation reveals that the highest value occurred during winter (889.7 g m^{-2}) followed by summer season (168.61 g m^{-2}). The highest total litterfall (leaf + wood litter) was also occurred during the winter (1044.42 g m^{-2}) followed by summer (248.54 g m^{-2}). The fall of wood litter was highest in winter (154.72 g m^{-2}) followed by summer (79.93 g m^{-2}).

At 23 years old teak plantation site the highest values of leaf litterfall was observed during winter 1295.38 g m^{-2}) followed by summer season (275.51 g m^{-2}). The wood litter was also observed highest in winter (155.31 g m^{-2}) followed by summer (82.91 g m^{-2}). The total litterfall was also observed highest during winter (1450.69 g m^{-2}) followed by summer season (358.42 g m^{-2}).

However, at 33 years old teak plantation site highest values of leaf litterfall (1386.67 g m^{-2}) and total litterfall (1545.77 g m^{-2}) occurred during winter followed by summer season. The fall of wood litter was highest in winter (159.58 g m^{-2}) followed by summer (89.16 g m^{-2}).

The maximum seasonal leaf fall, among the sites ranged between 889.7 – 1386.67 g m^{-2} and lowest between 144.38 – 237.79 g m^{-2}.

4.6.4 Turnover of litter

The turnover rate (K) of the litter was calculated indirectly following Jenny *et al*. (1949):

$$K=A/A+F$$

Where A is the annual increment of litter i.e. annual litterfall (Table-4.16) and F is the amount of the litter at steady state. Turnover time (t) is the reciprocal of the turnover rate and is expressed as t =1/K. In the present study the F value is the lowest value of the standing crop of litter within the annual cycle (during rainy season Table-

Table: 4.19: Turnover rate (K) and turnover time (t) of litter on the forest floor

Sites	K	t (yr)
19 years old teak plantation	0.65	1.52
23 years old teak plantation	0.70	1.42
33 years old teak plantation	0.69	1.43

4.11). The values for turnover rate and turnover time for the litter on each site are given in Table-4.19. The turnover rate on these sites ranged between 0.65-0.70 indicating about 69- 73% turnover of the litter each year. The turnover time of the litter on these sites ranged between 1.42-1.52 years.

4.7 Estimation of carbon storage pattern in an age series of teak plantation

The carbon concentration (Table-4.20) in bole, branch, leaf and coarse roots were 43.50 %, 45.67 %, 46.67 % and 35.73%, respectively. The total carbon stored (C) in trees varied between 54.06 and 100.68 t ha^{-1} (Table-4.21, 4.22 and 4.23). The total C increased with age of the plantation from 54.06 t ha^{-1} in 19 years old teak plantation to 100.68 t ha^{-1} in 33 years old teak plantation. Quantity of C in aboveground and belowground components of trees on different plantation was between 46.38 – 87.38 t ha^{-1} and 7.68 - 13.28 t ha^{-1}, respectively. In different components of trees on the three plantation sites the quantity of C varied from 27.62 - 50.05 t ha^{-1} in bole, 12.29 - 26.34 t ha^{-1} in branch, 6.47 - 11.01 t ha^{-1} in leaf and 7.68 - 13.28 t ha^{-1} in root. The relative contribution of aboveground and belowground components in the total C storage was 85.79 - 86.78 % and 13.19 – 14.20 %, respectively. Analysis of variance indicated that the variation in above ground carbon storage, below ground carbon storage and total carbon storage along age series of teak plantation were significantly different ($p < 0.05$). (Appendix - XXVII, XXVIII and XXIX)

4.7.1 Carbon storage pattern in 19 years old teak plantation

The total carbon estimated in 19 years old teak plantation (Table-4.21) was 54.06 t ha^{-1}, of which 46.38 t ha^{-1} was above ground and 7.68 t ha^{-1} below ground. The distribution of carbon in the different components was 27.62 t ha^{-1} in bole, 12.29 t ha^{-1} in branch, 6.47 t ha^{-1} in leaf and 7.68 t ha^{-1} in root. The bole, branch, leaf and root

Table 4.20: Carbon concentration in different components of tree

Components	**Carbon %**
Bole	43.50
Branch	45.67
Foliage	46.67
Coarse roots	35.73

comprised 51.09, 22.73, 11.96 and 14.20 per cent, respectively of the total carbon. Among the species *Tectona grandis* stored the highest carbon (52.65 t ha^{-1}) followed by *Diospyros melanoxylon* (0.75 t ha^{-1}) and *Cleistanthus collinus* (0.45 t ha^{-1}) which stored 97.39, 1.38 and 0.83 per cent of the total carbon on 19 years old teak plantation. However, lowest carbon was stored by *Lagerstroemia parviflora* (0.21 t ha^{-1}).

4.7.2 Carbon storage pattern in 23 years old teak plantation

The total carbon stored in 23 years old teak plantation (Table-4.22) was 84.38 t ha^{-1}, of which 72.93 t ha^{-1} was above ground and 11.45 t ha^{-1} below ground. The distribution of carbon in the different components was 42.69 t ha^{-1} in bole, 20.53 t ha^{-1} in branch, 9.71 t ha^{-1} in leaf and 11.45 t ha^{-1} in root. The storage of carbon in bole, branch, leaf and root was 50.59, 24.33, 11.50 and 13.56 per cent, respectively, of the total carbon. Among the individual species *Tectona grandis* constituted the highest carbon (77.92 t ha^{-1}) followed by *Lagerstroemia parviflora* (4.25 t ha^{-1}) and *Semecarpus anacardium* (0.85 t ha^{-1}) which shared 92.34, 5.03 and 1.00 per cent of the total carbon. However, lowest carbon was measured for *Madhuca indica* (0.23 t ha^{-1}).

4.7.3 Carbon storage pattern in 33 years old teak plantation

The total carbon measured in 33 years old teak plantation (Table-4.23) was 100.68 t ha^{-1} of which 87.38 t ha^{-1} was above ground and 13.28 t ha^{-1} below ground. The storage of carbon in the different components was 50.05 t ha^{-1} in bole, 26.34 t ha^{-1} in branch, 11.01 t ha^{-1} in leaf and 13.28 t ha^{-1} in root. The bole, branch, leaf and root stored 49.71, 26.16, 10.93 and 13.19 per cent carbon, respectively of the total carbon. Among the individual species *Tectona grandis* stored the highest carbon (86.98 t ha^{-1}) followed by *Cleistanthus collinus* (2.23 t ha^{-1}) and *Lagerstroemia parviflora* (2.06 t

Table 4.21: Storage of carbon (t ha^{-1} $\pm$ 1 SE) in different components of trees in 19 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	**Branch**	**Leaf**	**Root**	**Total**
Cleistanthus collinus Roxb.	0.2±0.05 (44.44)	0.16±0.06 (35.55)	0.03±0.01 (6.66)	0.06±0.02 (13.33)	0.45±0.09
Diospyros melanoxylon Roxb.	0.35±0.04 (45.66)	0.26±0.05 (34.66)	0.04±0.01 (5.33)	0.11±0.02 (14.66)	0.75±0.08
Lagerstroemia parviflora Roxb.	0.09±0.02 (44.85)	0.07±0.02 (35.33)	0.01±0.003 (4.76)	0.03±0.008 (14.28)	0.21±0.08
Tectona grandis Linn.	26.98±1.33 (51.24)	11.8±0.93 (22.41)	6.4±0.63 (12.15)	7.47±0.65 (14.18)	52.65±1.87
Total	27.62	12.29	6.47	7.68	**54.06**

Note: The values in parenthesis indicate relative percentage of total tree carbon stock.

Table 4.22: Storage of carbon (t ha^{-1} $\pm$ 1 SE) in different components of trees in 23 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	**Branch**	**Leaf**	**Root**	**Total**
Boswellia serrata, Roxb. exColebr.	0.18±0.04 (42.86)	0.17±0.05 (40.53)	0.02±0.002 (4.65)	0.05±0.01 (11.62)	0.43±0.07
Buchnania lanzan Spreng.	0.15±0.04 (48.38)	0.1±0.02 (32.25)	0.02±0.003 (6.45)	0.04±0.01 (12.90)	0.31±0.07
Diospyros melanoxylon Roxb.	0.19±0.01 (48.71)	0.12±0.01 (30.76)	0.02±0.004 (5.12)	0.06±0.008 (15.38)	0.39±0.02
Lagerstroemia parviflora Roxb.	1.83±0.54 (42.95)	1.55±0.62 (36.38)	0.28±0.10 (6.57)	0.6±0.20 (14.08)	4.25±0.81
Madhuca indica J.F. Gmel.	0.1±0.02 (45.45)	0.08±0.03 (36.36)	0.01±0.009 (4.54)	0.03±0.01 (13.63)	0.23±0.04
Semecarpus anacardium Linn.	0.35±0.03 (41.66)	0.34±0.03 (40.47)	0.04±0.009 (4.76)	0.11±0.01 (13.09)	0.85±0.05
Tectona grandis Linn.	39.89±1.18 (51.18)	18.18±0.87 (23.32)	9.3±0.55 (11.93)	10.56±0.55 (13.55)	77.92±1.65
Total	42.69	20.53	9.71	11.45	**84.38**

Note: The values in parenthesis indicate relative percentage of total tree carbon stock.

Table 4.23: Storage of carbon (t ha^{-1} $\pm$ 1 SE) of different components of trees in 33 years old teak plantation at Barnawapara Wildlife Sanctuary.

Species	Tree components				
	Bole	**Branch**	**Leaf**	**Root**	**Total**
Bridelica retusa Spreng.	0.41±0.07 (37.27)	0.51±0.11 (46.36)	0.05±0.01 (4.54)	0.13±0.04 (11.81)	1.09±0.14
Buchnania lanzan Spreng.	0.86±0.10 (48.04)	0.57+0.09 (31.84)	0.14±0.04 (7.82)	0.22±0.07 (12.29)	1.78±0.14
Cassia fistula Linn.	0.38±0.08 (40.42)	0.39±0.09 (41.48)	0.05±0.01 (5.31)	0.12±0.05 (12.76)	0.94±0.09
Cleistanthus collinus Roxb.	0.87±0.28 (39.01)	0.99±0.08 (44.39)	0.10±0.02 (4.48)	0.27±0.08 (12.10)	2.23±0.54
Diospyros melanoxylon Roxb.	0.19±0.01 (48.71)	0.12±0.03 (30.76)	0.02±0.004 (5.12)	0.06±0.01 (15.38)	0.39±0.05
Emblica officinalis Gaerth.	0.52±0.06 (36.11)	0.72±0.09 (50.00)	0.05±0.01 (3.47)	0.15±0.02 (10.41)	1.44±0.11
Lagerstroemia parviflora Roxb.	0.83±0.09 (40.29)	0.78±0.08 (37.86)	0.12±0.03 (5.82)	0.33±0.06 (16.01)	2.06±0.51
Lannea coromandelica Houtt.	0.18±0.01 (42.85)	0.17±0.01 (40.47)	0.02±0.004 (4.76)	0.05±0.008 (11.9)	0.43±0.02
Madhuca indica J.F. Gmel	0.69±0.15 (38.33)	0.82±0.21 (45.55)	0.08±0.01 (4.44)	0.21±0.08 (11.66)	1.8±0.28
Tectona grandis Linn.	44.5±1.11 (51.16)	20.61±0.80 (23.69)	10.31±0.52 (11.85)	11.56±0.54 (13.29)	86.98±1.56
Terminalia tomentosa Roth.	0.61±0.12 (39.61)	0.67±0.15 (43.50)	0.07±0.004 (4.54)	0.19±0.02 (12.33)	1.54±0.26
Total	50.05	26.34	11.01	13.28	**100.68**

Note: The values in parenthesis indicate relative percentage of total tree carbon stock.

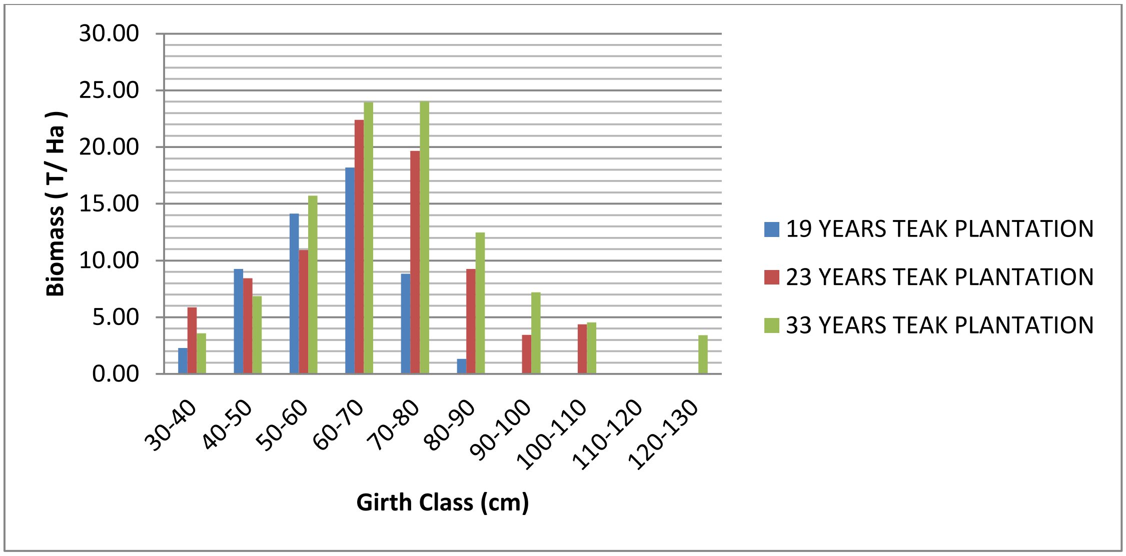

Fig. 4.17: Distribution pattern of carbon storage along the girth classes in an age series of teak plantation.

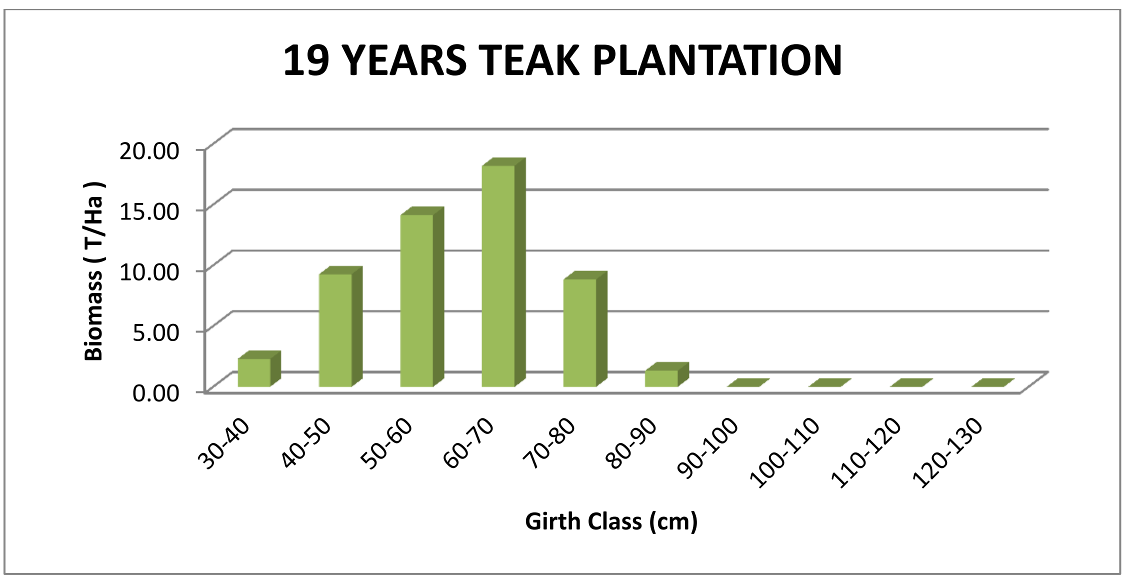

Fig 4.18: Distribution pattern of carbon storage across the girth classes in 19 years old teak plantation.

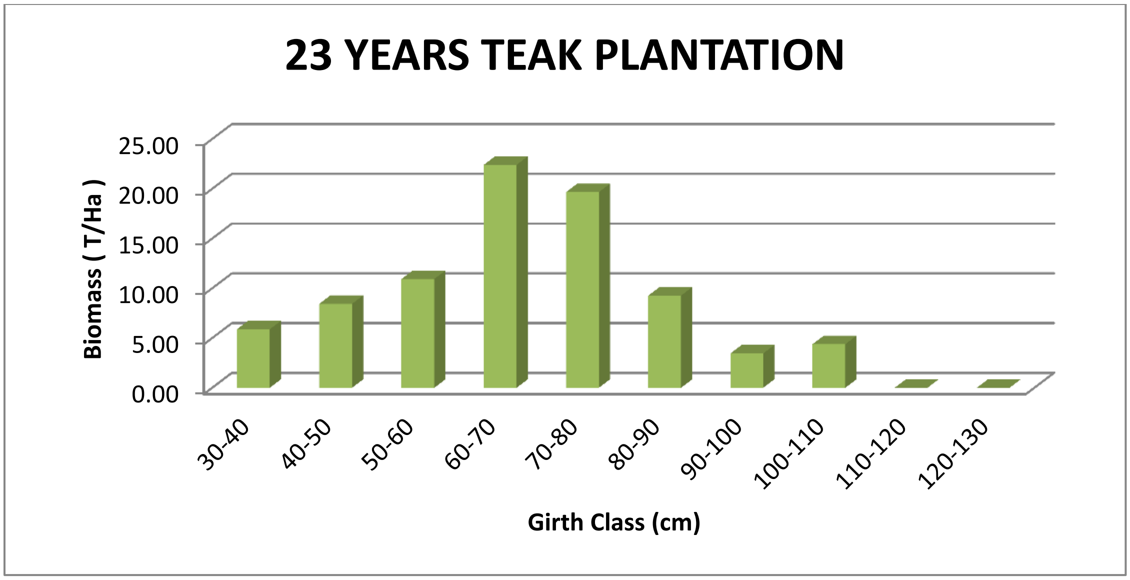

Fig 4.19: Distribution pattern of carbon storage across the girth classes in 23 years old teak plantation.

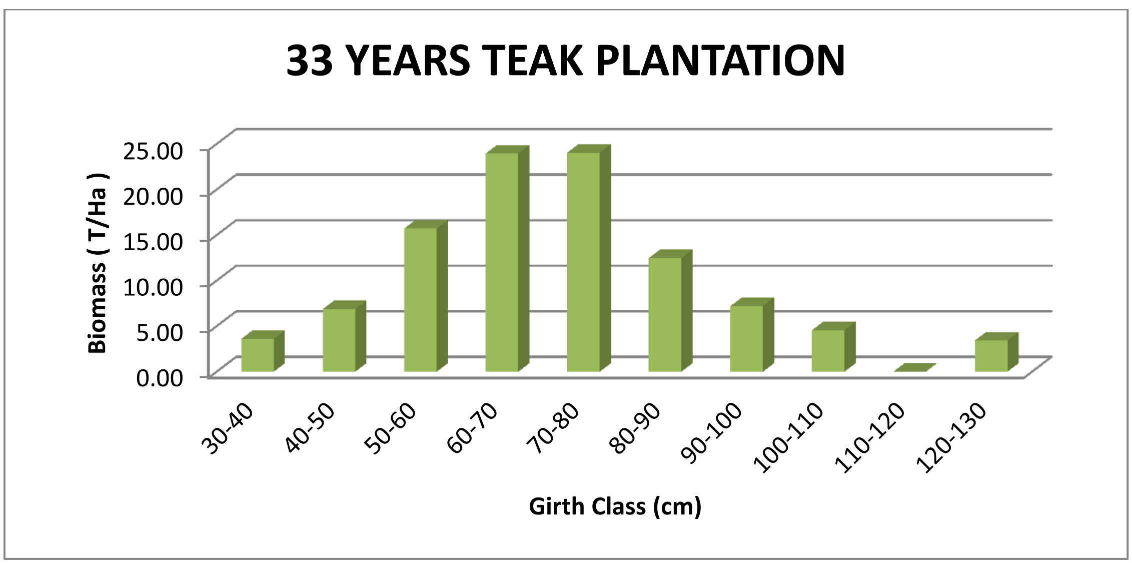

Fig 4.20: Distribution pattern of carbon storage across the girth classes in 33 years old teak plantation.

ha^{-1}) which constituted 86.39, 2.21, and 2.04 per cent of the total carbon. However, lowest carbon was measured for *Diospyros melanoxylon* (0.39 t ha^{-1}).

Distribution pattern of carbon in an age series of teak plantation

Distribution pattern of carbon across the girth classes also followed the similar pattern as was the case with biomass distribution. It was negligible in young individuals belonging to seedlings and saplings classes and highest storage was observed in middle girth classes in an age series of teak plantation (Fig. 4.17 - 4.20).

4.8 Quantification and variation in net primary productivity in an age series of teak plantation.

4.8.1 Girth increment

The number of stems marked and the percentage of total trees in each class are shown in Table 4.24 and ranges of increments (cm tree^{-1} yr^{-1}) are given in Table-4.26. A total of 60 individual trees of teak were measured for girth increments. Overall mean girth increments in all teak trees ranged between 0.75 to 3 cm tree^{-1} yr^{-1}. The highest mean girth increment in teak (3.00 cm tree^{-1} yr^{-1}) occurred in 101-110 cm girth class and lowest (0.75 cm tree^{-1} yr^{-1}) in 40-50 cm girth class. (Table-4.25)

4.8.1.1 Girth increment in 19 years old teak plantation

In 19 years old teak plantation, the highest mean girth increment (2.75 cm tree^{-1} yr^{-1}) was measured in 70-80 cm girth class and lowest (1.00 cm tree^{-1} yr^{-1}) in 31-40 cm girth class. (Table-4.25). The mean girth increment for two annual cycles recorded by each individual trees was ranged between 0.75 to 2.75 tree^{-1} yr^{-1}. (Table-4.26)

4.8.1.2 Girth increment in 23 years old teak plantation

In 23 years old teak plantation, the highest mean girth increment (2.41 cm tree^{-1} yr^{-1}) was measured in 81-90 cm girth class and lowest (0.75 cm tree^{-1} yr^{-1}) in 31-40 cm girth class. (Table-4.25). The mean girth increment for two annual cycles

Table 4.24: Number of teak trees marked for girth increment and their percentage in girth class

Girth Class (cm)	19 years old teak plantation		23 years old teak plantation		33 years old teak plantation	
	No. of individuals marked	Percent of total trees marked	No. of individuals marked	Percent of total trees marked	No. of individuals marked	Percent of total trees marked
31-40	3	15	2	10	1	5
41-50	4	20	3	15	5	25
51-60	8	40	1	5	6	30
61-70	2	10	8	40	2	10
71-80	1	5	5	25	4	20
81-90	2	10	1	5	1	5
91-100	0		0		0	0
101-110	0		0		1	5
TOTAL	**20**		**20**		**20**	

Table 4.25: Mean girth increment (cm) of each girth class of teak trees in an age series of Teak plantations.

Sites	Girth classes (cm)							
	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-110
19 years old teak plantation	1.00	1.25	1.56	1.66	2.75	1.37	-	-
23 years old teak plantation	0.75	1.25	1.25	1.65	1.91	2.41	-	-
33 years old teak plantation	0.8	1.15	1.08	1.2	2.12	1.66	-	3.00

Table 4.26: Range of mean girth increment (cm) of selected individual teak trees in two annual cycles in an age series of teak plantations

Sites	**Mean girth increment (cm) in 1 year**
19 years old teak plantation	0.75 - 2.75
23 years old teak plantation	0.75 - 2.75
33 years old teak plantation	0.5 – 3.00

measured for each individual trees was ranged between 0.75 to 2.75 $tree^{-1}$ yr^{-1}. (Table-4.26)

4.8.1.3 Girth increment in 33 years old teak plantation

In 33 years old teak plantation, the highest mean girth increment (3 cm $tree^{-1}$ yr^{-1}) was measured in 101-110 cm girth class and lowest (0.8 cm $tree^{-1}$ yr^{-1}) in 31-40 cm girth class. (Table-4.25). The mean girth increment for two annual cycles measured for each individual trees was ranged between 0.5 to 3.00 $tree^{-1}$ yr^{-1}. (Table-4.26)

4.8.2 Net primary production:

The total aboveground tree production on each site ranged between 21.32 – 30.51 t ha^{-1} yr^{-1} (Table-4.27). Foliage production contributed 64.83 – 72.53 per cent of the total tree net production; the contribution was maximum on 33 years old teak plantation site (72.53 %) and minimum on 19 years old teak plantation site (64.84 %). Among the perennial aerial parts branches and boles contributed between 7.99 & 9.99 % and 16.25 & 21.24 %, respectively. Highest contribution of bole and branches was calculated in 19 years old teak plantation (31.23 %) followed by 33 years old teak plantation (24.24 %).

Contribution of total root production (coarse + fine roots) on these sites was substantial and ranged between 3.47 – 5.35 t ha^{-1} yr^{-1}. Contribution of fine roots to total dry matter production was averaged 8.9 % (Table-4.27).

Analysis of variance indicated that the variation in aboveground and belowground tree production was statistically significant ($p<0.05$) and total tree productivity was also found statistically significant ($p<0.01$). (Appendix- XXX, XXXI and XXXII)

4.8.2.1 Net primary production in 19 years old teak plantation

Aboveground net primary production

In 19 years old teak plantation site the aboveground tree production was 21.32 t ha^{-1} yr^{-1}. The foliage production (14.66 t ha^{-1} yr^{-1}) contributed 64.83 % of the total tree net production. The bole (4.53 t ha^{-1} yr^{-1}) and branches (2.13 t ha^{-1} yr^{-1}) contributed 21.24 % and 9.99 % of the total tree net production, respectively. The net production of wood and miscellaneous litter was 2.92 t ha^{-1} yr^{-1} (Table-4.27).

Belowground net production (BNP)

In 19 years old teak plantation site the belowground net production was 5.35 t ha^{-1} yr^{-1}. The coarse root production (1.29 t ha^{-1} yr^{-1}) contributed 24.11 % of the belowground net production.

The net production of stand fine roots was 4.06 t ha^{-1} yr^{-1}. Contribution of fine roots to the belowground net production was 75.89 %. The contribution of fine roots to the total dry matter production was 13.72 %.

Total net primary production

The total net production is the sum total of the values for tree layer, fine roots, wood and miscellaneous litter. The total net production on 19 years old teak plantation was estimated 29.59 t ha^{-1} yr^{-1}. The contributions of aboveground net production, belowground net production and net production of wood and miscellaneous litter to the total net primary production were 72.05 %, 18.08 % and 9.86 %, respectively.

4.8.2.2 Net primary production on 23 years old teak plantation Aboveground net primary production

In 23 years old teak plantation site the aboveground tree production was 28.85 t ha^{-1} yr^{-1}. The foliage (21.03 t ha^{-1} yr^{-1}) contributed 69.38 % of the total tree net production. The bole and branches respectively, contributed 18.26 % and 8.83 % of

Table 4.27: Net production (t ha^{-1} $year^{-1}$ $\pm$ 1 SE) in Trees, stand fine roots, wood and miscellaneous litter in an age series of teak plantations.

Components	Age series of teak plantation		
	19 years old teak plantation	**23 years old teak plantation**	**33 years old teak plantation**
Trees			
Foliage	14.66±0.12	21.03±0.12	23.11±0.10
Branches	2.13±0.42	2.55±0.35	2.44±0.46
Bole	4.53±0.58	5.27±0.47	4.96±0.62
Coarse root	1.29±0.29	1.46±0.23	1.35±0.31
Total	**22.61**	**30.31**	**31.86**
Wood and miscellaneous litter	2.92±0.34	3.03±0.38	3.16±0.33
Stand fine root	4.06±0.21	2.87±0.21	2.12±0.17
Total vegetation	**29.59**	**36.21**	**37.14**

the total tree net production. The net production of wood and miscellaneous litter was 3.03 t ha^{-1} yr^{-1} (Table-4.27).

Belowground net production (BNP)

In 23 years old teak plantation site the belowground net production was 4.33 t ha^{-1} yr^{-1}. The coarse root production contributed 33.73 % of the belowground net production.

The net production of stand fine roots was 2.87 t ha^{-1} yr^{-1}. Contribution of fine roots to the belowground net production was 66.27 %. The contribution of fine roots to the total dry matter production was 7.92%.

Total net primary production

The total net production at 23 years old teak plantation was 36.21 t ha^{-1} yr^{-1}. The contributions of aboveground net production, belowground net production and net production of wood and miscellaneous litter to the total net primary production were 79.67 %, 11.95 % and 8.36 %, respectively.

4.8.2.3 Net primary production on 33 years old teak plantation

Aboveground net primary production

In 33 years old teak plantation site the aboveground tree production was 30.51 t ha^{-1} yr^{-1}. The contribution of foliage production to the total tree net production was 72.53 %. The bole and branches respectively contributed 16.25 % and 7.99 % of the total tree net production. The net production of wood and miscellaneous litter was 3.16 t ha^{-1} yr^{-1} (Table-4.27).

Belowground net production (BNP)

In 33 years old teak plantation site the belowground net production was 3.47 t ha^{-1} yr^{-1}. The coarse root production (1.35 t ha^{-1} yr^{-1}) contributed 38.93 % of the belowground net production.

The net production of stand fine roots was 2.12 t ha^{-1} yr^{-1}. Contribution of fine roots to the belowground net production was 61.07 %. The contribution of fine roots to the total dry matter production was estimated 5.70 %.

Total net primary production

The total net production at 33 years old teak plantation was 37.14 t ha^{-1} yr^{-1}. The contributions of aboveground net production, belowground net production and net production of wood and miscellaneous litter to the total net primary production were 82.14 %, 9.34 % and 8.50 %, respectively.

4.9 Quantification and variation in carbon sequestration in an age series of teak plantation

4.9.1 Carbon sequestration:

The carbon sequestration was determined by multiplying net primary productivity (Table-4.27) and carbon concentration of respective tree parts (Table-4.17). The total aboveground sequestration of carbon on each site ranged between 9.78 – 14.06 t ha^{-1} yr^{-1} (Table-4.28). Sequestration of carbon by foliage was 66.79 – 74.14 per cent of the total carbon sequestered by trees; the contribution was maximum on 33 years old teak plantation site (14.14 %) and minimum on 19 years old teak plantation site (66.79 %). Among the perennial aerial parts branches and boles contributed between 7.70 – 9.91 % and 14.85 – 19.23 %, respectively to the total carbon sequestration by trees. Highest contribution of bole and branches to the carbon sequestration was on 19 years old teak plantation (29.14 %) followed by 23 years old teak plantation (25.44 %).

Contribution of roots (coarse + fine roots) to the total carbon sequestration on these sites was ranged between 1.24 – 1.91 t ha^{-1} yr^{-1}. Mean contribution of fine roots to total carbon sequestration on the site was 7.32 % (Table-4.28).

Table-4.28: Carbon sequestration (t ha^{-1} $year^{-1}$ $\pm$ 1 SE) by trees, stand fine roots, wood and miscellaneous litter in an age series of teak plantations.

	Age series of teak plantation		
Components	**19 years old teak plantation**	**23 years old teak plantation**	**33 years old teak plantation**
Trees			
Foliage	6.84±0.66	9.81±0.56	10.78±0.54
Branches	0.97±0.29	1.17±0.24	1.12±0.31
Bole	1.97±0.39	2.29±0.31	2.16±0.41
Coarse root	0.46±0.18	0.52±0.14	0.48±0.19
Total	**10.24**	**13.79**	**14.54**
Wood and miscellaneous litter	1.33±0.72	1.38±0.67	1.44±0.66
Stand fine root	1.45±0.13	1.02±0.13	0.76±0.10
Total carbon sequestration	**13.02**	**16.19**	**16.74**

Analysis of variance indicated that the variation in aboveground and belowground carbon sequestration was statistically significant ($P<0.05$) and total carbon sequestration was also found statistically significant ($p<0.01$). (Appendix-XXXIII, XXXIV and XXXV)

4.9.1.1 Carbon sequestration on 19 years old teak plantation:

Aboveground carbon sequestration

In the 19 years old teak plantation site, the total aboveground carbon sequestration by trees was 9.78 t ha^{-1} yr^{-1}. The foliage contributed 66.79 % of the total carbon sequestered by trees. The bole and branches respectively contributed 19.23 % and 9.91 % of the total carbon sequestration by trees. The carbon sequestration by the wood and miscellaneous litter was 1.33 t ha^{-1} yr^{-1} (Table-4.28).

Belowground carbon sequestration

In 19 years old teak plantation site the total belowground carbon sequestration was 1.91 t ha^{-1} yr^{-1}. The carbon sequestration by coarse roots was 24.08 % of the total belowground carbon sequestration. Contribution of fine roots to the total belowground carbon sequestration was 75.92 %. The contribution of fine roots to the total carbon sequestration was 11.13 %.

Total carbon sequestration

The total carbon sequestration on the site is the sum total of the carbon sequestration values for tree, fine roots, wood and miscellaneous litter. The total carbon sequestration in 19 years old teak plantation was 13.02 t ha^{-1} yr^{-1}. The contributions of aboveground and belowground carbon sequestration by trees and that by wood and miscellaneous litter to the total carbon sequestration were 75.11 %, 14.66 % and 10.59 %, respectively.

4.9.1.2 Carbon sequestration on 23 years old teak plantation:

Aboveground carbon sequestration

On the 23 years old teak plantation site the total aboveground carbon sequestration by trees was 13.27 t ha^{-1} yr^{-1}. The foliage contributed 71.13 % of the total carbon sequestered by trees. The bole and branches respectively contributed 16.60 % and 8.84 % of the total carbon sequestration by trees. The carbon sequestration by the wood and miscellaneous litter was 1.38 t ha^{-1} yr^{-1} (Table-4.28).

Belowground carbon sequestration

In 23 years old teak plantation site the total belowground carbon sequestration was 1.54 t ha^{-1} yr^{-1}. The carbon sequestration by coarse roots (0.52 t ha^{-1} yr^{-1}) was 33.76 % of the total belowground carbon sequestration. Contribution of fine roots to the total belowground carbon sequestration was 66.24 % and to the total carbon sequestration on site was estimated 6.30 %.

Total carbon sequestration

The total carbon sequestration on 23 years old teak plantation site was 16.19 t ha^{-1} yr^{-1}. The contributions of aboveground and belowground carbon sequestration by trees and that by wood and miscellaneous litter to the total carbon sequestration were 81.96 %, 9.51 % and 8.52 %, respectively.

4.9.1.3 Carbon sequestration on 33 years old teak plantation:

Aboveground carbon sequestration

In 33 years old teak plantation site, the total aboveground carbon sequestration by trees was 14.06 t ha^{-1} yr^{-1}. The foliage (10.78 t ha^{-1} yr^{-1}) contributed 74.14 % of the total carbon sequestered by trees. The bole and branches respectively, contributed 14.85 % and 7.70 % of the total carbon sequestration by trees. The carbon sequestration by the wood and miscellaneous litter was 1.44 t ha^{-1} yr^{-1} (Table-4.28).

Belowground carbon sequestration

In 33 years old teak plantation site the total belowground carbon sequestration was 1.24 t ha^{-1} yr^{-1}. The carbon sequestration by coarse roots was 38.70 % of the total belowground carbon sequestration. Contribution of fine roots to the total belowground carbon sequestration was 61.30 % and to the total carbon sequestration was estimated 4.54 %.

Total carbon sequestration

The total carbon sequestration on 33 years old teak plantation site was 16.74 t ha^{-1} yr^{-1}. The contributions of aboveground and belowground carbon sequestration by trees and that by wood and miscellaneous litter to the total carbon sequestration were 83.89 %, 7.40 % and 8.60 %, respectively.

CHAPTER-V

DISCUSSION

CHAPTER-V

DISCUSSION

Forests are the natural storehouse of biomass and carbon (C). They sequester and store more C than any other terrestrial ecosystem and are important natural 'brake' on climate change (Gibbs *et al.*, 2007). Forest management practices can be used to reduce the accumulation of green house gases in the atmosphere through two different approaches. One is by actively increasing the amount or rate of accumulation of carbon in the area. The second is by preventing or reducing the rate of release of carbon already fixed. Plantations are a very efficient way of promoting biomass and carbon accumulation, and tend to be easier to manage than multi-species stands or natural forests (Evans, 1992).

Teak (*Tectona grandis*) is amongst the principal economic tree species commonly recommended for plantation programmes in dry tropical regions for timber production. The durability and workability of teak were recognized centuries ago, leading to its relatively widespread distribution and cultivation throughout the tropics. Today, teak ranks among the top five tropical hardwood species in terms of plantation area established worldwide.

Forest tree plantations have only had 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 major role in the future mitigation of climate change (Canadell *et al.*, 2007).

The estimates of carbon stock are also important for scientific and management issues such as forest productivity, nutrient cycling, and inventories of fuel wood and pulp. There is lac of qualitative and quantitave information on carbon sequestration in different soil and vegetation in teak plantations of Chhattisgarh region of India. Understanting of carbon dynamics in teak plantations is essential for sustainable management of carbon pools in aboveground and belowground compartments.

Therefore, the present study was carried out to quantify the biomass, carbon stock and carbon sequestration in vegetation and soil under an age series of teak plantation.

5.1 Physico-chemical properties of soil, soil carbon stock and microbial carbon biomass:

The chemical properties of soil across the age of plantation sites viz., 19 years old teak plantation, 23 years old teak plantation and 33 years old teak plantation is given in Table 4.23. Total nitrogen observed under soil in age series of teak plantation ranged from 0.09 to 0.14% for surface soil (0-10 cm) and 0.06 to 0.09% for lower soil layer (10-20 cm). Among the plantations, the 23 years old teak plantation contained maximum nitrogen content at both the soil depth as compare to the other plantations. Total carbon observed under soil in age series of teak plantation were 1.12 to 1.67% for surface soil (0-10 cm) and 0.74 to 1.25% for lower soil layer sample (10-20 cm). Among the plantations, the 23 years old teak plantation contained maximum carbon content at both the soil depth as compare to the other plantations. The concentration of available phosphorus (0-10 cm) under the 19 years old teak plantation and 33 years old teak plantation varied from 8.45 to 13.47 and in 10-20 cm soil layer it was varied from 11.61 to 15.26 kg ha^{-1}, respectively. The availability of phosphorus in 0-10 cm soil layer of 33 years old teak plantation was found to be higher as 13.47 kg ha^{-1} than the other plantations, where as in 10-20 cm layer, it was higher as 15.26 kg ha^{-1} in 23 years old teak plantation. It was recorded minimum in the 19 years old teak plantation. The result of available potassium for the soil (0-20 cm) were 313.9 to

329.6 kg ha^{-1}, 263.09 to 372.32 kg ha^{-1} and 255.74 to 288.56 kg ha^{-1} under 19 years old teak plantation, 23 years old teak plantation and 33 years old teak plantation, respectively. In all the study sites the potassium content was low in 33 years old teak plantation.

In general, most microbial activity occurs in the upper soil layers (0-20 cm) as soil at this depth is more nutritious and porous. Watanabe *et.al* (2009) also reported that in 14 years old plantation of teak, the total C and N, available P and exchangeable Ca at 0 to 20 cm soil depth were significantly higher than that of the 30-40 and 50-55 soil depth ($p < 0.05$). Burke (1989) suggested that nutrient accumulation is a dynamic ecosystem property and is influenced by slowly changing landscape pattern in semi-arid ecosystem; nutrient dynamics are closely linked to seasonal variation in temperature and moisture. Moreover, the higher values of mineral N, inorganic P and soil physical properties close to trees could be attributed to higher amount of organic matter inputs through litter fall, root mortality and herbaceous biomass**.** Singh *et al*. (2000) reported temporal variation in soil organic carbon, increased soil organic carbon which coincided with the periods of litter production. Subsequent to deforestation, decomposition rates of organic matter, both on the soil surface and within the top soil layers, are enhanced, rendering the system vulnerable to leakage of nutrients. Singh and Singh (2002) have reported the soil nutrients were significantly higher in the plantation area compared with the non-planted control plot. Soil pH, PO_4-P, Ca, Mg and K concentrations decreased with stand age whereas SOM, NH_4-N, NO_3-N, Cu, Zn and Mn increased, reverse trend was noticed in the present study. Kumar *et al.* (2010) have reported organic carbon between 2.23-2.81%, while concentration of nitrogen from 0.16-0.21% and that of phosphorus from 0.021-0.03 % in all three sites, which is compared with the present findings.

In the present study, the soil carbon stock in 0-20 cm soil layer was 23.76, 36.65 and 28.26 t ha^{-1} in 19 years, 23 years and 33 years old teak plantations. Tangsinmankong *et al.* (2007) studied the carbon stocks in soil of mixed deciduous forest and teak plantation. Results revealed that soil organic carbon from all sites decreased generally with the increasing depth from the surface soil to the lower layer soil. Similar observations were observed in the present study. Contrary to this they also showed the highest carbon stocks in soils of 6 years old teak plantation followed by the 24 and 15 years old teak plantations and mixed deciduous forest i.e., 157.03, 105.67, 78.78 and 70.96 t C ha^{-1} respectively. The dissimilarity of soil organic carbon may be due to forest fire, forest management and topography. Takahashi *et al.* (2009) studied the soil respiration in different ages of teak plantations in Thailand. They concluded that carbon dynamics in the soil under teak plantations were determined by the soil moisture regime, which is controlled by seasonal rainfall pattern and annual rainfall. Soil respiration in teak plantations had no clear difference between different stand ages. Chauhan *et al.* (2010) reported the soil organic carbon in natural forest as 2.2% and 1.5% in plantation forest whereas the available phosphorus was 10.7 kg ha^{-1} and 8.4 kg ha^{-1} for both natural and plantation forest. They reported the value of N as 209.2 kg ha^{-1} for natural forest and 170 kg ha^{-1} for plantation forest whereas the available K was 331 kg ha^{-1} for natural forest and 294.5 kg ha^{-1} for plantation forest. The values were found within the range for the present findings.

In the present study, the microbial biomass carbon in 0-10 cm soil layer was 228.01, 349.00 and 522.13 µ gm gm^{-1} of soil and in 10-20 cm soil layer it was 112.75, 202.18 and 318.03 µ gm gm^{-1} of soil in 19 years, 23 years and 33 years old teak plantations. These values are comparable with those (623 and 195µg gm^{-1} in 0-10 and 10-20 cm soil layer) for tropical forest as reported by Tripathi and Singh (2012). The microbial carbon biomass follows the same trend as observed by Tripathi and Singh (2012). It decreases with soil depth and proportion of clay content of soil.

5.2 Species structure and diversity in an age series of teak plantation

The structural analysis of vegetation revealed the variation in densities and basal cover of different teak plantation sites in an age series. The tree density in plantation across the age series ranged from 1100 to 1450 trees ha^{-1} and basal area from 27.52 to 45.84 m^2 ha^{-1}**.** The density of saplings and seedlings in plantation in the age series was ranged from 1000 to 2750 trees ha^{-1} and from 8500 to 13250 seedlings $ha^{-}1$, respectively. The basal area of saplings in plantations ranged from 0.26 to 0.37 m^2 ha^{-1} which resembles with the Singh *et al.* (2004) which reported that the density and basal area of the three Cottonwood clones (*Populus deltoides*) varied from 400 to 540 trees ha^{-1} and 6.8 to 24.1 m^2 ha^{-1}, respectively. In the present study higher density could be due to the restricted felling or thinning in the wildlife sanctuary area. The finding are also compare with Tyagi *et al.* (2009), where the tree density was 1800 trees ha^{-1} for 3 year, 1967 trees ha^{-1} for 6 year and 1600 trees ha^{-1} for 9 year old *Dalbergia sissoo* plantations (Table 5.1).

Thapa *et al.* (2011) reported 864 trees ha^{-1} density for teak plantation and 1110 trees ha^{-1} for sal plantation whereas the sapling density was 1432 trees ha^{-1} and 2880 trees ha^{-1} for teak and sal plantation and seedling density was 12800 seedlings ha^{-1} and 14450 seedlings ha^{-1} for teak and sal plantation, respectively which is in the range of the present study. They have also measured the basal area of teak and sal plantation as 38.32 m^2 ha^{-1} for teak plantation and 93.74 m^2 ha^{-1} for sal plantation, respectively.

According to Cordero and Kanninen (2003) the density of teak plantation varied form 156 trees ha^{-1} to 1600 trees ha^{-1} for 5 to 46 years old teak plantation while

Table 5.1: Certain vegetational properties of tropical forest and plantation

Forest/plantation Ecosystems	**Density (stems ha^{-1})**	**Basal cover (m^2 ha^{-1})**	**Number of species (ha^{-1})**	**Source**
Sub-tropical	400-540	6.8 to 24.1	-	Singh *et al.* (2004)
Teak forest	262-395	-	21	Dhanmanonda and sahunalu (1992)
Pure Sal forest	386-785	12.7-33.2	-	Sharma *et al* (1990)
Sariska Tiger Reserve	1352	131.9	-	Rodgers (1990)
Sal dominated closed forest	1220-1290	25.4-44.65	15-22*	Singh *et al*. (2003)
Sal dominated open forest	390-930	20.05-45.89	11-16*	Singh *et al*. (2003)
Dry Dipterocarp forest	554-789	-	35-37	Visaratana*et al*. (1986)
Mixed deciduous forest	253	-	14	Sahunalu *et al*. (1979), Kiratiprayoon *et al*. (1995)
Seasonally dry tropical forest	484	26.3	-	Sahu *et al.* (2008)
Dry tropical forest	1600-1967	-	-	Tyagi *et al.* (2009)
Dry tropical forest	156-1600			Cordero and Kanninen (2003)
Tropical forest	383-1079	-	-	Derwisch *et al*. (2009)
Tropical forest	566-723	-	-	Kraenzel *et al*. (2003)
Tropical moist deciduous	448-1217	21.43-34.05	31-59	Bhat *et al.* (2000)
Tropical moist deciduous	82-468	6.8-62.2	-	Upadhyay *et al.* (2008)
Tropical dry deciduous	458-728	5.96-19.31	-	Kumar *et al.* (2010)
Tropical dry deciduous	883	18.09	-	Krishnamurthy *et al.* (2010)
Teak plantation in tropical dry deciduous forest	1100-1450	27.52-45.84	4-11	Present study

*Represents the number of species in 0.1 ha.

in the present study shows the reverse trend in total density in respect to the age series plantation. In contrary to the present findings the reverse trend was also recorded by the Derwisch *et al*. (2009) which reported the higher density in the young plantation and it reduces as the plantation becomes mature or with the increase in the age of the plantation.

Density of teak plantation in Panama between 566 and 723 trees ha^{-1} (Kraenzel *et al*., 2003) which are 43.96% less to the lower limit and 47.61% less to the upper limit of the present estimates. Pande (2005) reported the density of teak forest in disturbed area of Satpura plateau and stated that the density was 690 trees ha^{-1} in site I, 950 trees ha^{-1} in site II, 1630 trees ha^{-1} in site III and 2500 trees ha^{-1} in site IV, respectively.

However, the tree density values were higher than the density (484 stems ha^{-1}) reported for Sal dominated forest of eastern Himalaya (Shankar, 2001); 82 to 468 stems ha^{-1} reported for moist deciduous forest (Upadhyay *et al.* 2008). The density in present study was higher than the range of 554 to 789 stems ha^{-1} reported for dry Dipterocarp forest (Visaratana *et al.*, 1986); of 458-728 stems ha^{-1} reported in tropics (Sundarapandian and Swamy, 2000) and of 575-855 stems ha^{-1} for Kalakad, Western Ghats (Parthasarthy, 1999). Compared to the present study the density of forest in Thailand, of mixed deciduous forest was 253 stems ha^{-1} (Sahunalu *et al.*, 1979) and of tropical rain forest was 818 to 1540 stems ha^{-1} (Kiratiprayoon, 1986). Tree density in the Vindhyan region ranges between 294 and 627 stems ha^{-1} for several dry tropical forest communities (Singh and Singh, 1991; Jha and Singh, 1990).

Khurana and Saxena (2009) have also reported the sapling and seedling density between 240 and 700 stems ha^{-1} and 535-695 stems ha^{-1}, respectively which were lower than present study.

Pande (2005) studied the ecological status of vegetation in Satpura plateau, M.P. Total density for tree layer ranged between 46.93-387.5 stems ha^{-1}, 114 to 714.95 stems ha^{-1} for shrubs and 15905 to 102078 stems ha^{-1} for herbs layer. Bhuyan *et al.* (2003) investigated that the stand density was highest in undisturbed stand, intermediate in the moderately disturbed stand and lowest in the highly disturbed stand. Singh *et al.* (2005) investigated that pure sal forest was characterized by high tree (1233 stems ha^{-1}) and under storey vegetation densities (1575 stems ha^{-1}). The degraded deciduous forest sites represent the degraded stage with low density of tree (633 stems ha^{-1}) and under storey plants (density 918 stems ha^{-1}).

Negi and Nautiyal (2005) reported that the tree densities ranged from 1010-1230 stems ha^{-l} in different compartment. Density of sapling ranges between 690-770 stems ha^{-1}. Sahoo *et al.* (2008) studied the phyto-sociological analysis of *Pinus kesiya* stands exposed to varying intensities of disturbance in north east India and suggested that the disturbance can lead to the formation of mixed forest and the mildly disturbed sites are the best for regeneration and more assemblage of plant species there by providing scope for proper silvicultural and management implications in the undisturbed forest stands to provide the growth of seedlings and saplings of the dominant species. Rastogi and Rastogi (2007) showed that density per ha of herbs, shrubs and trees varied between 1, 68,000-4, 97,800, 1, 8,800-42,112, 1,100-2,975, respectively. Various study also revealed the higher level of disturbance, altered structure, diversity, composition and other characteristics. Vegetation showed a trend of change from its original community structure (Chettri *et al.* 2006; Biswas 2007; Anitha *et al.* 2007).

The tree basal area values are within the range and comparable to the other tropical forest ecosystems (Yadav and Singh, 2010; Kumar *et al.*, 2010;

Krishnamurthy *et al.*, 2010; Swamy *et al.*, 2010; Baishya *et al.*, 2009; Pande, 2005; Shankar, 2001; Ravan, 1994; Verghese and Menon, 1998). Singh and Singh (1991) have reported the tree basal area between 9 and 14.79 $m^2\ ha^{-1}$ for dry tropical forests of Vindhyan region, India. Murphy and Lugo (1986) have estimated 17 to 40 $m^2\ ha^{-1}$ basal area in Puerto Rican sub tropical dry forests. Pande (1999) studied the vegetation of sal forest of Doon valley in relation to the magnitude of disturbance, their resource apportionment and the regeneration of Sal. The whole area was divided into five sites as per their disturbance magnitude. Total basal area (cm^2 /100 m^2) ranged between 2324-3775 for trees, 74-354 for shrubs and 1.28-30 for herbs. Negi and Nautiyal (2005) have estimated that total basal covers of tree species between 49.39 $m^2\ ha^{-1}$ and 64.74 $m^2\ ha^{-1}$ across the compartment. Rastogi and Rastogi (2007) reported the total basal cover ($m^2\ ha^{-1}$) of shrubs and trees ranged between 0.138-0.952 and 2.333-86.295, respectively. Barbhuiya *et al.* (2012) measured the basal area as 5.02 $m^2\ ha^{-1}$ for highly disturbed, 20.83 $m^2\ ha^{-1}$ for moderately disturbed and 85.55 $m^2\ ha^{-1}$ for undisturbed stands whereas for shrubs basal area it was 0.37 $m^2\ ha^{-1}$ for highly disturbed, 0.60 $m^2\ ha^{-1}$ for moderately disturbed and 2.61 $m^2\ ha^{-1}$ for undisturbed stand of tropical wet evergreen forest, north east India. These findings were within the range or nearer to present study.

The teak plantations are not considered species rich but have a diversity of life forms. Shannon index values in the present study in an age series of teak plantation ranged from 0.34-1.23 for tree, 1.87-2.4 for sapling, 1.54-2.95 for seedling, Concentration of dominance ranged from 0.68-0.91 for tree, 0.20-0.29 for sapling, 0.16-0.43 for seedling, Species richness ranged from 0.43-1.37 for tree, 0.38-0.64 for sapling, 0.33-1.05 for seedling. Equitability ranged from 0.24-0.51 for tree, 1.35-1.44

for sapling, 1.11-1.28 for seedling. Beta diversity ranged from 1.18-3.25 for tree, 1-1.50 for sapling and 1.45-4.0 for seedlings.

The diversity values in present study are comparatively lower than those reported in different tropical forests. Yadav and Singh (2010) studied the four site having dense, medium, regenerated and degraded forest in the Achankmar-Amarkantak Biosphere reserve and diversities in these forests were 1.46 to 2.24 (Shannon index), 0.61 to 0.83 (equitability), 2.95 to 6.06 (species richness), 0.41 to 0.53 (concentration of dominance) and 4.05 to 12.8 (Beta diversity). In mixed deciduous forests of Vindhyan region the Shannon and Weiner index and concentration of dominance ranged between 1.93 to 2.18 and 0.18 to 0.38, respectively and beta diversity were 3.1 (Singh and Singh, 1991). Bhadra *et al.* (2010) reported the Shannon Wiener (H') diversity index as 1.35 and Simpson value as 0.921. Swamy *et al.* (2010) reported the Shannon and Simpsons indices between 1.5 & 3.7 and 0.1 & 0.16, respectively and beta diversity was 2.01. Kumar *et al.* (2010) reported Shannon-Weiner Index between 0.67 and 0.79, concentration of dominance between 0.08 and 0.16, the species richness ranged between 21.41and 23.71, equitability index between 0.02 and 0.05 and beta diversity between 2.02 and 4.87. Sahu *et al.* (2008) showed the levels of human disturbance are associated with higher species diversity.

Contrary to the present results, Pitchaitamu *et al.* (2008) have stated that tree species richness varied along the disturbance of different stands. The undisturbed stand showed the highest species richness. Species diversity was lowest in the disturbed stand. Similarly, Bhuyan *et al.* (2003) measured highest species richness under disturbed site. Ranghubanshi and Tripathi (2009) have studied the effect of disturbances on floral diversity in dry tropical forests of Vindhyan highland and concluded that the species rich communities of dry tropical forests are not only being reduced in area but they are also becoming species poor and less diverse due to rapid deforestation and the community organization is also changing in response to increased anthropogenic disturbance. Khurana and Kalpana (2008) have concluded that high value of biodiversity in an area is an indicator of high level of biological disturbances.

Rastogi and Rastogi (2007) found diversity index between 0.918-0.967 for herbs, 0.743-0.876 for shrubs and 0.859 for trees. Similarity index were between 33-80% in herb layer, 22-48% in shrub layer. Negi and Nautiyal (2005) have found the value of diversity from 2.156 to 2.323, 2.53 to 2.67, 2.39 to 3.20 and 3.32 to 3.94 for trees saplings, seedlings and shrubs, respectively. The value of beta diversity was 1.42, 1.32, 1.16 and 1.30 for trees, saplings, seedlings and shrub layer, respectively. The maximum diversity of trees was 12 (species richness) and minimum up to 1 for trees, 9-14 for shrubs, 20-23 for herbs. Concentration of dominance (cd) shows reverse trend to diversity and it was 0.1201 for trees 0.13-0.15 for shrubs and 0.1 to 0.13 for herbs. Diversity index varies from 0 to 2.25 for trees, 1.53 to 2.31 for shrubs and 2.41 to 2.69 for herbs. Beta diversity between 2 sites of forests were 4 and 11 for trees, 1.25 and 3.67 for shrubs, 3.8 and 1.2 for herbs (Pande *et al.*, 2002). Pande (1999) observed the range of diversity index (Shannon Wiener index) as 0.89-2.31 for trees, 0.87-1.99 for shrubs and 0.64-2.34 for herbs. Diversity index was invariably higher for herbs followed by shrubs and trees. The tree diversity was higher for least disturbed sites (2.31) whereas, shrubs and herb density followed reverse trend.

The three life stages (seedlings, saplings and trees) for different species suggested their possible future status in the forest. The diameter distribution of trees has often been used to represent the population structure of forests (Saxena and Singh, 1984). In all the three teak plantation site (19 years, 23 years and 33 years of age) across the age series studied girth class showed individuals with small girth class A (<10 cm) were high. A greater population of individuals in lower size classes compared to larger classes as the structure represents frequent reproduction (Knight, 1975; West *et al.*, 1981). In the seedling layer, *Diospyros melanoxylon* was the dominant species among all the three teak plantation sites. This species was unable to reach as a dominant species in the sapling and the tree layer. This is because the human put the fire to burn the ground litter and to keep away the wild animals for good sprouts of grasses for their domestic animals. Due to this heavy stress, the species could not reach in the tree or sapling layer as a dominant species. According to West *et al.* (1981) such types of patterns indicate the heavy exploitation of older individuals and greater mortality among young individuals.

5.3 Pattern of biomass pattern in an age series of teak plantation

Carbon fixation through forestry is a function of the amount of biomass in a given area. Therefore, any activity or management practice that changes the amount of biomass in an area has an effect on its capacity to store or sequester carbon. In the last few years, there has been increasing interest in the quantification of the biomass of forest ecosystems and its potential C fixation (Usuga *et al.*, 2010). The aboveground biomass is a key variable in the annual and long term changes in the global terrestrial carbon cycle and other earth system interactions. It is also important in the modelling of carbon uptake and redistribution within ecosystems. Of most interest is live wood biomass, which is involved in the regulation of atmospheric carbon concentrations. Thus, its dynamics must be understood if annual spatial variations are to be related to spatial weather and climate variables. Other computations, which require an accurate estimate of biomass along with carbon emission and carbon sequestration rates, are defining the carbon status and flux in a

Table 5.2: Comparative account of stand biomass (t ha^{-1}) of certain tropical forests and plantations of the world

Forest type	Location	Stand biomass			Source
		Aboveground	Belowground	Total	
Tropical lower montane Rain	New Guinea	310	39	349	Edward and Grabb (1977)
Tropical wet	Cambodia	322	60	382	Hozum *et al.* (1969)
Tropical wet evergreen	India	-	-	440-588	Swamy *et al.* (2010)
Tropical Rain	Ghana	233	54	287	Greenland and Kowal (1960)
	Wisconsin, USA	1-358	-	-	Zheng*et al*. (2004)
	Thailand	167	-	-	Clark *et al*.(2001)
Tropical montane wet	Venezuela	347	73	420	Brun (1976)
Tropical Moist	Brazil Amazonia	377	104	481	Klinge and Herrera (1978)
	Ivory Coast	151.5	29	180.5	Clark *et al*. (2001)
	Calakmul, Campeche	116.37	-	-	Navar (2011)
	La Pila, S.L.P.	173.25	-	-	Navar (2011)
	Chuchupe, S.L.P.	167.43	-	-	Navar (2011)
	Chamela, Jalisco	136.42	-	-	Read & Lawrence (2008)
Tropical Plantations	Puerto Rica	-	-	0.4-506	Lugo *et al.* (1988)
Tropical premontane Moist	Papua-New Guinea	286	46	332	Enright (1979)
	Zaire	320	51	371	Freson *et al.* (1974)
	Ivory Coast	431	24	455	Huttel and Bernhard-Reversat (1975)
Sub-tropical lower montane wet	Jamaica	279	65	344	Tanner (1980)
Sub-tropical wet	Eleverde Puerto Rico	237	116	353	Crow (1980)
	Global pattern	228	89	317	Jordan (1971a)
Sub-tropical Moist	India	67.4-134.3	-	83.6-170	Lodhiyal *et al*.(1995)
	India	26.68-109.86	14.75-38.06	41.43-132.26	Sharma *et al*.(2002)
Sub-tropical Dry	India	28	12	40	Vyas *et al*. (1977)
	Puerto Rico Guanica	53	45	98	Murphy and Lugo (1986a)
Tropical Dry	Global pattern	3-273	10-45	78-320	Murphy and Lugo (1986b)
	India	67.4	-	-	Haripriya (2000)
	India	71.94-162.91	13.97-30.02	85.78-192.93	Singh *et al*. (2009)
	India	28.12-85.26	9.01-15.62	37.12-100.88	Pande (2005)
	India	83-87	13-17	183.7-298.3	Kumar *et al*. (2011)
	Puerto Rica	84.8	-	-	Clark *et al*. (2001)
	Nigeria	49.22-141.29			Mbaekwe and Mackenzie (2008)
	Chamela, Jalisco	47.74			Jaramillo *et al*. (2003)
	Mexico	126	17.1	143.1	Jaramillo *et al*. (2003)
	West Africa	29.88	-	-	Thenkabail *et al*.(2004)
	Baja California Sur	40.06	-	-	Navar (2011)
	Vado Hondo, Sinaloa	47.81	-	-	Navar (2011)
	Tiniaquis, Sinaloa	58.15	-	-	Navar (2011)
	Morelos	14.13	-	-	Navar (2011)
Teak plantation in Tropical Dry	India	99.08-197.87	20.29-37.26	119.37-235.14	Present study

given geopolitical unit for the assessment, for example carbon taxes and similar international CO_2 mitigation measures.

According to Swank and Schreuder (1974), the quantity of tree biomass per unit area constitutes the primary inventory data needed to understand the flow of nutrients and water through forest ecosystem. Tadaki (1977) has argued that foliage is a key part of the tree playing a most important role in primary production. The foliage biomass studies in Japanese forests are reviewed by Tadaki (1963 and 1966), Kira and Shidei (1967), Tadaki and Hatiya (1968) and Satoo (1970 and 1971). Information on belowground biomass is rather fragmentary, because of the numerous problems associated with root excavation, root losses during excavation, uncertainties in identification of roots of a given species and difficulties in distinguishing between woody and herbaceous parts and between live and dead parts (Bray, 1963 and Baskerville, 1966).

In the present study the total aboveground biomass was 104.27 t ha^{-1} for 19 years old teak plantation, 163.91 t ha^{-1} for 23 years old teak plantation and 196.32 t ha^{-1} for 33 years old teak plantation. Belowground biomass ranged from 21.49 to 37.78 t ha^{-1} across the different age series. These estimates are comparable with the estimates made by many workers (Table 5.2 and 5.3).

Table 5.2 includes a cross section of total biomass values for certain tropical forests. Total biomass ranged from 78-320 t ha^{-1} for variety of dry forests and 269-1186 t ha^{-1} for wet tropical forests (Murphy and Lugo 1986b).Total biomass in sal forest was 710 t ha^{-1} (Singh and Singh 1989). Proctor *et al.* (1983) and Rai and Proctor (1986) have reported 210-650 t ha^{-1} and 434-669 t ha^{-1} total biomass for tropical rain forests at Sarawak and Karnataka, India respectively.

Cordero and Kanninen (2003) estimated the aboveground biomass for 16 teak plantations from 10 different sites in Costa Rica and reported that per ha^{-1} aboveground biomass tended to increase with increasing age class (young, intermediate and mature). Foliage dry biomass varied between 3 and 9 t ha^{-1}, branch biomass between 11 and 54 t ha^{-1}, stem biomass between 70 and 221 t ha^{-1} and total aboveground biomass between 84 and 284 t ha^{-1} for the age series of 8 to 47 years teak plantations. Mbaekwe and Mackenzie (2008) have reported the findings for tropical forest of Nigeria and stated that the total aboveground biomass were 43.33 t ha^{-1} for 5 years old teak plantation, 114.44 t ha^{-1} for 8 years old teak plantation, 114.00 t ha^{-1} for 11 years old teak plantation and 134.27 t ha^{-1} for 14 years old teak plantation. The total bole biomass of present study (63.48-115.05 t ha^{-1}) was also comparable with Mbaekwe and Mackenzie (2008).

Kandya (1974) reported 63% of the biomass storage in the stem, 31.9% in the branches and the remaining in the foliage in a 20 years old teak growing in Sagar. Total aboveground biomass currently found for teak plantations in the present study is similar to that reported by Negi *et al.* (1990) in Tripura (138 t ha^{-1} at 20 years), but lower than the values found by Ola-Adams (1993) in South-Western Nigerian (378 t ha^{-1} at 18 years) plantation. Kumar *et al.* (2011) also reported the tree biomass in three different aged *Butea* forest ecosystems in Western India, of different age group (5, 10 and 15 years old) and stated that the biomass of trees increased with age from 183.7 to 298.3 t ha^{-1}. The all values of biomass of trees were low in 5 years old, moderate in 10 years old and high in 15 years old forest stands. The total forest biomass increased from 190.7 t ha^{-1} in the 5 years old to 306.3 t ha^{-1} 15 years old forest. A similar trend was also found in present study.

Lodhiyal *et al.* (1995) observed the increasing trend in biomass of poplar plantation with increasing age. The total biomass increased from 84.0 t ha^{-1} in the 5

Table 5.3: Comparative account of distribution of aboveground biomass (t ha^{-1}) in different tree components in certain forests.

Forests	Location	Above ground biomass	Percentage distribution			Source
			Bole	Branch	Foliage	
Dry sal	India	70.2	44	51	5	Singh (1979)
Moist sal	India	561	77	20	3	Singh and Singh (1989)
Tropical wet	Global pattern	216-1173	98.8*		1	Murphy and Lugo (1986b)
Tropical dry	Global pattern	30-273	97*		3	Murphy and Lugo (1986a)
Tropical dry deciduous	India	77	42	51	7	Singh and Mishra (1979)
Tropical dry	India	21.63	43-46	49-53	4-7	Singh and Singh (1991)
Central Himalayan pine	India	113-283	76	19	5	Chaturvedi and Singh (1987)
Central Himalayan oak	India	302	51	44	5	Rawat and Singh (1988)
Tropical evergreen forest	India	307				Ramchandran *et al.* (2007)
Tropical semi-evergreen	India	324				Baisya *et al.* (2009)
Moist evergreen forest	Thailand	439.98	83.13	15.67	1.2	Glumphabuter and Kaitpraneet (2007)
Dry evergreen forest	Thailand	340.56	83.1	15.7	1.2	Glumphabuter and Kaitpraneet (2007)
Tropical rain forest	Thailand	275				Terakunpisut *et al* (2007)
Sal dominated forest	Nepal	337-698				Shrestha *et al.* (2000)
Teak plantation tropical dry deciduous	India	104.28-196.32	58.6-60.88	25.81-29.37	12.02-13.30	Present study

***stems and branches are combined**

years old to 170.0 t ha^{-1} in the 8 years old plantation. The biomass accumulations for different tree components were also increased with the age of plantation increase. This result also supports the findings made by Singh *et al.* (2009) where they measured the total biomass for different forest sites, which was 192.933 Mg ha^{-1} in natural forest followed by 95.64 Mg ha^{-1} in 32 years old converted forest, 85.78 Mg ha^{-1} in 23 years old converted forest and 92.05 Mg ha^{-1} in 15 years old converted forest. The total above ground biomass in different forest plots ranged from 71.94 to 162.91 Mg ha^{-1} with highest in natural forest and lowest in 23 years old converted forest. The below ground biomass varied from 13.97 to 30.02 Mg ha^{-1} with the highest in natural forest and lowest in 23 years old converted forest.

Singh *et al.* (2004) studied biomass and productivity of an age series of three cottonwood clones (*Populus deltoides*) in central Himalayan, India. The three clones had one young (four years old), one middle age (six years old) and one mature (8 to 10 years) stand. Total tree biomass in investigated clones increased from young (32-42 t ha^{-1}) to mature stands (120-170 t ha^{-1}), the lowest and highest biomass being in IC and G-3 clones. Similar trends were also observed in present study. Biomass estimation studies were conducted in 3, 6 and 9 years old plantation of *Dalbergia sissoo* by Tyagi *et al.* (2009). Major portion of above ground biomass was contributed by bole and the remaining were shared by leaves, twigs, branches and bark. The contribution of leaves, bark and bole to the above ground biomass increased with the increase in age, biomass production was positively correlated with age.

In the present study the above ground biomass was ranged within 104.27 – 196.32 t ha^{-1}. The contribution of bole, branches and foliage to the total above ground biomass ranged between 58.60 - 60.88 %, 25.81 - 29.37 % and 13.30 - 12.02 %, respectively. It is observed that the contribution of bole and foliage to total above ground biomass decreases with increasing age, whereas contribution of branches increases with increasing age. The distribution of aboveground biomass in different tree components is compared in Table 5.3. The allocation of biomass in different components of sal, pine and oak forests was maximum in boles and minimum in foliage. However, in all the dry forests the branches contributed maximum to the total aboveground biomass. Similar trend was observed in present study. The average foliage biomass in the present study was within the range of 13.87 – 23.60 t $ha^{-1}$and the total biomass of branches and boles was within the range of 104.27 – 196.32 t ha^{-1} which is towards the lower end of range (209-1163 t ha^{-1}) for variety of tropical wet forests as reported by Murphy and Lugo (1986b).

Hall and Uhling (1991) estimated the biomass density of forests in South and South East Asia using the volume estimates and biomass expansion factors derived from Brown *et al.* (1989). Their biomass estimates for India ranged from 116 Mg ha^{-1} for undisturbed forest for 60-80 years and 35 Mg, 66 Mg and 84 Mg ha^{-1} for logged, unproductive and managed forests, respectively. However, the present estimates are comparable to 30 to 276 Mg ha^{-1} above ground biomass for variety of dry tropical forests of the world (Murphy and Lugo, 1986a).

Nascimento and Laurence (2002) quantified total above ground dry biomass (TAGB) within 201 ha plots in undisturbed site. TAGB values were very high averaging 397.7 ± 30.0 t ha^{-1}. The most important component of above ground biomass were large trees (< or > 10 cm dbh) which comprised 81.9% of TAGB followed by downed wood debris (7.0%), small trees, saplings and seedlings (< 10 cm dbh; 5.3%), lianas (2.1%), litter (1.9%), snags (1.5%) and stem less palms (0.3%). Among large trees above ground biomass was greatest in intermediate sized (20-50 cm DBH) stems (46.7% of TAGB), with very large < or > 60cm DBH) trees also containing substantial biomass (13.4% of TAGB). They also found that there were no significant correlations between large tree biomass and that of any other live or dead biomass components.

The average foliage biomass (19.42 t ha^{-1}) in the present study was higher than the range of 7 – 10 t ha^{-1} and the total biomass of branches and boles (90.40 – 172 t ha^{-1}) was towards the lower end of the range (209 – 1163 t ha^{-1}) reported for a variety of tropical wet forests (Murphy and Lugo, 1986a).

The contribution of coarse roots to total biomass in the present study was 17.09 %, 16.35 %, and 15.92 % for 19 years old, 23 years old and 33 years old teak plantations, respectively. These values are comparable with the range 8 – 50 % reported for the tropical dry forests (Murphy and Lugo, 1986b). The mean contribution of roots in 33 moist and wet tropical forests cited in Brown and Lugo (1982) was 16 %.

5.4 Forest floor biomass

Standing crop of litter (total forest floor material) acts as an input-output system of nutrients and the rates at which forest litter falls and subsequently decays, regulate energy flow, primary productivity and nutrient cycling in forest ecosystem (Sundarapandian and Swamy, 1999). Nutrient cycling rates in forests are usually inferred from a comparison of nutrient concentrations and amounts in litterfall, forest floor litter and crown drips (Proctor, 1987; Vitousek and Sanford, 1986). The quantity of forest floor material depends upon canopy closure, altitude and climate.

The seasonal mean forest floor biomass in age series of teak plantation sites across the forest circles varied from 7.78-9.93 t ha^{-1}, 8.84-10.5 t ha^{-1} and 9.85-12.4 t ha^{-1} for 19 years, 23 years and 33 years old teak plantation, respectively. Since the summer season followed peak litterfall period (winter) and the decomposition is most rapid during rainy season, the pattern of maximum forest floor mass during summer and minimum during rainy season is obvious. A seasonal variation in the standing crops of litter in tropical forests is related to the seasonality of litterfall inputs and the nature of the climate. When the climate is monsoonal, breakdown rates are depressed for considerable periods during the dry season (Swift *et al.*, 1981).

The relative contribution of forest floor categories to the total forest floor varied markedly in different months on all the sites (Table 5.4)**.** Except for the period of July-October, the contribution of fresh leaf litter category remained high in all months in all teak plantation sites. During July-October, the contribution of partially decayed litter remains greatest. On an average (across all seasons), the standing crop was maximum for fresh leaf litter, partially decayed litter on 33 years old teak plantation. However, the standing crop of wood litter was highest in 23 years old teak plantation site. (Table 5.4)**.**

The total quantity of forest floor material varied from season to season in all teak plantation sites. The minimum amount of forest floor mass on all sites occurred during rainy season and maximum during summer.

A cross section of standing crop values reported from certain tropical climatic zone are compared in Table 5.5. Madge (1965) has cited data indicating litter accumulation in the range of 1.7-14.7 t ha^{-1} within the tropical zone and of 3.6-39.9 t ha^{-1} in the temperate zone. Forest floor mass in the present study is in the lower part of the range (2.07-54.0 t ha^{-1}) reported for the tropics (Vogt *et al.*, 1986a). In general, standing crop of litter in the present study is comparable with several other studies in tropics and sub-tropics (Singh, 1995; Swamy *et al.*, 2010; Golley *et al.*, 1975; Yoda and Kira, 1969; Lugo *et al.*, 1978) but distinctly lower than those of tropical rain, tropical montane and tropical moist forests studied elsewhere. Few studies have

Table 5.4: Relative percentage of different forest floor components to the total forest floor biomass (% of total)

Components	Months											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
	19 years old teak plantation											
Fresh leaf litter	41.7	48.3	38.5	36.7	30.0	26.8	9.9	16.1	14.4	32.4	28.1	33.0
Partly decayed litter	30.5	42.3	48.0	49.5	64.4	49.9	64.6	61.8	61.4	35.5	39.8	40.2
Wood litter	27.7	9.4	13.5	13.8	5.5	23.3	25.5	22.1	24.2	32.1	32.1	26.7
	23 years old teak plantation											
Fresh leaf litter	35.5	38.9	34.6	40.2	26.2	34.1	9.2	23.6	14.5	41.0	24.5	28.1
Partly decayed litter	25.0	31.9	42.9	46.8	53.2	57.0	78.1	52.7	54.7	30.6	51.5	44.1
Wood litter	39.5	29.3	22.5	12.9	20.6	8.9	12.7	23.7	30.9	28.4	24.0	27.7
	33 years old teak plantation											
Fresh leaf litter	54.8	50.2	36.1	40.4	26.8	30.7	7.2	19.3	13.9	50.5	31.3	33.3
Partly decayed litter	25.5	36.5	53.0	49.8	62.5	54.5	67.0	60.9	55.6	20.4	50.2	40.2
Wood litter	19.7	13.3	11.0	9.9	10.7	14.9	25.8	19.7	30.6	29.1	18.4	26.5

Table 5.5: Litter layer accumulation in certain tropical forests of the world (t ha^{-1})

Forest vegetation	**Forest floor (t ha^{-1})**	**source**
Tropical forest	2.1-54.0	Vogt *et al* (1986)
	3.8-5.5	Sundrapandian and Swamy (2000)
Tropical rain forest	5.0	Jenny *et al.* (1949)
Tropical rain	2.5-10.5	Spain (1984)
Lowland rain forest	8.3-9.4	Odiwe and Muoghalu (2003)
Tropical premontane wet forest	4.8	Golley *et al.* (1975)
	16.5.0	Jenny *et al.* (1949)
Tropical dry evergreen	2.1-3.0	Visalakshi (1999)
	4.1-4.9	Pragasan and Parthasarathi (2005)
Tropical wet evergreen	11.7	Parthasarathi (1992)
	3.5-4.2	Swamy *et al.* (2010)
Tropical semi-evergreen	10.4	Parthasarathi (1992)
Tropical semi deciduous forest	5.0-8.0	Sanches *et al.* (2008)
Tropical montane wet	7.3	Brun (1976)
Tropical moist forest	3.4	Golley *et al.* (1975)
	4.3	Kira (1978)
	11.3	Klinge (1975)
	6.0	Klinge (1976)
	7.2	Klinge *et al.* (1975)
	5.4-7.2	Klinge and Herrera (1978)
Tropical dry forest	2.0	Madge (1965)
	3.6-4.0	Singh (1979)
Tropical dry forest	2.2-3.2	Singh (1979)
Sub-tropical moist forest	6.5	Drew *et al.* (1978)
	9.7	Dugger (1978)
	2.6-3.0	Yoda and Kira (1969)
Sub-tropical dry forest	3.4	Yoda and Kira (1969)
	3.8-8.7	Lugo *et al.* (1978)
Semi deciduous forest	5.5	Morellato (1992)
Teak plantation in tropical dry deciduous forest	7.78-12.42	Present study

reported seasonal variation in the standing crops of litter in tropical and sub-tropical forests. Hopkins (1966) reported yearly ranges of 50- 480 g m^{-2} and 180-550 g m^{-2}, respectively, from dry and moist Nigerian forests. Bernhard (1970) noted strong seasonal variation in Ivory Coast forests and recorded litter standing crops that ranged from less than 100 g to more than 350 g $m^{-2.}$

5. 5 Fine root studies:

Fine roots are the primary pathway for water and nutrient uptake by plants. Roots are the link between soil and plants. Seasonal periodism in root growth is common in woody plants and is reported for various tropical and temperate zones. Fine roots are physiologically the most active parts of the root system. Fine roots are chiefly responsible for water and nutrient uptake, usually in a symbiotic union with mycorrhizal fungi, and have a much shorter lifespan than coarser roots (Wells and Eissenstat, 2001). Although fine root biomass contributes relatively little to total tree biomass (usually < 5%), fine roots are major contributors to C litter inputs to the soil because of their rapid turnover (Norby and Jackson, 2000). Fine roots exert a significant influence on the soil profile development and when dead contribute substantially to the organic pool of the soil. Also the knowledge of fine root biomass is important for understanding energy flow and nutrient cycling. It was not until the 1970s that root studies were carried out in context of ecosystem functioning. Only in the last 2-3 decades have there been some attempts to understand roots as part of the entire forest system.

The roots near the soil surface undergo much rapid changes than the deep roots. Root productivity is one of the most difficult ecosystem parameters to measure and studies on root production have been partly hindered by the lack of simple and feasible techniques. Fine root production is regulated by the nutrient availability in forest litter accumulation. However, biomass alone is not indicative of the functional potential of the root system as an absorbing organ. Alterations in root system architecture may occur without a change in total root biomass (Hodge, 2004). Morphological plasticity of fine roots has been proposed as a mechanism by which plants respond to variation in soil nutrient supply (Hodge, 2004). A number of morphological root characteristics vary with soil nutrient availability and physical conditions. Mass-based specific root length (SRL) is often considered a measure of the ability of roots to proliferate in the soil and is thus related to their nutrient uptake (Persson and Ahlstrom, 2002). Root length density, root surface area, root tip and branching density are all considered to reflect stand absorptive potential (Eissenstat *et al.*, 2000; Craine, 2006). There are relatively few data on how root biomass and root morphology change in relation to forest stand age (Helmisaari and Hallbacken, 1999; Makkonen and Helmisaari, 2001; Claus and George, 2005), reflecting the difficulty of obtaining root biomass data and of comparing results obtained by different methods. A recent study showed that understory roots may contribute significantly to the forest soil C budget (Bakker *et al.*, 2006). Furthermore, there have been few attempts to quantify the contribution of fine roots of understory vegetation to total C litter inputs in forest soils.

At the whole-ecosystem scale it is well known that the proportion of total plant biomass that occurs below ground is strongly influenced by the availability of mineral nutrients. In fertile ecosystems, trees apportion relatively little of their total C resources to root production, but the opposite may occur within infertile ecosystems, presumably because more roots are needed to facilitate adequate nutrient uptake (Nadelhoffer, 2000). Alternatively, rapid fine-root turnover in fertile ecosystems may lead to higher root production even though fine-root biomass decreases with increasing fertility (Nadelhoffer, 2000; Burton *et al*., 2000). Soil nutrients have not only direct effects on root responses, but also indirect effects by influencing the distribution of plant species and the evolution of root responses within species. Furthermore, nutrient levels at broad scales may influence evolutionary responses of plants to fine-scale nutrient patterns. For example, it has been predicted that fast-growing species in high-fertility ecosystems will show high levels of morphological plasticity. However, recent evidence suggests that differences in root foraging between fast and slow growing species may be due simply to differences in relative growth rates among plant species rather than to evolutionary specialization (Aanderud *et al*., 2003).

Fine-root production and turnover are important regulators of the biogeochemical cycles of ecosystems and key components of their response to global change. Therefore, quantifying changes of soil carbon and fine root biomass could be an important consideration under large-scale afforestation or reforestation. The study was conducted with an objective of assessing the quantification and variation in the fine root biomass. The total mean biomass of the fine roots was 406.48 g m^{-2}, 287.83 g m^{-2} and 212.46 g m^{-2} for 19 years, 23 years and 33 years old teak plantation sites, respectively.

The fine root biomass decreases with age of the teak plantation. Fine roots are the important below ground components carrying out vital functions of water and nutrient absorption. The root mass of various tropical forest ecosystems are compared. Evidently root mass estimates varied greatly with respect to sampling depth and diameter class under consideration besides the forest types and their locations across the tropics. Fine root production also varies succinctly with site quality and species composition (Aerts *et al*., 1992; Fogel, 1983; Persson, 1982; Shaver and Billings, 1975). Our finding that fine root biomass was highest in the young stand for all root fractions agrees with the results of Makkonen and Helmisaari (2001), who found the largest fine root biomass in the pole stage stand of a Scots pine chronosequence. Higher root biomass in the young stand, which is in agreement with a similar finding described for young lodgepole pine, where the belowground biomass increased with tree density (Litton *et al.*, 2003). However, although individual older trees have finer root biomass than younger trees, because tree density decreases with the stand age, fine root biomass for the whole stand decreases with age. Also, Claus and George (2005) documented a clear effect of stand age on standing fine root biomass with highest values in young adult stands in forest chronosequences of European beech, Norway spruce and Turkey oak. Lodhiyal *et al.* (1995) observed the fine roots biomass as 1.2 t ha^{-1} for 5 years age plantation, 1.2 t ha^{-1} for 6 years age plantation, 1.1 t ha^{-1} for 7 years age plantations and 1.0 t ha^{-1} for 8 years age plantations, similar trend were also observed in present study which revealed that the fine root biomass was remain higher in young plantation than the mature ones. Fine root biomass in present study was found to be higher than the findings made by Kumar *et al.* (2011). Vanninen and Makela (1999) observed that the fine root biomass of pine stand differing in age was lower than the present findings in different age series of the plantations. Barbhuiya *et al. (*2012) estimated the fine root dynamics in undisturbed and disturbed stands of a tropical wet evergreen forest in India and stated that in the highly disturbed stand; more than 90% of the fine root biomass was recorded in the surface soil layer, whereas in the moderately disturbed and undisturbed stands the proportion averaged 67%. Root turnover also decreased with increasing soil depth, root size and intensity of stand disturbance. In the undisturbed, moderately disturbed and highly disturbed stands the annual fine-root turnover was 3181, 1701 and 822 kg ha^{-1} yr^{-1}, respectively. Yin *et al*. (1989) stated that forest removal would significantly influence fine root biomass production and mortality. Hence, both vegetation and physical environment are responsible for the control of fine root biomass (Persson, 1985). Moreover, the root system of different species may ramify the soil in different fashion, influenced by their requirement for microclimate, competitive ability apart from their genetic behaviour (Parthasarathy, 1988). Differences in fine root biomass estimates among studies may be a result of several factors, including local site conditions and sampling depth. For example, sampling to 20 cm depth instead of 40 cm depth can result in 15–25% differences in fine root biomass estimates (Cronan, 2003). In addition, the timing of sampling can bias the estimates by as much as 50–100% (Cronan, 2003). The study revealed that growth and accumulation of fine roots varied greatly with respect to species composition, tree density and basal area, season and soil characteristics.

5.6 Litterfall :

Litterfall is the major pathway for the return of organic matter and nutrients from aerial parts of the plant community to the soil surface, and fertility (Odiwe and Muoghalu, 2003). Climate is major determinant of litter production. The age of plantation also significantly affect the litter production. Litter production and decomposition rates have great importance in maintaining the fertility of the soil. A substantial portion of nutrients accumulated by plants is returned to the soil as litterfall followed by decomposition, i.e. the integrity of an ecosystem is maintained by these transfers of matter and nutrients (Rajendraprasad *et al.*, 2000). In tropical ecosystems, maintenance of soil organic pool is achieved by the high and rapid circulation of nutrients through the fall and decomposition of litter.

Being the teak plantation in the tropical climate 100 % leaf fall occurs each year. However, the leaf fall is fairly staggered in time encompassing about 8 months of the annual cycle, but 70-80 % leaves fall during the winter season, leaving little foliage to be shed in summer. The tendency of leaf fall to be concentrated during November to April months may be related to a combination of decreased temperature and soil water during this period.

The total annual litter fall production across the age series of teak plantation ranged between 14.94 to 22.57 t ha^{-1} yr^{-1}. The maximum litter fall production was noticed on 33 years old teak plantation site (22.57 t ha^{-1} yr^{-1}), followed by 23 years old teak plantation site (20.94 t ha^{-1} yr^{-1}) while minimum on 19 years old teak plantation site (14.94 t ha^{-1} yr^{-1}) sites. These values are found to be manyfold higher than those observed by Singh and Singh (1991) who measured 4.88-6.71 ha^{-1} yr^{-1} annual litterfall in the tropical deciduous forest of Vindhyan region, India. These values are compared with other tropical forests (Murphy and Lugo, 1986; Vitousek and Sanford, 1986; Parthasarthy, 1992; Singh, 1992; Visalakshi, 1993; Clark *et al.*, 2001; Glumphabuter and Kaitpraneet, 2007; Angelina and Jose, 1990; Swamy *et al*., 2010, Table 5.4).

A comparative account of the total litterfall of certain tropical forests of the world is given in Table 5.6.

According to Lutz and Chandler (1955), leaf fall exerts an important influence on physical, chemical and biological properties of soil and ultimately balance the nutrients of the forest soil. Carlisle *et al.* (1966) opined that 60% of the intrasystem nutrient input to the forest floor was accounted for the litterfall. Dantas and Phillipson (1989) have reported 8.04 t ha^{-1} yr^{-1} litterfall for primary forest and 5.04 t ha^{-1} yr^{-1} for a secondary forest at Amazonian "terra firme". Proctor (1983) has warned to be cautious while comparing litterfall values because of differences in definition of litter

Table 5.6 : Total litterfall (t $ha^{-1}yr^{-1}$) of certain tropical forests of the world.

Forest type	Location	Litterfall	Source
Tropical Rain forest	India	3.4-4.2	Rai and Proctor (1986)
	Australia	7.3-10.5	Spain (1984)
	Australia	8.0-12.0	Stocker *et al.* (1995)
	Sarawak	8.8-12.0	Proctor *et al.* (1983)
Lowland rainforest	Nigeria	9.9-12.5	Odiwe and Muoghalu (2003)
Amazon Rain	Brazil	7.3	Klinge and Rodrigues (1968)
Flood plain forest	Peruvian Amazon	6.92-7.1	Nebel *et al.* (2001)
Lower Rain	Ivory coast	9.4	Bernhard (1970)
Lower Montane	Elverde	5.5	Jordan (1971)
Tropical	Venezuela	7.3	Medina and Zelwer (1972)
Moist evergreen	Ivory coast	9-11.9	Bernhard-Reversat (1972)
Lower Montane	Panama	11.1	Haines and Foster (1977)
Rain forest formation	Australia	6.2-10.0	Lowman (1988)
	Australia	8.0-11.0	Stocker *et al. (*1995)
Tropical wet evergreen	India	4.4-5.7	Swamy *et al.* (2010)
Evergreen broadleaved forest	China	3.56-10.61	Zhou *et al.* (2006)
terra firme' rain	Amazon	5.0-8.0	Dantas and Philipson (1989)
Tropical rain	South America	8.01-8.61	Chave *et al.* (2010)
Wet tropical rain forest	North Queensland	5.0-6.0	Hernborn and congdon (1993)
Tropical wet	Global pattern	5.0-14.0	Murphy and Lugo (1986b)
Tropical moist	Global pattern	3.6-12.4	Vitousek and Sanford (1986)
	Ivory coast	5.9	Clark *et al* (2001)
Natural evergreen forest	Thailand	4.88-8.83	Glumphabuter and Kaitpraneet (2007)
Evergreen forest	India	4.4-6.4	Rajendraprasad *et al.* (2000)
Tropical dry evergreen	India	13.27-13.5	Pragasan and Parthasarthy (2005)
	India	5.1-11.1	Visalakshi (1993)
Tropical wet evergreen	India	6.14	Parthasarthy (1992)
Tropical semi evergreen	India	6.73	Parthasarthy (1992)
Tropical semi deciduous	Brazil	8-10.5	Sanches *et al.* (2008)
	Brazil	8.6	Morellato (1992)
Dry tropical	Global pattern	3.0-10.0	Murphy and Lugo (1986)
	India	4.88-6.71	Singh (1992)
Teak plantation in Dry Tropical	India	14.94-22.57	Present study

fraction, number of litter traps used, reliability of means, regeneration status of forests and methodology. He reported, for example, very wide ranges of values for tropical forest, 3.1-15.3 (African), 4.8-21.9 (S. American), 1.7-27 (Central American), 1.5-7.8 (India and Srilanka) and 2.8-23.3 t ha^{-1} (S.E. Asia). Zhou *et al* (2006) reported 3.56 to10.56 t ha^{-1} yr^{-1} litterfall production in subtropical monsoon evergreen broadleaved forest, China. Hornbon and Congdon (1993) reported 5.0 - 6.0 t ha^{-1} yr^{-1} for a tropical rainforest area in North Queensland, Australia. Kumar *et al*. (2011) measured 2.97-4.61 t ha^{-1} yr^{-1} litterfall in three different aged *Butea* forest ecosystems in western India, Rajasthan.

The results of present study are comparatively higher compared to the reported value of Sanches *et al.* (2008) in tropical semi deciduous forest of the Southern Amazon Basin, Brazil where annual litter production was between 8 and 10.5 t ha^{-1} yr^{-1}. Similarly, Odiwe and Muoghalu (2003) also reported higher value of litterfall (9.9-12.5 t ha^{-1} yr^{-1}) during their study in secondary lowland rainforest in Nigeria. Singh *et al.* (2011) reported 8.21 to 8.81 t ha^{-1} yr^{-1} litterfall in a rehabilitated sub tropical forest in North India.

The leaf litterfall in the present study accounted for 82-88 % of the total annual litterfall. Brown and Lugo (1982) reported 69-86% leaf and fruit litter production for tropical forest. Meentemeyer *et al*. (1982) calculated 70% leaf litter of total litter production in forests around world. In dry tropical forest of India leaf litterfall was 65-72% (Singh, 1992). In central Himalayan forests leaf litterfall accounted for 72-86% (Chaturvedi and Singh, 1987b; Rawat and Singh, 1989). Pragasan and Parthasarthy (2005) estimated the contribution of leaf litter between 67.9-71.4% to total litter production in tropical dry evergreen forests of India. Thus, the litterfall values obtained in the present study are within the reported range of several tropical forests. Sanches *et al*. (2008) estimated the leaf fall between 65-83% in tropical semi deciduous forest of the Southern Amazon Basin, Brazil. Glumphabuter and Kaitpraneet (2007) reported 58 -67% leaf litterfall of the total litterfall in natural evergreen forest of Eastern region of Thailand. Zhou *et al* (2006) found 56-76% leaf litterfall in subtropical monsoon evergreen broadleaved forest, China. Hornbon and Congdon (1993) reported 72-76% leaf litter fall of the total litterfall for a tropical rainforest area in North Queensland, Australia. Odiwe and Muoghalu (2003) observed 64-68% leaf litterfall of the total litterfall in secondary lowland rainforest in Nigeria. Angelina and Jose (1990) have measured 69-73% leaf fall in tropical deciduous forest on the pacific cost of México. Singh *et al*. (2011) reported that in a rehabilitated sub tropical forest in North India 68% leaf litter fall contribution to the total litterfall. Kumar *et al*. (2011) found 71-80% leaf litterfall of the total litterfall in three different aged *Butea* forest ecosystems in western India, Rajasthan.

The average annual wood litterfall across the circle was between 2.92–3.16 t ha^{-1} yr^{-1}. The contribution of wood litterfall in the present study was 12.54-17.57%. The percent contribution of wood litterfall to total annual litterfall was observed less than that observed by Bray and Gorham (1964) who estimated that the wood litterfall accounted for 33% to the total litterfall in tropical climate. Singh and Singh (1991) observed 28-35% wood litterfall of total litterfall in the tropical deciduous forest of Vindhyan region, India. Odiwe and Muoghalu (2003) observed 30% wood litterfall of total litterfall in secondary lowland rainforest in Nigeria. Angelina and Jose (1990) observed 26.7-31.2 % wood litterfall to the total litterfall in tropical deciduous forest on the pacific coast of México. Wood litterfall in the total litterfall for tropical forest were 19-25 % (Gaur and Pandey, 1976) and 24% (Singh, 1979). The lower values for wood litter (12-16%) have been reported by Zhou *et al*. (2006) in subtropical monsoon evergreen broadleaved forest, China. Hornbon and Congdon (1993) measured 24-28% wood litterfall of the total litterfall for a tropical rainforest area in North Queensland, Australia.

Brown and Lugo (1982) developed a predictive equation between litter production and T/P ratio: Y=16.0+16.7 logx-6.5x (where Y = total litterfall and x =T/P, T and P represented mean annual temperature and total rainfall, respectively) Using this equation the expected total litterfall for the present forest type (T/P = 2.30) is about 7.10 t ha_{-1} yr_{-1}, whereas the actual litterfall (average 16.23 t ha^{-1} yr^{-1}) is 2.28 times of the predictive value.

Bray and Gorham (1964) suggested that total net primary production of tropical forests could be estimated by a factor 3.3. Assuming 100% turnover of foliage, the total net production for the present study can be estimated to range between 11.7 -16.1 t ha^{-1} yr^{-1}. Brown and Lugo (1982) argued that Bray and Gorham's factor should be revised because it can vary between 1.5-5.0 depending upon life zones.

Using exponential models of breakdown, Jenny *et al*. (1949) and Olsen (1963) and many others have calculated coefficients based on litterfall input and standing crop of litter that reflect the turnover of organic matter on the forest floor. Because the assumption of simple exponential breakdown are unlikely to be met (Mindermann,1968; Bernhard-Reversat, 1972), K estimates must be considered as imperfect indices of the turnover of standing crops of litter (Spain, 1984).

The turnover rate (K) in the present study ranges from 0.68-0.72 and lie within the range of values calculated for other tropical forests (Olsen, 1963). Lugo *et al*. (1978) reported annual turnover rate of 0.34 for sub tropical dry forest at Puerto Rico.

Singh and Singh (1991) reported annual turnover rate 0.72 to 0.77 for tropical deciduous forest of Vindhyan region, India.

Turnover time in the present study ranged between 1.37-1.46 years and compares with several tropical and sub-tropical evergreen and deciduous forests (Vogt *et al.*1986a). According to Brown and Lugo (1982), turnover times are shorter in the Tropical basal life zone groups (0.57-0.88 yr) than in the sub-tropical groups (0.70-1.86 yr). Singh and Singh (1991) reported turnover time between 1.30 and 1.39 for tropical deciduous forest of Vindhyan region, India. The forest floor in dry forest is thus reasonably dynamic.

5.7 Net primary productivity

NPP is defined as the net flux of carbon between the atmosphere and terrestrial vegetation, which can be estimated on annual basis in terms of net biomass accumulation or net primary production. To understand the carbon and nutrient budgets of any ecosystem, an estimate of vegetation net primary productivity (NPP) is necessary as the vegetation play an important role in flow of nutrients in the ecosystem (Goward *et al.*, 1994). NPP is thus, considered an important indicator for determining the ecological status and relative significance of an ecosystem. Net primary productivity of an ecosystem is estimated by different methods ranging from simple biomass increments measurements to complex eco-physiological models.

The reliability of production estimate for a site depends mainly on the accuracy in determination of the annual biomass increment of trees. By using same tape at exactly the same location on the tree, systematic errors in successive measurements of girth marked trees were reduced. The mean girth increment values between 0.5 to 3.00 cm tree^{-1} yr^{-1} obtained in the present study compare with the ranges of 0.25 - 3.0 cm tree^{-1} yr^{-1}, 1.5 - 2.5 cm tree^{-1} yr^{-1} and 0.29 – 1.49 cm tree^{-1} yr^{-1}

reported for dry tropical forests of Vindhya region, India (Singh and Singh, 1991a) Puerto Rican moist tropical forest (Crow and Weaver, 1977) and dry tropical forest at Ghana (Lieberman, 1982).

Inferring fine root production from changes in standing crop alone does not account for simultaneous and compensating processes of production and turnover. The potential for large underestimates by this approach has been acknowledged (Persson 1978; Fairley and Alexander, 1985; Santantonio and Hermann, 1985; Vogt *et al*. 1986 b). However, sample variation in the estimation of standing crops may inflate estimates of fine root production and mortality by creating more “dynamics” than actually exists (McClaugherty *et al*., 1982; Singh *et al*., 1984b; Lauenroth *et al*.,1986).

Kurz and Kimmins (1987) have argued that the estimates of fine root production and mortality from sequential sampling of fine root biomass include three major sources of uncertainty: (1) the possibility of simultaneous occurrence of the two major processes that determine live fine root biomass (production and mortality), (2) uncertainty regarding the accuracy of the estimates of live and dead fine root biomass; and (3) uncertainty whether the selected sampling dates coincide with the peaks and troughs in the seasonal pattern.

Coarse+ fine roots production in the present teak plantations sites in an age series yielded between 3.47 and 5.35 and t ha^{-1} yr^{-1}. Belowground production in tropical forests ranged from 1.4-5.5 t ha^{-1} as reviewed by Brown and Lugo (1982).

Singh and Singh (1991) found that the contribution of roots to NPP was substantial and ranged from 2.9-5.3 t ha^{-1} yr^{-1}.

Vogt *et al.* (1986a) estimated the contribution of fine roots to the total dry matter input to the forest floor in the range of 20-77% for a variety of forests. In the

Table 5.7 : Total net production of certain forests of the world

Forest type	**Location**	**Net production (t/ha/yr)**	**Reference**
Tropical rain forests	Brazil	16.8	Klinge and Rodrigues (1968)
	Malaysia	19.2	Bullock (1981)
	Ghana	24.3	Nye (1961)
	Ivory coast	24.6	Bernhard-Reversat (1972)
	Thailand	28.6	Kira *et al.* (1967)
	Florida, USA	3.1-21.7	Clark *et al.* (2001)
Temperate Forest	California, USA	6-14	Busing and Fujikori (2005)
Tropical humid	Ivory coast	13.4	Muller and Nielsen (1965)
Montane Rain	Jara	24.3	wanner (1970)
Montane Rain	Puerto Rico	10.3	Jordan (1971b)
Evergreen rain	Ivory coast	13.6-17.0	Bernhard-Reversat *et al.* (1978)
Tropical wet Evergreen	India	18.8-27.7	Swamy *et al.* (2010)
Evergreen Forest	Thailand	7.46-29.81	Glumphabuter and Kaitpraneet (2007)
Tropical wet	Global pattern	13.0-28.0	Murphy and Lugo (1986)
Tropical dry	Global pattern	8.0-21.0	Murphy and Lugo (1986)
Dry tropical	India	14	Singh and Mishra (1979)
Tropical dry forests	India	11.3-19.2	Singh and Singh (1991)
Tropical dry deciduous	India	7.2-8.88	Pande (2005)
Sub tropical forest	India	24.05	Singh *et al.* (2011)
Tropical forest	India	21.1-33.2	Kumar *et al.* (2011)
Age series of teak plantation in tropical environment	India	29.59-37.14	Present study

present study fine roots contributed 31.97-49.09% of the total dry matter deposition (wood and miscellaneous litter + coarse root + fine rootmortality) in soil. Raich and Nadelhoffer (1989) found direct relationship between aboveground litter production and belowground carbon allocation in forests. In the present study the belowground transfers were 0.9-1.5 times aerial input (i.e. litterfall). This compared with root inputs of 0.97 times aerial inputs in a 120 yr old scot pine stand studied by Persson *et al*. (1980) and root inputs of 0.7 times aerial inputs in dry forest of Vindhyan range reported by Singh and Singh (1991). Much higher belowground inputs are reported for old Douglas fir stand (5.4 times aerial inputs, Cromack, 1981), 23 and 180 yr old silver fir stands (4.7-5.2 times aerial inputs, Grier *et al*., 1981) and yellow poplar stand (2.3 times, Harris *et al*., 1980). The transient carbon flowing through the belowground components may result in still greater proportional allocation. Perry *et al*. (1989) reported that plants allocate a high proportion of photosynthate to roots. About 70-80 % of net primary production being allocated to roots and mycorrhizal fungi in Pacific silver fir (Vogt *et al*., 1982) and in Douglas fir ecosystems (Fogel and Hunt, 1983). Thus in importance as a pathway of carbon and nutrient flux the fine roots evidently approach or exceed aboveground litterfall.

The total aboveground tree production on each site in age series of teak plantation ranged between 21.32 – 30.51 t ha^{-1}. These values are considerably higher than the range 11.6-17.2 t $ha^{-1}yr^{-1}$ reported for tropical wet evergreen forest of Western Ghat, India (Swamy *et al.* 2010). Singh and Singh (1991) reported the lower values of net primary production between 3.8 and 8.4 t $ha^{-1}yr^{-1}$ in dry tropical forest.

Biomass accumulation ratio (biomass /net production=BAR) has been used to characterize the production conditions in forest communities by Whittaker (1966) and, Woodwell and Whittaker (1968). It expresses the quantum of biomass retained

Table 5. 8 : Biomass accumulation ratios of different components and total tree layer on the age series of teak plantation.

Components	Sites		
	19 years old teak plantation	**23 years old teak plantation**	**33 years old teak plantation**
Bole	14.01	18.62	23.20
Branch	12.64	17.63	23.64
Root	16.66	21.94	27.53
Total tree	5.68	6.58	7.45

per unit of net production. The ratio is largely governed by the disappearance and accumulation rates of perennial biomass. In natural forests the differences in biomass accumulation ratio results mainly due to varied contribution of tree size and rate of wood increments as affected both by the environmental conditions and age of trees. The average biomass accumulation ratio in the present forest tree vegetation was 5.68 in 19 years old teak plantation site, 6.58 in 23 years old teak plantation site and 7.45 in 33 years old teak plantation site. This value among different sites in age series ranged between 5.68 and 7.45 (Table: 5.8). The biomass accumulation ratios in the present study are comparable with dry deciduous forest of Vindhyan region (8.2-10.9) Singh and Singh (1991) and Central Himalayan pine forest (14.0) Chaturvedi and Singh (1987a). Bargali *et al.* (1991) estimated the biomass accumulation ratio ranged from 0.81 to 5.93 for 2-8 years old Eucalyptus plantations. Biomass accumulation ratios are much lower than those reported for Central Himalayan sal (44.0) and oak forests (24.0) (Singh and Singh, 1989; Rawat and Singh, 1988).

The total vegetation production in the present study varied from 29.59 t $ha^{-1}yr^{-1}$ for 19 years old teak plantation site to 37.14 t $ha^{-1}yr^{-1}$ for 33 years old teak plantation site in an age series. This appears many fold higher than dry forest of Vindhyan range 11.3 - 19.2 t $ha^{-1}yr^{-1}$ Singh and Singh (1991). The result of NPP was also higher than the findings made for the other tropical forest (Murphy and Lugo, 1986; Singh and Misra, 1979 and Negi *et al.,* 1995). This is comparable with the findings made by Swamy et al. (2010), who observed the total NPP as 18.8-23.7 Mg $ha^{-1}yr^{-1}$ for evergreen forest of Western Ghats, India. Net production assessed in the present study is compared with those for other tropical forests in Table: 5.7. Kumar *et al.* (2011) reported the total vegetation production from 21.1-33.2 t $ha^{-1}yr^{-1}$ and Singh *et al.* (2011) estimated total NPP as 24.05 t $ha^{-1}yr^{-1}$ for *Butea* forest of western India and

Subtropical forest in north India, respectively. Glumphabuter and Kaitpraneet (2007) studied the natural evergreen forest of Thailand and reported the NPP of three forests sites which varied from 7.46 t $ha^{-1}yr^{-1}$ for hill evergreen forests, 13.24 t $ha^{-1}yr^{-1}$ for moist-evergreen forests and 28.91 t $ha^{-1}yr^{-1}$ dry evergreen forests. Summarizing the production estimates in uneven aged forests and plantations, Whittaker and Woodwell (1971) indicated a range of 10-50 t $ha^{-1}yr^{-1}$ (mean 20 t $ha^{-1}yr^{-1}$) in tropical and 6-30 t $ha^{-1}yr^{-1}$ ($\bar{x}$ =13 t $ha^{-1}yr^{-1}$) in temperate regions.

Leith (1973) has based his Miami model on the relationship of net primary productivity to mean annual temperature [$Y=3000/1+e^{1.315-0.119x}$, where Y= net primary productivity (g m^{-2} yr^{-1}) and x= mean annual temperature (^{o}C) and mean annual precipitation ($Y=3000(1-e^{-0.000664x})$, where Y= net primary productivity (g m^{-2} yr^{-1}) and x= mean annual precipitation (mm yr-1)]. Using these temperature and precipitation-based models the NPP for the present study is calculated as 25.67 t $ha^{-1}yr^{-1}$ and 15.86 t $ha^{-1}yr^{-1}$, respectively. Compared to these calculated estimates the measured net production in present age series of teak plantations ranged between 29.59-37.14 t $ha^{-1}yr^{-1}$ and averaged 34.31 t $ha^{-1}yr^{-1}$.

The differences in average net production rates among teak plantations in an age series s may be partly caused by age of plantations site factors and management. Compared with evergreen leaves, the deciduous habit of the leaves is a drawback for dry matter production, because it can prevent tree from fully utilizing the climatically favourable periods. The low productivity of deciduous broad leaf forests is probably caused by their short leafy period and partly by their small leaf area index (Tadaki, 1966), while evergreen forests are favoured by greater leaf surface and larger duration of photosynthetic activity.

5.8 Carbon storage and carbon sequestration in an age series of teak plantation

Land use change and its impact on global climate are important factors that make it necessary to improve our knowledge of carbon (C) cycling in forest ecosystems. Forests can play an important role in capturing and storing C from the atmosphere, thereby mitigating CO_2 emissions (e.g., Watson 2000; Houghton 2005). Tropical plantations are of particular interest due to their relatively fast growth.

Tropical deforestation has become a significant source of increased atmospheric CO_2 concentration, hence efforts to promote several actions for reducing emissions from deforestation and forest degradation (REDD) in the international society, one important example of which is afforestation in deforested areas (Gibbs *et al.,* 2007). Recently, Pan *et al.* (2011) estimated that the global average of the gross emission rate of tropical deforestation was 2.9 petagrams of carbon (Pg C y^{-1}) from 1990 to 2007 and that tropical regrowth forests were partially compensated for by a carbon sink of 1.6 Pg C y^{-1} within an area of 557 Mha. In contrast, the carbon sink from intact forests, not substantially affected by direct human activities, was 1.19 Pg C y^{-1} within an area of 1392 Mha, suggesting that tropical plantations acted as strong carbon sinks due to rapid biomass accumulation.

Nowadays, one of the incentives for planting teak is to meet the demand in terms of carbon sequestration by indigenous tree species, at least in India, with high economical return (Pibumrung *et al.,* 2008; Jayaraman *et al.,* 2010). Teak plantation production varies widely among countries and depending on soil conditions (Enters, 2000; Kaosa-ard, 1998). For example, the mean annual increment ranged from 2.0 m3 ha^{-1} y^{-1} in poor sites in India to 17.6 m3 ha^{-1} y^{-1} in prime sites in Indonesia with 50 year rotation periods (Pandey & Brown, 2000). Thus, the quantative illustration of carbon cycling in teak plantations is useful for understanding the key carbon sequestration channels, which may serve as the basis for improving forest management.

In this study, we estimated above and belowground carbon stocks and carbon sequestration in age series of teak plantations in tropical environment at Barnawapara Wildlife Sanctuary in Chhattisgarh state in central India.

In the present study the carbon storage was found 54.06, 84.38, and 100.68 t ha^{-1} in 19 years, 23 years and 33 years old teak plantation sites in an age series of teak plantation.

The present estimates of carbon storage pattern in age series of teak plantation are resembled with the Kraenzel *et al.* (2003) and other estimates (Table 5.9). They have reported that the carbon storage of harvest age teak (*Tectona grandis*), Panama, of 20 years old teak plantation trees in four sites. The aboveground tree carbon storage varied from 86.8 t C ha^{-1} to 122.2 t C ha^{-1}, whereas the total tree carbon storage were ranged between 99.8 t C ha^{-1} to 140.6 t C ha^{-1}, respectively.

In this study it is observed that the above and belowground carbon storage in an age series of teak plantation increases with the age of the plantation. Pestri *et al.* (2007) also observed the same trend in his study of estimation of aboveground carbon content in mixed deciduous forest and teak plantations. In his studies, the aboveground carbon content found in the teak plantation trees aged 6, 10, 15, and 23 and 24 years old and in the mixed deciduous forest was 29.76, 33.84, 29.38, 49.72, 37.58 and 60.06 t ha^{-1}, respectively. Moreover he concluded that the density of stands was positively related to the aboveground carbon content. Namely, the greater the density of tree stands, the greater the aboveground carbon content. Similar trend were also found in present study but the total carbon was slightly higher and increasing as the age of plantation increasing. According to the Singh *et al.* (2009), the carbon storage was maximum in natural forest (96.44 Mg ha^{-1}) followed by 32 years old

Table 5.9: Comparative account of carbon storage (t ha^{-1}) in certain tropical forests and plantations of the world

Forest type	**Location**	**Carbon storage**	**Source**
Tropical humid forest	U.S.	3.2-27.5	Shepherd and Montagnini (2001)
Subtropical moist forest	Australia	498	Keith *et al.* (2008)
Tropical forest		180 (aboveground)	Jaramillo *et al.* (2003)
	Panama	99.8-140.6	Kraenzel *et al.*(2003)
	Global pattern	46-183	Brown and Lugo (1982)
	Thailand	126	Gajaseni (2000)
	Australia	111-248	Keith *et al.* (2008)
	Thailand	15.97	Viriyabuncha *et al.*(2002)
	Thailand	29.38-60.06	Petsri *et al.*(2007)
	India	33.7 (aboveground)	Haripriya (2000)
	Thailand	48.14-137 (aboveground)	Terakunpisut *et al.*(2007)
	India	42.88-96.44	Singh *et al*. (2009)
Teak plantation (12 years old)	India	5.52	Adalarasan *et al.* (2007)
Teak plantations (19, 23 and 33 years old)	India	54.06-100.68	Present study

converted forest (47.801 Mg ha^{-1}), 15 years old converted forest (46.25 Mg ha^{-1}) and 23 years old converted forest (42.88 Mg ha^{-1}). In the present study the total carbon storage pattern is much higher i.e. 52.85% for 33 years teak plantation and 52.70% for 23 years teak plantation, respectively.

Previous reports on carbon stocks in teak plantations in several countries are summarized in Table 5.10. Among the reference data, the site productivity of the teak in this watershed was the highest value. The increase rate of carbon stock was between 10.01 and 14.3 Mg C ha^{-1} yr^{-1} was almost equivalent to 24 m3 ha^{-1} yr^{-1} for the stem volume increment, which would represent the very good mean annual increment of teak plantations (Enters, 2000; Kiyono *et al.,* 2007). This is probably due to the soil properties: well drained, sandy loam soils rich in calcium, and high soil pH (Takahashi *et al.,* 2009), namely ideal soil conditions for teak growth (Kaosa-ard, 1998; Tanaka *et al.,* 1998).

In present study, the carbon sequestration in trees ranged from 10.24 to 14.54 t ha^{-1} yr^{-1}. In fine roots it was ranged from 0.76 to 1.45 t ha^{-1} yr^{-1} and in wood and miscellaneous litter it was between 1.33 and 1.44 t ha^{-1} yr^{-1} in wood and miscellaneous litter. The total carbon sequestration in an age series of teak plantation was ranged between 13.02 – 16.74 t ha^{-1} yr^{-1}.

These values resemble with those observed by Thomas (2005). He recorded the rate of carbon accumulation as 15.5 t C ha^{-1} yr^{-1} in 11 year old plantation of teak in Costa Rica, while values for forests were between – 1.3 and + 1.7 t C ha^{-1} yr^{-1}. He concluded that management objectives and site qualities have a strong impact on the performance of the *T. grandis* plantations. The comparative account of carbon sequestration in certain tropical forests and plantations of the world is given in Table-5.11.

Table 5.10: Comparison of carbon stocks in teak plantations in the seasonally dry tropics.

Country	Carbon storage (t C ha^{-1})				Stand age (yr)	Tree density (ha-1)	Soil pH	Source
	AG	BG	Litter	Soil				
Panama	91.8	13.8	3.6	225 (200cm)	20	586	6.6	Kraenzel *et al.*,
	122.2	18.4	3.3		20	566	6.2	(2003)
	117.1	17.6	3.2		20	621	5.9	
	86.8	13.1	3.5		20	723	6.1	
Nigeria	21.2		0.8		5	1184		Mbaekwe *et al.*,
	57.2		2.2		8	1088		(2008)
	57		1.4		11	1100		
	67.1		1.5		14	988		
India	17.8	4.9			16	2500	7.9	Pande, (2005)
India	78.7				20	217	5	Chandrashekara,
	92.2				20	250	5.4	(1996)
	96				20	300	5.7	
	70.9				15	233	5.1	
	56.1				15	217	5.4	
	82.2				15	333	5.8	
Thailand	43.7	13.8		56.7 (50cm)	15			Meunpong *et al.*, (2010)
Myanmar				95 (50cm) 161 (50cm)		20 30		Swe *et al.* (2012)
Thailand	35.6	9.1		221 (50cm)	17	844		Hiratsuka *et al.*,
	41.2	8.2		137(50 cm)	22	544		(2005)
Thailand	24.1	4.4		108 (100cm)	6	530	7.1	Takahashi *et al.*,
	141	23.2	2.5	123 (100cm)	20	565	6.2	(2012)
Panama	0.6				1		4.6	Derwisch *et al.*,
	0.8				2		5.2	(2008)
	38				10		5.2	
Costa Rica	84	3		152(100cm)	11		6.3	Thomas, (2005)
India	46.38	7.68	1.23	23.76(20cm)	19	1100	6.1	Present Study
India	72.93	11.45	1.74	36.65(20cm)	23	1440	6.2	Present Study
India	87.38	13.28	1.92	28.26(20cm)	33	1450	6.4	Present Study

However, the rates of carbon sequestration in an age series of teak plantation in present study found to be higher those reported by Koppad and Rao (2013). They estimated the carbon sequestration in 5 and 10 year old teak plantations to quantify the effect of management on carbon sequestration capability of trees. In 10 years old teak plantation, the rate of carbon sequestration was 5.479 and 2.900 t C $ha^{-1}yr^{-1}$, in better and poorly managed plantations, respectively. Whereas, the carbon sequestration in 5 years old plantation was 1.791 and 0.816 t C $ha^{-1}yr^{-1}$, in better and poorly managed plantations, respectively. They concluded that the management practices *viz.,* application of organic and chemical fertilizer, irrigation, weed management and intercultural operation influenced productivity of teak plantations in turn helps to sequester considerable quantity of carbon from the atmosphere.

The total aboveground sequestration of carbon on each site ranged between 9.78 – 14.06 t ha^{-1} yr^{-1} (Table 4.25). Foliage contributed 66.79 – 74.14 % of the total carbon sequestration by trees; the contribution was maximum on 33 years old teak plantation site (74.14 %) and minimum on 19 years old teak plantation site (66.79 %). Among the perennial aerial parts branches and boles contributed between 7.70 – 9.91 % and 14.85 – 19.23 %, respectively, to the total carbon sequestration by trees. Highest contribution of bole and branches to the carbon sequestration occurred on 19 years old teak plantation (29.14 %) followed by 23 years old teak plantation (25.44 %).

Contribution of roots (coarse + fine roots) to the total carbon sequestration on these sites was substantial and ranged between 1.24 – 1.91 t ha^{-1} yr^{-1}. Contribution of fine roots to total carbon sequestration on the site was averaged 7.32 % (Table 4.21). However, there is no relationship between fine root biomass and the amount of carbon stored in the soils as reported by Swe *et al.* (2012).

Table 5.11: Comparative account of carbon sequestration in certain tropical forests and plantations of the world

Country	Forest type	Carbon sequestration	Source
India	Tropical Dry	0.05-5.3 t C ha^{-1} yr^{-1}	Chaturvedi *et al.*(2011)
Panama	Tropical	191.1 Mg C ha^{-1}	Derwisch *et al.* (2009)
Costa Rica	Humid tropical lowlands	7.1-5.3 t C ha^{-1} yr^{-1}	Fonseca *et al.* (2011)
South Carolina	Piedmont forests	1.19 Tg C yr^{-1}	Huifeng and Wang (2008)
India	Tropical (Gravelia plantation)	11.322 Mg C ha^{-1} yr^{-1}	Jangra *et al.* (2010)
India	Tropical (Teak plantation)	1-8 Mg C $ha^{-1}yr^{-1}$	Kaul *et al.* (2010)
America	Red spruce-Fraser fir forests	2.18-3.11 Mg C ha^{-1} yr^{-1}	Miegroet *et al.* (2007)
Costa Rica	Tropical 1. Natural forests 2. 11-yr teak plantation	 -1.3 and + 1.7 t C ha^{-1} yr^{-1}. 2.9 to 15.5 t C ha^{-1} yr^{-1}	Thomas (2005)
India	Tropical 1. 5-yr teak plantation 2. 10-yr teak plantation	 1.791 t C $ha^{-1}yr^{-1}$ 5.479 t C ha-1yr-1	Koppad and Rao (2013)
India	Tropical 1. 19-yr teak plantation 2. 23-yr teak plantation 3. 33-yr teak plantation	 13.02 t C ha^{-1} yr^{-1} 16.19 t C ha^{-1} yr^{-1} 16.74 t C ha^{-1} yr^{-1}	 Present study Present study Present study

The rate of carbon sequestration follows the fixed trend as Current Annual Increment (C.A.I.). It is lower in initial stage of plantation growth due to small crown size (photosynthetic area). Later, it becomes higher in middle age of plantation due to faster growth of trees due to availability of nutrients, moisture and sunlight and less competition. When the canopies of trees in plantation get closed, trees start competing each other for site factors viz. sunlight, moisture and nutrients. The competition reduces the growth rate of plantation. The rate of carbon sequestration also becomes stable at this stage. Kaul *et al.* (2010) also reported the same trend in their study regarding the C storage and sequestration potential of carbon of selected tree species in India. They observed that the net primary productivity was highest (3.7 Mg $ha^{-1}yr^{-1}$) when a 60-year rotation length was applied but decreased with increasing rotation length (e.g., 1.7 Mg $ha^{-1}yr^{-1}$) at 150 years. Although, they have not mentioned the rate of carbon sequestration, but it is understood that carbon sequestration is positively correlated with net primary productivity. In our study the rate of carbon sequestration is almost same and appears to be stabilized (16.19 and 16.74 t C ha^{-1} yr^{-1}) in 23 and 33 years old teak plantations. Following the trend, it will start decreasing with increasing age of plantation. However, apart from age, the carbon sequestration also depends upon species, density / spacing, climate, soil, physiography, biotic pressure and management practices. In 19 years old teak plantation, the carbon sequestration was 13.02 t C ha^{-1} yr^{-1}. Contrasting to the general trend, it is lower than that of 23 and 33 years old plantations. It may be concluded that the slower rate of carbon sequestration in 19-yr old teak plantation is due to the lower tree density (1100 trees ha^{-1}) than 23 and 33 years old plantations (tree densities 1440 and 1450 trees ha^{-1}, respectively).

Strategies for sustainable teak plantation management:

Soil carbon stock usually increased over time after planting trees (Sakai *et al*., 2010), due to carbon input from litterfall and the turnover of dead roots (Richter *et al.*, 1999), meaning the higher growth of forest plantation would lead to higher soil carbon accumulation. However, despite high production in the plantation studied and contrasting to the trend, the soil carbon in 23 year old teak plantation was found considerably higher than that in 33 years old teak plantation in an age series. It is speculated that surface soil erosion spoiled the soil carbon sequestrated under the plantation. During the present study it was found that surface soil was eroded due to raindrop splashes in the rainy season, especially in 33 years old teak plantation which seemed to prevent soil carbon accumulation in the top soil layer. The poor understory vegetation, dark conditions under the teak canopy, and quick litter decomposition seemed to create soil conditions leading to a bare and exposed surface. A similar observation of erosion under teak plantations was reported by Ogawa *et al.* (1961), Tangtham (1992), and Boley *et al.* (2009). This risk of soil erosion in teak plantations, caused by large raindrops falling from broad and large teak leaves, has been pointed by Hall and Calder (1993) and Calder (2001). Another possible risk of preventing carbon accumulation in the soil would be forest fires. Although teak resists fire, litter on the forest floor is lost if fires occur in the dry season, which is considered to be the main cause of low soil carbon accumulation in Myanmar teak plantations (Suzuki *et al.*, 2007).

Similarly, in Panama, Kraenzel *et al.* (2003) also observed that teak plantations on abandoned land promoted no significant increases in soil carbon storage, despite considerable biomass growth. After harvesting, tree stumps remained and decomposed, which may have contributed to the belowground carbon stock to some extent in the short-term. However, for long-term soil carbon storage, undergrowth vegetation with deep rooting systems may help accumulate carbon stock in the subsurface layer.

The sandy loam texture, nutrient status, soil pH, the overall favourable physico-chemical properties of soil at 33 years old teak plantation site would promise high future productivity of the soil. Takahashi *et al* (2011) suggests that teak plantations in this type of productive site are likely to be harvestable with a short rotation cycle, e.g. 20 – 30 years. Such short rotation is also beneficial in terms of carbon sequestration. However, ideal sites for teak plantation now face competition with agricultural crops and teak is often planted in sites with poor fertility (Enters, 2000), which would thus require longer rotation periods. Appropriate management should be selected in accordance with the site characteristics and management intensity. For sustainable forest management, there is still scope to improve teak plantations from several perspectives, e.g. biodiversity, carbon sequestration, and wood quality (Nair & Souvannavong, 2000).

General criticisms of monoculture plantations in terms of reducing biodiversity were periodically reviewed (e.g. Hartley, 2002; Brocherhoff *et al.* 2008), with poor undergrowth vegetation in young teak plantations with narrow spacing an example of a serious case. To improve monoculture plantations, mixture with other species, *Gmelina arborea* (ghamar) in our case, would be a live option, although silvicultural prescriptions must be developed. The landscape design of plantations and corridor arrangements may also be helpful (Fischer *et al.*, 2006; Brocherhoff *et al.*, 2008).

Lastly, because teak takes up high levels of nutrients and returns them to the surface soil, the aggrading effect of soil fertility was found on degraded land in Costa

Rica (Boley *et al.*, 2009). Similarly, calcium enrichment under teak plantations was observed in Myanmar (Suzuki *et al.*, 2007). If suitable management for top soil conservation is applied, e.g. spacing, weed management, fire control, and mixed planting, teak is likely to represent promising species for land rehabilitation.

CHAPTER-VI

SUMMARY, CONCLUSION AND SUGGESTIONS FOR FUTURE RESEARCH WORK

CHAPTER- VI

SUMMARY, CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH WORK

The present study was aimed to quantify the biomass, carbon stock and carbon sequestration in an age series of teak plantation in tropical environment at Barnawapara Wildlife Sanctuary, Chhattisgarh.

The study area is located at Barnawapara Wildlife Sanctuary (21° 20’ 0” to 21° 25’47” North latitudes and 82° 21’ 17” to 82° 26’ 27” East longitudes) in Raipur Forest Division. The general topography of area is undulating due to formation of rockout crop. The slopes of hillocks are moderate to steep. Tilsa pathar is the highest with an approximate altitude of 463 m above m.s.l. The streams and nalas flowing in the area have steep bank rich in alluvial soil and sustain a rich variety of vegetation.

The climate of study area is dry humid tropical comprised of three seasons viz. rainy, winter and summer. The rainy season commences from the mid-June to October. The winter season, which commences from the beginning of November and last till the end of February. The summer commences from the beginning of March. It is quite prolonged and lasts till monsoon sets in. The mean monthly maximum temperature varies from 27.3° C in January to 41.8° C in May and mean monthly minimum temperature ranges from 12.7° C in December to 27.3° C in May. The average annual rainfall in the study area ranges from 1200-1350 mm. The highest amount of rainfall occurs in July. Number of rainy days varies from 90-100 days.

Soils of Barnawapara area are grouped into three classes viz., Inceptisols, Alfisols and Vertisols. The Inceptisols are immature soils mostly sandy loam having light texture and shallow to moderate depth. They are low in organic matter and available nutrients, which support mainly grassland and degraded forests, these soils are commonly found in eastern and southern aspects. Alfisols occur in midland situation, which are moderately deep and hence have good water holding capacity and bear luxuriant vegetation, on the other hand Vertisols are deep clayey soils having good water holding capacity and are supporting rich vegetation. Some of these lands are utilized for cultivation of agricultural crops.

The study was carried out in an age series of teak plantation comprising 19 years old teak plantation near Hardi village, 23 years old teak plantation near Lalbandha reservoir and 33 years old teak plantation near Pakshi vihar bird watch tower at Barnawapara Wildlife Sanctuary.

Major findings are:

Summary:

I. Physico-chemical properties of Soil and Total Carbon Stock in soil

The soil of all the teak plantations in an age series is characterized by sandy loam structure with considerably varying proportions of sand (53 – 66 %), silt (26 – 27 %) and clay (8 – 20 %). The soil pH was within the range 6.12 – 6.44.

- In 0 – 10 cm soil layer, the moisture content was between 7.25 – 9.93 % and bulk density was between 1.24 – 1.31 gm^{-3}. In 10 – 20 cm soil layer, the moisture content was between 7.25 – 10.66 % and bulk density was between 1.22 – 1.33 gm^{-3}.
- In 0 – 10 cm soil layer the soil pH ranged between 6.12 and 6.41. The total Nitrogen content ranged between 0.09 and 0.14 %. The total Carbon ranged between 1.12 and 1.67 %. The C:N ratio ranged between 11.00 and 12.48. The microbial carbon biomass (MCB) ranged between 228.01 and 522.13 $\mu\ g\ g^{-1}$ of soil. The available phosphorus ranged between 8.45 and 13.47 kg h^{-1}. The available potassium ranged between 288.56 and 372.32 kg h^{-1}.
- In 10 – 20 cm soil layer the soil pH ranged between 6.16 and 6.44. The total Nitrogen content ranged between 0.06 and 0.09 %. The total carbon was

between 0.74 and 1.25 %. The C:N ratio ranged between 11.45 and 13.93. The microbial carbon biomass (MCB) ranged between 112.75 – 318.03 μ g g^{-1} of soil. The available phosphorus ranged between 11.61 and 15.26 kg h^{-1}. The available potassium ranged between 255.74 and 329.62 kg h^{-1}.

- ❖ Across the age series of teak plantation, in the surface soil (0-10 cm) layer, the total soil carbon stock was between 13.90 and 21.37 t ha^{-1} and in lower soil (10-20 cm) layer it ranged between 9.85 and 15.28 t ha^{-1}.
- ❖ In 0-20 cm layer, the total carbon stock was between 23.76 and 36.65 t ha^{-1}.

II. Species structure and diversity in an age series of teak plantation

- ❖ Density of tree across the age series was 1100 trees ha^{-1} comprising 4 species in 19 years old teak plantation, 1440 trees ha^{-1} comprising 7 species in 23 years old teak plantation and 1450 trees ha^{-1} comprising 11 species in 33 years old teak plantation. The total basal area of the tree layer across the age series was 27.52 m^2 ha^{-1} in 19 years old teak plantation, 42.65 m^2 ha^{-1} in 23 years old teak plantation and 45.84 m^2 ha^{-1} in 33 years old teak plantation.
- ❖ The sapling layer density was 2500 saplings ha^{-1} comprising 6 species at 19 years old teak plantation, 2750 saplings ha^{-1} comprising 4 species at 23 years old teak plantation and 1000 saplings ha^{-1} comprising 4 species at 33 years old teak plantation. The total basal area of the sapling layer across the age series was 0.35 m^2 ha^{-1} in 19 years old teak plantation, 0.37 m^2 ha^{-1} in 23 years old teak plantation and 0.26 m^2 ha^{-1} in 33 years old teak plantation.
- ❖ The seedling layer density was 13250 seedlings ha^{-1} comprising of 9 species at 19 years old teak plantation, 8500 seedlings ha^{-1} comprising of 4 species at 23 years old teak plantation and 13250 seedlings ha^{-1} comprising of 11 species at 33 years old teak plantation.

- The forest sites characterised by poor species content. Exponential relationship between density vs. girth showed small structure as 89-94% individuals had $\leq$ 10 cm girth and only 1.5-3.7% were in girth classes exceeding 50 cm GBH.
- The Shannon index values in different teak plantations in an age series were ranged between 0.34 and 1.23 for tree layer, 1.87 and 2.4 for sapling layer and 1.54 and 2.95 for seedling layer.
- Concentration of dominance ranged from 0.68 - 0.91 for tree layer, 0.20 - 0.29 for sapling layer and 0.16 - 0.43 for seedling layer in an age series of teak plantations.
- Species richness in different teak plantations in an age series ranged from 0.43 - 1.37 for tree layer, 0.38 - 0.64 for sapling layer and 0.33 - 1.05 for seedling layer.
- Equitability ranged from 0.24 – 0.51 for tree layer, 1.35 – 1.44 for sapling layer and 1.11 - 1.28 for seedling layer in different plantations in an age series.
- Beta diversity among all the teak plantations in an age series ranged from 1.18 – 3.25 for tree layer, 1.0 – 1.5 for sapling layer and 1.45 – 4.0 for seedling layer.

III. Biomass, Forest floor biomass, Fine root biomass, Litterfall and Net Primary Productivity

- The total biomass across the age series of teak plantation varied from 125.76 t ha^{-1} to 233.49 t ha^{-1}. The total biomass of teak trees varied from 122.48 t ha^{-1} to 201.87 t ha^{-1}.
- Total above ground biomass was between 104.27 t ha^{-1} and 196.32 t ha^{-1} and total below ground biomass was between 21.49 t ha^{-1} and 37.17 t ha^{-1}, across the age series of teak plantation.

- The distribution of biomass in different components was as follows : 49.14 – 50.47% in bole, 21.40 – 24.63% in branch, 10.08 – 11.02% in leaf and 16.13 – 17.08% in root.
- The biomass of fresh leaf litter across the age series of teak plantation site varied from 90.35 g m^{-2} to 138.04 g m^{-2} in rainy season, from 323.32 g m^{-2} to 510.16 g m^{-2} in winter season and from 473.64 g m^{-2} to 615.52 g m^{-2} in summer season.
- The biomass of partially decayed litter across the age series of teak plantation site varied from 397.55 g m^{-2} to 484.47 g m^{-2} in rainy season, from 324.92 g m^{-2} to 400.49 g m^{-2} in winter season and from 226.81 g m^{-2} to 272.77 g m^{-2} in summer season.
- The biomass of wood litter across the age series of teak plantation site was from 290.77 g m^{-2} to 363.33 g m^{-2} in rainy season, from 281.23 g m^{-2} to 340.32 g m^{-2} in winter season and from 292.74 g m^{-2} to 354.19 g m^{-2} in summer season.
- The total forest floor biomass across the age series of teak plantation sites varied from 778.67 g m^{-2} to 985.85 g m^{-2} in rainy season, from 929.47 g m^{-2} to 1250.97 g m^{-2} in winter season and from 993.19 g m^{-2} to 1242.48 g m^{-2} in summer season.
- The mean total live and dead fine root biomass varied from 212.46 g m^{-2} to 406.84 g m^{-2}.
- The fine root production across the age series varied from 235.55 g m^{-2} to 456.14 g m^{-2} in rainy season, 202.03 g m^{-2} to 385.82 g m^{-2} in winter season and from 199.80 g m^{-2} to 378.54 g m^{-2} in summer season.
- The total litterfall across the age series of teak plantation varied from 1494.91

g m^{-2} to 2257.82 g m^{-2}. The total fall of leaf litter varied from 1202.7 g m^{-2} to 1940.99 g m^{-2}. The total fall of wood litter varied from 292.21 g m^{-2} to 316.83 g m^{-2}.

- ❖ The biomass of leaf litter across the age series of teak plantation sites was varied from 144.38 g m^{-2} to 237.79 g m^{-2} in rainy season, from 889.7 g m^{-2} to 1386.67 g m^{-2} in winter season and from 168.61 g m^{-2} to 316.55 g m^{-2} in summer season.
- ❖ The biomass of wood litter across the age series of teak plantation sites varied from 57.57 g m^{-2} to 68.58 g m^{-2} in rainy season, from 154.72 g m^{-2} to 159.58 g m^{-2} in winter season and from 79.93 g m^{-2} to 89.16 g m^{-2} in summer season.
- ❖ The total litterfall across the age series of teak plantation sites was varied from 201.95 g m^{-2} to 306.37 g m^{-2} in rainy season, from 1044.42 g m^{-2} to 1545.77 g m^{-2} in winter season and from 248.54 g m^{-2} to 405.71 g m^{-2} in summer season.
- ❖ The turnover rate across the teak plantation sites in an age series ranged between 0.65-0.70 indicating about 69- 73% turnover of the litter each year. The turnover time of the litter on these sites ranged between 1.42-1.52 years.
- ❖ Overall mean girth increments in all teak trees ranged between 0.75 to 3 cm $tree^{-1}$ yr^{-1}. The highest mean girth increment in teak (3.00 cm $tree^{-1}$ yr^{-1}) occurred in 101-110 cm girth class and lowest (0.75 cm $tree^{-1}$ yr^{-1}) in 40-50 cm girth class.
- ❖ The total net production is the sum total of the values for tree, fine roots, wood and miscellaneous litter. The total net production across the age series of teak plantation varied from 29.59 to 37.14 t $ha^{-1}y^{-1}$.
- ❖ The total aboveground tree production on each site ranged between 22.61 - 31.86 t ha^{-1} yr^{-1}. Foliage production contributed 64.83 – 72.53 per cent of the

total tree net production. Among the perennial aerial parts branches and boles contributed between 7.99 and 9.99 % and 16.25 and 21.24 %, respectively.

- Contribution of total root production (coarse + fine roots) on these sites was substantial and ranged between 3.47 - 5.35 t ha^{-1} yr^{-1}. Contribution of fine roots to total dry matter production was averaged 8.9 %.

IV. Carbon Storage Pattern and Carbon Sequestration

- The carbon concentration in bole, branch, leaf and coarse roots were 43.50 %, 45.67 %, 46.67 % and 35.73%, respectively. The total carbon stored (C) in trees across the age series of teak plantation varied from 54.06 to 100.68 t ha^{-1}.
- The total C in aboveground and belowground components of trees on different plantation across the age series was varied from 46.38 t ha^{-1} - 87.38 t ha^{-1} and 7.68 t ha^{-1} - 13.28 t ha^{-1}, respectively.
- In different components of trees on the three plantations in an age series, the quantity of C varied from 27.62 - 50.05 t ha^{-1} in bole, 12.29 - 26.34 t ha^{-1} in branch, 6.47 - 11.01 t ha^{-1} in leaf and 7.68 - 13.28 t ha^{-1} in root.
- The relative contribution of aboveground and belowground components in the total C storage was 85.79 - 86.78 % and 13.19 – 14.20 %, respectively.
- The total carbon stored across the age series of teak plantation was distributed in different components as follows : 49.71 – 51.09 % in bole, 22.73 – 26.16 % in branch, 10.93 – 11.96 % in foliage and 13.19 – 14.20 % in coarse roots.
- The carbon storage pattern across the age series reflects that the carbon storage was negligible in young individuals belonging to seedlings and saplings classes and highest storage was observed in middle girth classes in an age series of teak plantation.

- The carbon sequestration ranged from 10.24 to 14.54 t ha^{-1} yr^{-1} in trees, from 0.76 to 1.45 t ha^{-1} yr^{-1} in fine roots and from 1.33 to 1.44 t ha^{-1} yr^{-1} in wood and miscellaneous litter.
- The total carbon sequestration on the site is the sum total of the carbon sequestration values for tree, fine roots, wood and miscellaneous litter. The total carbon sequestration across the age series of teak plantation varied from 13.02 to 16.74 t ha^{-1} yr^{-1}.
- The total aboveground sequestration of carbon on each site ranged between 9.78 – 14.06 t ha^{-1} yr^{-1}. Foliage contributed 66.79 – 74.14 % of the total carbon sequestered by trees. Among the perennial aerial parts branches and boles contributed between 7.70 – 9.91 % and 14.85 – 19.23 %, respectively, to the total carbon sequestration by trees.
- Contribution of roots (coarse + fine roots) to the total carbon sequestration on these sites ranged between 1.24 – 1.91 t ha^{-1} yr^{-1}. Contribution of fine roots to total carbon sequestration on the site was averaged 7.32 %.
- Across the age series of teak plantation, the contribution of trees to the total carbon sequestration on the sites ranged between 75.11 - 81.89 %. The contributions of root components and wood and miscellaneous litter to the total carbon sequestration on these sites were between 7.40 – 14.66 % and 8.60 – 10.59 %, respectively.

Conclusion and Suggestions for Future Research Work

There is a worldwide concern over the global warming trends. Carbon dioxide (CO_2) emissions are one of the primary contributors to the increase in greenhouse gases (GHGs) level. Increase in concentration of green house gases in atmosphere resulting to global warming. Which would cause reduction in rainfall; yield potentiality of crops and replacement of species. Hence, the Kyoto protocol put a target on industrial countries to reduce the green house gases emission by 5.5 per cent by 2008 to 2012 over the 1990 levels. Deforestation and biomass burning are some of causes of increasing carbon concentration in atmosphere. Establishment of forest plantation on degraded forest lands, wastelands, community lands and in agricultural land would not only fulfill the target of covering the forest areas but also mitigate the carbon content from atmosphere. Absorption of CO_2 in the biomass directly depends on the productivity of tree species. Hence proper input management plays an important role in biomass productivity. Forest plantations, accounting for 130 million ha is approximately 3 per cent by area of world's forest and play an important role in sequestering carbon.

The tropical deciduous forest is an economically important forest ecosystem, and as a result, a large area of this forest had been disturbed through logging and agriculture resulting in a highly degraded land. Also land-use change or deforestation can modify carbon storage in above ground biomass, below ground biomass and in soil layers. This research showed that the teak plantations have the potential to enhance carbon stock through plant biomass and soil. However, it is concluded that the magnitude and quality of carbon stock is depended on the complex interaction between climate, soil, tree species, density, age of plantation and management, and the composition of litter, as determined by the dominant species. Thus, one management strategy is ecological restoration by increasing the rate of establishment of plantations, particularly comprising the tree species with high carbon stock in biomass such as teak. But central to a forest's community is its diversity of species. Thus, some communities and ecosystems might be more stable if the diversity is enhanced even though some individual species may not persist. It is observed that teak plantations are generally devoid of the understorey vegetation. Also, the pure plantations are not desirable from ecological point of view. Therefore, if we try to enhance under storey plantation in teak plantations with some high carbon stock species in the early stages, the processes of carbon sequestration can be further accelerated. A variety of native species for understory plantation should be selected in order to conserve biodiversity. Some studies in Thailand have indicated that some primary species, as well as a few climax species, could regenerate naturally in the understory layer of teak plantations (Kaewkrom *et al.*, 2005). The similar study can be conducted in India in order to decide suitable native species for planting in teak plantations as understorey crop. However, the advantage of carbon sequestration in secondary forests / plantations is an important strategy to ameliorate changes of CO_2 into the atmosphere by acting as an important carbon sink.

ABSTRACT

"BIOMASS, CARBON STOCK AND CARBON SEQUESTRATION IN AN AGE SERIES OF TEAK PLANTATION IN TROPICAL ENVIRONMENT"

By

RAJESH ANANDRAO ALONE

ABSTRACT

In the present study the attempt has been made to quantify the "Biomass, Carbon Stock and Carbon Sequestration in an Age series of Teak Plantation in Tropical Environment" at Barnawapara Wildlife Sanctuary of Raipur Forest Division in Raipur district (Chhattisgarh), during the year 2010-2013. The study was conducted in age series of teak plantation viz. 19 years, 23 years and 33 years old plantations in tropical environment. The variation in soil characteristics, species structure, composition, diversity, biomass, forest floor biomass, fine root biomass, litterfall, productivity and carbon sequestration and across the teak plantation sites were quantified.

The soil of all the teak plantations in an age series is characterized by sandy loam structure with considerably varying proportions of sand (53 – 66 %), silt (26 – 27 %) and clay (8 – 20 %). Bulk density ranged from 1.22 to 1.33 gm^{-3}. Moisture content ranged from 7.05 to 10.66 %. The soil pH was within the range 6.12 – 6.44. Total N and C were between 0.06 - 0.14 % and 0.74 - 1.67 %, respectively. Available P and K were between 8.45 – 15.26 kg ha^{-1} and 255.74 – 372.32 kg ha^{-1}, respectively. The C:N ratio was between 11.00 – 13.93. The microbial biomass carbon was between 112.75 - 522.13 μ g g^{-1} of soil. The total soil carbon stock in 0-10 cm and 10-20 cm soil layer was ranged between 13.90 - 21.37 t ha^{-1} and 9.85 – 15.28 t ha^{-1}, respectively.

In the present study, a total of 1100, 1440 and 1450 trees ha^{-1} were encountered in 19, 23 and 33 years old teak plantations, respectively. The basal area of tree species across the age series was 27.52, 42.65 and 45.84 m^2 ha^{-1} in 19, 23 and 33 years old teak plantations, respectively. The total biomass across the age series of teak plantation varied from 125.76 t ha^{-1} to 233.49 t ha^{-1}. The above ground biomass and below ground biomass was between 104.27 - 196.32 t ha^{-1} and 21.49 - 37.17 t ha^{-1}, respectively. The total forest floor biomass was between 778.67 and 985.84 g m^{-2} in rainy season, within 929.47 to 1250.97 g m^{-2} in winter season and within 993.19 to 1242.48 g m^{-2} in summer season. The mean total live and dead fine root biomass

varied from 212.46 g m^{-2} to 406.84 g m^{-2}. The total litterfall across the age series of teak plantation varied from 1494.91 g m^{-2} to 2257.82 g m^{-2}. The range of the NPP were 22.61 to 31.86 t ha^{-1} yr^{-1} for trees, 2.12 to 4.06 t ha^{-1} yr^{-1} for fine roots and 2.92 to 3.16 t ha^{-1} yr^{-1} for wood and miscellaneous litter.

The total carbon stored in trees across the age series of teak plantation varied from 54.06 to 100.68 t ha^{-1}. The carbon sequestration was ranged from 10.24 to 14.54 t ha^{-1} yr^{-1} in trees, 0.76 to 1.45 t ha^{-1} yr^{-1} in fine roots and 1.33 to 1.44 t ha^{-1} yr^{-1} in wood and miscellaneous litter.

This research concluded that the teak plantations have the potential to enhance carbon stock through tree biomass and soil. The magnitude and quality of carbon stock is depended on the complex interaction between climate, soil, density, age of plantation, composition of litter and management practices.

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APPENDICES

APPENDIX - I

Allometric relationship between the log dry weight (kg) of different components (Y) on log girth (X, cm) for trees in natural forests (Based on Singh, K.P. and Misra , R. 1979). All equations are of the form Log Y = a+ b log X.

Species	component	Correlation coefficient r	intercept log a	slope b	Standard error of estimate (SEE)	Standard error of b (SE of b)
Anogeissus latifolia (n=23)	Bole	0.9977	-1.8132	2.0630	0.0346	0.0304
	Branch	0.9970	-2.4915	2.6983	0.0523	0.0460
	Leaf	0.9798	-3.2713	2.4708	0.1251	0.1100
	Root	0.9938	-2.3785	2.2849	0.0635	0.0558
	Total	0.9979	-1.8287	2.4177	0.0391	0.0344
Diospyros melanoxylon (n=21)	Bole	0.9961	-2.3639	2.4012	0.0498	0.0486
	Branch	0.9941	-3.7528	3.1466	0.0805	0.0785
	Leaf	0.9678	-2.7088	1.9890	0.1217	0.1186
	Root	0.9923	-2.5205	2.2442	0.0659	0.0643
	Total	0.9988	-2.2359	2.5331	0.0289	0.0282
Buchanania lanzan (n=24)	Bole	0.9957	-2.3043	2.3252	0.0567	0.0459
	Branch	0.9929	-4.6363	3.6077	0.1140	0.0923
	Leaf	0.9858	-2.9857	2.2339	0.1000	0.0810
	Root	0.9976	-2.6984	2.2529	0.0413	0.0334
	Total	0.9952	-2.4411	2.6143	0.0679	0.0549
Pterocarpus marsupium (n=21)	Bole	0.9937	-2.1871	2.3169	0.0632	0.0597
	Branch	0.9936	-3.3958	2.9497	0.0814	0.0769
	Leaf	0.9916	-2.3706	1.7609	0.0558	0.0527
	Root	0.9754	-2.9550	2.4184	0.1326	0.1253
	Total	0.9969	-2.1540	2.4860	0.0474	0.0448
Phyllanthus emblica (n=21)	Bole	0.9970	-2.2675	2.3179	0.0436	0.0415
	Branch	0.9914	-3.1576	2.8571	0.0910	0.0867
	Leaf	0.9910	-2.2645	1.7667	0.0574	0.0547
	Root	0.9964	-2.1898	2.0283	0.0417	0.0397
	Total	0.9987	-2.0281	2.4227	0.0297	0.0283
Flaourtia ramontchi (n=15)	Bole	0.9850	-2.0747	2.2774	0.0818	0.1106
	Branch	0.9939	-2.7468	2.7141	0.0617	0.0833
	Leaf	0.9902	-2.6635	2.0118	0.0583	0.0788
	Root	0.9898	-2.5309	2.2709	0.0671	0.0907
	Total	0.9940	-1.9179	2.4300	0.0548	0.0740
Lagerstroemia parviflora (n=18)	Bole	0.9957	-2.2277	2.2908	0.0492	0.0534
	Branch	0.9898	-2.9451	2.6849	0.0888	0.0964
	Leaf	0.9853	-2.7657	2.0988	0.0840	0.0911
	Root	0.9920	-3.0475	2.5876	0.0758	0.0822
	Total	0.9965	-2.0908	2.4470	0.0472	0.0512
Saccupetalum tomentosum (n=24)	Bole	0.9933	-2.4161	2.5060	0.0657	0.0810
	Branch	0.9937	-3.9360	3.2905	0.0838	0.1033
	Leaf	0.9936	-2.7398	2.0922	0.0536	0.0660
	Root	0.9957	-3.1304	2.6249	0.0549	0.0676
	Total	0.9972	-2.4028	2.6826	0.0456	0.0561
Ggrewia	Bole	0.9925	-2.4946	2.4910	0.0723	0.0768

Species	component	Correlation coefficient r	intercept log a	slope b	Standard error of estimate (SEE)	Standard error of b (SE of b)
tiliaelfolia (n=18)	Branch	0.9661	-2.7396	2.6410	0.1660	0.1764
	Leaf	0.9910	-2.3512	1.8503	0.0590	0.0626
	Root	0.9977	-2.6802	2.3433	0.0371	0.0394
	Total	0.9893	-2.0260	2.4495	0.0852	0.0905
Eriolaena hookeriana (n=12)	Bole	0.9932	-2.8174	2.7104	0.0579	0.1004
	Branch	0.9880	-3.4809	3.1303	0.0893	0.1548
	Leaf	0.9927	-2.3127	1.7989	0.0400	0.0693
	Root	0.9855	-2.8021	2.4096	0.0758	0.1314
	Total	0.9969	-2.4665	2.7390	0.0395	0.0685
Acacia catechu (n=12)	Bole	0.9938	-2.0973	2.3131	0.0508	0.0819
	Branch	0.9906	-3.1626	2.9565	0.0800	0.1290
	Leaf	0.9822	-2.2882	1.6889	0.0634	0.1022
	Root	0.9920	-2.1735	2.0756	0.0518	0.0835
	Total	0.9949	-1.9235	2.4333	0.0482	0.0777
‘Other species’(Total of all species) (n=200)	Bole	0.9874	-2.1725	2.2880	0.0842	0.0260
	Branch	0.9569	-3.2888	2.9420	0.2051	0.0635
	Leaf	0.9678	-2.6977	2.0403	0.1219	0.0377
	Root	0.9697	-2.0645	2.2913	0.1327	0.0410
	Total	0.9844	-2.0854	2.4750	0.1015	0.0314
Tectona grandis (n=15)	Bole	0.9950	-2.3687	2.3636	0.0520	
	Branch	0.9900	-3.2713	2.6579	0.0850	
	Leaf	0.9960	-2.8054	2.2401	0.0430	
	Root	0.9540	-2.2276	2.0172	0.1450	
	Total	0.9940	-1.9663	2.3001	0.0560	

n = no. of trees felled.

APPENDIX-II

Analysis for TOTAL CARBON %

Design applied : 3-Factor Factorial CRD
Arcsine transformation applied

ANOVA TABLE

Source	D F	M S	F Cal	S Em	CD (5%)
Site	2	19.98603115	161.863 **	0.0556	0.1556
Year	1	0.12991188	1.052 NS	0.0454	-
Site x Year	2	0.00560828	0.045 NS	0.0786	-
Soil depth	1	17.24635568	139.675 **	0.0454	0.1270
Site x Soil depth	2	2.87611139	23.293 **	0.0786	0.2200
Year x Soil depth	1	0.00081877	0.007 NS	0.0642	-
Site x Year x Soil depth	2	0.00643577	0.052 NS	0.1111	-
Error	108	0.12347532			
CV% = 5.72		(** Significant at p<0.05)			

A = Site, B = Year, C = Soil depth

Site x Year Mean Table

	B 1	B 2	A
A 1	5.4721	5.5586	5.5154
A 2	6.8735	6.9444	6.9090
A 3	5.9862	6.0262	6.0062
B	6.1106	6.1764	

Site x Soil depth Mean Table

	C 1	C 2	A
A 1	6.0837	4.9471	5.5154
A 2	7.4057	6.4122	6.9090
A 3	6.0784	5.9339	6.0062
C	6.5226	5.7644	

Comparison of Site x soil depth interaction means with Critical Difference (0.05)

Interaction	A1C2	A3C2	A3C1	A1C1	A2C2	A2C1
Interaction mean	4.9471	5.9339	6.0784	6.0837	6.4122	7.4057
Critical Difference (CD) Compared	a	b	b	b	c	d

Year x Soil depth Mean Table

	C 1	C 2	B
B 1	6.4871	5.7341	6.1106
B 2	6.5581	5.7947	6.1764
C	6.5226	5.7644	

Site x Year x Soil depth Mean Table

	C 1	C 2	AB
A 1 B 1	6.0510	4.8933	5.4721
B 2	6.1164	5.0009	5.5586
A 2 B 1	7.3666	6.3803	6.8735
B 2	7.4448	6.4441	6.9444
A 3 B 1	6.0437	5.9287	5.9862
B 2	6.1132	5.9392	6.0262
C	6.5226	5.7644	

APPENDIX – III

Analysis for TOTAL NITROGEN %

Design applied : 3-Factor Factorial CRD
Arcsine transformation applied

ANOVA TABLE

Source	D F	M S	F Cal	S Em	CD (5%)
Site	2	1.04609713	90.373 **	0.0170	0.0476
Year	1	0.01553612	1.342 NS	0.0139	-
Site x Year	2	0.00248211	0.214 NS	0.0241	-
Soil depth	1	2.69511530	232.833 **	0.0139	0.0389
Site x Soil depth	2	0.33476883	28.921 **	0.0241	0.0674
Year x soil depth	1	0.00001091	0.001 NS	0.0196	-
Site x Year x Soil depth	2	0.00113827	0.098 NS	0.0340	-
Error	108	0.01157534			

CV% = 6.12 (** Significant at $p<0.05$)

A = Site, B = Year, C = Soil depth

Site x Year Mean Table

	B 1	B 2	A
A 1	1.6697	1.6326	1.6512
A 2	1.9565	1.9312	1.9439
A 3	1.6813	1.6754	1.6784
B	1.7692	1.7464	

Site x Soil depth Mean Table

	C 1	C 2	A
A 1	1.8337	1.4686	1.6512
A 2	2.1644	1.7234	1.9439
A 3	1.7249	1.6318	1.6784
C	1.9077	1.6079	

Comparison of Site x soil depth interaction means with Critical Difference (0.05)

Interaction	A1C2	A3C2	A2C2	A3C1	A1C1	A2C1
Interaction mean	1.4686	1.6318	1.7234	1.7249	1.8337	2.1644
Critical Difference (CD) Compared	a	b	c	c	d	c

Year x Soil depth Mean Table

	C 1	C 2	B
B 1	1.9187	1.6196	1.7692
B 2	1.8966	1.5963	1.7464
C	1.9077	1.6079	

Site x Year x Soil depth Mean Table

	C 1	C 2	AB
A 1 B 1	1.8465	1.4929	1.6697
B 2	1.8209	1.4443	1.6326
A 2 B 1	2.1819	1.7311	1.9565
B 2	2.1468	1.7156	1.9312
A 3 B 1	1.7278	1.6348	1.6813
B 2	1.7220	1.6289	1.6754
C	1.9077	1.6079	

APPENDIX – IV

Analysis for AVAILABLE PHOSPHORUS (Kg / ha)

Design applied : 3-Factor Factorial CRD

ANOVA TABLE

Source	D F	M S	F Cal	S Em	CD (5%)
Site	2	130.57448095	11.950 **	0.5227	1.4635
Year	1	5.28259664	0.483 NS	0.4267	-
Site x Year	2	0.35450974	0.032 NS	0.7391	-
Soil depth	1	95.21725763	8.714 **	0.4267	1.1949
Site x Soil depth	2	78.08195033	7.146 **	0.7391	2.0697
Year x Soil depth	1	0.10175683	0.009 NS	0.6035	-
Site x Year x Soil depth	2	0.32172872	0.029 NS	1.0453	-
Error	108	10.92671951			

CV% = 27.36 (** Significant at p<0.05)

A = Site, B = Year, C = Soil depth

Site x Year Mean Table

	B 1	B 2	A
A 1	10.3488	9.7216	10.0352
A 2	13.6416	13.2698	13.4557
A 3	12.8845	12.6246	12.7546
B	12.2916	11.8720	

Site x Soil depth Mean Table

	C 1	C 2	A
A 1	8.4582	11.6122	10.0352
A 2	11.6435	15.2678	13.4557
A 3	13.4714	12.0378	12.7546
C	11.1910	12.9726	

Comparison of Site x soil depth interaction means with Critical Difference (0.05)

Interaction	A1C1	A1C2	A2C1	A3C2	A3C1	A2C2
Interaction mean	8.4582	11.6122	11.6435	12.0378	13.4714	15.2678
Critical Difference (CD) Compared	a	b	b	b	bc	c

Year x Soil depth Mean Table

	C 1	C 2	B
B 1	11.4300	13.1533	12.2916
B 2	10.9521	12.7919	11.8720
C	11.1910	12.9726	

Site x Year x Soil depth Mean Table

	C 1	C 2	AB
A 1 B 1	8.7091	11.9885	10.3488
B 2	8.2074	11.2358	9.7216
A 2 B 1	11.8630	15.4202	13.6416
B 2	11.4240	15.1155	13.2698
A 3 B 1	13.7178	12.0512	12.8845
B 2	13.2250	12.0243	12.6246
C	11.1910	12.9726	

APPENDIX – V

Analysis for AVAILABLE POTASSIUM %

Design applied : 3-Factor Factorial CRD

ANOVA TABLE

Source	D F	M S	F Cal	S Em	CD (5%)
Site	2	30349.64173416	8.576 **	9.4058	26.3375
Year	1	2317.99349651	0.655 NS	7.6798	-
Site x Year	2	240.98950738	0.068 NS	13.3018	-
Soil depth	1	53207.32657331	15.036 **	7.6798	21.5045
Site x Soil depth	2	39677.10571487	11.212 **	13.3018	37.2469
Year x Soil depth	1	324.90724524	0.092 NS	10.8609	-
Site x Year x Soil depth	2	275.18563978	0.078 NS	18.8116	-
Error	108	3538.75394897			

CV% = 19.58 (** Significant at p<0.05)

A = Site, B = Year, C = Soil depth

Site x Year Mean Table

	B 1	B 2	A
A 1	324.4864	319.0432	321.7648
A 2	324.9232	310.4976	317.7104
A 3	275.4080	268.9064	272.1572
B	308.2725	299.4824	

Site x Soil depth Mean Table

	C 1	C 2	A
A 1	313.9080	329.6216	321.7648
A 2	372.3272	263.0936	317.7104
A 3	288.5680	255.7464	272.1572
C	324.9344	282.8205	

Comparison of Site x soil depth interaction means with Critical Difference (0.05)

Interaction	A3C2	A2C2	A3C1	A1C1	A1C2	A2C1
Interaction mean	255.7464	263.0936	288.5680	313.9080	329.6216	372.72
Critical Difference (CD) Compared	a	a	ab	b	b	c

Year x Soil depth Mean Table

	C 1	C 2	B
B 1	330.9749	285.5701	308.2725
B 2	318.8939	280.0709	299.4824
C	324.9344	282.8205	

Site x Year x Soil depth Mean Table

	C 1	C 2	AB
A 1 B 1	315.5936	333.3792	324.4864
B 2	312.2224	325.8640	319.0432
A 2 B 1	383.7456	266.1008	324.9232
B 2	360.9088	260.0864	310.4976
A 3 B 1	293.5856	257.2304	275.4080
B 2	283.5504	254.2624	268.9064
C	324.9344	282.8205	

APPENDIX – VI

Analysis for C:N RATIO

Design applied : 3-Factor Factorial CRD
Logarithmic transformation applied

ANOVA TABLE

Source	D F	M S	F Cal	S Em	CD (5%)
Site	2	26.99779899	13.512 **	0.2235	0.6258
Year	1	9.16865125	4.589 **	0.1825	0.5110
Site x Year	2	0.88470224	0.443 NS	0.3161	-
Soil depth	1	28.49479139	14.261 **	0.1825	0.5110
Site x Soil depth	2	6.02909122	3.017 **	0.3161	0.8851
Year x Soil depth	1	0.22474431	0.112 NS	0.2581	-
Soil x Year x Soil depth	2	0.54429232	0.272 NS	0.4470	-
Error	108	1.99813308			

CV% = 6.90 (** Significant at $p<0.05$)

A = Site, B = Year, C = Soil depth

Site x Year Mean Table

	B 1	B 2	A
A 1	19.1175	19.9659	19.5417
A 2	20.6597	21.2163	20.9380
A 3	20.8632	21.1168	20.9900
B	20.2135	20.7663	

Site x Soil depth Mean Table

	C 1	C 2	A
A 1	19.3498	19.7337	19.5417
A 2	20.0110	21.8650	20.9380
A 3	20.6471	21.3329	20.9900
C	20.0026	20.9772	

Comparison of Site x soil depth interaction means with Critical Difference (0.05)

Interaction	A1C1	A1C2	A2C1	A3C1	A3C2	A2C2
Interaction mean	19.3498	19.7337	29.0110	20.6471	21.3329	21.8650
Critical Difference (CD) Compared	a	a	ab	bc	cd	d

Year x Soil depth Mean Table

	C 1	C 2	B
B 1	19.7695	20.6575	20.2135
B 2	20.2357	21.2969	20.7663
C	20.0026	20.9772	

Site x Year x Soil depth Mean Table

	C 1	C 2	AB
A 1 B 1	19.1016	19.1335	19.1175
B 2	19.5980	20.3338	19.9659
A 2 B 1	19.7297	21.5897	20.6597
B 2	20.2922	22.1404	21.2163
A 3 B 1	20.4771	21.2493	20.8632
B 2	20.8170	21.4165	21.1168
C	20.0026	20.9772	

APPENDIX-VII

Analysis for TREE DENSITY (No. of trees ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	110
23 years old teak (T-2)	144
33 years old teak (T-3)	145

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**p value**	**F-table**
Treatments	2	7940	3970	10.419**	0.004	3.354131
Error	27	10290	381.111	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 14.672

CD(0.01) = 24.193 CD(0.05) = 17.910

Treatment No.	**T 3**	**T 2**	**T 1**
Treatment Average	145	144	110
Critical Difference (CD) Compared	a	a	b

APPENDIX-VIII

Analysis for SAPLING DENSITY (No. of trees ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	10
23 years old teak (T-2)	11
33 years old teak (T-3)	8

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-table**
Treatments	2	46.666	23.333	0.741	0.48	3.354
Error	27	850	31.484	-	-	
Total	29	-	-	-	-	

Coefficient of Variation = 58.041
Treatments found to be Non Significant

APPENDIX-IX

Analysis for SEEDLING DENSITY (No. of trees ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	53
23 years old teak (T-2)	34
33 years old teak (T-3)	54

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-table**
Treatments	2	2540	1270	7.639**	0.003	**3.354**
Error	27	4490	166.292	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 27.434
CD(0.01) = 15.985 CD(0.05) = 11.830

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 1	T 2
Treatment Average	54	53	34
Critical Difference (CD) Compared	a	a	b

APPENDIX-X

Analysis for TREE BASAL AREA (m^2 ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	2.752
23 years old teak (T-2)	4.261
33 years old teak (T-3)	4.589

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F table**
Treatments	2	19.158	9.574	20.709**	3.53962E-06	3.354
Error	27	12.488	0.464	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 17.585
CD(0.01) = 0.847 CD(0.05) = 0.620

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	4.589	4.261	2.752
Critical Difference (CD) Compared	a	a	b

APPENDIX-XI

Analysis for SAPLING BASAL AREA (m^2 ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	0.039
23 years old teak (T-2)	0.031
33 years old teak (T-3)	0.024

Anova Table

Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	F-table
Treatments	2	0.006	0.003	0.646	0.532	3.354
Error	27	0.015	0.005	-	-	
Total	29	-	-	-	-	

Coefficient of Variation = 68.314
Treatments found to be Non Significant

APPENDIX-XII

Analysis for ABOVE GROUND BIOMASS (t ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	10.425
23 years old teak (T-2)	16.395
33 years old teak (T-3)	19.427

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-table
Treatments	2	419.114	209.552	23.801**	1.09687E-06	3.354
Error	27	237.656	8.809	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 19.247

CD(0.01) = 3.675 CD(0.05) = 2.725

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	19.427	16.395	10.425
Critical Difference (CD) Compared	a	b	c

APPENDIX-XIII

Analysis for BELOW GROUND BIOMASS (t ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	2.148
23 years old teak (T-2)	3.222
33 years old teak (T-3)	3.755

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-table
Treatments	2	13.354	6.677	21.309**	2.8E-06	3.354
Error	27	8.466	0.314	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 18.406
CD(0.01) = 0.698 CD(0.05) = 0.517

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	3.755	3.222	2.148
Critical Difference (CD) Compared	a	b	c

APPENDIX-XIV

Analysis for TOTAL BIOMASS (t ha^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	12.574
23 years old teak (T-2)	19.617
33 years old teak (T-3)	23.172

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-table**
Treatments	2	582.116	291.05	23.531**	1.21E-06	3.354
Error	27	333.872	12.368	-	-	
Total	29	-	-	-		

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 19.059

CD(0.01) = 4.357 CD(0.05) = 3.220

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	23.172	19.617	12.574
Critical Difference (CD) Compared	a	b	c

APPENDIX-XV

Analysis for FRESH LEAF LITTER (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	73.941
23 years old teak (T-2)	79.845
33 years old teak (T-3)	105.31

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	5557	2778.658	48.109**	1.26E-09	3.354
Error	27	1560	57.766	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 8.800
CD(0.01) = 9.414 CD(0.05) = 6.976

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	105.31	79.845	73.941
Critical Difference (CD) Compared	a	b	b

APPENDIX-XVI

Analysis for PARTIALLY DECAYED LITTER (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	79.108
23 years old teak (T-2)	87.126
33 years old teak (T-3)	96.474

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-table
Treatments	2	1511.6	755.808	35.173**	3.03E-08	3.354
Error	27	580.18	21.489	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 5.294
CD(0.01) = 5.744 CD(0.05) = 4.259

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	96.474	87.126	79.108
Critical Difference (CD) Compared	a	b	c

APPENDIX-XVII

Analysis for WOOD LITTER (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	72.064
23 years old teak (T-2)	80.158
33 years old teak (T-3)	88.159

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-table**
Treatments	2	1294.7	647.345	10.604**	0.003	3.354
Error	27	1647.4	61.011	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 9.741
CD(0.01) = 9.679 CD(0.05) = 7.162

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	88.159	80.158	72.064
Critical Difference (CD) Compared	a	b	c

APPENDIX-XVIII

Analysis for TOTAL FOREST FLOOR BIOMASS (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	225.114
23 years old teak (T-2)	247.129
33 years old teak (T-3)	289.943

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	F-table
Treatments	2	21735	10867.428	59.088**	1.38E-10	3.354
Error	27	4966.4	183.944	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 5.333
CD(0.01) = 16.800 CD(0.05) = 12.440

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	289.943	247.13	225.114
Critical Difference (CD) Compared	a	b	c

APPENDIX-XIX

Analysis for < 1 mm LIVE FINE ROOTS (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	260.478
23 years old teak (T-2)	175.406
33 years old teak (T-3)	123.482

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	47837.21	23918.608	450.699**	5.14E-12	3.88
Error	12	636.849	53.074	-	-	
Total	14	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 3.900
CD(0.01) = 14.076 CD(0.05) = 10.035

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	260.478	175.406	123.482
Critical Difference (CD) Compared	a	b	c

APPENDIX-XX

Analysis for < 1 mm DEAD FINE ROOTS (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	77.902
23 years old teak (T-2)	53.275
33 years old teak (T-3)	39.054

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	3864.768	1932.384	126.859**	8.48E-09	3.88
Error	12	182.796	15.238	-	-	
Total	14	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 6.871

CD(0.01) = 7.540 CD(0.05) = 5.377

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	77.902	53.275	39.054
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXI

Analysis for > 1-5 mm LIVE FINE ROOTS (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	50.076
23 years old teak (T-2)	40.954
33 years old teak (T-3)	31.996

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	817.054	408.527	15.998**	0.004	3.88
Error	12	306.392	25.532	-	-	
Total	14	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 12.329
CD(0.01) = 9.762 CD(0.05) = 6.967

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	50.076	40.954	31.996
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXII

Analysis for > 1-5 mm DEAD FINE ROOTS (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	18.371
23 years old teak (T-2)	18.18
33 years old teak (T-3)	17.927

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	0.493	0.241	0.001	0.998	3.88
Error	12	1388.123	115.676	-	-	
Total	14	-	-	-	-	

Coefficient of Variation = 59.222
Treatments found to be Non Significant

APPENDIX-XXIII

Analysis for TOTAL FINE ROOTS (g m^{-2})

Treatment means

S.No	Average
19 years old teak (T-1)	406.839
23 years old teak (T-2)	287.826
33 years old teak (T-3)	212.451

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	96043.38	48021.687	237.558**	2.24E-10	3.88
Error	12	2425.78	202.14	-	-	
Total	14	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 4.701
CD(0.01) = 27.471 CD(0.05) = 19.590

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	406.839	287.826	212.451
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXIV

Analysis for LEAF LITTERFALL (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	1202.694
23 years old teak (T-2)	1790.329
33 years old teak (T-3)	1941.004

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	3043680	1521840.2	168.145**	5.75E-16	3.354
Error	27	244365.3	9050.569	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 5.783
CD(0.01) = 117.893 CD(0.05) = 87.302

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	1941.004	1790.329	1202.694
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXV

Analysis for WOOD LITTERFALL (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	292.21
23 years old teak (T-2)	303.718
33 years old teak (T-3)	316.836

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	3035.225	1517.617	0.438	0.646	3.354
Error	27	93163.96	3450.519	-	-	
Total	29	-	-	-	-	

Coefficient of Variation = 19.303

Treatments found to be Non Significant

APPENDIX-XXVI

Analysis for TOTAL LITTERFALL (g m^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	1494.914
23 years old teak (T-2)	2094.047
33 years old teak (T-3)	2257.841

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	3226139	1613069.3	148.134**	2.8E-15	3.354
Error	27	294007.1	10889.153	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 5.352

CD(0.01) = 129.318 CD(0.05) = 95.761

Treatment No.	T 3	T 2	T 1
Treatment Average	2257.841	2094.047	1494.914
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXVII

Analysis for ABOVE GROUND CARBON STORAGE IN TREE LAYER (t ha^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	4.634
23 years old teak (T-2)	7.288
33 years old teak (T-3)	8.642

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	83.139	41.564	23.813**	1.1E-06	3.354
Error	27	47.139	1.747	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 19.273
CD(0.01) = 1.633 CD(0.05) = 1.215

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	8.642	7.288	4.634
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXVIII

Analysis for BELOW GROUND CARBON STORAGE IN TREE LAYER (t ha^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	0.763
23 years old teak (T-2)	1.149
33 years old teak (T-3)	1.336

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	1.706	0.858	21.046**	3.1E-06	3.354
Error	27	1.093	0.045	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 18.606
CD(0.01) = 0.245 CD(0.05) = 0.188

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	1.336	1.149	0.763
Critical Difference (CD) Compared	a	a	b

APPENDIX-XXIX

Analysis for TOTAL CARBON STORAGE IN TREE LAYER (t ha^{-2})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	5.401
23 years old teak (T-2)	8.442
33 years old teak (T-3)	9.981

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	108.64	54.32	23.616**	1.2E-06	3.354
Error	27	62.111	2.305	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 19.097
CD(0.01) = 1.876 CD(0.05) = 1.399

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	9.981	8.442	5.401
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXX

Analysis for ABOVE GROUND NET PRIMARY PRODUCTIVITY (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	21.318
23 years old teak (T-2)	28.853
33 years old teak (T-3)	30.518

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	480.691	240.345	7.389**	0.007	3.354
Error	27	879.19	32.568	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 21.211
CD(0.01) = 7.075 CD(0.05) = 5.236

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	30.518	28.853	21.318
Critical Difference (CD) Compared	a	a	b

APPENDIX-XXXI

Analysis for BELOW GROUND NET PRIMARY PRODUCTIVITY (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	5.361
23 years old teak (T-2)	4.334
33 years old teak (T-3)	3.471

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	17.9	8.95	67.172**	3.3E-11	3.354
Error	27	3.59	0.132	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 8.300
CD(0.01) = 0.453 CD(0.05) = 0.339

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	5.361	4.334	3.471
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXXII

Analysis for TOTAL NET PRIMARY PRODUCTIVITY (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	26.689
23 years old teak (T-2)	33.198
33 years old teak (T-3)	33.99

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	321.513	160.756	4.442*	0.024	3.354
Error	27	976.661	36.177	-	-	
Total	29	-	-	-	-	

(*Treatments found Significant at 5% level of Significance CD(0.05)= 5.512)

Coefficient of Variation = 19.224

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	33.99	33.198	26.689
Critical Difference (CD) Compared	a	a	b

APPENDIX-XXXIII

Analysis for ABOVE GROUND CARBON SEQUESTRATION (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	9.785
23 years old teak (T-2)	13.27
33 years old teak (T-3)	14.063

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	103.628	51.814	7.555**	0.004	3.354
Error	27	185.172	6.854	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 21.164

CD(0.01) = 3.243 CD(0.05) = 2.402

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	14.063	13.27	9.785
Critical Difference (CD) Compared	a	a	b

APPENDIX-XXXIV

Analysis for BELOW GROUND CARBON SEQUESTRATION (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	1.913
23 years old teak (T-2)	1.554
33 years old teak (T-3)	1.24

Anova Table

Source of variation	Degrees of freedom	Sum of squares	Mean sum of squares	F cal	F prob	F-Table
Treatments	2	2.286	1.148	67.172**	3.3E-11	3.354
Error	27	0.453	0.01	-	-	
Total	29	-	-	-	-	

(Treatments found Significant at 1% and 5% level of significance)**

Coefficient of Variation = 8.300
CD(0.01) = 0.166 CD(0.05) = 0.116

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 1	T 2	T 3
Treatment Average	1.913	1.554	1.24
Critical Difference (CD) Compared	a	b	c

APPENDIX-XXXV

Analysis for TOTAL CARBON SEQUESTRATION (t ha^{-2} yr^{-1})

Treatment means	
S.No	**Average**
19 years old teak (T-1)	11.708
23 years old teak (T-2)	14.825
33 years old teak (T-3)	15.303

Anova Table						
Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean sum of squares**	**F cal**	**F prob**	**F-Table**
Treatments	2	76.501	38.25	5.139*	0.018	3.354
Error	27	200.978	7.445	-	-	
Total	29	-	-	-	-	

(*Treatments found Significant at 5% level of Significance CD(0.05)= 2.507)

Coefficient of Variation = 19.560

Comparison of Treatment Means with Critical Difference (0.05)

Treatment No.	T 3	T 2	T 1
Treatment Average	15.303	14.825	11.708
Critical Difference (CD) Compared	a	a	b