MODELING CARBON DYNAMICS IN TEAK PLANTATIONS OF KERALA

By

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(2011-27-101)

THESIS

Submitted in partial fulfillment of the
requirement for the degree of

DOCTOR OF PHILOSOPHY IN FORESTRY

Faculty of Forestry
Kerala Agricultural University

DEPARTMENT OF TREE PHYSIOLOGY AND BREEDING
COLLEGE OF FORESTRY
VELLANIKKARA, THRISSUR - 680 656
KERALA, INDIA
2015

DECLARATION

I, hereby declare that this thesis entitled "**MODELING CARBON DYNAMICS IN TEAK PLANTATIONS OF KERALA**" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

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ACKNOWLEDGEMENT

My deep admiration I evince my heartfelt gratitude and unforgettable owe to my major advisor ***Dr. A.V. Santhoshkumar****, Associate Professor and head, Department of Tree Physiology and Breeding, College of Forestry for his valuable guidance, support, and inspiration, critical advice, encouragement and friendly cooperation throughout the course of my research work. Words are not enough to express my gratitude and respect to him. I consider myself lucky to have him as my advisor.*

My in depth obligation to my committee members, ***Dr. P Suresh Kumar****, Professor, Radio Tracer Lab,* ***Dr. T. K. Kunhamu****, Associate professor and head, Department of Silviculture and Agroforestry,* ***Dr. S. Sandeep****, Scientist, Kerala Forest Research Institution (KFRI) and* ***Dr. Sunil K. Mukundan****, Assistant professor Department of Agriculture Meteorology for serving as my committee members and being with me throughout my research work and during preparation of the manuscript. I also want to thank my committee for letting my defense be an enjoyable moment and for their brilliant comments, suggestions and support. Thanks to you.*

I take this opportunity to recognize ***Dr. K. Vidyasagaran****, Dean, College of Forestry for his support during the study.*

I thank all the faculty members of College of Forestry, ***Dr. S. Gopakumar, Dr. Nameer, P. O, Dr. E.V. Anoop, Dr.V. Jamaludheen, Dr. Asha K. Raj, Mr Binu N. K., Dr. Jijeesh C. M.*** *and* ***Mr K. Sreenivasan*** *for their encouragement and support.*

With great pleasure I thank my Plant Physiology and breeding team ***Mr. Anoob, Raneesh, Freddy, Mobin, Ringyao Jajo, Harsha, Lakshmy J Rajan, Kavya, Ajeesh, Mohammed Anees, Prashanth*** *for the immense help and support they rendered in all the ways possible throughout my research work.*

I owe my sincere thank to ***The Kerala Forest Department*** *for providing me with such useful information and study site for my research work and also I thank* ***Rajiv Gandhi National Fellowship*** *by University Grant Commission (UGC) for the financial support rendered.*

I acknowledge the field assistance by **Rahees, Ajay, Abhijith,** and **Nithin Mohan.** I deeply thank **Kiran Mohan** for helping me outin the field work. I also express my appreciations to **Lakshmy J Rajan** and **Anoob** for helping me with my thesis.

Words cannot really express the power of relations that i experienced from my lovely juniors **Niyas, Vikas, Faizan, Aneesh, Vikram** and **Jeevan.** I thank them for their support, help and encouragement for successfully and happily completing my three years of the study.

I also thank my class mates **Jyothi Krishnan, Nijil, Bhimappa** and all other juniors for their encouragement and support. The help rendered by **Jyothi** chechi, **Mini** chechi, **Linson** chettan, **Sujatha** chechi will always be remembered. I thank **Prema** chechi, **Reshmi** chechi and **Sally** chechi for their blessings and care.

I also thank all the staff members of academic block especially **Madhu** sir who was always helping hand throughout my academic issues. I also thank all other non-teaching staff of the college for their blessings and care

I take this place to thank my family and relatives. I thank my **Father, Mother, Sisters, Brothers** and my **Uncle** for always being with me and allowing to follow my heart. I thank **Niveditha, M, Hemanth Kumar, Balaji,** and my friends for their constant motivation, help, support, love and care. I would also like to thank all my other countless well-wishers.

Lastly I bow my head in front of All Almighty God and thank for helping me through tough thick and thin of life, protecting me by showering his blessings and for giving ability to do work and complete the research successfully.

Manjunatha, M

Dedicated to my Parents,
Sisters, Brothers, Uncle and
My beloved Teachers

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Introduction

I. INTRODUCTION

Increase in atmospheric carbon dioxide (CO_2) concentration has been suggested to raise the mean global temperature and perhaps disturb climates in unforeseen ways (IPCC, 2007). While the effort to reduce the increasing emission rate of atmospheric CO_2 and other greenhouse gases has mainly been based on emission reductions, the interest in using soils and vegetation as carbon (C) sinks is increasingly becoming popular (Lal, 2001; Olsson *et al.*, 2001; Byrne, 2011).

The threat of global climate change has prompted policy makers to consider ways of offsetting greenhouse gas emissions through carbon sequestration projects which help remove CO_2 from the atmosphere (Kucharik, 2004). Several studies have indicated that forest establishment and restoration offer one of the most attractive means to mitigate global warming (Moulton and Richards, 1990; Adams *et al.*, 1993; Parks and Hardie 1995; Alig *et al.*, 2002). This is because forests have the potential to sequester large amounts of carbon, the technology for establishing large areas of additional forests already exists, the costs of forest carbon sequestration at low levels are relatively modest, and forests have environmental benefits beyond carbon sequestration.

Carbon sequestration primarily involves the uptake of atmospheric CO_2 during photosynthesis and the transfer of fixed C into vegetation, detritus, and soil pools for "secure" (i.e. long-term) storage (Nair *et al.,* 2010). Carbon sequestration potential of tree species becomes relevant in this respect. It varies with species, climate, soil and management. Forest plantations have significant impact as a global carbon sink (Montagnini and Porras, 1998). Young plantations can sequester relatively larger quantities of carbon while a mature plantation can act as a reservoir. Long rotation species such as Teak (*Tectona grandis*) has long carbon locking period compared to short duration species and has the added advantage that most of the teak wood is used indoors extending the locking period further. The soil in teak plantations continue to accumulate carbon and thus act as a sink always. Globally, soils contain approximately 1500 Pg of carbon, making it the largest terrestrial carbon pool (Davidson, 2000; Lal, 2004).

The carbon storage at the stand level can be divided into aboveground and belowground pools. Each can be partitioned into sub-segments: the former into specific plant parts (stem, leaves, etc., of trees and herbaceous components), and the latter into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons. The total amount sequestered in each compartment differs greatly depending on a number of factors including the eco-region, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use. On an average, the aboveground parts and the soil (including roots and other living biomass) are estimated to hold roughly one-third and two-third, respectively, of the total C stored in tree-based land use systems (Lal, 2010).

Globally, forest plantations cover approximately 264 million hectares. They account for 7 percent of global forest area. Out of this, just over half is located in the tropics. The global plantation resource is currently meeting about 35 per cent of demand of wood and this is expected to rise to 46 per cent by 2040 (FAO, 2010; Trevor *et al.*, 2011).

The first ever teak plantation in India, and also possibly in the world, was raised in Nilambur in 1842 which marked the beginning of monoculture in the South Indian forests. Large extent of moist deciduous forests was subsequently converted to monoculture teak plantations.

Today, teak ranks third among tropical hardwood species in terms of plantation area established world-wide, covering 2.25 million ha, with 94 per cent in Tropical Asia, major area being in India and Indonesia. About 4.5 per cent of teak plantations are in tropical Africa and the rest are in tropical America (Krishnapillay, 2000; Katwal, 2003). Kerala Forest Department has about 57,885 ha under teak, out of which, approximately 64 per cent is in the first rotation and the remaining 36 per cent is in the second and third rotation ages (Balagopalan *et al.,* 1998; Prabhu, 2003). 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 (Pandey and Brown, 2000a; Hallett *et al.,* 2011).

One of the incentives for planting teak is to meet the demand in terms of carbon sequestration by indigenous tree species, 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 edaphic and climatic conditions (Enters, 2000; Kaosard, 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 and Brown, 2000b).

Soil organic matter (SOM) is the key indicator to measure the potential of soil to increase the carbon sequestration. Measurements of SOM or SOC in an ecosystem alone reveal little about how C has changed in the past or will change in the future. But predicting the effect of climate and/or land-use change needs the accurate dynamic models. Primarily two processes control soil carbon storage: primary production (input) and decomposition (output). The use of simulation model that incorporates understanding of basic ecosystem processes and which have been validated across a range of climate, soil and management condition provide a means of investigating interaction between components of ecosystem (Smith *et al.,* 1997). Well-designed modeling studies can suggest which components and processes are most sensitive to climate and what kind of management practices may be most successful in ameliorating negative effects due to perturbation in the ecosystem.

Modeling has been used as an effective methodology for analyzing and predicting the effect of land-management practices on the levels of soil carbon.

The popular model in this regard in CENTURY carbon model (Parton *et al.*, 1987; Parton and Cole, 1988). Although simple conceptually, the problem of these models is that they require information on the size and turnover rate of each tree compartment (Stem, leaf, branches, bark and roots) which is difficult to obtain from field studies. However, they can provide useful information on the effect of temperature, moisture and soil texture on the turnover of C in soils. FAO has developed a model as a methodological framework for the assessment of carbon stocks and the prediction of Carbon Sequestration scenarios that links SOC turnover simulation models (particularly CENTURY) to geographical information systems and field measurement procedures (FAO, 1999).

The present study was carried out with the objectives; this study is designed to estimate the carbon stocks in teak plantations. The study also aims at development of a system dynamic model for carbon prediction for teak plantations. The study also envisages compare carbon prediction using various models for carbon sequestration in teak plantations with the model developed during the study.

Review of Literature

2. REVIEW OF LITERATURE

In Kerala, with few exceptions, conversion of natural forest for raising plantations mostly monocultures, has been a common practice since 1960's. The biological uniformity of monoculture plantations has led to anxieties on soil deterioration and consequent reduction in site quality. The basic underlying reasons for these are fragility of top soil, disturbances to the decomposer activity when mixed forest litter is replaced by uniform plantation litter, repeated exposure of the soil to sun, the removal of organic matter and nutrients in harvest and effect of associated management practices (Balagopalan and Jose, 1997).

2.1. Soils in plantations

2.1.1 Physical properties of soil

Soil texture is the most fundamental attribute of soil fertility. Soil fertility increases with clay content, but highly clayey soils are prone to drought in dry areas and to flooding in wet areas. Clay soils lowered the production than sandy soil in arid areas; the plant production higher in wet areas due to the interacting effect on the soil water retention (Scholes, 1990).

Pure teak stands have been associated with physical soil deterioration such as erosion. However, there is limited conclusive evidence in this regard except when the teak is planted either on steep slopes where there is limited undergrowth or where excessive burning has taken place (Centeno, 1997). Balagopalan (1995) studied the soil characteristics in natural forests (evergreen and moist deciduous forests), grassland, teak plantations and cashew in the Malayattoor Forest Division, Kerala. Most soil properties differed significantly due to various vegetation types except gravel and silt. Soils of the plantations were found to be more deteriorated than that in the natural forests. Joshi *et al.* (1997) reported that the detrimental effects on soil physical properties increased bulk density and decreased soil moisture content in soils of 18 year old plantations of *Populus deltoids* when compared to natural forest in the low montane subtropical belt of the Kumaun Himalaya.

Okoro *et al.* (2000) studied 28 year old even aged contiguous monocultures of teak, idigbo (*Terminalia ivorensis*), opepe (*Nauclea diderrichii*) and gmelina (*Gmelina arborea*) and found that soil texture was not affected by plantation activities. Zerfu (2002) reported that land use change from farmland to Eucalyptus plantation or vice-versa did not cause pronounced change on soil bulk density. Rathod and Devar (2003) studied that morphological and physical properties of soils of teak plantations of different ages an increase in compaction was noticed in the older teak plantations. They also observed a change in texture from loamy sand to sandy loam in young plantations of teak.

Kumar *et al.* (2011) studied the moist deciduous and evergreen forests of Konni Forest division (Kerala) and observed that the moist deciduous habitat has soil gravel content ranging from between 7-20 %. Generally the soil is sandy loam and moderately acidic. The sand content varies between 60-85%. High organic carbon content was present. In evergreen forest gravel content ranged between 10-17 %. The soil was sandy loam and strongly acidic. Very high organic carbon content was present. Sand content varied between 70-85%.

2.1.2 Chemical properties of soil

Krishnakumar *et al.* (1991) compared the ecological impacts of plantations of *Hevea brasiliensis,* and *Tectona grandis* and natural forest on soil properties, nutrient enrichment, understorey vegetation and biomass recycling. The study indicated that all stand types retained high organic matter input that helped to enrich the soils. Teak had the highest organic matter content in the surface layer and depletion of organic matter with depth was also highest for teak and less for natural forests. The depletion pattern for rubber was close to that of natural forests.

Mongia and Bandyopadhyay (1992) indicated that organic matter content, cat ion exchange capacity (CEC) and exchangeable cat ions are higher in the soils of natural forests and mixed plantations when compared to the soils under monocultures. It was also observed that plantation forestry results in soil compaction and nutrient immobilization in the standing biomass. Mongia and Bandayopadhyay (1994) found that soil N, P, K, organic carbon and pH were found to be low under teak, rubber, oil palm and padauk plantations than natural forests.

Dagar *et al.* (1995) observed significant decreases in soil pH, organic matter, extractable phosphorus and exchangeable potassium contents in areas cleared for commercial plantation in the Andaman and Nicobar Islands. They also concluded that nutrient cycling was negatively affected by the monoculture of commercial plantations. Joshi *et al.* (1997) studied the soils in 18 year old plantations of *Populus deltoides*, and nearby natural forest in the low montane subtropical belt of the Kumaun Himalaya reported that soil organic carbon, nitrogen, phosphorus and potassium decreased with increasing plantation age.

Okoro *et al.* (2000) studied in 28-year-old even-aged contiguous monocultures, located in the lowland rain forest belt of southwestern Nigeria, consisting of teak, idigbo (*Terminalia ivorensis*), opepe (*Nauclea diderrichii*) and gmelina (*Gmelina arborea*) the study revealed significant losses in soil calcium and available phosphorus. However, the effective cat ion exchange capacity, pH and magnesium contents of the soils were not affected by plantation activities. The soil organic carbon content was also found to be not affected. Significant variation of some of the properties with depth was observed for plantation soils. Amponsah and Meyer (2000) studied soils of natural forests converted to teak plantations (21.3 ± 5.1 years) in Ghana and found that in the 0-20cm depths, soil organic matter content, total nitrogen, and available phosphorus significantly decreased in soils where natural forests were replaced with teak plantations. Similar results were found for the 20-40cm soil depths.

Chamshama *et al.* (2000) compared chemical properties of soils under first rotation teak and natural forests at Tanzania. The soil pH and exchangeable cations from the teak plantations were not significantly different from those of the natural forests. In general, there was a decrease in total nitrogen in the young plantations but an increase in the semi-mature plantations. In both young and semi-mature stands, there was a decrease in available phosphorus.

Pande (2004) reported that the differences in nitrogen, phosphorus, potassium and organic carbon contents were observed due to plantation activities of sal, teak, eucalypt and pine at Forest Research Institute, Dehra Dun. The available per cent of nutrients (phosphorus, potassium, calcium and magnesium) were highest in eucalypt and lowest in sal, while teak followed pine. The order of importance for nitrogen was: teak>sal>eucalypt>pine and for organic carbon, it was teak>eucalypt>sal>pine. These soil nutrient variations were related to litter fall and subsequent decomposition. Geetha and Balagopalan (2005) studied soil fertility variations within a rotation period in teak plantations in Kerala. Result showed that organic carbon in teak plantations varied from 0.9 to 2.3%. The mean values of nitrogen varied from 0.21 to 0.27%. In all, organic carbon and nitrogen were significantly lower than that in the natural forest.

2.2 Carbon Sequestration

Global warming is one of the major environmental issues of the 21st century. This phenomenon is affecting global climate by increasing earth's temperature due to increased atmospheric concentrations of greenhouse gases (GHGs), the most common of which is carbon dioxide (CO_2) (IPCC, 2007). At the current rate of CO_2 emissions, its concentration in the atmosphere is expected to be doubled by the end of 21st century. Realizing the threat of global warming, United Nations (UN) established the Intergovernmental Panel on Climate Change (IPCC) and created the Kyoto Protocol as the first international agreement on mitigating GHGs. The goal of this protocol was to reduce the GHGs of committed countries by at least 5% compared to the 1990 level by the period 2008-2012. In order to reduce the GHGs in the atmosphere, the United Nations Framework Convention on Climate Change (UNFCCC, 2007) defines carbon sequestration as the process of removal of carbon from the atmosphere and depositing it in a reservoir. It entails the transfer of atmospheric CO_2, and its secure storage in long-lived pools (UNFCCC, 2007).

Carbon sequestration primarily involves the uptake of atmospheric CO_2 during photosynthesis and the transfer of fixed C into vegetation, detritus, and soil pools for "secure" (i.e. long-term) storage (Nair *et al.,* 2010). It occurs in two major segments namely, aboveground and belowground, each of which can be partitioned into sub-segments; the former being divided into specific plant parts (stem, leaves, etc., of trees and herbaceous components), and the latter into living biomass such as roots and other belowground plant parts, soil organisms, and C stored in various soil horizons. The total amount sequestered in each compartment differs greatly depending on a number of factors including the eco-region, the type of system (and the nature of components and age of perennials such as trees), site quality, and previous land use (Lal, 2010). On average, the aboveground parts and the soil (including roots and other living biomass) are estimated to hold roughly one-thirds and two-thirds, respectively, of the total C stored in tree-based land use systems.

2.2.1 Forests as carbon stocks

Globally forest covers 31 per cent of the total land area, and altogether about 4033 million hectares (Mha) of which a tropical forest comprises of 44 per cent (1623.6 Mha) and boreal forests constitutes 34 per cent (1254.6 Mha) (FAO, 2010).

The areas of planted forest constitute about seven per cent (264 Mha) of the total forest area. The total global forest carbon stock was 861 Gt C in 2011 of which 383 Gt C (44%) was stored in the soil (to 1-meter depth), 363 Gt C (42%) in live biomass (above and belowground), 73 Gt C (8%) in deadwood, and 43 Gt C (5%) in litter. Tropical forests store 471 Gt C (55%), and fifty six per cent of this carbon is stored in biomass and 32 per cent in soil. The boreal forest sink is 272 Gt C (32%), and only 20 per cent is in the biomass, while 60 per cent is in the soil. Terrestrial ecosystems (forest and soil) also provide several other ecosystem services than carbon storage (IEA, 2013). Nabuurs *et al.,* 2007 estimated that the world's terrestrial ecosystems could mitigate from 1 to 2.3 Gt of carbon yearly, and the total global net forest sink was estimated to vary from 1.1 to 2.7 Gt of carbon every year between 1995 and 2050. In other words, forests sequester about 2.4 Gt C or 8.7 Gt CO_2 equivalents per year from the atmosphere. This amount is about 24 – 28% of current annual fossil fuel emissions in the world. In the 1990s, the carbon stock only increased by 0.7 Gt C per year.

Global carbon stocks in the terrestrial ecosystem (plants and soil) are about 2400 Gt (FAO 2010). A recent study by Pan *et al.* (2011) estimated that the terrestrial forest carbon uptake have been 4 Pg C during 1990 to 2007 with a net sink of 1.1 Pg C per year. This was equivalent to 50% of the fossil fuel carbon emissions in 2009 and about 13% of the total global CO_2 emissions. The tropical forests alone account for 70 per cent (2.9 Gt). Harris *et al.* (2012) estimated that tropical deforestation accounted for about 10% of global emissions and 0.81 Gt C per year between 2000 and 2005. Tropical forest re-growth creates a carbon sink of 1.6 Pg C yearly. Terrestrial ecosystems (forest and soils) emit carbon to atmosphere through deforestation, photosynthesis, the burning of forest lands and decomposition of wood. Deforestation is mainly caused by anthropogenic activities. Annual global land-use change, deforestation and forest degradation emissions totals to about 1.6 Gt C. This is approximately 16 per cent of global carbon emissions.

2.2.2 Measurement of Carbon Sequestration in tree biomass

Estimation of biomass of the forests is very helpful in calculating the flux of greenhouse gases from the atmosphere (Waterworth, 2001). Estimation of carbon can be derived from the biomass and commonly calculated from stem volume and basic density of the tree. The standard multiple factor of 0.5 is often used for the conversion of biomass to total carbon, most estimation are usually based on measurements that are for limited regions/forests.

Paul and Raturi (1989) studied production and growth of biomass in *Acacia nilotica* under rain fed conditions in forest plantations of India. Total biomass production was 41. 25 t ha^{-1} when plantation was three years old. The study revealed that contribution of stem biomass was 44.1 per cent in total tree biomass. The total biomass in first class tree (Classes on the basis of wood defects) was 21.392 kg $tree^{-1}$ as against 3.536 kg $tree^{-1}$ of third class. When comparison of first class trees with third class trees was carried out, it was found that first class trees had higher percentage of photosynthetic tissues and allocated maximum biomass in the stem portion.

Rana *et al.* (1989) conducted destructive sampling study to determine total tree biomass in central Himalayan forests of altitudinal gradient 300-2200m. At early succession, lower biomass was estimated (199 t ha^{-1}) and the highest value was 787 t ha^{-1} for chir pine (*Pinus roxburghii*) forests. The net primary productivity was in the range of 12.8 to 27.9 t ha^{-1} $year^{-1}$ and related to elevation. Study revealed that the entire elevation range seems to have potential to support high biomass and productivity values. The biomass allocation in stem, branches, twigs, leaves and roots of Chir pine were 63.33, 11.57, 3.38, 3.21 and 18.9 percent of total tree biomass respectively.

Toky and Bisht (1993) reported that biomass and its allocation pattern in nine important fuel wood trees. Upper and belowground biomass and allocation patterns in six years old trees of *Acacia nilotica, Albizzia lebbeck, Azadirachta indica, Dalbergia sissoo, Melia azedarach, Morus alba, Prosopis cineraria* and *Zizyphus mauritiana* were estimated. The maximum (39-65 percent) was allocated in tree bole and a lesser amount in branches (22-40 percent) and roots (9-29 percent). Root biomass ranged from 2.2 kg tree^{-1} in acacia to 8.7 kg tree^{-1} in *Albizzia lebbeck.*

Tropical dry forest ecosystems were studied to measure biomass by using published models (Cairns *et al.*, 2003). Biomass regression models were developed for specific species. Total aboveground tree biomass was found to be 225 Mg ha^{-1}. The comparison of the biomass of 195 large trees was done with individual tree biomass calculated with a generic regression model. It was found that the generic model underestimate of biomass by 31 per cent. Dixon *et al.* (1993) made carbon estimations by measuring the volume of stem wood and multiplying it with species-specific wood density; this was then multiplied by 1.6 to get an estimation of whole tree biomass, carbon content was assumed as 50 per cent of the estimated whole tree biomass, and root biomass was excluded. In another study,

Tandon *et al.* (1999) examined allocation of biomass in *Acacia nilotica* in India. Five trees at five different ages were harvested and regression models were used to get a prediction of total aboveground biomass. The study revealed that a linear model and the aboveground biomass significantly increased after 13 years of age. Allometric equations developed based on biophysical properties of trees validated by occasional measurements of destructive sampling are widely used in forestry for estimating standing volumes of forests (Fernandez Nunez *et al.* (2010)). With increasing understanding about the role of forests in sequestering C, various allometric equations have been developed for different forest types. Annual estimates of C sequestered by tree biomass of *Eucalyptus globulus, Pinus pinaster, Pinus* *radiata* and *Castanea sativa* in Spain were 5.14, 1.58, 1.11, and 0.52 Mg C ha^{-1}, respectively (Pardos, 2010).

2.2.3 Soil Carbon Sequestration

Soil plays a major role in global C sequestration (Lal, 2002). Out of the total stock of C in the soil + plant system, soils store significantly higher proportion of C than the vegetation. The global soil C pool is 2300 Pg, which is three times the size of atmospheric C (770 Pg) and 3.8 times the size of biotic pools (610 Pg) (Lal, 2001). However, the idea of soil C sequestration did not get adequate recognition due to inadequate understanding of the role of soil in global C cycle and the processes involved (Lal, 2002). The measurements of carbon on a whole soil basis give information about their total concentrations, but other analytical procedures are needed to determine details of the form and recalcitrance of the stored C as well as where it is stored. In order to gain a better understanding of such details of C sequestration in soils, attention has been focused on the study of soil C (Nair *et al.*, 2010).

Soil carbon stock was mainly determined by the balance of flow of carbon into the soil as dead organic matter and carbon output as heterotrophic respiration (Berg and McClaugherty, 2003). Litter input varies in its amount, quality and vertical distribution within soil depending on the type of vegetation and decomposition of these litter decomposition is a complex set of processes involving various physical, chemical and biological mechanisms that continuously transform organic matter from compound to compound, finally leading to the release of carbon as carbon dioxide (CO_2) or methane (CH_4) from soil to atmosphere.

Follett *et al.* (2001) have summarized the role that soil plays in the global C cycle and states that there are two types of C pools in the pedosphere: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SOC pool is estimated to be over twice as large as the atmospheric CO_2-C pool and 4.5 times larger than the C pool in land plants. In comparison, they found that the SIC pool is 1.1 times larger than the atmospheric pool and 1.4 times larger than the land plants pool. Together, the SOC and the SIC pools contain 3.2 times the C found in the atmosphere and 4 times the C found in terrestrial vegetation. Forest soils are estimated to hold 1100 Pg carbon which about half of the global stock of soil carbon (Jobbágy and Jackson, 2000). The vertical distribution of carbon in forest soil is shallower than in scrublands or grasslands, which makes the carbon stock of forest soils sensitive to changes in different environmental factors such as climate.

It is important to know the dynamics of carbon in forest soils and its responses to changes in climate or forest management, since large forest areas make small changes in stocks noticeable on a national or continental scale, where the forest area (26.3 million hectares in total) covers about 87 per cent of the total land area (Metla, 2006). Soils hold the largest stock of terrestrial organic carbon in the biosphere. The global soil organic carbon stock in the top 1 m and 3 m of mineral soil has been estimated to be 1500 Pg (1 Pg = 1015 g) and 2300 Pg, respectively (Jobbágy and Jackson, 2000).

2.2.4 Dynamics of soil organic matter

Carbon is continuously transformed from inorganic atmospheric carbon dioxide (CO_2) into organic carbon by the photosynthetic accumulation of carbon in plants. It is then transformed back into the inorganic form by the decomposition of dead plant material through macro- and microorganisms in the soil (FAO, 2005). The relatively long residence time of carbon in soils both as sinks and sources makes them an interesting area in the global climate change discussions. Soil Organic Matter (SOM) is often used as a general indicator of soil quality because of its pronounced positive influence on physical, chemical and biological conditions in soils. SOM can be described as a more or less decomposed organic compound that stem from residues from plants, trees, animal droppings, dead animals, etc. The organic residues turn into SOM by chemical and biological decomposition (Tan, 2003). The carbon content of SOM ranges from 40 per cent to 58 per cent (Brady and Weil, 1999).

Components of plant residues can be subdivided into a metabolic and a structural group. The metabolic group consists of sugars, proteins and starches with low C/N ratios and is readily metabolized by the soil microbes. The structural group covers the components comprising the plant structure of the cell walls, including lignin, polyphenols, cellulose and waxes. When the plant residues enter the soil, the microbes will start digesting the plant residues which then will be divided into what can be described as three major groups namely active, slow and passive carbon pool based on the turnover rates. In general the active fraction comprises no more than 10 to 20 per cent of the SOM in the soils (2 to 4 per cent of the total soil organic carbon). The active fraction is the most susceptible to changes. The slow pool makes up about 55 per cent and the rest is allocated to the passive pool (30 to 40 %) (Metherell *et al.*, 1993).

Carbon turnover rates can be defined based on the time it takes to decompose and mineralize SOM into CO_2 and immobilize nutrients. The turnover rates are basically controlled by the characteristics of the plant residues (specifically the amount of lignin content), temperature, humidity, biological activity, nutrients availability and aeration (soil texture) (Batjes, 1999). Higher temperatures, good aeration and high biological activity cause increased decomposition of carbon and higher humidity and lignin contents cause SOM to accumulate. Although estimates of C fluxes to and from the atmosphere are still associated with relative high uncertainties, ca. ±20% (IPCC, 2007), total global emissions of CO_2 from soils are recognized to contribute one of the largest fluxes and small changes in global soil respiration might have a pronounced impact on the concentration of CO_2 in the atmosphere (Schlesinger and Andrews, 2000).

Approximately 14 per cent of global SOC down to three meters is stored in peatland soils (Parish *et al.*, 2008; Eglin *et al.*, 2010), which have more than 30% of organic (dry) matter content (FAO, 2005). However, the FAO definition of organic soil, namely histosol, is more complex and refers additionally to the thickness of soil layers, their organic content, the origin of the material, the underlying material, clay content and water saturation (IUSS, 2007). Changes in SOC are mainly due to the balance between carbon losses by microbial decomposition in form of carbon dioxide (CO_2, under aerobic conditions) as well as in form of methane (CH_4, under anaerobic conditions), and carbon gains through plant inputs (Davidson and Janssens, 2006). Both processes are driven by climate conditions and human induced management. They differ however, in their individual response to the same environmental drivers (Eglin *et al.*, 2010). Generally, SOC turnover is postulated to exhibit higher temperature sensitivity than Net Primary Productivity (NPP). It is further assumed that SOC turnover increases exponentially with temperature up to about 35-40°C (Kirschbaum, 1995), while NPP follows a sigmoid shape which reaches saturation at about 30°C (Lieth, 1973).

2.2.5 Carbon dynamics for different land uses

The SOC varies with the land-use system (Davidson and Ackerman, 1993). Depending on land-use type, changes in vegetation cause changes in the SOC accumulation. Changes beneficial to SOC are increase in the rate of organic matter production, changes in the decomposability of organic matter that increase organic C, placing of organic matter deeper in the soil, and enhancing physical protection and aggregation (Post and Kwon, 2000). Trees have the potential of producing larger quantities of aboveground and belowground biomass compared to shrubs or herbs.

More biomass results in increased production of aboveground litter and belowground root activity and these make trees an important factor for SOC sequestration (Lemma *et al.*, 2007).

Forests are land use systems with high tree population and play a major role in C sequestration (Lal, 2005). Forest ecosystems store more than 80 per cent of all terrestrial aboveground C and more than 70 per cent of all SOC (Six *et al.*, 2002). When forests are converted to treeless system they lose SOC. The conversion of forest to agricultural system results in depletion of SOC by 20 – 50 per cent (Post and Mann, 1990; Davidson and Ackerman, 1993). Andre *et al.* (2011) conducted an experiment on soil organic carbon dynamics, functions and management in West African agro-ecosystems. They found that total system carbon in different vegetation and land use types indicates that forests, woodland and parkland have the highest total and aboveground carbon contents demonstrating potential for carbon sequestration.

Ashman *et al.* (2003) conducted experiment on the links between soil aggregate size class, soil organic matter and respiration rate artifacts of the fractionation procedure. They proposed that soil organic carbon was significantly higher under forest and tree crops in comparison to pasture, no tilled and tilled plots. Chan *et al.* (2010) carried out an experiment on soil carbon storage potential under perennial pastures in the mid-north coast of New South Wales, Australia, The data of his study suggested that soils under introduced perennial pastures (mainly tropical C4 perennials) can potentially store similar amounts of soil carbon as those under native forests (mainly woodlands with C3 tree species). Their results indicated that improved pastures can store more carbon than native pastures.

Ellis *et al.* (2006) conducted experiment on measuring long-term ecological changes in densely populated landscapes using current and historical high resolution imagery. They found that the highest soil organic carbon densities within landscapes were found in agricultural lands, especially paddy, the lowest soil organic carbon densities were found in nonproductive lands, and forest lands tended toward moderate soil organic carbon densities. Due to the high soil organic carbon densities of agricultural lands and their predominance in village landscapes, most village soil organic carbon was found in agricultural land, except in the tropical hilly region, where forestry accounted for about 45% of the soil organic carbon stocks.

Boley *et al.* (2009) studied effects of active pasture, teak (*Tectona grandis*) and mixed native plantations on soil chemistry in Costa Rica. They reported that 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). Bonsu *et al.* (2011) conducted experiment on estimates of CO_2 emissions from soil organic carbon for different land uses. The study showed that soil organic carbon sequestered was highest in the virgin forest soil, followed by one year old cassava farm, recent maize farm (slash and burnt), rubber plantation and fallowed secondary forest, in that decreasing order. Using the virgin forest as the standard of comparison, the one-year old cassava had emitted 13,860 kg ha^{-1} CO_2, the recent maize farm (Slash and burnt) had emitted 77,770 kg ha^{-1} CO_2, the fully established rubber plantation had emitted 88,550 kg ha^{-1} CO_2, while the fallowed secondary forest had emitted 94,710 kg ha^{-1} CO_2. The study confirms that whenever the virgin forest is intact, the potential to sequester organic carbon is always high. Once the forest is converted to different land uses through vegetation removal decarboxylation processes set in to reduce soil organic carbon with accompanying CO_2 emissions.

Fu *et al.* (2001) reported that the highest soil organic carbon densities were found in paddy land in each region where this land, with rainfed and irrigated agriculture usually following behind this. Observation of higher soil organic carbon densities in flooded paddy soils were explained by natural fertility of wetlands and other lowlands and by the long-term use of organic fertilizers and flooding, which provide a strong supply of organic carbon and lower decomposition rates, respectively. Houghton *et al.* (2005) found that transforming forests into cropland reduces soil organic carbon densities substantially. The observation that paddy and irrigated lands tend to have higher soil organic carbon levels than forestry land was explained by farmer selection of the most "naturally fertile" lands, especially floodplains, for intensive agriculture, and the use of carbon-rich organic fertilizers.

Manojlovic *et al.* (2011) conducted an experiment on effects of land use and altitude on soil organic carbon. The results of the study showed that the highest soil organic carbon stock under forest and lowest under grass, a decreasing trend in soil organic carbon from higher to lower altitudes, the lowest cumulative soil respiration under forest and the highest under grass. This study demonstrates that the land use system and altitude are important factors affecting soil organic carbon.

Olson *et al.* (2011) estimated the soil organic carbon concentrations of various soil layers, to a depth of 0.5 m in upper Mississipi River Valley. The woodland landscape had significantly higher soil organic carbon in the surface layers on all landscape segments than at the cultivated site. For both woodlands and croplands land uses, the subsurface layers had similar soil organic carbon levels. Results suggested that the cropland landscape retained 52% of the total soil organic carbon on a volumetric basis during the previous 150 years of cultivation, soil erosion, and agricultural use. The other 48% of the soil organic carbon was either deposited in the water or released to the atmosphere.

Post and Kwon (2000) reported that sequestration of atmospheric CO_2 into soil organic carbon dictates acquisition of research data on equilibrium level of soil organic carbon pool under different land uses and associated soil management practices and the rate of change of soil organic carbon pool with change in land use and management. Important land uses and practices with the potential to sequester soil organic carbon include conversion of cropland to pastoral and forest lands, conventional tillage to conservation and no tillage, no manure use to regular addition of manure, and to soil specific fertilization rate.

Singh *et al.* (2011) studied the concentration and stock of carbon in the soils affected by land uses and climates in the western Himalaya, India. They found that in all climatic conditions, other than temperate, soil organic carbon stocks were greater in natural ecosystems like forests and pastures (112.5 to 247.5 Mg ha^{-1}) than agriculture (63 to 120.4 Mg ha^{-1}). In temperate climate, soil organic carbon stock in agriculture (253.6 Mg ha^{-1}) on well formed terraces was a little higher than forest (231.3 Mg ha^{-1}) on natural slope.

2.3 Modeling and Soil Organic Carbon

Models, and particularly process models, are applied in order to permit examination beyond the limits set by measurements. The idea is that the exact process description of the models makes them applicable beyond the ranges of data behind them. This idea motivates the continuous development of models with a growing number of factors and complex internal structures. Taking into account the heterogeneity of the soil matrix and processes of decomposition in soil, these models are highly approximate estimations. An alternative approach is to accept the incomplete process description and create simple models that adopt only the most important interactions and features of the processes, but which cover the necessary information in their parameters defined on the basis of extensive data.

Computer models are important tools for assessing regional carbon sequestration and other environmental impacts on forest management practices. Models in general are useful as tools of synthesis and can guide further studies (Oreskes *et al.,* 1994). The modeling process itself is a learning process in which modelers must explicitly define their notions about the modeled system, thus rendering the model a catalyst of interdisciplinary communication.

Parton *et al.* (1987) divided the large SOC pool in the pedosphere in three, according to dynamics and residence time. Based on their division, the active carbon pool is composed of mainly live microbes, microbial products, and SOM, with a short turnover time of one to five years. The slower pool of carbon is physically protected and is an organic form more resistant to decomposition (20-40 years). The passive pool, which is the recalcitrant and slower reactive carbon, has a turnover rate of 200 to 1500 years. He used these categories and turnover times to develop and calibrate the CENTURY model that simulates C and N cycling and dynamics. This model has also been expanded to simulate P and S cycling.

Grace *et al.* (2006) developed a model called SOCRATES to predict long-term changes in soil organic carbon in terrestrial ecosystems. This they argued was because the maintenance of soil organic carbon in terrestrial ecosystems was critical for long-term productivity. They contend that simulation models of SOC dynamics are valuable tools in predicting the dynamics of carbon storage and developing management strategies for the mitigation of greenhouse gas emission. However, they observed that the utility of using models is generally reduced due to need for specific data.

Del Grosso *et al.* (2001) simulated the interaction of carbon dynamics and nitrogen trace gas fluxes using the DAYCENT model. The authors used this model to compare the effects of land management on SOM, nitrous oxide emissions, plant production, and NO_3 leaching for a Great Plain soil that has been used for wheat fallow rotations and for a Midwestern soil used for corn/winter and wheat/pasture rotations. Results of their study show that some type of agriculture can dramatically reduce soil C levels from what they were in the native condition, and that the loss can be reversed by perennial cropping, N fertilizer, irrigation, organic matter additions, no-till cultivation, and reversion to the native condition.

According to Del Grosso *et al.* (2001) DAYCENT simulations suggest that soils that are depleted in SOM can temporarily compensate for greenhouse gas emissions by changing land management, but observed however, that net carbon sequestration will not continue for more than 10 to 50 years, under such conditions. McGuire *et al.* (2001) studied the IBIS model simulations which projected an increase in biomass, NPP and soil organic carbon (SOC) in all the teak grids. In the A2 scenario, the percentage increase in biomass averages around 130–150%, while it is around 90–110 per cent in the B2 scenario. These large increases are primarily due to the CO_2 fertilization effect: previous studies have shown that IBIS simulates a higher fertilization effect compared to other models

The higher sensitivity of IBIS to CO_2 fertilization is due to the following reason: Currently, IBIS simulates the effects of changes in the supply of sunlight, water and CO_2 to vegetation—limitations of important nutrients like nitrogen and phosphorous in the tropical soils are not considered. The addition of nitrogen and phosphorous cycles might diminish the magnitude of response to elevated CO_2 (Hungate *et al.*, 2003). Gassman *et al.* (2003) used EPIC to estimate regional soil carbon and other environmental indicators in the entire 12-state North Central region of the U.S. They found that EPIC is a robust tool for regional analyses of soil carbon changes, nutrient and erosion losses, and other environmental indicators in response to variations in management practices, cropping systems, climate inputs, and soil types.

There are a number of differences in the ways in which Century simulate SOM turnover processes. The CENTURY SOM model; however, is part of a larger ecosystem model that simulates crop, grass and tree growth and the effects of different management practices on both plant production and SOM.

2.4 CENTURY Model

Although many models are developed to simulate soil organic C, N and S, some models are considered better in predicting the result such as ROTH Chemist and Century model. Century model has been used in this study because of its:

1. Ability to model a diverse array of ecosystems

2. Capability to simulate a wide range of land use and management options

3. Extensive use and testing around the world on a diverse array of systems

4. User friendliness

Century is a tool for predicting SOM dynamics across climate, land use type, and treatment within site (Kelly *et al.,* 1997). A comparative study was done to assess the performance of nine different models using datasets from seven long-term experiments (Smith *et al.,* 1997). Result showed that CENTURY, ROTH-C and DAISY model met the criteria of the good model performance across all the simulation, most of the times. More over Century model performance was found to be the better for grass, forests and crop system among all the models.

Parton *et al.* (1988) used CENTURY model for the simulation of SOC in semi arid agro ecosystem. They simulated the carbon stock in different pools. The simulated values for resistant, slow, active fraction were 44 per cent, 11 per cent and 16 per cent respectively as compared to estimated value (based on soil fractionation data) 48, 10 and 17 per cent. CENTURY was used to simulate soil and biomass carbon over a period of 25 to 50 years under a series of land use and management option in semi-arid pan of Senegal (Tschakert *et al.*, 2004). Simulation resulted in C dynamics ranging from -0.13t C/ha/yr from a worst case millet sorghum rotation to +0.9gt/ha/y on intensively managed agricultural fields.

Paustian *et al.* (1996) used CENTURY model to model climate and management impacts on soil carbon in semi-arid agro ecosystem. They reported that differences between management systems at all the sites were greater than those induced by perturbation of climate. Parton *et al.* (1994) reported that century model accurately simulates total organic C and N dynamics and net plant productivity also across wide range of managed and natural tropical ecosystem. Probert, *et al.* (1995) compared the two models APSIM and CENTURY to simulate nitrogen and crop yield. Result of this experiment showed that CENTURY performed better than APSIM model in predicting relative yields of nitrogen treatments but was less satisfactory than APSIM for grain yield, soil water and drainage.

Carter *et al.* (1993) simulated SOC and nitrogen in cereal and pasture system using CENTURY model. They reported that the model correctly predicted the temporal trend in organic matter changes and successfully simulated the positive effect and negative effects of N fertilizer and fallow, respectively, on soil C and N contents. They also advocated that the model is better in predicting the long term than short-term temporal variation. Ardo and Olsson (2003) used GIS and the CENTURY model to assess soil organic carbon in the Sudan, a semi-arid environment. They compiled a climate, land cover, and soil database and integrated it with the CENTURY ecosystem model. This enabled them to estimate historical, current and future pools of SOC as a function of land management and climate. They concluded that grassland and savannah SOC variations depend on grazing intensity and fire return interval, and that land management may affect future amounts of SOC in semi-arid areas thereby turning them from sources into sinks of carbon.

Ingrid *et al.* (1990) used the CENTURY model coupled to a GIS to simulate spatial variability in storage and fluxes of carbon and nitrogen within grassland ecosystems. The GIS contained information on driving variables required to run the model. These were soil texture, monthly precipitation and monthly minimum and maximum temperatures. They overlaid polygon maps of the above variables to produce a driving variable map of the study region. The final map had 768 polygons in 160 unique classes. The model was run to a steady state for each class and NPP, SOM, net N mineralization and trace gas emission were mapped back into the GIS for display. Variation in all of the above properties occurred within the region. NPP was primarily controlled by climate and patterns followed spatial variation in precipitation. Soil organic matter, in contrast, was controlled largely by soil texture within this climate range. Error associated with aggregation within the study area showed that spatial averages over the study area could be used to drive simulations of NPP, which is linearly related to rainfall. They concluded that more spatial detail was needed to be preserved for accurate simulation of SOM, which is non-linearly related to texture.

Using the CENTURY model, Smith *et al.* (2000) estimated the rate of SOC change in agricultural soils of Canada for the period 1970 to 2010. This estimation was based on the estimated SOC change for 15% of the 1250 agriculturally designated soil landscape of Canada (SLC) polygons. Simulations were carried out for two to five crop rotations and for conventional and no-tillage. The results indicate that the agricultural soils in Canada, whose SOC are currently very close to equilibrium, will stop being a net source of CO_2 and will become a sink by the year 2000. Rates of carbon change for the years 1970, 1990, and 2010 were estimated to be -67, -39, and 11 kg C ha^{-1}. The results also revealed that the rate of decline in the carbon content of agricultural soils in Canada has slowed considerably in the 1990s as a result of an increase in the adoption of no-tillage management, a reduction in the use of summer fallowing, and an increase in fertilizer application. It was estimated that the proportion of agricultural land storing SOC will have increased from 17% in 1990 to 53% by the year 2000.

Mikhailova *et al.* (2000) used the CENTURY model to simulate the soil organic matter dynamics after conversion of native grassland to long-term continuous fallow for 50 years. The model was simulated such that the parameters are adjusted to the pre-management scenario. The results of the simulations corresponded to the results of the soil organic carbon that was obtained before the fallow. This shows that the use of models to simulate soil organic carbon fluxes is valid.

Yongqiang *et al.* (2007) examined carbon dynamics of grasslands on the Qinghai-Tibetan Plateau and the roles it may play in regional and global carbon cycles. They used the CENTURY model to examine temporal and spatial variations of SOC in grasslands on the Plateau for the period from 1960 to 2002. According to the authors, the model successfully simulated the dynamics of aboveground carbon and soil surface SOC at the soil depth of 0–20 cm and the simulated results agreed well with the estimates. Some outcomes of their study revealed that an examination of SOC for eight typical grasslands showed different patterns of temporal variation in different ecosystems in 1960–2002. The extent of the temporal variation according to the study increased with the increase of SOC in the ecosystem. They found that SOC increased first and then decreased quickly during the period from 1990 to 2000. Spatially, SOC density obtained for the equilibrium condition declined gradually from the southeast to the northwest on the plateau and showed a high heterogeneity in the eastern plateau. The results suggest that (i) SOC density in the alpine grasslands showed remarkable response to climate change during the 42 years, and (ii) that net carbon exchange rate between the alpine grassland ecosystems and the atmosphere increased from 1990 to 2000.

Tschakert *et al*, (2004) used the CENTURY model to evaluate 25 management options on C stocks in Senegal. During the first 25 years, net C changes amounted to between −3.2 Mg C ha^{-1} and +10.8 Mg C ha^{-1}. The highest gains were achieved by 'optimal' agricultural intensification (crop rotation, fallow, manure, *Leucaena* pruning, and increased fertilization), followed by plantation of *F. albida* at 250–300 trees per hectare (+5.8 Mg C ha^{-1}). Net C changes thus ranged between −0.13 and +0.43 Mg C ha^{-1} $year^{-1}$. During the second 25 year period of maintaining the same management options, C changes decreased substantially for all management options (−0.74 to +5.30 Mg C ha^{-1}). Over the entire simulation period, annual C gains were thus 0.22 Mg C ha^{-1} $year^{-1}$ for *F. albida* plantations and 0.27 Mg C ha^{-1} $year^{-1}$ for 'optimal agricultural intensification'.

CENTURY (Parton *et al.,* 1993) was tested against a multi-year, multi-site data set on plant production and soil C and N dynamics in several grassland ecosystems and then used to simulate the responses to general circulation model derived climate change (Ojima *et al.,* 1993; Cole *et al.,* 1993). The model has also been extended for simulating soil carbon dynamics of the tropical forests (Parton *et al.,* 1989; Sanford *et al.,* 1991; Vitousek *et al.,* 1994; Townsend *et al.*, 1995).

CENTURY 4.0 has been linked with three biogeographical models to evaluate continental-scale response of terrestrial ecosystems to climate change and doubled CO_2 (Schimel *et al.,* 1997). Kelly *et al.* (1998) and Smith (1998) have reported comparisons of CENTURY 4.0 simulations and within-site, and between-treatment observations from seven long-term experiments in forests of the eastern United States. Sulistyawati, (2011) studied the simulation of carbon dynamics of *Acacia mangium* forest at Parungpanjang, Bogor using CENTURY model. The parameterization was done by adjusting the model parameters to the characteristics of *Acacia mangium* and the environment condition of the study area. The validation was conducted by comparing the simulation results to empirical data from the field measurements of carbon stocks in *Acacia mangium* stands of 2nd, 4th, 6th, and 8th years old. The validation process demonstrated that the output of simulation approaches the empirical data. Pattern of the simulated dynamics in 50 years showed that the carbon accumulated in the forest system, *Acacia mangium* biomass, and necromass increase as the age of stand increases.

Simulation results from the CENTURY model suggest that total system carbon has decreased by 71 percent from 1850 to 1991 (Nuraziza, 1992). Losses of tree carbon amounted to 0.2 t ha^{-1} yr^{-1} and those for soil to 0.05t ha^{-1} yr^{-1}. Future changes of soil carbon, as simulated for 25 different management practices for the next 50 years, ranged from -3.8 t C ha^{-1} under no inputs to +13.5t C ha^{-1} under optimum agricultural intensification. Since the majority of all carbon gains occurred during the first 25 years of the simulation period, which also corresponds to the time horizon envisioned by pilot carbon offset programs, it was worth noting the annual rate of soil carbon changes for this part, ranging from -0.13 t C ha^{-1} yr^{-1} to +0.43t Cha^{-1} yr^{-1} Simulated changes in crop yields matched increases and decreases in soil carbon, ranging from 62 per cent to 200 per cent under the worst and best management scenario respectively.

Study was conducted to simulate soil organic matter dynamics on an Acrisol under no-tillage and different plowed systems using Century model (Leite *et al.*, 2003). Soil C stocks simulated by Century model showed tendency to recovery only under no-tillage. Simulated amounts of C stocks of slow and active pools were more sensitive to management impacts than total organic C. The values estimated by Century of soil C stocks and organic carbon in the slow and passive pools fitted satisfactorily with the measured data.

Shrestha (2007), estimated modeled soil carbon pool under different land uses, the simulation results showed that there was a loss of SOC pool in the first temporal block (1950-1970) from equilibrium value of 6.8 kg C m^{-2} to 3.9 kg C m^{-2} both in the cultivated and forest soils. The model predicts increases in SOC in response to better management of forest and intensified cultivation with the use of higher agricultural input. In the projection period, the SOC pool in the managed forest was increased from 3.70 to 4.28 kg C m^{-2} under prevailing climate scenario, while it reached to only 4.21 kg C m^{-2} under the climate change scenario. A similar effect was observed in the cultivated soil indicating that under climate change scenario SOC sequestration was reduced.

The 'slow' soil carbon (SOM2) pool was divided into light (L) intermediate (I), heavy (H) fractions of macro-organic matter and resistant fractions, represents the 50-150μm size fraction (Sitompul *et al.,* 2000). The modified CENTURY model simulated the dynamics of L, I and H fractions as well as total organic carbon (C %) under sugarcane with a coefficient of determination (R^2) of 0.90, 0.95 and 0.98, respectively. Without further adjustments the model was applied to woodlots of *Gliricidia sepium* and *Peltophorum dasyrrachis*. The model accounted for 60% of the variation in measured light (L) fraction in the 0-5 cm layer under *Gliricidia* and *Peltophorum*, but only for 40% of the variation in the I and H fraction data.

Farage (2007) used CENTURY and ROTHC to explore the effects of modifying agricultural practices to increase soil carbon stocks. Modeling showed that it would be possible to make alterations within the structure of the current farming systems to convert these soils from carbon sources to net sinks. Annual rates of carbon sequestration in the range 0.08–0.17 Mg ha^{-1} $year^{-1}$ averaged over the next 50 years could be obtained. The most effective practices were those that maximized the input of organic matter, particularly farmyard manure (up to 0.09 Mg ha^{-1} $year^{-1}$), maintaining trees (0.15 Mg ha^{-1} $years^{-1}$) and adopting zero tillage (up to 0.04 Mg ha^{-1} $year^{-1}$).

Sitompul *et al.* (2010) simulated the soil organic matter dynamics after conversion of forest by slash and burn method to food crops or to a sugarcane estate. The CENTURY model 3 was used to simulate the soil organic matter dynamics on the basis of simulation were compared with observations on SOM dynamics. The predicted SOM dynamics vary substantially between vegetation, crop management and fractions of SOM. Forest removal followed by rice or sugarcane cultivation causes a considerable decrease in active, slow, and total soil carbon particularly with former management.

Li *et al.* (2012) studied that comparing predictions of long term soil carbon dynamics under various cropping management systems using K-model and CENTURY model. Both K-model and CENTURY could predict the dynamics of SOC when site-specific soil and climate data are used to initialize simulations. Very similar annual carbon decomposition rates were simulated by the single carbon pool K-model and the 3-carbon pool CENTURY model. However, compared with experimental measurements of SOC, K-model produced relative smaller errors than CENTURY (<0.1 kg C m^{-2} vs. 0.08-0.48 kg C m^{-2}, and within ±5% vs. ±5%-45%), mainly resulting from smaller biases of predicted crop production. They concluded that when detailed site-specific soil and climate data are not available for initialization and feeding the running of model, K-model can still reasonably predict the dynamics of SOC with its auto-correction function, but CENTURY produces poor results.

The CENTURY ecosystem model was used to investigate how land use and climate affect SOM and plant growth. Bhattacharyya *et al.* (2007) has evaluated CENTURY model using two long-term fertilizer trials representing humid and semi-arid sites from India. He also modeled soil organic carbon stocks and changes in the Indo-Gangetic Plains (IGP) and predicated that, there will be a 21% decrease in SOC stocks in the IGP from 1967 to 2030. Authors have tested CENTURY model and estimated the carbon turn over in climate changing scenario.

2.5 System Dynamics Simulation Modeling

A system is a combination of components, which act together in achieving a specific objective. A component is a single functioning unit of a system (Ogata, 2004). Systems are not limited to physical ones; the concept of a system can be extended to abstract dynamic phenomena, such as those encountered in economics, transportation, population growth, biology, and climate science. A system is considered dynamic if its present output depends on past input. If it does not, the system is considered static. System dynamics is a method of learning complex processes. Like many other disciplines, system dynamics has witnessed various changes in its philosophy, strategy, and technique, in the course of its ongoing evolution.

Sterman (2000) states: 'System Dynamics is fundamentally interdisciplinary. Because we are concerned with the behaviour of complex systems; system dynamics is grounded in the theory of nonlinear dynamics and feedback control developed in mathematics, physics, and engineering. Because we apply these tools to the behaviour of human as well as physical and technical systems, system dynamics draws on cognitive and social psychology, economics, and other social sciences. Because we build system dynamics models to solve important real world problems, we must learn how to work effectively with groups of busy policy makers and how to catalyze sustained change in organizations'. The use of system dynamics modeling has been expanding at a faster rate, because of its unique ability to represent the real world by drawing complex, non-linear feedback loops between social and physical systems.

According to Pruyt (2006), System dynamics is not a philosophy, methodology or method, and that it is more than just a theory of structure, set of techniques or tools. A model is simply a representation or reconstruction of the real world, or, in other words, a conceptual construction of an issue under investigation. The modeler is an observer who, by the act of modeling, creates a new world (Schwaninger *et al.,* 2008). By compromising among adequacy, time, and cost of further improvement, it is possible to achieve only a degree of confidence in a model.

Forrester (1994) states that the mental model that people operating in the real system almost always fall back on is the competitive model. In his opinion, a system dynamics model creates much more clarity and unity than prior mental models, and that the "adequacy" decision usually generates little controversy among real-world operators who are constrained by time and budget. It is obvious that an attempt to design a system should start with a prediction of its performance before the system itself can be designed in drawing or actually built (Ogata, 2004).

System dynamics modeling is based on a continuous feedback mechanism, incorporating the hypothesis of causal connections of parameters and variables as a functional form, which should be fully transparent rather than of the black box type. The formalization of mental models by system dynamics increases transparency with respect to quality and quantity. Such a model is able to endure all sorts of logical and empirical experimentations to check the strength of the interrelationship, and this ability enhances its falsifiability. In this sense, a system dynamics model is a candidate for a theory. This consideration is applicable to properly constructed models that make their underlying assumptions explicit, that operationalize their variables and parameters and that submit themselves to adequate procedures of model validation (Barlas, 1996; Sterman, 2000; Schwaninger and Grasser, 2008).

System dynamics modeling is engaged in building quantitative and qualitative models of complex problems and then experimenting and analyzing the behaviour of these models over time. Such models are often able to reflect the influence of unappreciated causal relationships, dynamic complexity and structural delays which could lead to counterintuitive outcomes of less-informed efforts to improve the situation. The motivational and perceptional scope of system dynamics modeling helps to manage engineering projects in a more efficient and transparent way.

2.5.1 Basics of System Dynamics Modeling

Much of the art of system dynamics modeling is discovering and representing the feedback process, with stock and flow structures, time delays, and non linearities to help determine the dynamics system (Sterman, 2000).

Feedback: Feedback is a process that occurs when the output of an event depends on the event's past or future. Therefore, when any event is a part of a cause-and-effect chain and works as a loop, the event is called a feedback into itself (Simonovic, 2009). A feedback system should have a closed-loop structure that brings results from the past action of the system back to control future action. The basic example of a feedback system is a simple thermostat that functions to maintain a constant temperature. The thermostat senses a difference between desired and actual room temperature, and activates the heating unit. The addition of extra heat helps to achieve the desired temperature and after achieving the required level, the heating is turned off automatically until the room temperature again falls below the desired one.

The actions of system actors can be basically of two kinds, which can be referred to as negative and positive feedback effects. Those actions that attempt to control an organization by introducing a balancing mode are called negative feedback (or self-correcting) effects, and those that attempt to initiate growth in a reinforcing pattern are called positive feedback (self-reinforcing) effects. Every system, from the very simple to the most complex, consists of a network of positive and negative feedback. A system's behaviour arises from the combined effect or interaction of these loops. Therefore, the way that organizations respond to such actions is very important in developing and understanding the system dynamics model.

Delay: Delays are a critical source of dynamics in nearly all systems. Some delays breed danger by creating instability and oscillation. Others provide a clear light by filtering out unwanted variability and enabling managers to separate signals from noise. Delays are pervasive and take time to measure and report information. Sterman (2000) defines delay as a process whose output lags behind its input in some fashion. The time delay is the delay between the decision and its effects on the state of the system. Delay in the feedback loops may create instability.

Stocks and Flows: Stocks are also called accumulations or states or levels. Stocks characterize the state of the system and generate the information upon which decisions and actions are based. Stocks give system inertia but also create a delay. A stock variable is measured at one specific time, and represents a quantity existing at that point in time, which may have accumulated in the past.

2.5.2 STELLA model

STELLA is a computer software program with an interface for building dynamic models that realistically simulate biological systems (Rice *et al.,* 2002). The procedure used in STELLA modeling involves, (1) Constructing a relational model of the system using icons that represent satate and rate variables and arrows and flows that represents interrelated components. (2) Quantifying the relationships among elements in the model and (3) running the observe the system dynamics (American society for Horticultural Science, 2004; Rice *et al.,* 2002)

Ruth *et al.* (2002), development of dynamic models in STELLA can be done with great ease because of the graphical interface. The basic functional elements not only allow better classification of variables in the system but also make it easier to describe the relationships between them (ITC, 2004). For a dynamic model it is necessary to execute a number of computations at a single time step. In STELLA the process of running these computations is automated thus making model development faster (Ruth, 2002).

The outputs can be obtained both in digital and graphical form. While the digital output can be used for further analysis, graphical outputs enable visualization of the results. The major disadvantage of STELLA is that it is point-based software. As such, the software was considering the entire study area as a single unit. Therefore, variation of an element within the system is not considered.

2.5.3 Input Data

The data used for the development of the models are as follows. Carbon is found in different pools. Terrestrial carbon stocks of all carbon stored in ecosystems is in living plant biomass (above- and below-ground), dead plant biomass (above and belowground), Soil (in soil organic matter and, in negligible quantities, as animal and microorganism biomass) In the IPCC guidelines, these pools are described as above-ground biomass, belowground biomass, dead wood and litter, and soil carbon.

Materials and Methods

3. MATERIALS AND METHODS

3.1 Geographical features of Kerala

3.1.1 Physiography

The study was carried out in the state of Kerala which lies between 8^0 18' and 12^0 48' N latitude and 74^0 52' and 77^0 22' E longitude. It is a linear strip of land, extending on about 560 km in the south-western part of India, bordered by the Arabian Sea in the west and the Western Ghats in the east. It is a highly diversified land in its physical features as well as the agro-ecological conditions. The undulating topography ranges from below the mean sea level (MSL) to 2694 m above MSL.

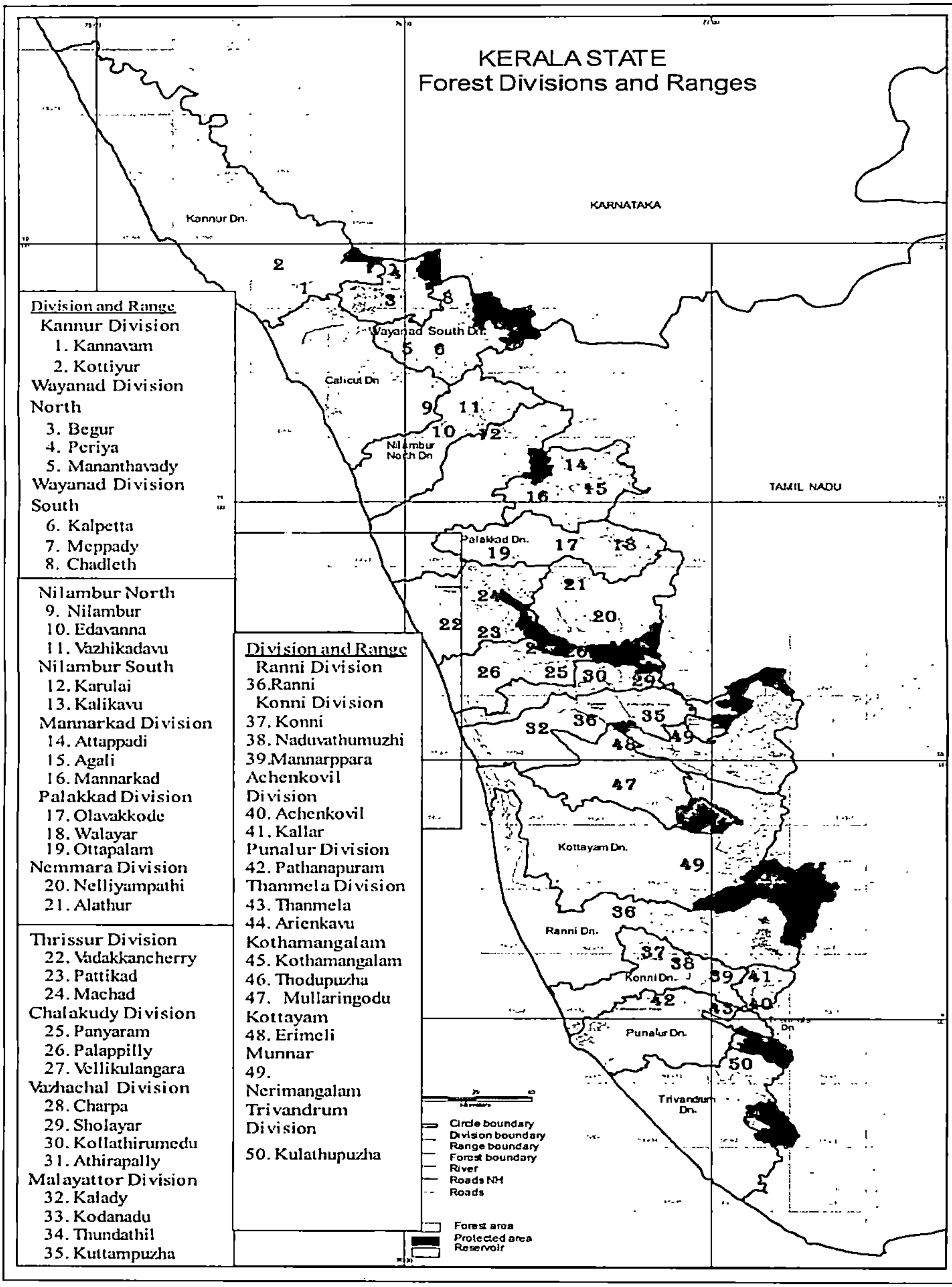
3.2 Study location

The study was carried out in the teak plantations of Kerala. The existing teak plantations of different age classes and natural forests were selected for studying the soil carbon dynamics of teak monoculture in the forest divisions (Fig.1)

3.2.1 Sampling design

3.2.1.1 Vegetation sampling

To compare the soil in teak plantations of different age, soil in natural forests were used as a base line. As the plantations were established by clear felling the natural forests, it can be assumed that initial soil conditions were similar. Hence any variation in soil conditions in teak plantations of different age classes can be considered as a result of various plantation activities and based on this a time sequence is reconstructed. The clear felling of natural forests for establishing plantations was stopped in 1980's and the data on teak plantations were collected from Kerala Forest Research Institute records. Kerala Forest Department has about 57,885 ha under teak, out of which, approximately 64 per cent is in the first rotation



Division and Range
Kannur Division
1. Kannavam
2. Kottiyur
Wayanad Division North
3. Begur
4. Periya
5. Mananthavady
Wayanad Division South
6. Kalpetta
7. Meppady
8. Chadleth
Nilambur North
9. Nilambur
10. Edavanna
11. Vazhikadavu
Nilambur South
12. Karulai
13. Kalikavu
Mannarkad Division
14. Attappadi
15. Agali
16. Mannarkad
Palakkad Division
17. Olavakkode
18. Walayar
19. Ottapalam
Nemmara Division
20. Nelliyampathi
21. Alathur
Thrissur Division
22. Vadakkancherry
23. Pattikad
24. Machad
Chalakudy Division
25. Panyaram
26. Palappilly
27. Vellikulangara
Vazhachal Division
28. Charpa
29. Sholayar
30. Kollathirumedu
31. Athirapally
Malayattor Division
32. Kalady
33. Kodanadu
34. Thundathil
35. Kuttampuzha

Division and Range
Ranni Division
36. Ranni
Konni Division
37. Konni
38. Naduvathumuzhi
39. Mannarppara
Achenkovil Division
40. Achenkovil
41. Kallar
Punalur Division
42. Pathanapuram
Thanmela Division
43. Thanmela
44. Arienkavu
Kothamangalam
45. Kothamangalam
46. Thodupuzha
47. Mullaringodu
Kottayam
48. Erimeli
Munnar
49. Nerimangalam
Trivandrum Division
50. Kulathupuzha

Note: The numbers indicate the location of plot taken from each range forest

Figure.1 Location map of experimental sites

and the remaining 36 per cent is in the second and third rotation ages (Balagopalan *et al.,* 1998; Prabhu, 2003). Only those plantations that were in close proximity with natural forest were selected for the study. Teak plantations were divided into 5 age classes for sampling. The age classes were 0-5, 06-10, 11-20, 21-30 and above 30 years. The reason for selecting these five age groups was that the first and second mechanical as well as the silvicultural thinning would be over during the period 5-25years after the establishment while third and fourth silvicultural thinning would be over during the period 25-45 years, after which there will not be further operations in the plantations. From each age classes, thirty plantations were randomly selected. In each randomly selected plantation, a quadrant of 50 m x 50 m size was established (Fig 2 & Table 1). Out of the 150 plots thus made, 50 plots were used for the validation of the model which is developed (Table 2). Girth at breast-height (1.37 m above ground) was recorded on all the trees in these plots using a tape and height was measured using a hypsometer. The measured biomass was converted into carbon by allometric equations (Thomas *et al.,* 2013).

For litter collection, a specially designed circular litter traps each having an area of 0.24 m^2 (Hughes *et al.,* 1987), made of four 210 cm long (2-3 mm in thickness) galvanized iron wires, were installed at each site in a random manner at a uniform height of 0.75 cm. The total litter was collected from each plot throughout a year at an interval of three months and then weighed in the field to determine the fresh weight. A representative sample of litter was then collected, brought to the laboratory and dried in the oven for 48 hours at 70° C for determining the dry weight.

3.2.1.2 Soil sampling methodology

For the parameterization of the model, 10 plantations from each age class were selected for soil collection and thus a total of 50 soil samples were taken. Soil pits of 1m x 1m x 1m were dug in each sample plot. In the slopes, the pit was taken

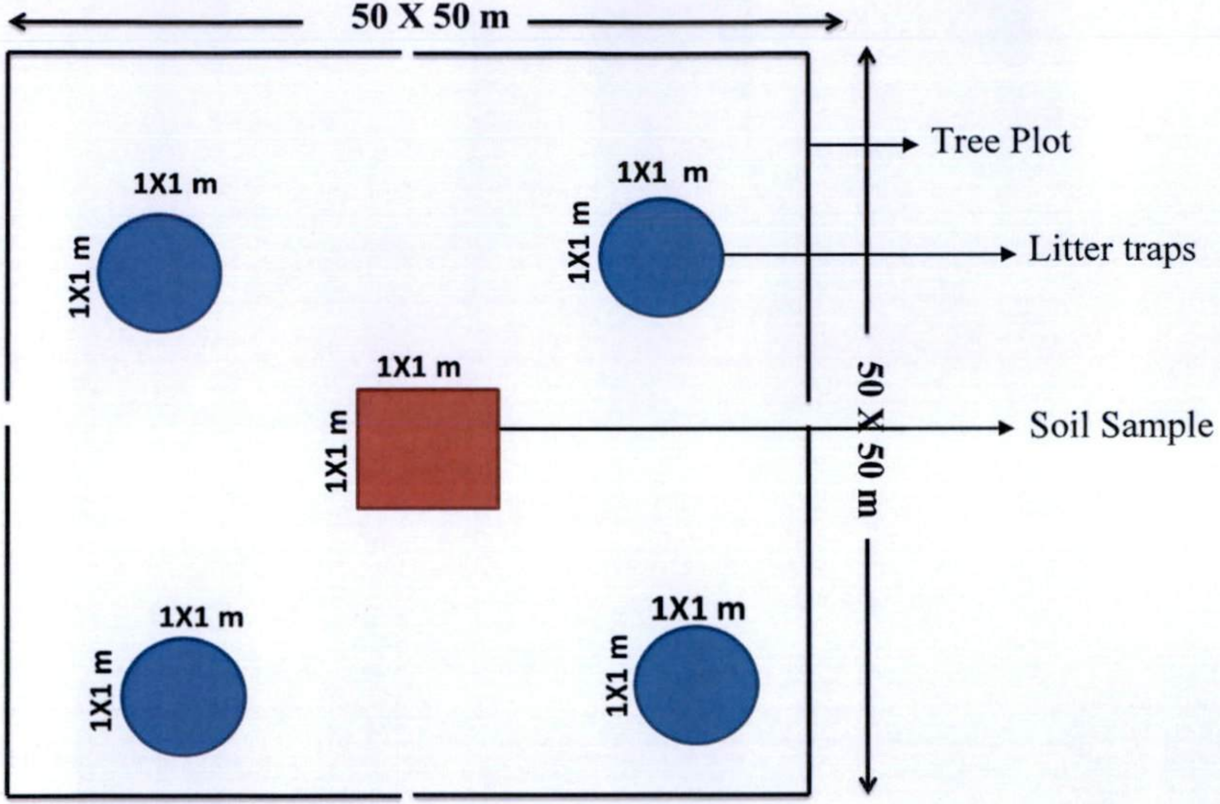


Figure 2 Sampling design showing a site (50 x50m^2) Soil sample (1X1m^2) and Leaf litter collection (1X1m^2)

Table 1 Description of study site for teak growing areas in Kerala

Divisions	**Ranges**	**Divisions**	**Ranges**
Kannur	1.Kannavam	Vazhachal	26. Palappilly
	2.Kottiyur		27. Vellikulangara
Wayanad North	3. Begur		28. Charpa
	4. Periya		29. Sholayar
	5. Mananthavady		30. Kollathirumedu
Wayanad South	6. Kalpetta		31. Athirapally
	7. Meppady	Malayattor	32. Kalady
	8. Chadleth		33. Kodanadu
Nilambur North	9. Nilambur		34. Thundathil
	10. Edavanna		35. Kuttampuzha
	11. Vazhikadavu	Ranni	36. Ranni
Nilambur South	12. Karulai	Konni	37. Konni
	13. Kalikavu		38. Naduvathumuzhi
Mannarkad	14. Attappadi		39. Mannarppara
	15. Agali	Achenkovil	40. Achenkovil
	16. Mannarkad		41. Kallar
Palakkad	17. Olavakkode	Punalur	42. Pathanapuram
	18. Walayar	Thanmela	43. Thanmela
	19. Ottapalam		44. Arienkavu
Nemmara	20. Nelliyampathi	Kothamangalam	45. Kothamangalam
	21. Alathur		46. Thodupuzha
Thrissur	22. Vadakkancherry		47. Mullaringodu
	23. Pattikad	Kottayam	48. Erimeli
	24. Machad	Munnar	49. Nerimangalam
Chalakudy	25. Panyaram	Trivandrum	50. Kulathupuzha

Table 2 Details of soil sample plots in different age classes of Teak plantations

Sl No.	**0-5 Year**	**6-10 Year**	**11-20 Year**	**21-30 Year**	**>30 Year**
1.	Achenkovil 2007	Chadleth 2003	Thanmela 1995	Kodanadu 1983	Athirapally 1954
2.	Pattikad 2007	Kannavam 2000	Konni 1999	Begur 1981	Charpa 1974
3.	Nagarampara 2007	Sholayar 2000	Pathanapuram 1993	Alathur 1990	Kalady 1949
4.	Vazhachal 2007	Erimeli 2003	Kollathirumedu 1994	Athirapally 1980	Kaliyar 1951
5.	Nelliyampathi 2007	Ottapalam 2004	Nerimangalam 1994	Vellikulangara 1983	Machad 1967
6.	Mannarppara 2008	Karulai 2001	Thodupuzha 1992	Kollathirumedu 1990	Mullaringodu 1967
7.	Nilambur 2007	Kottiyur 2000	Naduvathumuzhi 1998	Periya 1985	Palappilly 1974
8.	Edavanna 2007	Walayar 2000	Kothamangalam 1996	Mananthavady 1979	Periyaram 1962
9.	Mannarkad 2007	Meppady 2002	Olavakkode 1991	Kuttampuzha 1978	Ranni 1963
10.	Kallar 2008	Kalpetta 2000	Arienkavu 1990	Vazhikadavu 1988	Thundathil 1960

Plate.1 Different age classes of teak plantations in Kerala

Plate 2. Collection of soil samples in different age class of teak plantations in Kerala

along the direction of the slope. Soils collected from each pit in different horizons were air-dried, cleaned off visible roots and thoroughly ground using a wooden mortar and pestle taking care not to break the stones. This soil is then passed through a 2 mm sieve to separate the gravel. The amount of gravel in each sample thus obtained was recorded and the soil stored in the airtight containers for further analysis (Plate 1 & 2).

3.3 Soil analysis

3.3.1. Physical properties of soil

3.3.1.1 Soil texture

Particle-size separates were analyzed by International Pipette method (Piper, 1942). Twenty gram of soil was treated with 60 ml of 6 % H_2O_2 to destroy the organic matter in the soil, and with 200 ml of 0.2N HCL to remove $CaCo_3$. It was stirred well and kept on a water bath for 30 minutes or until effervescence ceased. The soil was then washed until it was free of chlorine (tested with silver nitrate solution). To this, 400 ml distilled water, 8 ml of 1 N NaOH and phenolphthalein indicator was added. The suspension, pink in colour, was then stirred and transferred to an 1000 ml measuring jar and the made up with distilled water. The temperature of the suspension was noted and contents shaken thoroughly with repeated inversions. At the end of four minute, 20 ml of the suspension was pipette out into a pre-weighed porcelain dish (W2) from a depth of 10 cm from the surface and evaporated on a water bath. This was then dried in an oven at 105°C and weighed after cooling (W1) to get a measure of silt and clay. The cylinder was shaken well and at the end of six hours, 20 ml of suspension was pipette out into another weighed porcelain dish (X_2). This was evaporated on a water bath and dried in an oven at 105°C and weighed alter cooling (X_1). This gives the amount of clay alone. The weight of silt was calculated by subtracting the weight of clay from that of silt + clay fraction. The remaining suspension was decanted into beaker by repeated washings, transferred to a pre-weighed dish (Y_2), dried in an oven and weighed again (Y_1). From this the weight of sand fraction was calculated as follows.

$$\text{Per cent of Clay + Silt} = \frac{(W1 - W2 - 0.0064)\ X\ 1000\ X\ 100}{20\ X\ 20}$$

W1= Wt. of dish + clay + silt +NaOH

W2 = Wt. of empty dish

Weight of sodium hydroxide alone = 0.0064g

$$\text{Per cent of Clay} = \frac{(X1 - X2 - 0.0064)\ X\ 1000\ X\ 100}{20\ X\ 20}$$

X1 = Wt. of the dish+clay +NaOH

X2 = Wt. of empty dish

$$\text{Per cent of Sand} = \frac{(Y1 - Y2)\ X100}{20}$$

Y1= Wt. of 'dish+' sand

Y2= Wt. of empty dish

3.3.1.2 Bulk density

Bulk density of soil indicates the degree of compactness of the soil and is defined as mass per unit volume. Bulk density varies with particle size distribution, organic matter content, mechanical composition and depth of soil. Core sample technique was used for measuring the bulk density of soils (Sankaram, 1966). The length and diameter of the soil auger sampler were measured using digital vernier calipers. The core sampler was horizontally hammered into the soil to a soil depth of 100 cm. The soil sticking to the outside of the core sampler was removed to enable easy withdraws of the sampler along with the sample from the field. The bottom of the sampler was covered with a lid to prevent the soil sliding from the sampler and transported to the laboratory. The soil inside the core was pushed out and with markings at different profiles. The soil was cut at different depth soils of one meter and each sample was air dried and weighed. The bulk density was calculated by using the formula

$$\text{Bulk density (g/cm}^3) = \frac{\text{Soil weight}}{\text{Core volume } (\pi r^2 l)}$$

Where r is the radius and l is the length of the core sampler.

3.3.1.3 Particle density

Particle density was calculated by the method described by Black (1965). Standard flasks of 25 ml capacity were washed with distilled water, dried and weighed. Ten grams of soil was transferred to the flask and weighed accurately (Ws). The flask was then half filled with distilled water, by adding water slowly through the sides of the cylinder, allowing it to soak the soil completely. The cylinder was then boiled gently on a water bath and tapped intermittently to remove the entrapped soil air. The flask was cooled to room temperature, filled up to the mark with cool boiled water. Wiped with filter paper to remove any water sticking to the sides and weighed (Wsw). The flask was then emptied, washed and filled up to the mark with distilled water wiped with filter paper and weighed (Ww). The particle density was calculated using the formula

$$\text{Particle density (g/cm}^3) = \frac{[Dw(Ws - Wa)]}{(Ws - Wa) - (Wsw - Ww)}$$

3.3.1.4 Pore space

The per cent pore space is an important soil physical property and indicates the soil volume occupied by soil air or soil water. Pore space was calculated from bulk density and particle density values as described below (Sankaram, 1966)

$$\text{Pore space} = 1 - \left(\frac{\text{BD}}{\text{PD}}\right) X100$$

Where BD= Bulk Density

PD=Particle Density

3.3.1.5 Maximum water holding capacity

Maximum water holding capacity was calculated by the method described by Sankaram (1966). A plastic container of 8 cm diameter and 9.5 cm height, with holes drilled at the bottom was taken. Whatmann filter paper (No. 1) of appropriate size was placed at the bottom of the container so as to cover the holes. The container with filter paper was weighed (W_a). Soil was gently poured into the container to fill it, tapped 20 times from a height of 2 cm and weighed (W_b). This was then kept overnight in a trough with sufficient water to saturate the soil. The excess water was drained and the weight determined (Wc). The maximum water holding capacity was calculated using the formula

$$\text{Maximum Water Holding Capacity (\%)} = \frac{(\text{Weight of saturated soil} - \text{Weight of dry soil})}{\text{Weight of Dry soil}} \text{X } 100$$

Where, Weight of saturated soil = (Wc – Wa) and weight of dry soil – (Wb – Wa).

3.3.2 Chemical Properties

3.3.2.1 Soil pH

The soil pH was determined in an l: 2.5 (Soil water) suspension by using ELICO, L1614 pH meter (Jackson. 1958). The pH meter was calibrated for pH 4.0. 7.0 and 9.2 using buffer solutions, prepared from readily available buffer tablets. Ten gram of air-dried soil was weighed accurately in a beaker and 25 ml of distilled water was added. The contents were stirred with a glass rod and allowed to stand for 30 minutes. The pH of the supernatant solution was measured with utmost care with the glass electrode just touching the soil layer.

3.3.2.2 Carbon, Nitrogen and Sulphur estimation

The total carbon, nitrogen, and sulfur were determined using a CHNS analyzer; (NA 1500, Carlo Erba Instruments). For the analysis, freeze-dried and crushed samples were weighed (5-10 mg) and mixed with an oxidizer (V_2O_5) in a tin capsule, which was then combusted in a reactor at 1000 °C. The sample and container melted, and the tin promote a violent reaction (flash combustion) in a temporarily oxygen enriched atmosphere. The combustion products CO_2, SO_2, and NO_2 were carried by a constant flow of carrier gas (helium) that passes through a glass column packed with an oxidation catalyst of tungsten trioxide (WO_3) and a copper reducer, both kept at 1000 °C. At this temperature, the nitrogen oxide is reduced to N_2. The N_2, CO_2, and SO_2 are then transported by the helium to, and separated by, a 2 m long packed column (Poropak Q/S 50/80 mesh) and quantified with a thermal conductivity detector (TCD) (set at 290°C.)

3.3.2.3 Available phosphorus

Available phosphorus was extracted using Bray's No.1 extract ant (0.03N ammonium fluoride + 0.025N hydrochloric acid) (Bray and Kurtz, 1945) and phosphorus content was determined spectrophotometrically by ascorbic acid reduced molybdophosphoric blue color method (Watanabe and Olsen. 1965). Standard solutions of 1, 3, 5, 10 and 15 mgl^{-1} were prepared by appropriate dilutions for preparation of standard curve. The soil extract was prepared by shaking 5 g of soil with 50 ml of Bray's No.1 extractant and filtered with No. 42 filter paper. The solution was re-filtered with activated charcoal. Five ml of extractant was pipetted into 25 ml volumetric flask and carefully acidified with 5N Sulphuric acid to pH 5. To this 7.5 ml of boric acid was added to prevent interference with fluorine. To this four ml of coloring reagent was added and the volume made up to mark. The coloring reagent was prepared by dissolving ascorbic acid (1.056g) in antimony potassium tartarate and ammonium molybdate solution (12g of ammonium molybdate was dissolved in 250 ml of distilled water and 0.297g of antimony potassium tartarate was dissolved) in 100 ml of distilled water separately. Both these solutions were added to 2000 ml of volumetric flask. It was mixed thoroughly and made up to the mark. The solution was allowed to settle for 10 minute. The blue colour developed was read at 660nm in a Spectrophotometer. The process was repeated with standard phosphorus solution of varying concentrations to prepare a standard curve. From the standard curve, concentration of phosphorus in the extract was read.

3.4 Plant Analysis

3.4.1 Total nitrogen

Nitrogen was estimated by Microkjeldahl method (Tandon, 2009). 10 ml of the digested sample were taken and transferred to vacuum jacket of Microkjeldal distillation apparatus. In a conical flask, 10 ml of four per cent boric acid solution was taken containing bromocresol green and methyl red indicator, to which the condenser outlet of the flask was dipped. After adding the aliquot, the funnel of the apparatus was washed with 2-3 ml of de-ionized water and 10 ml of 40 per cent NaOH solution was added. Finally 5 ml aliquot was added to the flask containing 10 ml of boric acid.

After completion of distillation, the boric acid was titrated against N/200 H_2SO_4. Blank was also run and titration was carried out to the same end point as that of sample. The nitrogen content of plant sample was calculated as follows

$$\text{N in \%} = \frac{\text{TV x } 0.00007\text{x } 100\text{x}100}{0.5 \text{ x } 5} \left(1 \text{ ml of} \frac{N}{10} H_2SO_4 = 0.00014\text{g N}\right)$$

- Weight of sample =0.5 g
- Normality of H_2SO_4 = N/200
- Volume of digestion = 100ml
- Aliquot taken 5 ml
- Titration value (TV) = sample titration value – blank titration value.

3.4.2 Phosphorus

For the analysis of P, diacid extracts were prepared (Tandon, 2009). One gram ground plant material was placed in 100 ml volumetric flask. 10 ml of acid mixture was added and content of the flask was mixed by swirling. The flask was placed on low heat hot plate in a digestion chamber. Then the flask was heated at higher temperature until the production of red NO_2 fumes ceases. The contents are further evaporated until the volume was reduced to about 3 to 5 ml but not to dryness. The completion of digestion was confirmed when the liquid becomes colorless. After cooling the flask, add 20 ml of deionized or glass-distilled water. Volume was made up with deionized water and solution was filtered through Whatman No.1 filter paper. Aliquot of this solution were used for the determination of Phosphorus. Add 10 ml of vanadomolybdate reagent to each flask. Make up the volume with deionized water shake thoroughly. Read the transmittance or absorbance of solution after 30 minutes at 420 nm with spectrophotometer or colorimeter using blue filter.

$$\text{P in \%} = \text{sample conc. (ppm)X} \frac{1}{\text{Wt. of sample(g)}} \text{X} \frac{100}{\text{Aliquot (ml)}} \text{X} \frac{\text{Final volume (ml)}}{10000}$$

3.4.3 Sulphur

A 10 ml of aliquot from plant digest (described under Phosphorus) was pipetted and the procedure described for standard curve preparation was followed. Sulphur concentration was calculated from the standard curve (Tandon, 2009).

$$\text{S in \%} = \frac{R}{4} X \frac{100}{\text{Sample}} X \frac{100}{1{,}000{,}000}$$

3.4.2.4 Lignin estimation

Acid detergent fiber (ADF) concentrations in feed samples were determined according to the procedure of Van Soest *et al.* (1991). One gram of air dry sample was weighed into beaker of the refluxing apparatus. 100 ml acid detergent solution and 2 ml decahydronaphathalene was added to this. Heat to boiling 5 to 10 minutes, reduced heat as boiling begins in order to avoid foaming. Reflux for 60 minutes from onset of boiling. Filter through a weighed glass crucible on a filter manifold. Rinse the sample into the crucible with minimum of boiling water. Filter liquid and repeat washing procedure. Wash twice with acetone in the same manner. Break up all lumps so that the solvent may come in content with all particles of fibre. Hexane should be added while crucible still contains some acetone. Suck the acid detergent fibre free hexane and dry at 100 ^{0}C for 8 hours in hot air oven and weighed.

$$\text{Acid detergent Fibre (\%)} = \frac{(\text{Wt. of crucible} + \text{Fibre}) - \text{Wt. of Crucible}}{\text{Wt. of the sample}} X100$$

After that fill the crucible containing ADF with 72 per cent of H_2SO_4 and stir with glass rod to smooth the paste and break the lumps. Let glass rod remain in the crucible. Refill with 72 per cent H_2SO_4 and stir at hourly intervals as acid drains away. Crucible need not be kept full at all times. Keep the crucible at room temperature. After 3 hours off as much acid as possible. Wash the contents with hot water until it is free from acid. Then remove the glass rod. Dry the crucible at 100^{0}C for 8 hours, and weighed after cooling, use muffle furnace at 500 to 550 ^{0}C for 3 hours cool and weighed.

$$\text{Acid detergent Lignin (\%)} = \frac{\text{(Wt.of crucible+residue after acid treatment)} - \text{(Wt.of Crucible+Ash)}}{\text{Wt.of the sample}} \text{X100}$$

3.5 Secondary data

Weather data - Rainfall, Maximum and Minimum temperature of all the four zones for 11 years (2000-2012) obtained from Meteorological substation at Ambalaveli, Kerala. Monthly average value, standard deviation and skewness for rainfall were calculated, Data was compiled and average values were calculated.

3.6 CENTURY model - development and working

The program "CENTURYM" is a FORTRAN representation of the CENTURY Soil Organic model which was developed by Parton *et al.* (1987). It simulates C, N, P, and S dynamics through an annual cycle to centuries and millennia. Forest system can selected as a producer submodel with the flexibility of specifying potential primary production curves which represent the site-specific plant community.

The CENTURY model obtains input values through twelve data files. Each file contains a certain subset of variables; for example, the *cult.100* file contains the values related to cultivation. Within each file there may be multiple options in which the variables are defined for multiple variations of the event. For example, within the cult.100 file, there may be several cultivation options defined such as plowing. For each option, the variables are defined to simulate that particular option. Each data input file is named with a ".100" extension to designate it as a CENTURY file. These files can be updated and new options created through the FILE.100 program (Fig.3).

3.6.1 Soil Organic Matter Submodel

The SOM submodel is based on multiple compartments and is similar to other models of SOM dynamics (Jenkinson and Rayner, 1977; Jenkinson, 1990; van Veen and Paul, 1981). The pools and flows of C are illustrated in Fig.7. The model includes three soil organic matter pools (active, slow and passive) with different potential decomposition rates, above and belowground litter pools and a surface microbial pool which is associated with decomposing surface litter.

3.6.2 Model Parameterization

The model was parameterized to simulate soil organic matter dynamics in the top 20 cm of the soil. The model does not simulate organic matter in the deeper soil layers and increasing the soil depth parameter (*fix.100*) does not have much impact on the model. To simulate a deeper soil depth (0-30 or 0-40 cm depth) the soil organic matter pools must be initialized appropriately. As a general rule deeper soil depths have older soil carbon dates (Jenkinson *et al.,* 1992) and lower decomposition rates (lower temperature at deeper depths). Thus, it would be assumed that the fraction of total SOM in the passive SOM would be greater. The major change for initializing the model for deep soil depths is adjusting the fraction of SOM in the different pools (more C in passive SOM). The initial soil C levels should reflect the observed soil C levels over that depth and the decomposition rates should be decreased for all of the SOM pools. To increase the soil depth from 20 cm to 30 cm, the decomposition rates should be decreased by 15%. The other adjustment would be to increase the rate of formation of passive SOM; the recommended way is to increase the flow of C from active and slow SOM to passive SOM.

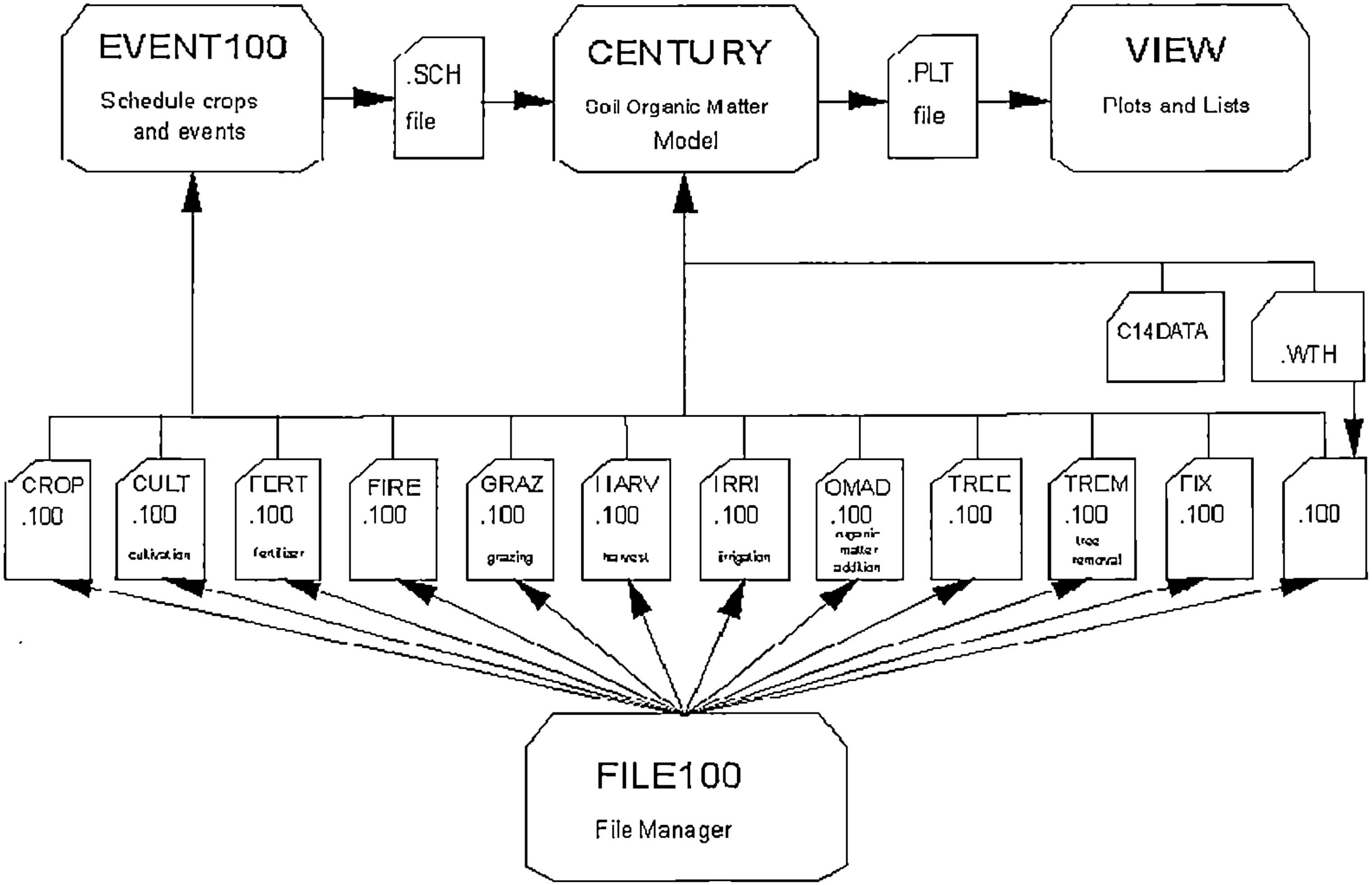


Figure 3 The Century model environment showing the relationship between programs and the file structure

3.6.3 Carbon Sequestration Potential in Teak plantations:

The Modelling of carbon sequestration in teak (*Tectona grandis*) was done using the CENTURY model.5 (Parton *et al.,* 1987). The procedure involved collecting the relevant site data, including weather, land cover, and soil data. The parameters were prepared to be compatible with the models using a .100 file for the site specific parameters which include latitude and longitude of site, fraction of sand, silt, and clay in the soil, bulk density of soil, and the number of soil layers to simulate. Site specific event options such as CROP.100, CULT.100, FIRE.100, FERT.100, TREE.100, SITE.100 and HARV.100 were created. The next step was the creation of schedule files which determined the order and types of events that were included in the simulation and, the simulation was run. Finally, the model outputs were examined for accuracy with NPP. This is because if the net primary productivity (NPP) that the model is predicting for the site is not correct, then none of the other model outputs can be expected to be representative of the conditions at the site. Thus, the simulated carbon values were compared with the carbon baseline data obtained from teak plantation, and simulation results from literature.

The general procedure followed for running the model is as follows: The site data (location and soil), was collected and entered the site specific parameters into a <site>.100 file. The site specific event options (crop, cultivation, fire, fertilizer, etc) were created in the event.100 file and the schedule file (which determines the order and types of events) using the event.100 utility was created. The simulation was then run. Schematic diagram of the input files needed for running the simulation is given in figure.4

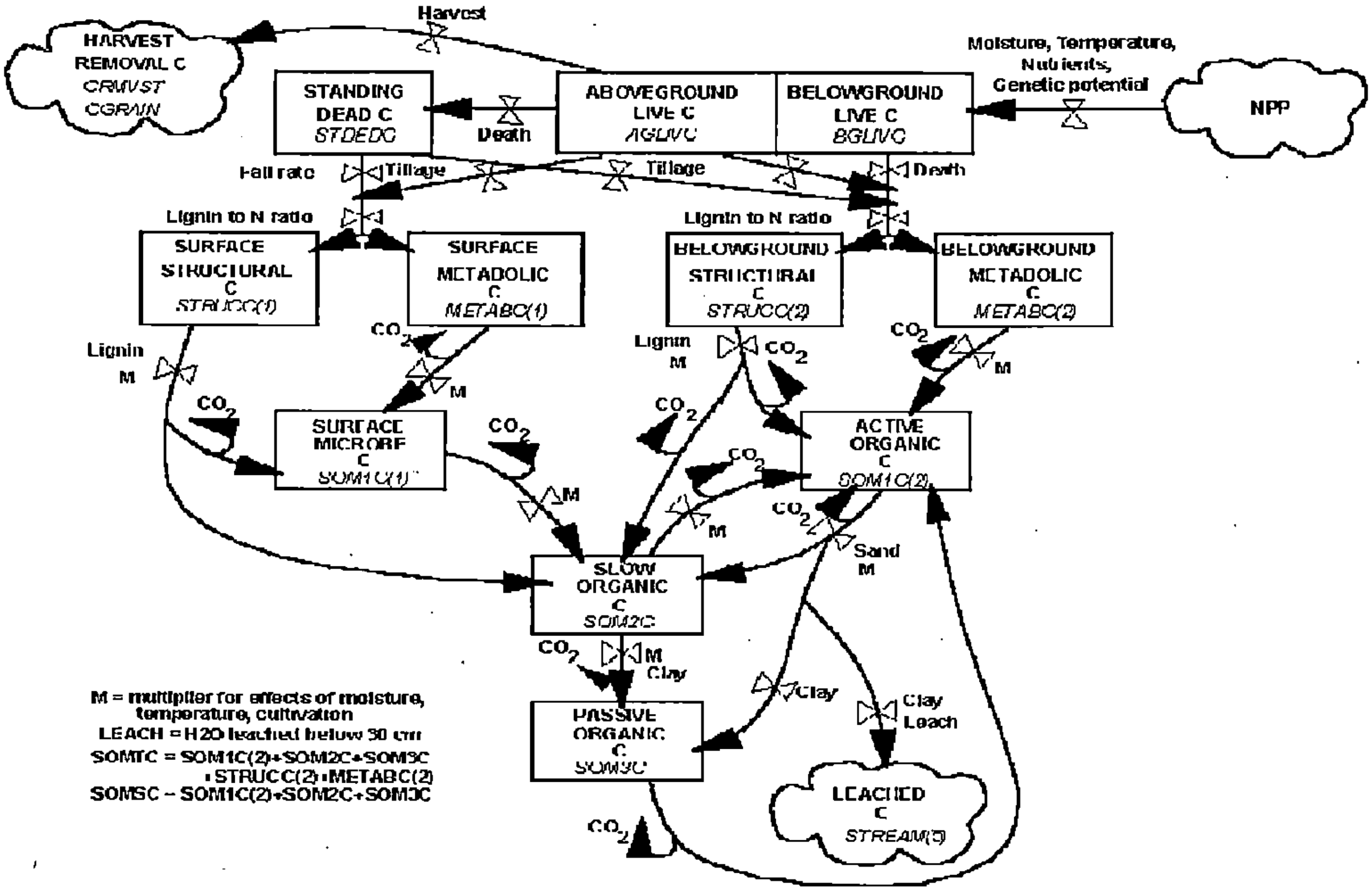


Figure 4. The pools and flows of carbon in the CENTURY model. The diagram shows the major factors which control the flows

3.7 Modeling standardization and validation

3.7.1 Model Parameterization

Parameterization was made by reviewing all the parameters of *.100* files in the Century model. The parameters of Century are given in twelve different *.100* files viz., crop.*100*, cult.*100*, fert.*100*, fire.*100*, fert.*100*, graz.*100*, harv.*100*, irri.*100*, omad.*100*, tree.*100* and site.*100* files.

Parameterization was mainly done for two *.100* files viz., tree.*100* and site.*100.*

3.7.1.1 *Weather file*

Monthly precipitation, minimum monthly temperature and maximum monthly temperature were used from 2000 to 2012. These records were obtained from the meteorological sub-station of Ambalavayal for Wayanad district and from nearby areas of study sites. Monthly temperatures were averaged from the 12 years of observations. Monthly precipitation was determined using monthly mean, standard deviation and skewness values from the data (Table 3)

3.7.1.2 *.100 files*

The following section described the individual *.100* files used to parameterize century for teak plantations in Kerala. Default values refer to those values listed for the parameters in the Century manual.

3.7.1.2.1 *Crop.100*

The *crop.100* file contains the parameters that govern the effect produced by crop cultivation. The parameter *prdx(1)* narrates potential aboveground monthly

Table 3. Temperature and precipitation in site.100 file of teak plantation in Kerala

Month	**Temperature (^{0}C)**		**Precipitation (cm)**		
	Min	**Max**	**Mean**	**Std**	**Skew**
January	22.40	32.79	0.07	0.21	3.61
February	22.64	34.45	2.21	4.74	2.61
March	24.13	35.29	3.69	6.05	2.17
April	24.89	34.41	9.69	6.93	1.10
May	24.76	32.74	22.25	19.77	1.50
June	23.48	29.92	65.91	9.95	0.46
July	23.00	29.24	56.49	24.59	1.48
August	23.08	29.50	45.41	14.35	0.01
September	23.12	30.32	31.07	18.91	1.14
October	23.08	31.12	31.34	14.96	1.12
November	23.12	31.57	8.90	9.04	1.28
December	22.58	31.74	0.91	1.30	1.73
VARIABLE	*tmn2m*	*tmnx2m*	*precip*	*prcstd*	*prcskw*

production for crops (gC/m^2). *pltmrf* specifies planting month reduction factor to limit that influence seedling growth and *fulcan* depicts value of above ground live matter at full canopy cover, above which potential production is not reduced. *frtc(1)* and *frtc(2)* provides initial and final fraction of C allocated to roots. *frtc* (3) depicts time after planting (months with soil temperature greater than rtdtmp) at which the final value is reached. The parameter *biomax* specifies biomass level (gram biomass per square meter) above which the minimum and maximum C/E ratios of new shoot increments equal *pramn* and *pramx* respectively. *prbmn (3,2)* and *prbmx(3,2)* gives parameters for computing minimum and maximum C/N ratio for belowground matter as a linear function of annual precipitation respectively. Parameter *fligni(1,1)* indicates lignin content fraction based on annual rainfall for aboveground material while *fligni(1,2)* gives lignin content fraction based on annual rainfall for belowground material. *himax* details harvest index maximum (fraction of aboveground live C in grain) and *hiwsf* depicts harvest index water stress factor. *himon(1)* details the number of months prior to harvest in which to begin accumulating water stress effect on harvest index. The parameter *efrgrn(3)* narrates fraction of the aboveground E which goes to grain and *vlossp* specifies fraction of aboveground plant N which is volatilized (occurs only at harvest). *fsdeth(4)* depicts the level of aboveground C above at which shading occurs and shoot senescence increases.

Parameter *fallrt* specifies fall rate (fraction of standing dead which falls each month) and *rdr* gives maximum root death rate at very dry soil conditions (fraction/month). *rtdtmp* details the physiological shutdown temperature for root death and change in shoot/root ratio.

3.7.1.2.2 *Cult.100*

The *cult.100* denotes the cultivation options for carbon modeling. *cult.100* contains two important variables *cultra* and *clteff. cultra* has the following parameters options. *cultra(1,2,3)* denotes fraction of above live biomass, which is transferred to standing dead (*cultra(1)*), surface litter (*cultra(2))* and top soil layer (*cultra(3)). Cultra(4)* and *cultra(5)* denotes fraction of standing dead which is transferred to surface litter and top soil layer respectively. Fraction of surface litter and root transformed to soil layer is given as *cultra(6)* and *cultra(7)* respectively.

3.7.1.2.3 *Fert.100*

Rates of nitrogen additions were determined using Kerala forest working plan records and values were given in *feramt* (1 to 3). The amount of N, P and K was expressed in terms of gram per meter square. In the first year of teak planting, the average NPK added were 30 g m^{-2} yr^{-1} and from 4th year, 50 g m^{-2} yr^{-1}. For each rate of application, the *feramt(1)* parameter was set to the appropriate value. All other parameter values were set to zero (*aufert*=0).

3.7.1.2.4 *Fire.100*

The fire.*100* file parameters were modified to medium fire in teak plantations. Default values were used in two parameters; *fdereml* which indicates the fraction of standing dead plant material removed by a fire event as it was set as 0.7 and second one *fderem2,* specifies the fraction of surface litter removed by a fire event which was set as 0.3. The studies conducted by Balagopalana and Alexander 1987; Jeremy *et al* ., 2009 and Suzuki *et al* ., 2007 reported that the fraction aboveground materials of N, P and S removed by a fire event were used for estimate *fret 1* to *fret 3* parameters (0.2, 1.0, 0.1) and also the effect of fire on increase in maximum C/N ratio of shoots (*fnue 1*) and roots (*fnue 2*) are 10 and 30 (Haripiya.2003).

3.7.1.2.5 *Graz.100*

graz.*100* file was modified depending on the animal and type of grazing . *graz.100* contains *flgrem*, *fdgrem* and *gfcret* indicating fraction of live shoots removed by a grazing event, fraction of standing dead removed by a grazing even and fraction of consumed C which is excreted in faces and urine respectively. It contains the same parameters as low intensity grazing (GM), with the exception of *grzeff* (the grazing effect on production), which was set to zero. The *feclig* indicates the lignin content of feces

3.7.1.2.6 *Harv.100*

The harv.*100* file contains different parameters of harvest. Two important options available are *rmvstr,* that specify the fraction of the aboveground residue removed (T90S - 90% of teak removal) and *remwsd* that indicates fraction of the remaining residue that was left standing (T10S - 10% teak tree straw removal), were added in the Century manual to provide a variety of removal options (Thomas *et al* ., 2013). These values were set to be 0.90 or 0.10 in *rmvstr*. To assist with the nomenclature, name of the option that removed 90% of the tree was changed from TS to T90. The remaining parameters were set at zero.

3.7.1.2.7 *Irri.100*

The *irri.100* file specifies a parameter called *auirri,* which controls the automatic irrigation depending on the irrigation type,. The values can be fixed at 0, 1, 2 and 3, to provide various types of irrigation methods. The other parameters namely *fawhc,* indicates the fraction of available water holding capacity beyond which automatic irrigation will be used (when *auirri* = 1 or 2), *irraut* specifies amount of water to automatically applied (in centimeters), and *irramt* indicates amount of water to be applied regardless of soil water status estimates (in centimeters).

3.7.1.2.8 *omad.100*

omad.100 file contains parameters for providing organic fertilizer. This option models manure additions to different land use including forests, cropland, grassland, or savanna fields. Parameters used are *astgc*, that indicates the grams of C added with the addition of organic matter (g/m^2), *astlbl* that specifies fraction of added C which is labeled (when C is added as a result of the addition of organic matter), *astlig* that details lignin fraction content of organic matter and *astrec* that stipulates C/N, C/P, C/S ratios of added organic matter.

3.7.1.2.9 *tree.100*

The tree.*100* file parameter gives information on vegetation and physiological characteristics of a tree. The parameters are *prdx* (3) and *prdx* (4) (plant production variables). *prdx* (3) provides values of maximum gross primary production (GPP), expressed in terms of biomass gram per unit area per month. *prdx* (4) is concerned with regulation of maximum net primary production (NPP) expressed in biomass added every month. In century, total plant primary production is assumed to be distributed to all the parts of the plant and net primary production is allocated into five different plant components of the tree (leaves, fine roots, branches, stems, and coarse roots). The parameters that governs this allocation are *cerfor*, *fcfrac*, *wooddr*, *leafdr* and *wdling (1to5)* indicates the lignin fraction of tree components.

The parameter *cerfor* generally gives the maximum, minimum and initial C to N, P and S ratios that is contained in five different components of the tree. In this study, *cerfor* was used only for studying the C/N ratio. The *fcfrac* parameter indicates the value of carbon allocated from net primary production to different tree parts based on the characteristic of the tree. The *wooddr* specifies the fraction of biomass turnover rates of five different tree components, *wdlig* (1) to *wdlig* (5) details the fraction of lignin, which determines the rate of decomposition of litter in the tree components and *leafdr* gives the death rate of leaf for each month. The values of parameters discussed above are included in the appendices (Appendices IV).

3.7.1.2.10 *site.100*

Site.100 file gives information related to environment and site characteristics. The parameters included are *precip* (1-12), *precstd* (1-12) and *precskw* (1-12) which indicates the precipitation for January to December, standard deviation and skewness respectively expressed in terms of centimeters per month. *tmn2m* (1-12) and *tmx2m* (1-12) indicates the minimum and maximum temperature.

The estimates of the site.*100* file is based on the C, N and S pools in biomass by components (leaf, fine roots, branches, large woods, coarse root, dead large wood and standing dead trees) from *tree.100* data. Soil carbon pools with different turnover rates (fast, intermediate and slow), C/N and C/P ratios of soil organic matter, soil pH and bulk density were also used for the estimation. The calculation of carbon pools by turnover rate C/N, C/P, and C/S ratios of soil organic matter, the death rate of forest compartments and leaf area control are estimated based on the formulas in the Century parameterization work book.

3.7.2 Model evaluation

The century model output was compared with field data of SOC (0-20cm) to evaluate the performance of the century model. Visual examination of graphic output allows qualitative evaluation. The measured and modeled datasets were compared qualitatively through graphs and quantitavely by a numbers of statistical tests were used to evaluate the CENTURY model performance. The selected parameters were: the sample correlation coefficient (r), the coefficient of determination (CD), the root mean square error (RMSE), and EF which is modelling efficiency (Smith *et al.*, 1996).

3.8. STELLA Software

3.8.1 Description

The dynamic models were developed using the STELLA software. STELLA is a graphical non-spatial programming language. Because of its capabilities to represent interactions between elements in a dynamic system, the software was widely used to model dynamic systems (Tangirala *et al.*, 2003). Models are generally built using the following four components (Stocks, Flows, controllers, connectors) (Ruth *et al.*, 2002).

3.8.2 Model Structure in STELLA

STELLA is a modeling tool for building a dynamic modeling system by creating a pictorial diagram of a system and then assigning the appropriate values and mathematical functions to the system (Isee Systems, 2006). The key features of STELLA consist of the following four tools (Fig. 5): (1) stocks, which are the state variables for accumulations; they collect whatever flows into and out of them; (2) flows, which are the exchange variables that control the input, output, and exchanges of information between the state variables; and (3) converters, which are the auxiliary variables; these variables can be represented by constant values or by values depending on other variables, curves, or functions of various categories; and (4) connectors, which provide connections between modeling features, variables, and elements. STELLA has been widely used in the biological, ecological, and environmental sciences (Ouyang *et al.,* 2012). A complete description of the STELLA package can be found in Isee Systems (2006).

3.8.3 Modelling Approaches

In modelling ecological and economic systems, purposes can range from developing simple conceptual models, in order to provide a general understanding of

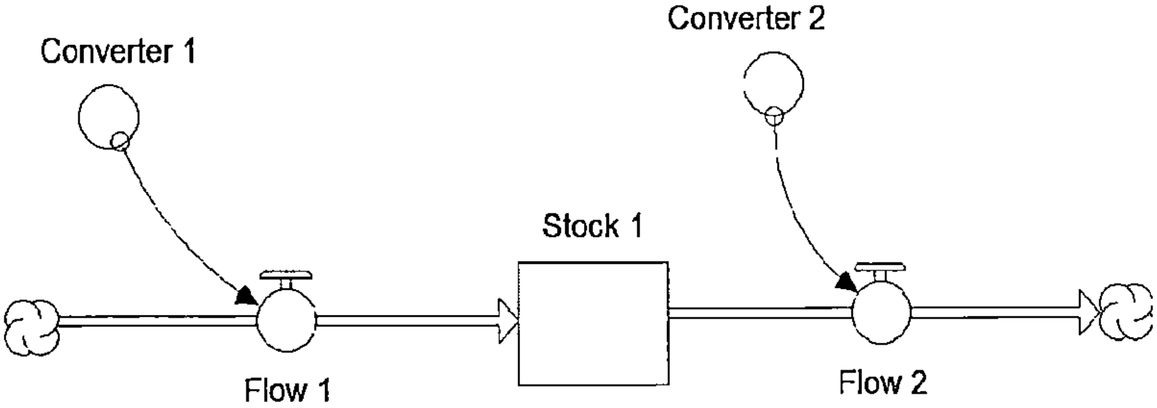


Figure.5 A schematic diagram showing the four key features of STELLA (1) stock, (2) flow, (3) converter, and (4) connector

system behavior, to detailed realistic applications aimed at evaluating specific policy proposals. It is inappropriate to judge this whole range of models by the same criteria. At minimum, the three criteria of *realism* (simulating system behavior in a qualitatively realistic way), *precision* (simulating behavior in a quantitatively precise way), and *generality* (representing a broad range of systems' behaviors with the same model) are necessary. The models presented in carbon issue were aimed at developing basic understanding of the system dynamics and therefore emphasized generality over realism and precision. This does not preclude later versions of the models aimed toward more realism and precision, of course. In fact, general, or `scoping', models to be seen as the logical first step in a multistep modelling process where the general model sets the stage for later, more precise and realistic research and management models (Costanza and Ruth, 1997).

Results

4. RESULTS

The results of the study "Modelling carbon dynamics in teak plantations of Kerala" are furnished in this chapter. These analysis pertain to the estimation of long term trends in carbon sequestration which are considered relevant in explaining the present and future conversion of teak plantation to other types of land use in Kerala.

4.1 Climate

The Kerala fall under a tropical climate where the coastal location and high variation in relief influences the climatic characteristics to a large extent. While most of the areas are under tropical dry and wet conditions with high maritime influence, certain areas in the eastern parts experience subtropical type of climate.

4.1.1Temperature

The average annual temperature is $24\ ^{0}$ C. The average monthly temperature in summer (February to May) is 32^{0} C (Fig 6). March is the hottest month with an average monthly temperature of 35^{0} C. From June onwards, the temperature gradually comes down due to the advent of monsoon. An increasing trend in temperature is noted in October and November. The average temperatures of 25^{0} C during December to January were the coolest months. The seasonal and diurnal variations in temperature are not uniform throughout the state. In some places of the state such as in Palakkad, the mean seasonal variation is less than the diurnal variation, but in the high ranges, which are typically sub-tropical, the diurnal variation is very high ($>15^{0}$C in some months)

4.1.2 Rainfall

The study areas experienced rainfall during winter: there was very little or no rainfall during summer. Maximum monthly precipitation occurs in June and can be

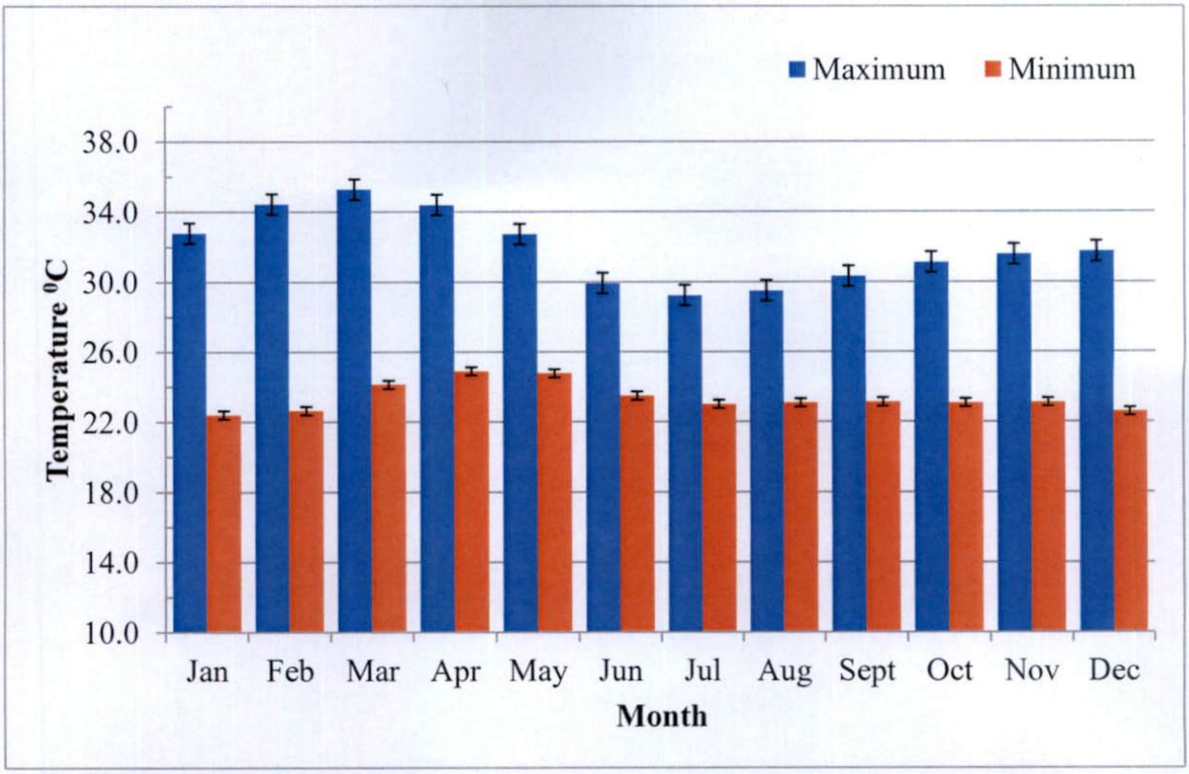


Figure 6. Monthly maximum and minimum temperatures in Kerala (2000-2012).

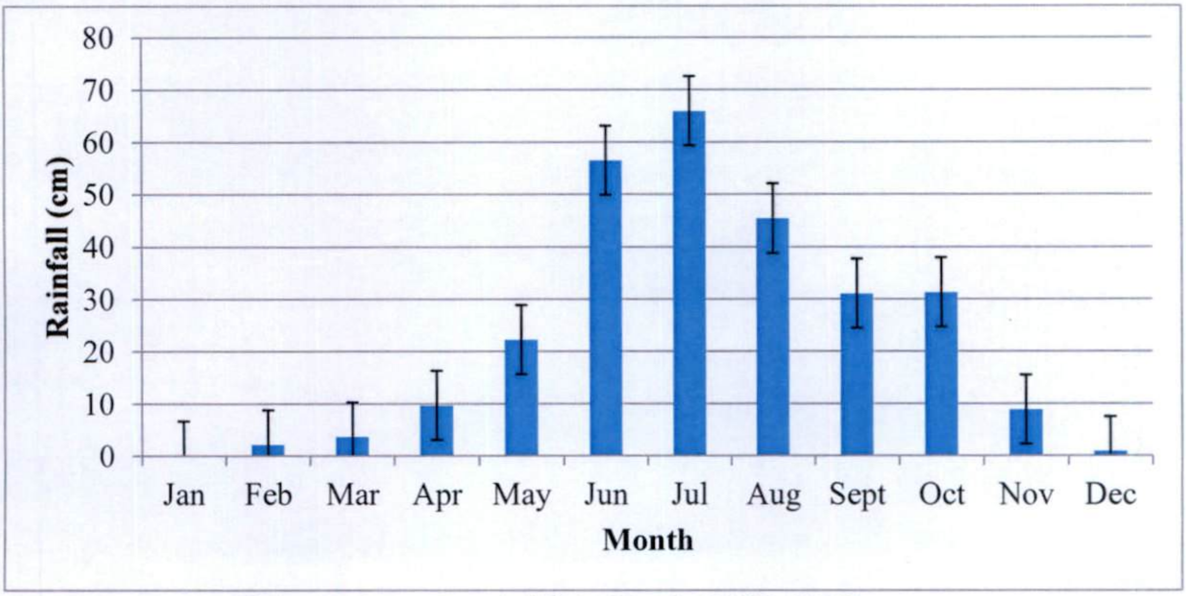


Figure 7. Average rainfall in Kerala (2000-2012).

up to 69 cm and from June onwards, the rainfall gradually comes down to 9 cm in the month of November (Fig 7).

4.2 Soils

Climate, geology, relief, vegetation and weathering processes are the main factors influencing soil formation. Precambrian crystalline rocks, tertiary sedimentary formations, quaternary and recent deposits constitutes the parent materials in Kerala.

4.3 Soil studies

4.3.1 Physical properties

Results of the study on soil physical properties *viz.,* soil texture, water holding capacity, soil porosity, bulk density and soil moisture in teak plantations of Kerala is presented below.

4.3.1.1 Soil Texture

The texture analysis revealed that the texture was sandy loam for all the sites and at different depth of soils in teak plantations of Kerala (Table 5).

The sand percentage varied from 67.61 % to 72.2 % at a depth of 0-20 cm. The silt content varied from 11.21 % to 12.90 %, while the clay varied from 12.73 % to 14.82 % at 0-20 cm. The sand content at 20-40 cm was found to be from 68.80 % to 72.90 %. The silt content at this depth was 10.80 % to 12.45 %, while the clay ranged from 11.92 % to 14.61 %.

Table 5. Particle size distribution of soil at different depths under the different age class of teak plantations in Kerala

Parameters	**Depth** (cm)	**0-5Y**	**6-10Y**	**11-20Y**	**21-30Y**	**>30Y**
Sand (%)	**0-20**	71.00 ± 4.29	72.20 ± 5.94	67.61 ± 8.63	70.00 ± 8.74	71.80 ± 2.60
	20-40	70.90 ± 3.90	72.90 ± 4.33	68.70 ± 6.49	71.20 ± 8.94	72.20 ± 2.27
Silt (%)	**0-20**	12.80 ± 1.31	11.71 ± 2.75	12.90 ± 2.62	11.21 ± 2.57	12.30± 2.62
	20-40	12.45 ± 1.50	11.78 ± 2.01	13.00 ± 1.33	10.80 ± 3.15	12.40 ± 1.88
Clay (%)	**0-20**	14.42 ± 2.01	14.20 ± 1.68	12.81 ± 1.13	12.73 ± 2.21	14.82 ± 1.61
	20-40	14.12 ± 2.02	14.00 ± 1.88	11.92 ± 2.02	12.40 ± 1.77	14.61 ± 1.57

4.3.1.2 Water Holding Capacity

The study on water holding capacity varied from 38.35 % to 39.87 % at a depth of 0-20 cm, while at 20-40 cm depth, varied from 37.82 % to 41.39 % (Table 6).

4.3.1.3 Soil Porosity

The soil porosity percentage ranged from a lowest value of 54.25 % to a maximum of 55.46 % at a depth of 0-20 cm, while at 20-40 cm was found varied from 53.88 % to 55.70 % (Table 6).

4.3.1.4 Bulk Density

Generally the bulk density values were higher in deeper layer of soil (Table 7). In the depth of 0-20 cm, 20-40cm 40-60cm and 60-100 cm, bulk density values varied from 1.07 to 1.09 gcm^{-3}, 1.10 to 1.16 gcm^{-3}, 1.13 to 1.24 gcm^{-3} and 1.15 to 1.36 gcm^{-3} respectively.

4.3.2 Chemical properties of Soil

4.3.2.1 Soil pH

The soil pH varied from 5.60 to 5.91 and 5.66 to 5.88 at a depth of 0-20 cm and 20-40 cm respectively (Table 6).

4.3.2.2 Nitrogen

The total nitrogen content in teak plantations ranged from 0.07 % to 0.34 % and it varied from 0.43 % to 1.23 % in natural forests (Table 8). The total nitrogen in soils was highest in the surface and decreased with the depth in both teak plantation

Table 6. Water holding capacity, Soil Porosity, and pH at different depths under the different age class of teak plantations

Parameters	**Depth cm**	**0-5Y**	**6-10Y**	**11-20Y**	**21-30Y**	**>30Y**
WHC (%)	0-20	38.94 ± 1.00	39.84 ± 1.81	38.35 ± 1.92	39.87 ± 1.36	38.65 ± 2.49
	20-40	37.82 ± 3.64	40.46 ± 1.83	40.15 ± 2.25	41.39 ± 2.65	39.97 ± 2.64
Soil porosity (%)	0-20	55.46 ± 1.95	55.16 ± 2.68	54.25 ± 3.19	55.36 ± 2.35	54.87 ± 2.43
	20-40	55.70 ± 1.83	54.47 ± 2.70	53.88 ± 3.15	54.55 ± 2.13	54.77 ± 2.20
pH	0-20	5.70±0.39	5.60±0.18	5.72 ±0.30	5.49 ±0.28	5.91 ±0.0.28
	20-40	5.66± 0.27	5.88 ±0.27	5.77±0.20	5.73 ±0.27	5.73±0.31

Table 7. Bulk density at different depths in different age class of teak plantations

Depth (cm)	**0-5 Year**	**6-10 Year**	**11-20 Year**	**21-30 Year**	**>30 Year**
0-20	1.09 ± 0.03	1.09 ± 0.06	1.08 ± 0.06	1.09 ± 0.09	1.07 ± 0.05
20-40	1.10 ± 0.04	1.13 ± 0.07	1.12 ± 0.04	1.16 ± 0.12	1.13 ± 0.03
40-60	1.13 ± 0.03	1.24 ± 0.20	1.22 ± 0.13	1.19 ± 0.08	1.14 ± 0.06
60-100	1.15 ± 0.02	1.31 ± 0.18	1.36 ± 0.28	1.23 ± 0.15	1.20 ± 0.06

and natural forest. The analysis of variance indicated that, no significant difference of total nitrogen in soils among different age classes of teak plantations.

The analysis of variance showed that, the total nitrogen was significantly different between teak plantation and natural forests. The highest total nitrogen recorded in natural forests was 1.20 % and lowest was 0.75 % at a depth of 0-20 cm while at 20-40 cm depth, the highest total nitrogen in natural forest was 0.84 % and the lowest was 0.43 %.

4.3.2.3 Available phosphorus

The available phosphorus varied from 1.31 to 4.81 mg kg^{-1} in teak plantations and from 2.92 to 4.82 mg kg^{-1} in natural forests (Table 9). The highest values were recorded at 0-20cm depth of both teak plantation and natural forest.

In teak plantations, the available phosphorus in the depth of 0-20 cm and 20-40 cm showed no significant difference while, at 40-60 cm depth, the age class of 6-10 Y (2.92 mg kg^{-1}) and 11-20 Y (1.29 mg kg^{-1}) were significantly different. At 60-100 cm depth, no significant difference were observed in available phosphorus among the different age classes of the plantations.

Teak plantation and natural forests did not differ in available phosphorus at different soil depths. In natural forest, the highest available phosphorus was recorded at 0-20 cm depth (4.85 mg kg^{-1}) and the lowest observed at the depth of 20-40 cm (3.16 mg kg^{-1}).

Table 8. Total soil nitrogen at different depths of teak plantations and natural forests

Vegetation type	Depth (cm)	0-5 Year	6-10 Year	11-20 Year	21-30 Year	>30 Year
Teak plantation	**0-20**	0.34 ± 0.35	0.21 ± 0.13	0.22 ± 0.14	0.21 ± 0.13	0.18 ± 0.11
	20-40	0.19 ± 0.17	0.15 ± 0.08	0.16 ± 0.10	0.19 ± 0.14	0.18 ± 0.10
	40-60	0.11 ± 0.09	0.09 ± 0.03	0.10 ± 0.05	0.15 ± 0.13	0.13 ± 0.12
	60-100	0.13 ± 0.08	0.16 ± 0.14	0.08 ± 0.05	0.11 ± 0.06	0.07 ± 0.08
Natural forest	**0-20**	1.20 ± 0.49	1.09 ± 0.45	0.97 ± 0.25	1.10 ± 0.39	0.75 ± 0.42
	20-40	0.84 ± 0.31	0.68 ± 0.45	0.68 ± 0.38	0.76 ± 0.28	0.43 ± 0.17

Table 9. Status of available phosphorus ($mgkg^{-1}$) in soils at different depths of teak plantations and natural forests

Vegetation type	Depth (cm)	0-5 Year	6-10 Year	11-20 Year	21-30 Year	>30 Year
Teak plantation	**0-20**	4.68 ±1.69	4.50 ± 0.89	4.06 ± 2.04	3.62 ± 1.70	4.81 ± 2.11
	20-40	3.21 ±1.43	3.60 ± 1.44	2.15 ± 1.06	3.78 ± 2.68	2.94 ± 1.31
	40-60	1.87 ± 0.68	2.92 ± 1.52	1.29 ± 0.78	1.99 ± 1.00	2.27 ± 1.36
	60-100	1.26 ± 0.38	2.26 ± 1.79	1.24 ± 0.98	1.48± 0.46	2.33 ± 2.06
Natural forest	**0-20**	4.18 ± 0.17	4.85 ± 1.77	4.11 ± 0.73	4.82 ± 2.77	4.22 ± 1.32
	20-40	3.49 ± 0.81	4.54 ± 0.60	2.92 ± 0.34	3.36 ± 1.44	3.16 ± 1.04

4.3.2.4 Sulphur

The sulphur varied from 0.23 to 0.09 % in teak plantations, while in natural forest sulphur was negligible to be noticed in the analysis (Table 10). The analysis of variance showed that there was no significant difference in Sulphur between the age classes of teak plantations.

4.3.2.5 Soil carbon

Generally the soil carbon in soils was highest in the surface and decreased with the depth in both teak plantation as well as natural forest (Table 11). The analysis of variance for soil carbon in different age class and depths showed no significant difference of soil carbon between the age classes of plantations.

When comparing teak plantation and natural forest based on depth, natural forest had higher soil organic carbon than teak plantation. The analysis of variance showed that the soil organic carbon was significantly different from natural forest to teak plantations. The highest soil organic carbon in natural forest was 2.51 %, followed by 2.47, 2.46, 1.92 % and the lowest was 1.77 %. In the 0-20 cm depth, the highest soil carbon was 2.91 % which was followed by 2.88 %, 2.20 %, and lowest was 1.97 %. At the depth of 20-40 cm, the highest soil carbon was 2.05 % followed by 2.01 %, 1.84% for the lowest was 1.68 %.

Table 10. Sulphur (%) in Soils at different depths of teak plantations and natural forests

Vegetation type	Depth (cm)	0-5 Year	6-10 Year	11-20 Year	21-30 Year	>30 Year
Teak plantation	**0-20**	0.23 ± 0.09	0.09 ± 0.008	0.08 ± 0.07	0.26 ± 0.18	0.11 ± 0.03
	20-40	0.14 ± 0.09	0.07 ± 0.032	0.04 ± 0.08	0.19 ± 0.07	0.07 ± 0.03
Natural forest	**0-20**	Trace	Trace	Trace	Trace	Trace
	20-40	Trace	Trace	Trace	Trace	trace

Table 11. Soil carbon (%) in soils at different depths of teak plantations and natural forest

Vegetation type	Depth (cm)	0-5Y	6-10Y	11-20Y	21-30Y	>30Y
Teak plantation	**0-20**	2.17±0.96	1.98 ± 0.48	2.48 ±1.16	1.89 ± 0.72	1.89 ±1.02
	20-40	1.92 ±0.60	1.45 ± 0.54	1.80 ± 0.81	1.50 ± 0.69	1.32 ± 0.92
	40-60	1.43 ±0.44	1.11 ±0.39	1.21 ± 0.73	1.38 ± 0.79	0.99 ± 0.89
	60-100	1.18 ± 0.47	1.26 ± 0.59	0.49 ±0.45	0.68 ±0.33	0.48±0.39
Natural forest	**0-20**	2.88± 0.59	2.91± 0.41	2.91±0.46	1.97 ± 0.62	2.20 ±0.59
	20-40	2.05 ±0.65	2.05 ±0.12	2.01 ±0.49	1.68 ±0.49	1.84±0.50
	40-60	1.38 ±0.30	1.22 ±0.23	1.17 ±0.27	1.29 ±0.27	1.13 ±0.12
	60-100	0.81 ±0.22	0.80 ±0.28	0.71 ±0.28	0.72 ±0.45	0.82 ±0.14

Table 12. Concentration of nutrients in leaf litter of different age class of teak plantations

Age class	Nitrogen (%)	Phosphorus (%)	Sulphur (%)	Lignin (%)
0-5	1.1 ± 0.10	0.36 ± 0.30	0.01 ± 0.001	24.8
6-10	1.7 ± 0.74	0.77 ± 0.37	0.01 ± 0.001	21.7
11-20	1.3 ± 0.17	0.54 ± 0.31	0.03 ± 0.017	23.1
21-30	1.6 ± 0.47	0.60 ± 0.23	0.01 ± 0.004	19.9
>30	1.6 ± 0.75	0.36 ± 0.11	0.03 ± 0.021	22.7

Table 13. Biomass distribution in various compartments at different age class of teak (Thomas *et al.*, 2009)

Compartments	**Mean biomass (kg/tree)**				
	5Year	**10Year**	**20Year**	**30Year**	**40Year**
Wood	49.56 ± 2.80	91.50 ± 8.55	142.28 ± 54.00	254.34 ± 94.50	480.48 ± 67.55
Bark	6.22 ± 0.05	14.86 ± 2.03	19.40 ± 4.37	28.26 ± 9.24	44.63 ± 10.30
Branches	-	26.91 ± 11.53	27.53 ± 22.14	38.38 ± 25.34	95.93 ± 23.65
Root	8.33 ± 0.50	21.28 ± 3.24	48.51 ± 15.00	87.60 ± 20.40	131.28 ± 25.00
Total	67.81	154.59	237.72	408.57	752.32

Table 14. Carbon content in different compartments at different age classes of teak plantation (Thomas *et al.*, 2009)

Compartments	**Mean biomass (kg/tree)**				
	5Year	**10Year**	**20Year**	**30Year**	**40Year**
Wood	23.26 ± 1.50	42.09 ± 4.21	65.45 ± 24.25	116.99 ± 24.40	221.02 ± 21.24
Bark	2.86 ± 0.30	4.77 ± 0.45	6.21 ± 2.06	9.04 ± 3.22	14.28 ± 2.36
Branches	-	11.30 ± 3.23	11.56 ± 7.24	16.12 ± 11.7	40.29 ± 12.30
Root	3.33 ± 0.15	8.94 ± 1.65	20.86 ± 6.00	38.55 ± 9.35	57.76 ± 8.54

4.4 Simulation results by CENTURY model for Soil Organic Carbon (SOC) Change in teak plantations of Kerala

Different scenarios (Kerala teak plantation site)

Sl No.	Scenarios
Scenario 1	Teak plantations with silvicultural practices and operations
Scenario 2	Teak plantations with silvicultural practices: Replanting of teak plantations
Scenario 3	Teak plantations with silvicultural practices: Forest fire damages (in different intervals)
Scenario 4	Teak plantations with silvicultural practices: Conversion to Natural forests
Scenario 5	Teak plantations with silvicultural practices: Conversion to Agroforestry practices (teak trees and ginger cultivation)
Scenario 6	Teak plantations with silvicultural practices: Conversion to Ginger cultivation
Scenario 7	Teak plantations with silvicultural practices: conversion to Agriculture (Root vegetables (tuber crops) + pulses)

4.4.1. Simulated SOC in teak plantations of Kerala.

The total SOC was measured at different age classes of teak plantations. The age classes of 1 to 5, 6 to 10, 11 to 20, 21 to 30 and more than 30 years showed an average SOC value of 4563.7 g C m^{-2}, 3829.58 g C m^{-2}, 3502.82 g C m^{-2}, 3194.10 g C m^{-2} and 3103.12 g C m^{-2} respectively whereas the century model simulated average values were found to be 3966.06 g C m^{-2}, 3568.08 g C m^{-2}, 3214.19 g C m^{-2}, 3040.03 g C m^{-2} and 2917.09 g C m^{-2} respectively.

A linear relationship (r^2=0.915) was found between measured and simulated total SOC values and a t test was used to ascertain whether the difference between measured and simulated values of total SOC was significant (Fig 9). The tests revealed that the CENTURY model is reliable in simulating the carbon dynamics in teak plantations.

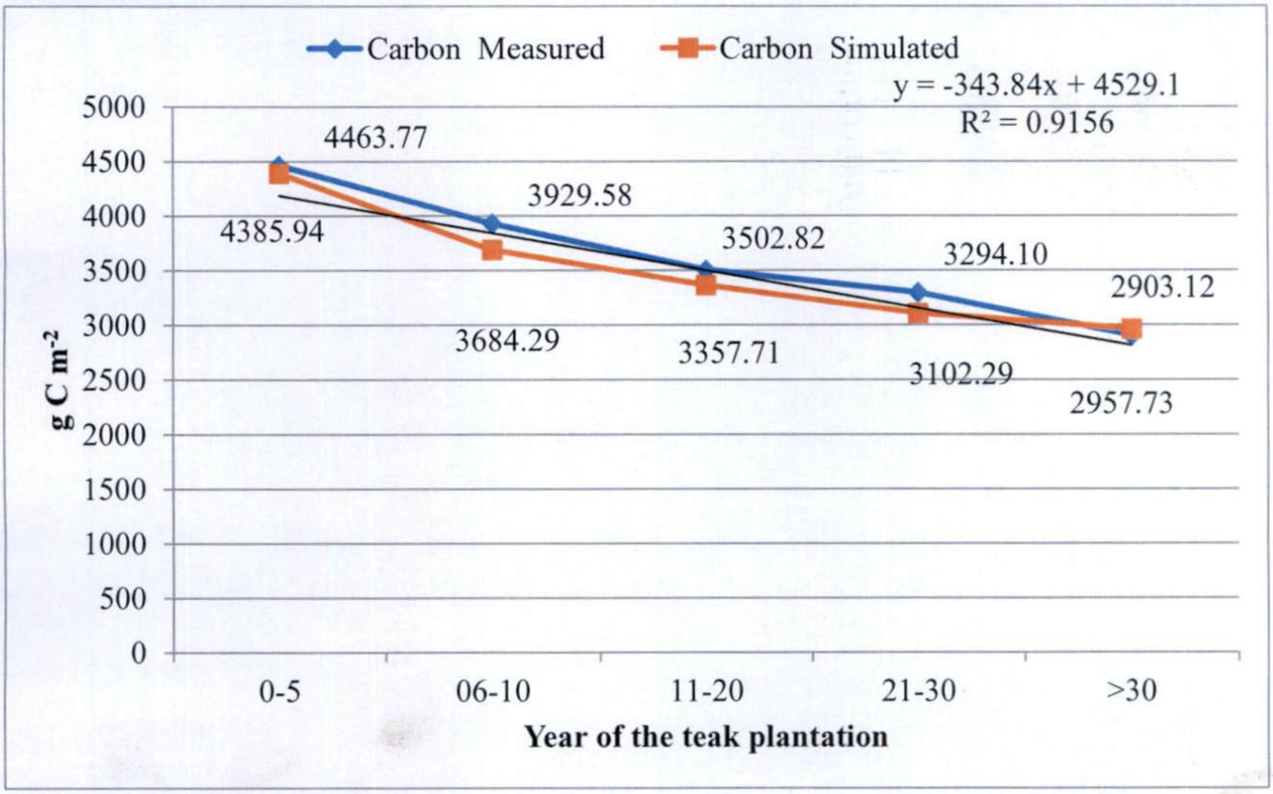


Figure 9. Measured and Century simulated Soil Organic Carbon stocks in teak plantations of Kerala

4.5. Scenario 1; Teak plantations with silvicultural practices:

This scenario assumes that teak plantations were raised after clearing the natural forests, adopting normal silvicultural thinning schedules that take place at each growth stage. The CENTURY model simulated results of the dynamics of total SOC in different carbon pools such as active, slow, and passive carbon during the establishment of equilibrium state of the teak plantation.

In the beginning of plantation establishment, the simulated data shows that the total SOC declined from 6168 g C m^{-2} to 3916 g C m^{-2} at 10 years of establishment (Fig 10 & Table 17). Further it decreased to 2912 g C m^{-2} by the age of 46 years and decreased further with age at the rate of 9.24 g C m^{-2} year up to 80 years of age (Table 17).

The simulation of active carbon indicated that in the first year, teak plantation had an active carbon of 6.25 g C m^{-2} which declined sharply to 2.88 g C m^{-2} by the end of 3rd year and increased to 10.17 g C m^{-2} by 9th year. By the end of 16th year the active pool stabilized around 12 g C m^{-2} (Fig 10). In effect, the active carbon doubled by 80th year of establishment of plantation (Table 17). The slow carbon reduced from 3700.2 g C m^{-2} to 1224.83 g C m^{-2} (Fig 10) at the age of 22, and finally stabilized at 920 g C m^{-2} at an age of 80 years. Passive carbon more or less remained stable. It decreased from 2150.84 g C m^{-2} to 1912 g C m^{-2} at the age of 50 years (Fig 10) and marginally declining to 1757 g C m^{-2} at the end of 80 years.

Table 17. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in teak (*Tectona grandis.*) plantations of Kerala

Year	**Total SOC**	**Active carbon**	**Slow carbon**	**Passive carbon**
1	6168.0	6.25	3700.2	2150.8
2	5559.0	3.404	3301.5	2147.8
3	5197.0	2.882	2929.9	2144.3
4	4986.0	5.484	2665.2	2140.8
5	4776.0	5.697	2420.2	2136.7
6	4653.0	8.353	2254.5	2133.0
7	4530.0	8.638	2104.8	2129.0
8	4394.0	8.938	1976.0	2124.9
9	4046.0	10.174	1880.9	2121.0
10	3916.1	8.218	1757.8	2116.1
11	3830.7	9.948	1678.8	2111.4
12	3749.8	10.101	1603.5	2106.6
13	3658.7	9.251	1518.9	2101.5
14	3614.1	11.763	1480.0	2097.0
15	3568.1	11.796	1439.2	2092.3
16	3512.7	11.135	1389.4	2087.4
17	3478.3	11.947	1360.3	2082.7
18	3432.6	11.019	1320.9	2077.4
19	3402.8	12.277	1296.2	2072.8
20	3371.6	12.152	1270.5	2067.9
21	3337.7	11.945	1242.1	2063.1
22	3315.1	12.529	1224.8	2058.4
23	3268.9	10.77	1185.1	2052.8
24	3243.1	11.719	1165.4	2047.5
25	3214.2	11.573	1142.0	2042.1
26	3173.4	10.705	1107.5	2036.5
27	3161.1	12.468	1100.6	2031.6
28	3145.6	12.369	1090.3	2026.5
29	3119.4	11.622	1069.6	2021.2
30	3107.9	12.285	1063.2	2016.2
31	3087.4	11.471	1048.6	2010.7
32	3076.4	12.45	1042.5	2005.8
33	3063.9	12.319	1035.4	2000.7
34	3047.7	12.108	1024.5	1995.7
35	3040.0	12.605	1021.8	1990.9
36	3012.7	11.049	1000.7	1985.1
37	3001.4	11.878	995.2	1979.7
38	2986.3	11.716	985.5	1974.4
39	2960.2	10.906	965.3	1968.7
40	2957.7	12.517	968.1	1963.7
41	2952.1	12.403	967.5	1958.6
42	2936.0	11.708	956.6	1953.4
43	2932.7	12.352	958.2	1948.4

Year	Total SOC	Active carbon	Slow carbon	Passive carbon
44	2921.1	11.599	952.4	1942.9
45	2917.1	12.512	953.0	1938.2
46	2911.7	12.401	952.6	1933.1
47	2902.1	12.204	948.2	1928.2
48	2900.1	12.688	950.9	1923.5
49	2879.7	11.204	936.5	1917.8
50	2874.0	12.023	936.4	1912.6
51	2864.4	11.869	931.9	1907.3
52	2843.8	11.081	917.0	1901.8
53	2845.4	12.662	923.6	1897.0
54	2843.7	12.543	926.6	1892.0
55	2831.6	11.871	919.6	1886.9
56	2831.5	12.517	924.2	1882.1
57	2823.6	11.782	921.7	1876.8
58	2822.4	12.687	925.0	1872.2
59	2819.8	12.581	927.2	1867.3
60	2812.9	12.387	925.2	1862.6
61	2813.2	12.871	930.1	1858.0
62	2795.6	11.403	918.2	1852.6
63	2792.2	12.227	920.1	1847.5
64	2784.8	12.074	917.6	1842.4
65	2766.4	11.287	904.6	1837.2
66	2769.7	12.869	912.7	1832.5
67	2769.7	12.747	917.2	1827.8
68	2759.2	12.078	911.5	1822.8
69	2760.6	12.733	917.4	1818.2
70	2754.2	11.996	916.2	1813.2
71	2754.2	12.903	920.5	1808.7
72	2752.9	12.797	923.7	1804.1
73	2747.1	12.6	922.6	1799.5
74	2748.4	13.089	928.3	1795.1
75	2732.0	11.614	917.3	1790.0
76	2729.6	12.444	920.0	1785.1
77	2723.2	12.288	918.2	1780.3
78	2705.7	11.495	906.0	1775.2
79	2709.9	13.087	914.6	1770.8
80	2710.6	12.961	919.7	1766.2
81	2700.9	12.289	914.6	1761.5
82	2703.0	12.949	920.9	1757.1

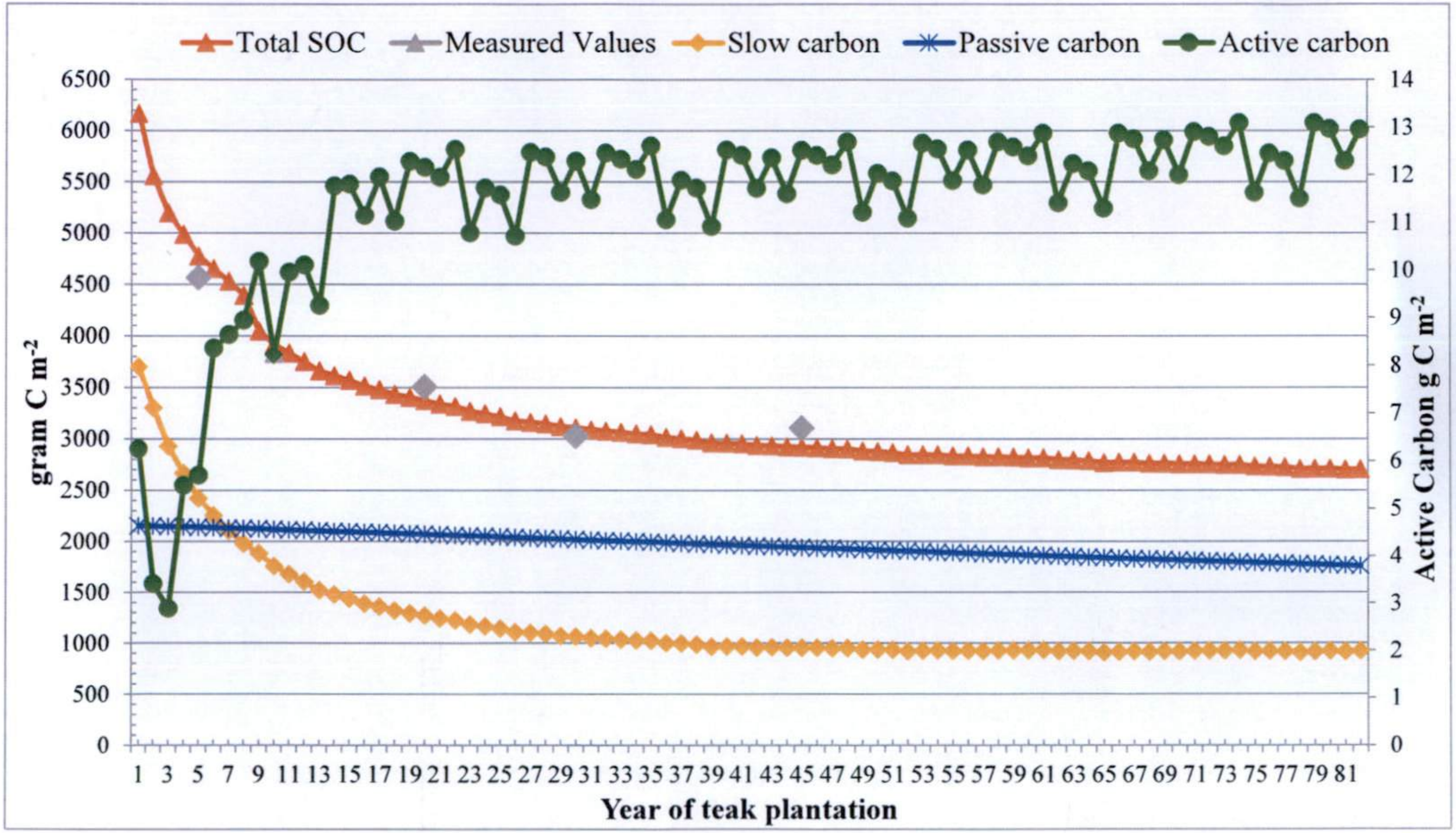


Figure 10. Simulation and measured results of CENTURY model for individual SOM pools at teak plantation, Kerala

4.6. Scenario 2. Teak plantations: Replanting of teak plantations after a rotation of 50th year

This scenario assumes that teak plantations were replanted after harvesting the previous crop, after rotation of age 50th, adopting normal silvicultural thinning schedules that are in vague. The results simulated by CENTURY model shows that, the total carbon in replanting after the first rotation was observed to be 2864.40 g C m^{-2} at the first year of planting. Total carbon increased to 2919.05 g C m^{-2} by 3rd year before declining to 2652.05 g C m^{-2}, by 10th year. Total carbon then increased to 2702.98 g C m^{-2} by the age of 30th year (Fig 11 & Table 18). The difference observed in total carbon in replanted teak plantation was 102.23 g C m^{-2} as compared to old teak plantation at 30th year of replanting.

The active carbon pool in replanted area was observed to be 11.86 g C m^{-2} at the first year of planting, which increased to 17.17 g C m^{-2} by the time of 3rd year. Then it declined to 7.46 g C m^{-2} at age of 10th year and the trend further proceeded in a fluctuating manner from 10.64 g C m^{-2} to 12.47 g C m^{-2} to an age of 30 year (Fig 12). At the end of simulation period, active carbon increased by 0.62 g C m^{-2} than teak plantation. Initially, the slow carbon started to increase from 936.36 g C m^{-2} to 989.72 g C m^{-2} to an age of 3 years. This then declined to 777.61 g C m^{-2} (Fig 13 & Table 18) at an age of 12th year, slow carbon increased then to 1016.13 g C m^{-2} at an age of 30th year of simulation period. A slight increase in the passive carbon (1759 g C m^{-2}) was noticed in replanted teak plantation as compared to that of the old teak plantation (1757 g C m^{-2}) (Fig 14).

Table 18. Simulated total soil organic carbon and different carbon pools in replanted teak plantations of Kerala (g C m^{-2})

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Teak Replanted	Teak plantation	Teak Replanted	Teak plantation	Replanted Teak	Teak plantation	Replanted Teak
1	2864.41	2864.41	11.87	11.87	931.94	931.94	1907.31	1907.31
2	2843.81	2843.81	11.08	11.08	917.02	917.02	1901.80	1901.80
3	2845.39	2919.76	12.66	17.17	923.55	989.73	1896.97	1897.35
4	2843.69	2889.51	12.54	7.46	926.64	969.39	1892.02	1892.23
5	2831.57	2831.77	11.87	6.54	919.59	920.25	1886.90	1886.72
6	2831.54	2782.79	12.52	6.36	924.24	877.94	1882.11	1881.66
7	2823.61	2734.02	11.78	6.03	921.74	835.62	1876.81	1876.08
8	2822.40	2705.31	12.69	6.83	924.99	811.85	1872.19	1871.24
9	2819.80	2684.72	12.58	7.15	927.22	796.17	1867.32	1866.18
10	2812.91	2668.93	12.39	7.33	925.20	784.95	1862.57	1861.31
11	2813.19	2668.50	12.87	8.29	930.08	788.75	1858.00	1856.67
12	2795.57	2652.06	11.40	6.90	918.16	777.61	1852.59	1851.21
13	2792.18	2659.46	12.23	8.42	920.05	789.77	1847.51	1846.12
14	2784.78	2663.42	12.07	8.52	917.59	798.17	1842.45	1841.08
15	2766.41	2655.28	11.29	7.77	904.64	795.02	1837.16	1835.83
16	2769.70	2675.43	12.87	10.23	912.65	819.45	1832.51	1831.25
17	2769.66	2685.95	12.75	9.89	917.18	834.22	1827.76	1826.60
18	2759.20	2685.18	12.08	9.28	911.55	837.92	1822.84	1821.82
19	2760.61	2702.47	12.73	10.65	917.41	859.07	1818.25	1817.35
20	2754.19	2710.00	12.00	9.78	916.19	871.48	1813.16	1812.38
21	2754.22	2723.41	12.90	11.17	920.46	888.56	1808.73	1808.10
22	2752.86	2735.38	12.80	11.21	923.69	904.67	1804.07	1803.62
23	2747.11	2741.06	12.60	11.10	922.60	914.55	1799.52	1799.27
24	2748.44	2756.57	13.09	12.07	928.31	933.87	1795.14	1795.11
25	2731.98	2748.09	11.61	10.06	917.29	930.58	1789.96	1790.17
26	2729.61	2760.52	12.44	11.61	919.97	947.44	1785.10	1785.56
27	2723.19	2766.94	12.29	11.63	918.25	957.92	1780.25	1780.99
28	2705.75	2758.24	11.50	10.66	905.98	953.89	1775.19	1776.21
29	2709.85	2779.17	13.09	13.31	914.59	978.68	1770.75	1772.06
30	2710.60	2789.96	12.96	12.93	919.68	993.32	1766.20	1767.83

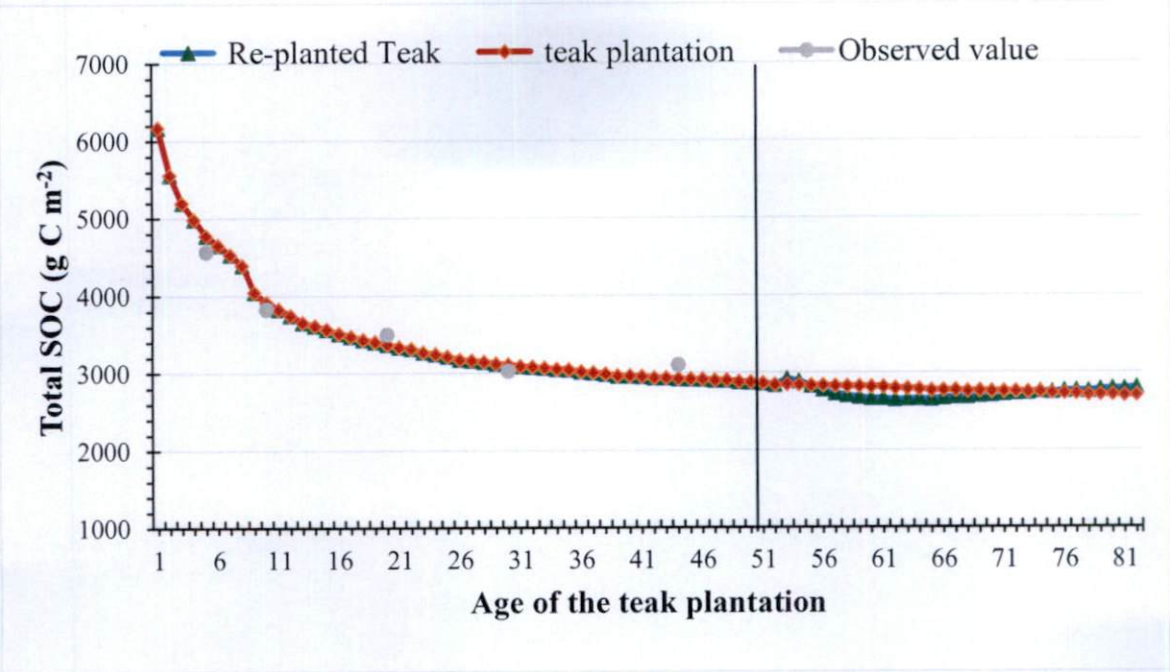


Figure 11. Simulation results of model for Total soil organic carbon in replanted teak plantations of Kerala in relation to observed values.

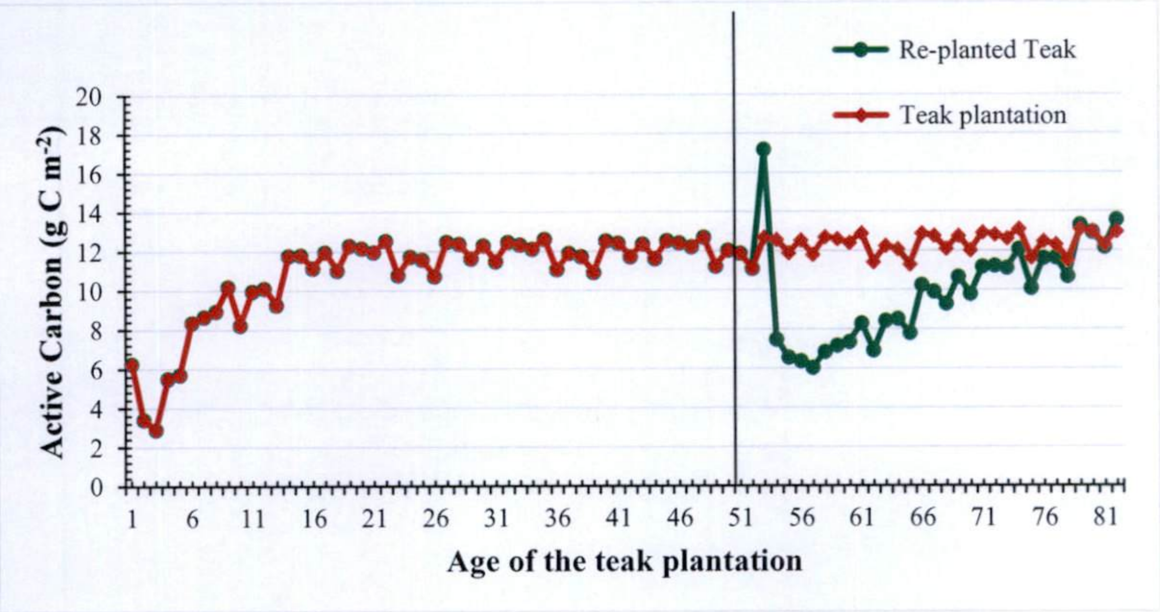


Figure 12. Simulation results of model for active carbon pool in replanted teak plantations.

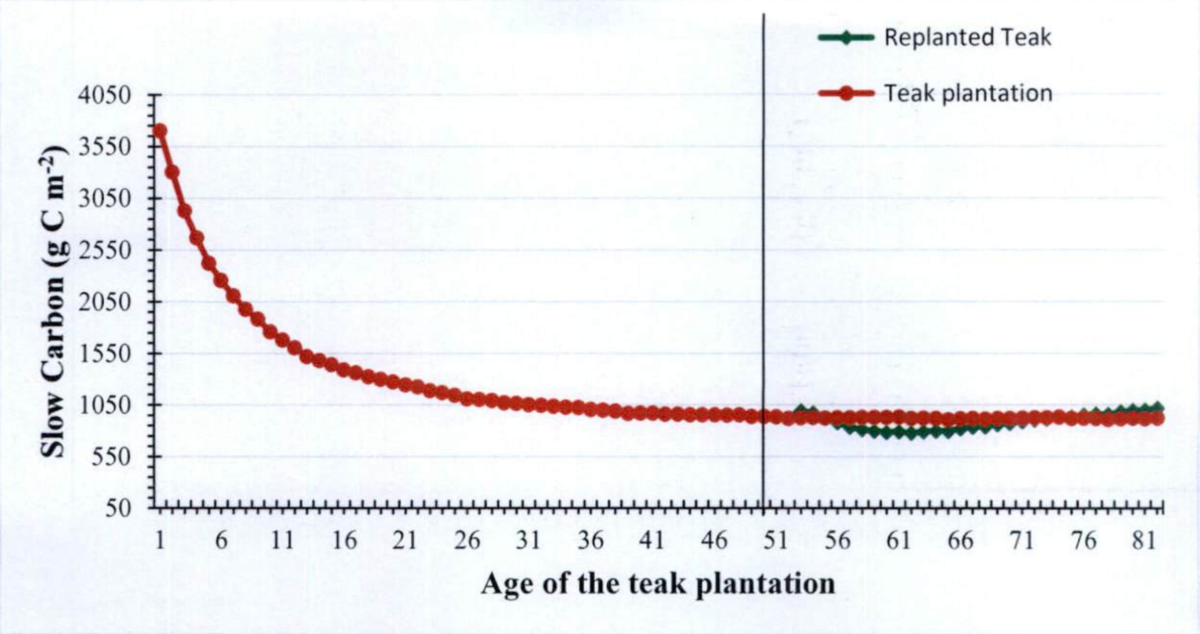


Figure 13. Simulation results of model for slow carbon pools in replanted teak plantation.

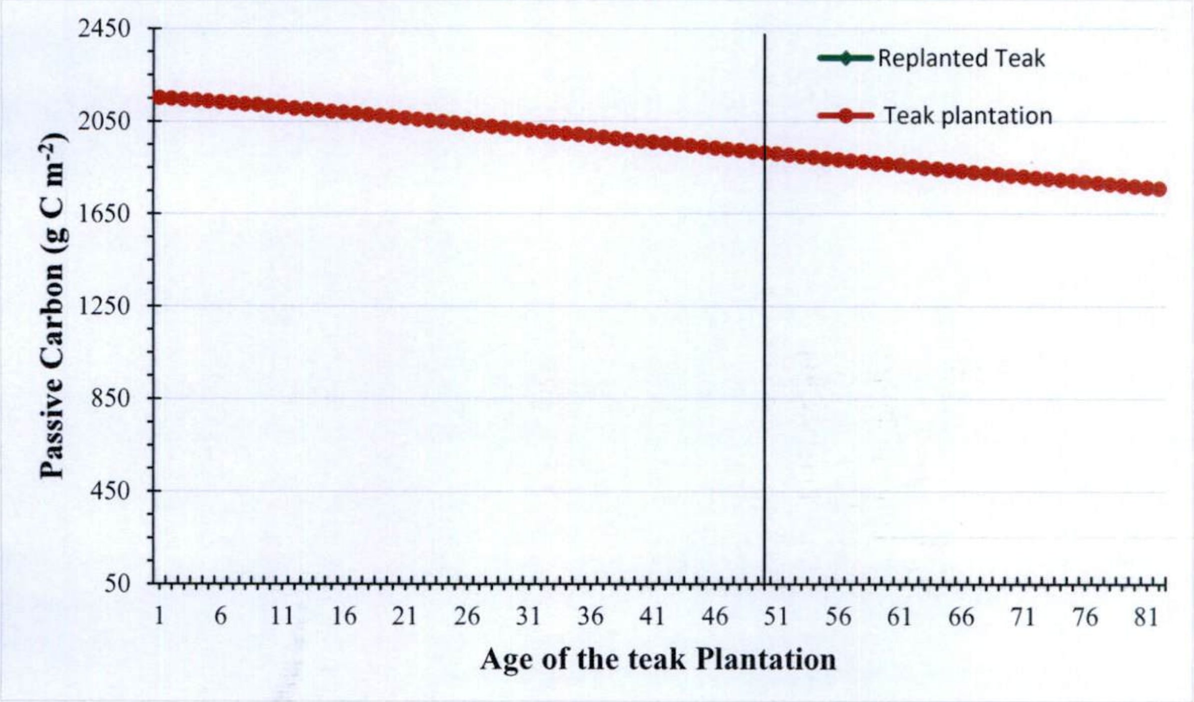


Figure 14. Simulation results of passive carbon pool in replanted teak plantation scenario.

4.7 Scenario 3. Teak plantation with silvicultural practices: Forest fire damages

Teak is vulnerable to low intensity fires only for its preliminary five years; after which, it has no effect on the tree as well as on the wood quality. Century model is used to predict the soil carbon pools in such fire affected areas. This scenario relates to the teak plantations that were affected by forest fire.

The total SOC observed slowly declined from 2864.40 g C m^{-2} to 2298.30 g C m^{-2} by the age of 22nd year (Fig 15 & Table 19). The SOC has steadily increased and stabilized at 2343.22 g C m^{-2} at the age of 30th year which was the final simulated age. The simulated values of total SOC in fire damaged teak plantation is found to be lesser after 56th year as compared to that of without fire.

The figure 16 indicat the active carbon which was initially 11.87 g C m^{-2} at the first year of fire and subsequently increased to 20.59 g C m^{-2}. The values decreased to 4.42 g C m^{-2} and kept declining to 1.86 g C m^{-2} from the age of 10 to 17 years. From the age 18 to 32, the active carbon increased from 3.44 to 9.19 g C m^{-2}. The slow carbon content in the decreased from 931.94 g C m^{-2} to 477.43 g C m^{-2} from the age of 1 to 21 years (Fig 17 & Table 19). Slow carbon was found to increase from 496.14 g C m^{-2} to 585.01 g C m^{-2} from the age of 21 to 32. The simulated values of slow carbon in plantations without forest fire were found to be more by 335.90 g C m^{-2} than that in the fire damaged area. The passive carbon values showed a slight variation from 1907.30 to 1741.54 g C m^{-2} by the end of 30th year of simulation (Fig 19).

Table 19. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in fire affected teak plantations of Kerala

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Fire	Teak plantation	Fire	Teak plantation	Fire	Teak plantation	Fire
1	2864.41	2864.41	11.87	11.87	931.94	931.94	1907.31	1907.31
2	2843.81	2843.81	11.08	11.08	917.02	917.02	1901.80	1901.80
3	2845.39	2845.39	12.66	12.66	923.55	923.55	1896.97	1896.97
4	2841.65	2843.69	12.54	12.42	926.64	924.64	1892.02	1892.04
5	2828.86	2831.57	11.87	11.77	919.59	916.95	1886.90	1886.92
6	2829.71	2831.54	12.52	12.54	924.24	922.43	1882.11	1882.14
7	2822.08	2823.61	11.78	11.78	921.74	920.25	1876.81	1876.82
8	2768.32	2822.40	12.69	20.59	924.99	871.29	1872.19	1871.74
9	2720.35	2819.80	12.58	4.43	927.22	829.66	1867.32	1867.14
10	2661.38	2812.91	12.39	3.45	925.20	776.95	1862.57	1862.16
11	2611.44	2813.19	12.87	3.19	930.08	733.13	1858.00	1857.28
12	2557.68	2795.57	11.40	2.89	918.16	686.59	1852.59	1851.33
13	2502.66	2792.18	12.23	2.19	920.05	638.44	1847.51	1845.74
14	2450.43	2784.78	12.07	1.92	917.59	592.88	1842.45	1840.06
15	2401.04	2766.41	11.29	1.78	904.64	550.57	1837.16	1833.97
16	2361.26	2769.70	12.87	1.75	912.65	517.02	1832.51	1828.66
17	2326.25	2769.66	12.75	1.83	917.18	488.24	1827.76	1823.12
18	2304.31	2759.20	12.08	3.45	911.55	472.57	1822.84	1817.28
19	2298.21	2760.61	12.73	4.92	917.41	471.98	1818.25	1811.90
20	2292.73	2754.19	12.00	5.45	916.19	472.56	1813.16	1805.96
21	2294.59	2754.22	12.90	6.55	920.46	479.44	1808.73	1800.77
22	2298.30	2752.86	12.80	7.01	923.69	488.42	1804.07	1795.33
23	2300.88	2747.11	12.60	7.29	922.60	496.15	1799.52	1790.04
24	2308.80	2748.44	13.09	7.93	928.31	508.96	1795.14	1784.96
25	2306.85	2731.98	11.61	7.27	917.29	512.92	1789.96	1778.95
26	2313.99	2729.61	12.44	8.03	919.97	525.52	1785.10	1773.36
27	2318.45	2723.19	12.29	8.11	918.25	535.22	1780.25	1767.81
28	2315.34	2705.75	11.50	7.72	905.98	537.75	1775.19	1762.01
29	2326.07	2709.85	13.09	8.95	914.59	553.34	1770.75	1756.97
30	2334.39	2710.60	12.96	8.97	919.68	566.47	1766.20	1751.81

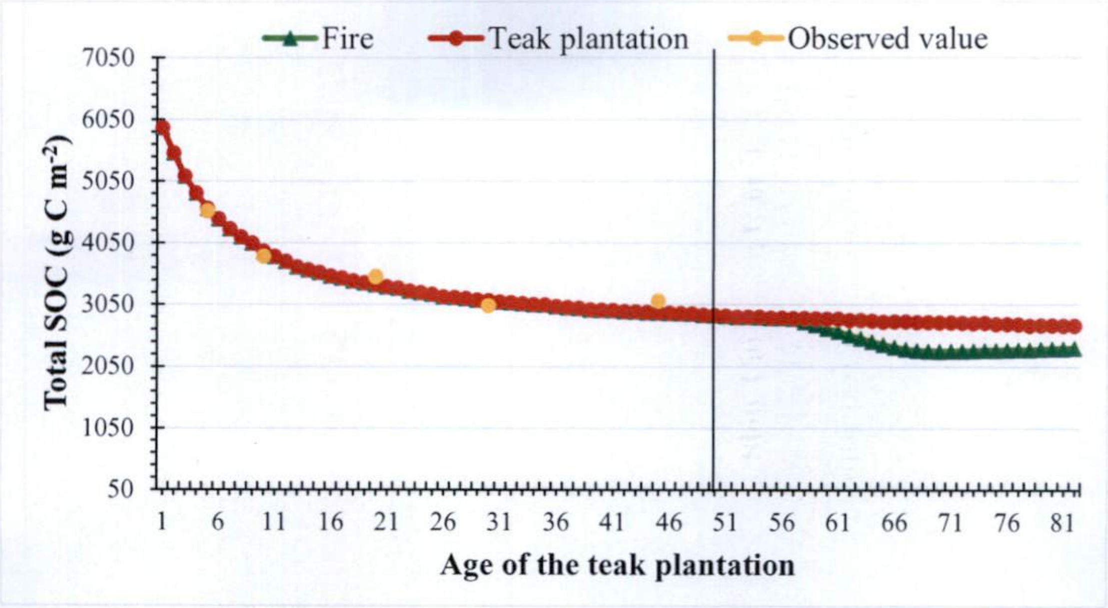


Figure 15. Simulation results of model for total soil organic carbon in forest fire damaged in teak plantation scenario.

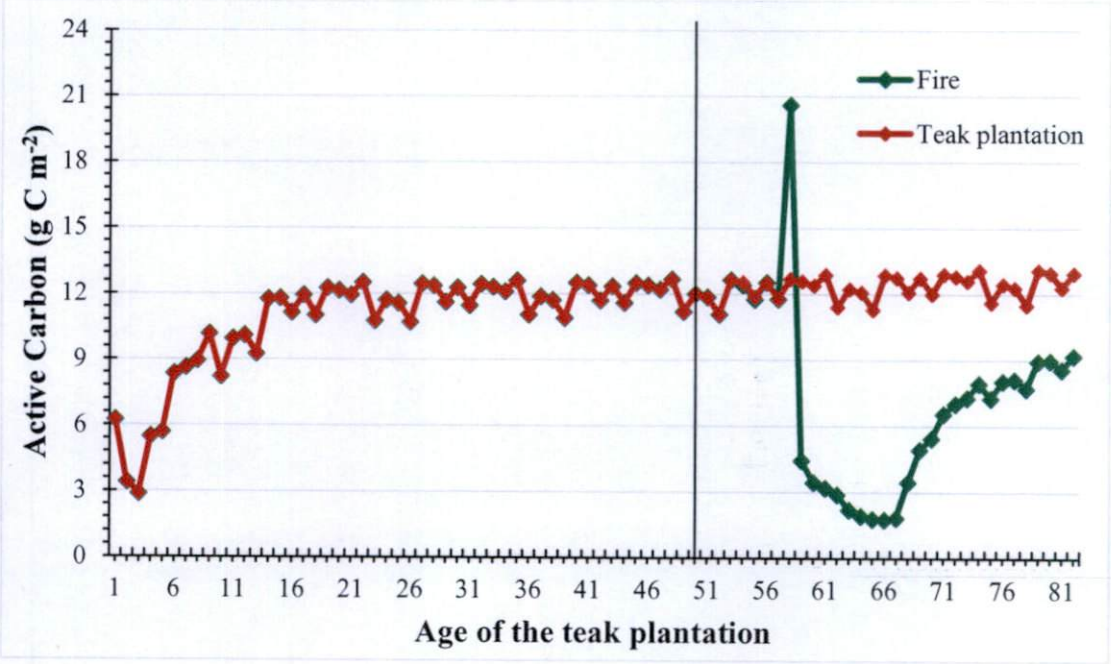


Figure 16. Simulation results of model for active carbon in forest fire damaged in teak plantation scenario.

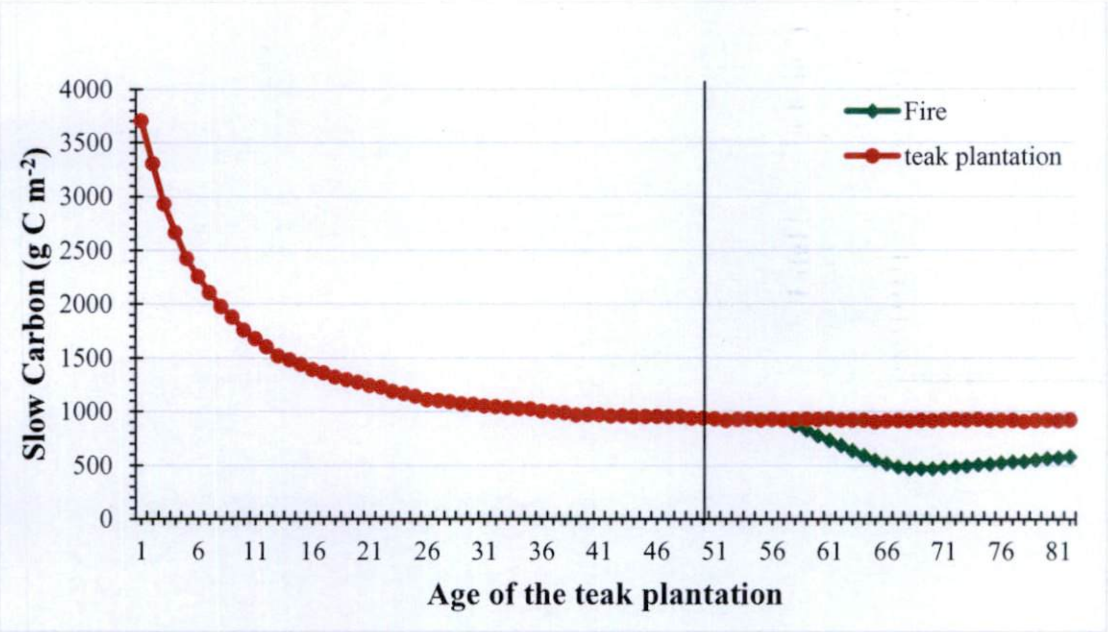


Figure 17. Simulation results of model for slow carbon pool in forest fire damaged in teak plantation scenario.

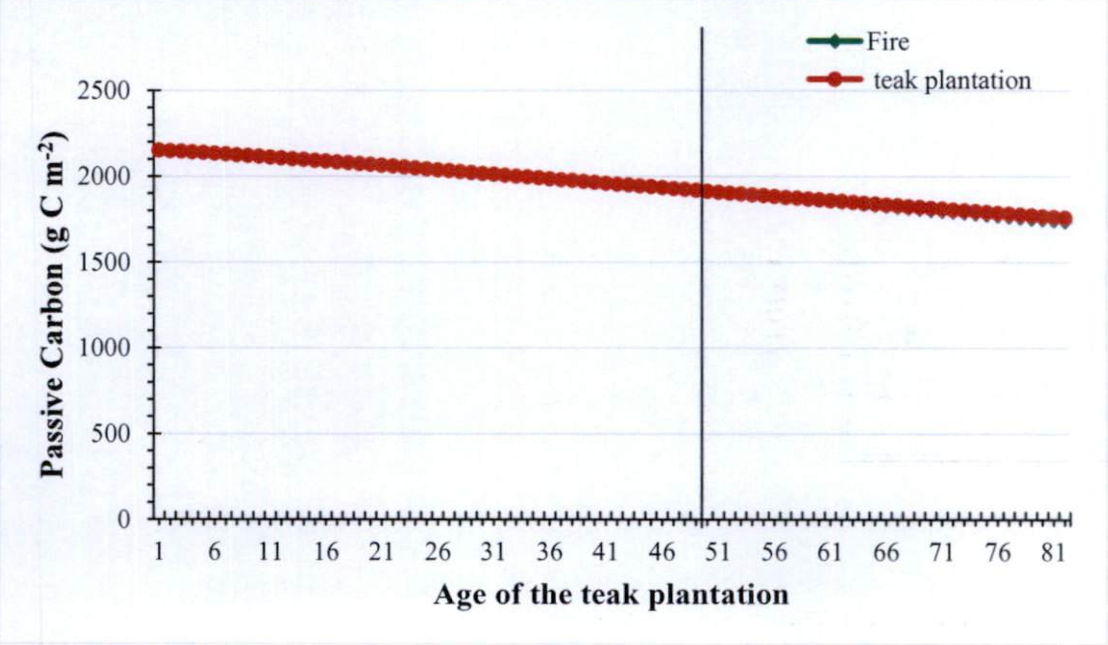


Figure 18. Simulation results of model for passive pools in forest fire damaged in teak plantation scenario.

4.8. Scenario 4. Teak plantation with silvicultural practices: conversion to natural forest.

This scenario assumes a teak plantation that is being converted to natural forest. During the initial period the total soil organic carbon was observed to be 2829.40 g C m^{-2}, and then the values started to decline to 2294.54 g C m^{-2} by the age of 13 (Fig 19 & Table 20). Total organic carbon increased to a rate of 2865.95 g C m^{-2} by the age of 30 year i.e. at the end of simulation period. The simulated values of total SOC of natural forest increased by 162.97 g C m^{-2} year^{-1} as compared to that of the actual teak plantation.

The active carbon was found to decrease from 10.94 to 3.03 g C m^{-2} within a 13 year period, and then it slowly increased to 15.13 g C m^{-2} after the 13th year (Fig 20 & Table 20). After that the values kept fluctuating from 10.25 to 11.02 g C m^{-2}. Slow carbon initially declined from 898.62 to 388.75 g C m^{-2} within a 12 year period. After over a period of time of 30 years of simulation, it increased to 814.84 g C m^{-2} (Fig 21 & Table 20). Finally the slow carbon pool kept increasing at a rate of 31.95 g C m^{-2} as compared to that of teak plantations.

The passive carbon pool in natural forest was found to decrease from 1907.51 to 1757.11 g C m^{-2} as compared to that of the teak plantation which also decreased from 1906.56 to 1738.97 g C m^{-2} (Table 20 & Fig 22).

Table 20. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in teak converted to natural forests of Kerala

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Natural forest	Teak plantation	Natural forest	Teak plantation	Natural forest	Teak plantation	Natural forest
1	2864.41	2829.41	11.87	10.74	931.94	898.63	1907.31	1906.56
2	2843.81	2800.99	11.08	10.11	917.02	876.27	1901.80	1900.81
3	2845.39	2748.53	12.66	11.03	923.55	829.69	1896.97	1895.84
4	2843.69	2678.78	12.54	4.67	926.64	770.24	1892.02	1890.24
5	2831.57	2595.77	11.87	3.47	919.59	696.33	1886.90	1884.14
6	2831.54	2521.63	12.52	3.13	924.24	629.92	1882.11	1878.46
7	2823.61	2445.47	11.78	3.03	921.74	561.69	1876.81	1872.15
8	2822.40	2384.55	12.69	4.19	924.99	507.12	1872.19	1866.45
9	2819.80	2331.14	12.58	5.31	927.22	460.16	1867.32	1860.30
10	2812.91	2289.78	12.39	7.17	925.20	424.48	1862.57	1854.43
11	2813.19	2265.68	12.87	8.79	930.08	405.26	1858.00	1848.85
12	2795.57	2242.99	11.40	9.78	918.16	388.76	1852.59	1842.17
13	2792.18	2294.54	12.23	15.31	920.05	445.31	1847.51	1836.04
14	2784.78	2329.88	12.07	13.21	917.59	485.86	1842.45	1830.04
15	2766.41	2352.69	11.29	11.90	904.64	513.97	1837.16	1823.88
16	2769.70	2383.61	12.87	12.82	912.65	549.16	1832.51	1818.61
17	2769.66	2411.01	12.75	12.48	917.18	580.86	1827.76	1813.29
18	2759.20	2429.45	12.08	11.81	911.55	603.78	1822.84	1807.88
19	2760.61	2457.26	12.73	12.60	917.41	635.55	1818.25	1802.89
20	2754.19	2479.25	12.00	11.83	916.19	662.19	1813.16	1797.45
21	2754.22	2503.90	12.90	12.83	920.46	690.61	1808.73	1792.76
22	2752.86	2525.33	12.80	12.56	923.69	716.37	1804.07	1787.84
23	2747.11	2537.96	12.60	12.12	922.60	733.58	1799.52	1783.07
24	2748.44	2553.20	13.09	12.41	928.31	753.19	1795.14	1778.48
25	2731.98	2651.24	11.61	11.91	917.29	766.79	1789.96	1773.06
26	2729.61	2659.06	12.44	12.61	919.97	769.71	1785.10	1768.00
27	2723.19	2561.45	12.29	12.40	918.25	779.93	1780.25	1762.96
28	2705.75	2652.64	11.50	11.62	905.98	779.40	1775.19	1757.69
29	2709.85	2561.46	13.09	13.23	914.59	789.78	1770.75	1753.09
30	2710.60	2766.46	12.96	13.01	919.68	826.26	1766.20	1748.38

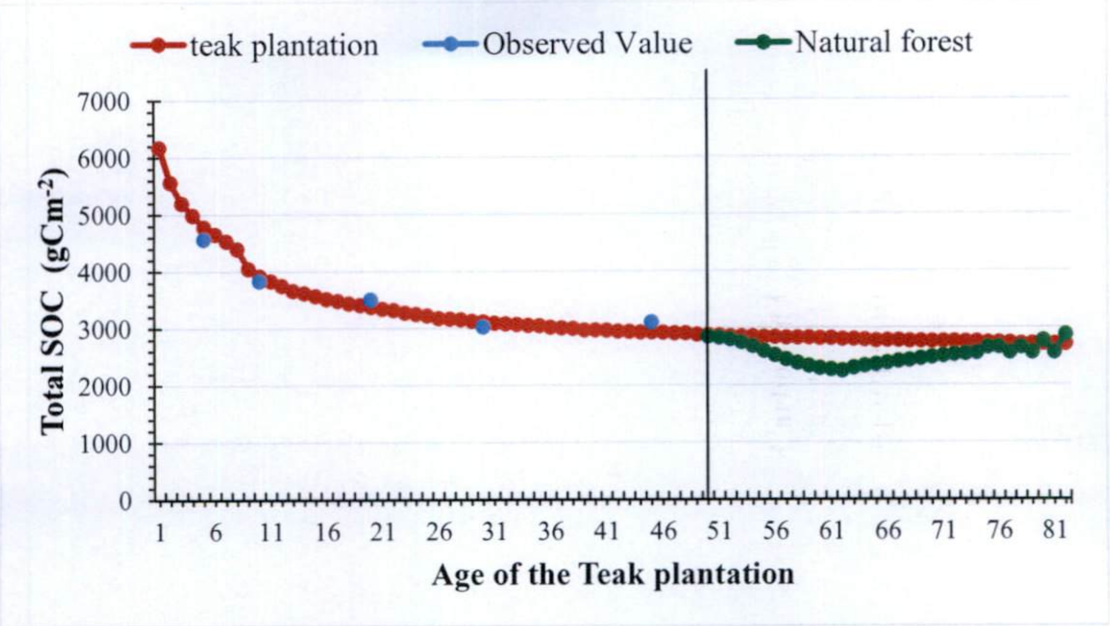


Figure 19. Simulation results of model for total soil organic carbon under the teak plantation converted to natural forests scenario.

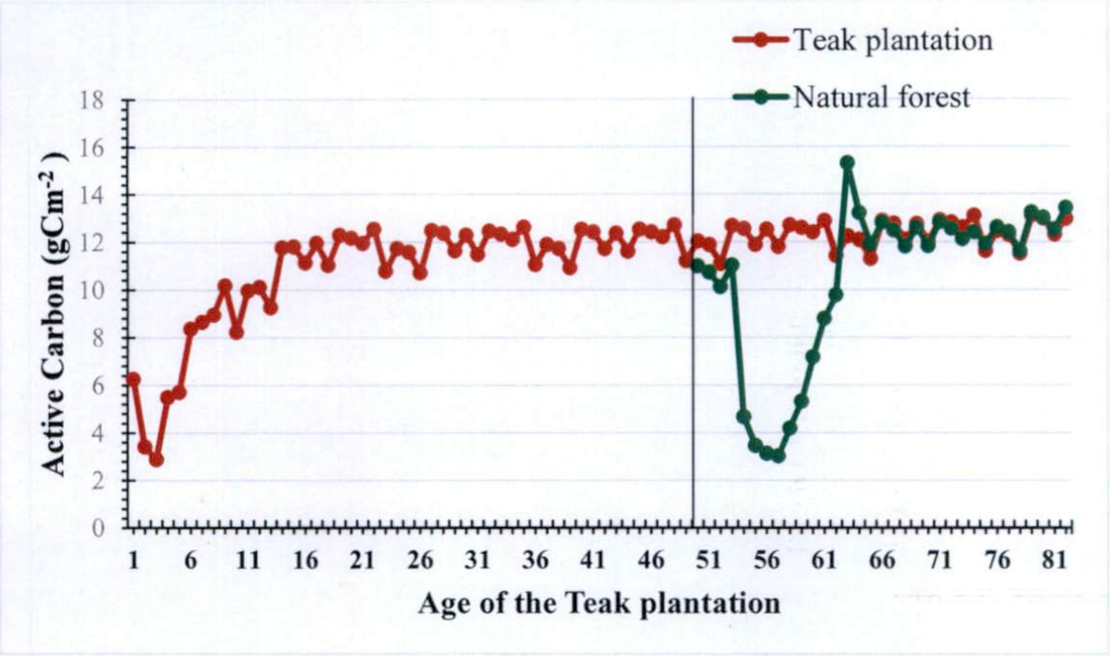


Figure 20. Simulation results of active carbon pool under the teak plantation converted to natural forest scenario.

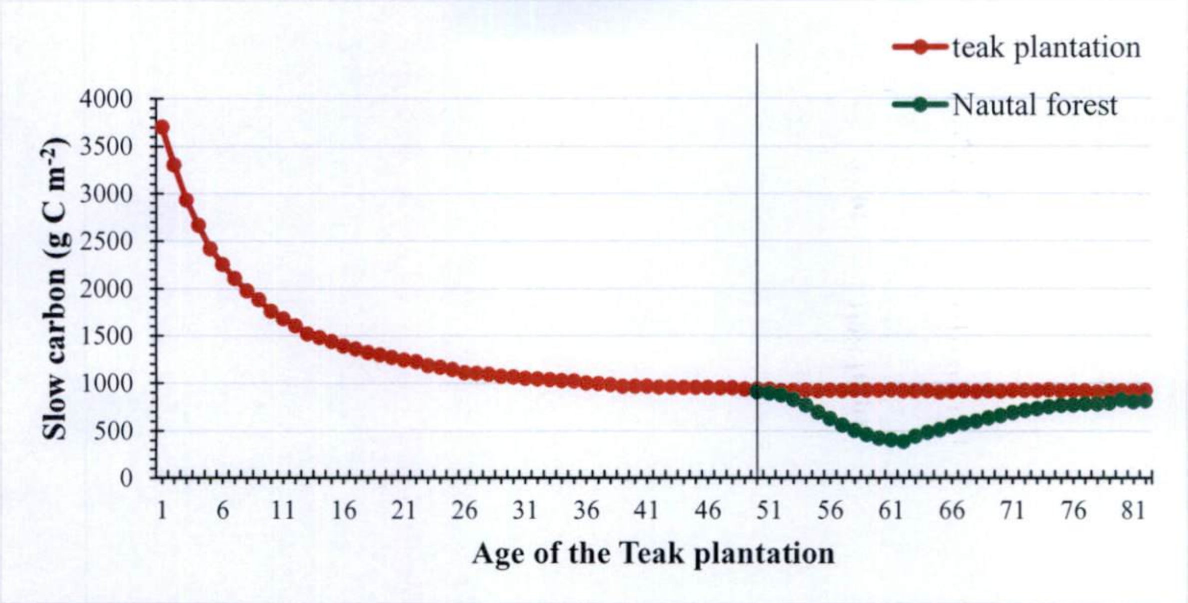


Figure 21. Simulation results of model for slow carbon pool under the teak plantation converted to natural forests scenario.

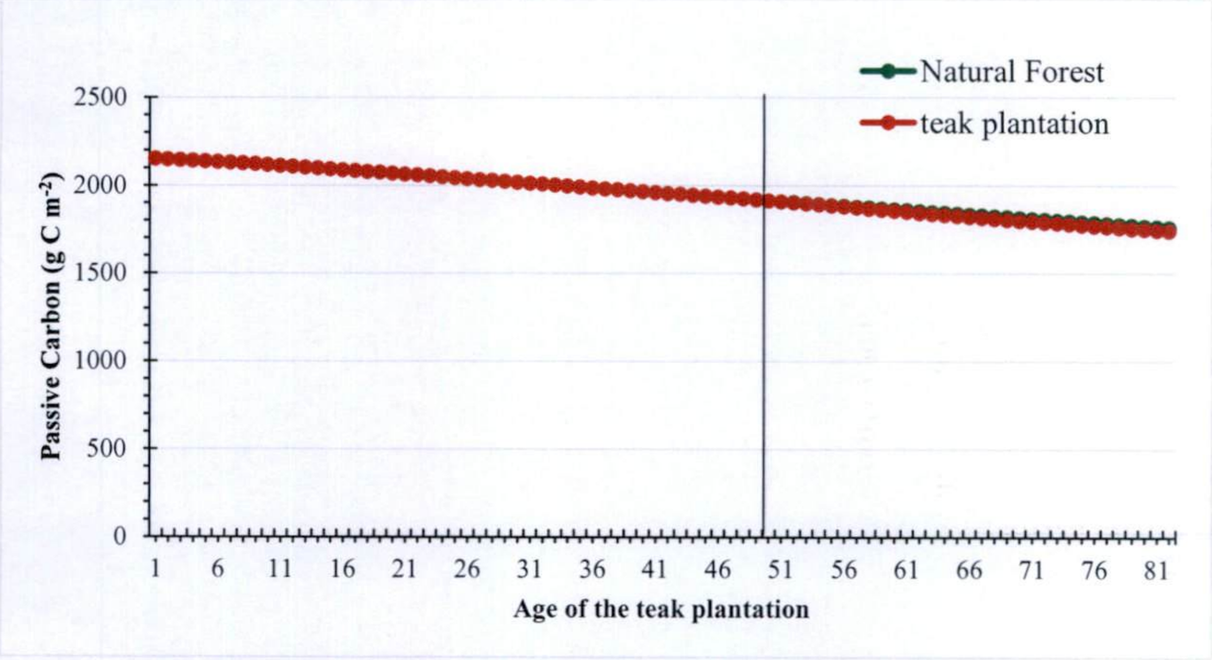


Figure 22. Simulation results of passive carbon pool under the teak plantation converted to natural forests scenario.

4.9. Scenario 5. Teak plantation with silvicultural practices: conversion to agroforestry system (Teak trees with Ginger cultivation).

The potential of agroforestry systems to sequester C has increased over the past decade; still, it remains an under-recognized option for mitigating global warming. Due to the extended time frame needed to evaluate changes in SOM, simulation models provide an opportunity to study these long-term trends and help to identify factors that lead to the accumulation or loss of SOC as a result of modifications to land management practices. Although the Century model has been successfully employed in converting a monocrop of teak into agroforestry systems before, little information is available on its application in Kerala.

This scenario depicts a teak plantation being converted to an agroforestry (teak and ginger cultivation) system. The model simulated the total SOC, when teak plantation was converted to agroforestry system. The SOC declined from 2864.40 to 2577.63 g C m^{-2} over a period of 7 years (Fig 23 &Table 21). Then the values increased at 2546.43 g C m^{-2} at the age of 30 years. A difference of 156.55 g C m^{-2} was observed for the total SOC in agroforestry system when compared to that of the teak plantation.

The active carbon pool declined from 11.86 to 2.07 g C m^{-2} at a 5 year period, and then increased to 11.05 g/m^2 at the 30th year of simulation. The figure 24 shows a decrease of 1.89 g C m^{-2} as compared to that of the teak plantation. The simulated slow carbon decreased from 931.94 to 695.10 g C m^{-2} at the age of 8 years. The slow carbon then increased to 780.97 g C m^{-2} at the end of 30 years. The total difference noticed due to the conversion of teak plantation to agroforestry system was 140.01 g C m^{-2} (Fig 25). The passive carbon pool exhibited a decrease from 1907.30 to 1743.92 g C m^{-2} at the end of the simulated period (Fig 26 &Table 21).

Table 21. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in teak converted to agroforestry

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Agroforestry	Teak plantation	Agroforestry	Teak plantation	Agroforestry	Teak plantation	Agroforestry
1	2864.41	2864.41	11.87	11.87	931.94	931.94	1907.31	1907.31
2	2843.81	2843.81	11.08	11.08	917.02	917.02	1901.80	1901.80
3	2845.39	2784.25	12.66	5.20	923.55	864.96	1896.97	1896.71
4	2843.69	2706.40	12.54	3.00	926.64	795.46	1892.02	1890.98
5	2831.57	2625.20	11.87	2.07	919.59	722.39	1886.90	1885.04
6	2831.54	2587.32	12.52	5.02	924.24	685.20	1882.11	1879.91
7	2823.61	2577.65	11.78	6.26	921.74	681.02	1876.81	1874.21
8	2822.40	2586.45	12.69	8.26	924.99	695.10	1872.19	1869.12
9	2819.80	2593.65	12.58	8.61	927.22	707.63	1867.32	1864.04
10	2812.91	2590.11	12.39	8.37	925.20	709.96	1862.57	1858.71
11	2813.19	2594.51	12.87	9.05	930.08	719.87	1858.00	1853.54
12	2795.57	2579.63	11.40	8.05	918.16	711.19	1852.59	1847.73
13	2792.18	2579.86	12.23	9.08	920.05	717.42	1847.51	1842.07
14	2784.78	2579.75	12.07	9.39	917.59	722.57	1842.45	1836.66
15	2766.41	2567.07	11.29	8.77	904.64	715.61	1837.16	1831.03
16	2769.70	2573.31	12.87	10.27	912.65	727.18	1832.51	1825.81
17	2769.66	2578.02	12.75	10.43	917.18	736.72	1827.76	1820.72
18	2759.20	2571.60	12.08	9.88	911.55	735.42	1822.84	1815.49
19	2760.61	2574.49	12.73	10.31	917.41	743.36	1818.25	1810.32
20	2754.19	2567.16	12.00	9.57	916.19	741.80	1813.16	1804.68
21	2754.22	2570.33	12.90	10.65	920.46	749.71	1808.73	1799.71
22	2752.86	2574.41	12.80	10.90	923.69	758.45	1804.07	1794.83
23	2747.11	2569.34	12.60	10.44	922.60	758.57	1799.52	1789.74
24	2748.44	2572.55	13.09	10.93	928.31	766.67	1795.14	1784.81
25	2731.98	2556.16	11.61	9.58	917.29	756.01	1789.96	1779.31
26	2729.61	2555.54	12.44	10.49	919.97	760.89	1785.10	1773.95
27	2723.19	2554.80	12.29	10.65	918.25	764.98	1780.25	1768.84
28	2705.75	2541.06	11.50	9.83	905.98	756.60	1775.19	1763.53
29	2709.85	2546.97	13.09	11.29	914.59	767.47	1770.75	1758.60
30	2710.60	2551.29	12.96	11.35	919.68	776.28	1766.20	1753.80

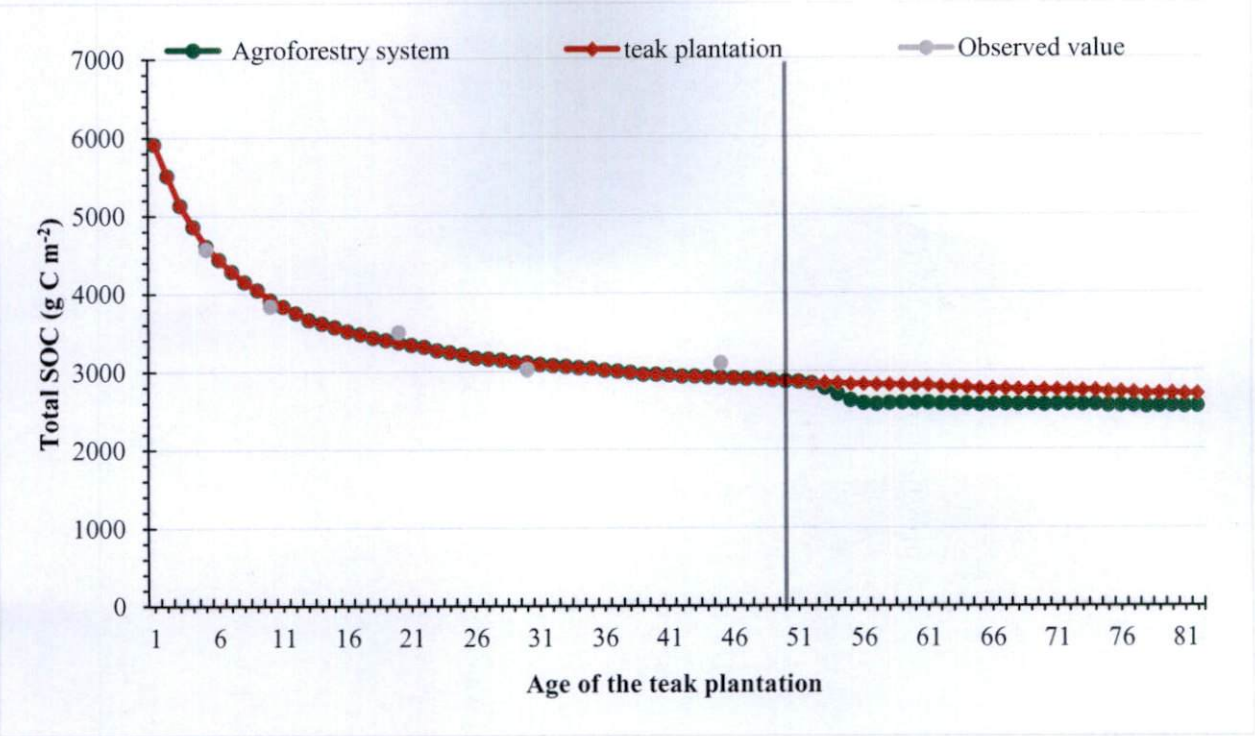


Figure 23. Simulation results of total soil organic carbon under the teak plantation converted to agroforestry practices scenario (teak and ginger cultivation).

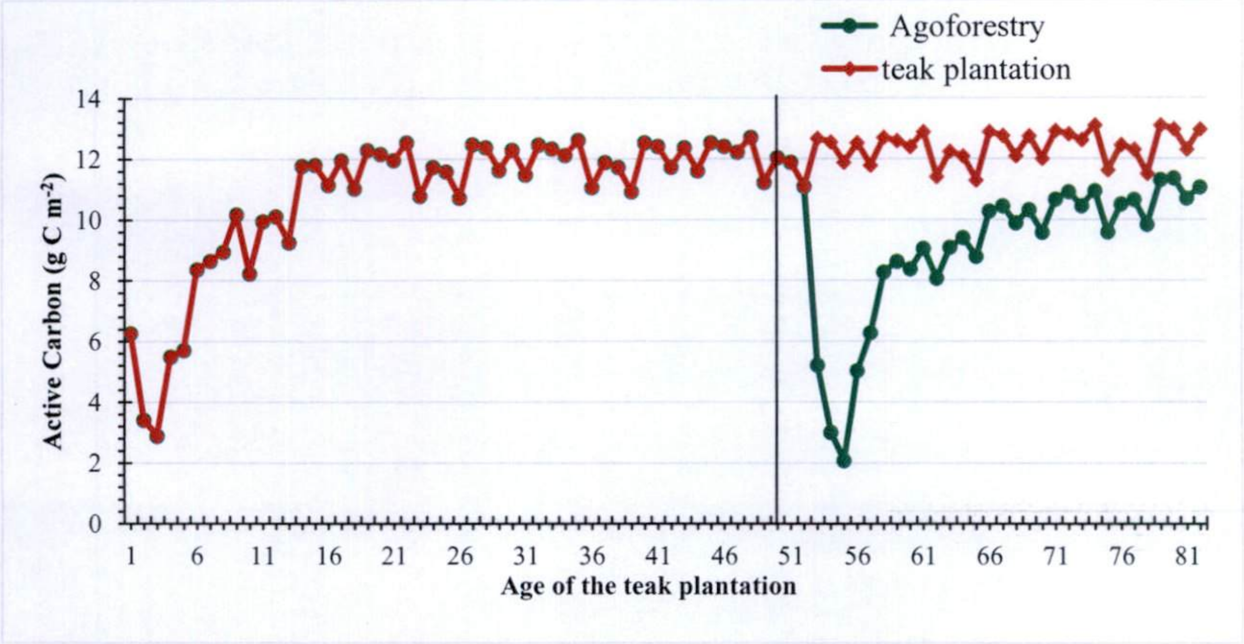


Figure 24. Simulation results of active carbon pool under the teak plantation converted to agroforestry practices scenario (teak and ginger cultivation).

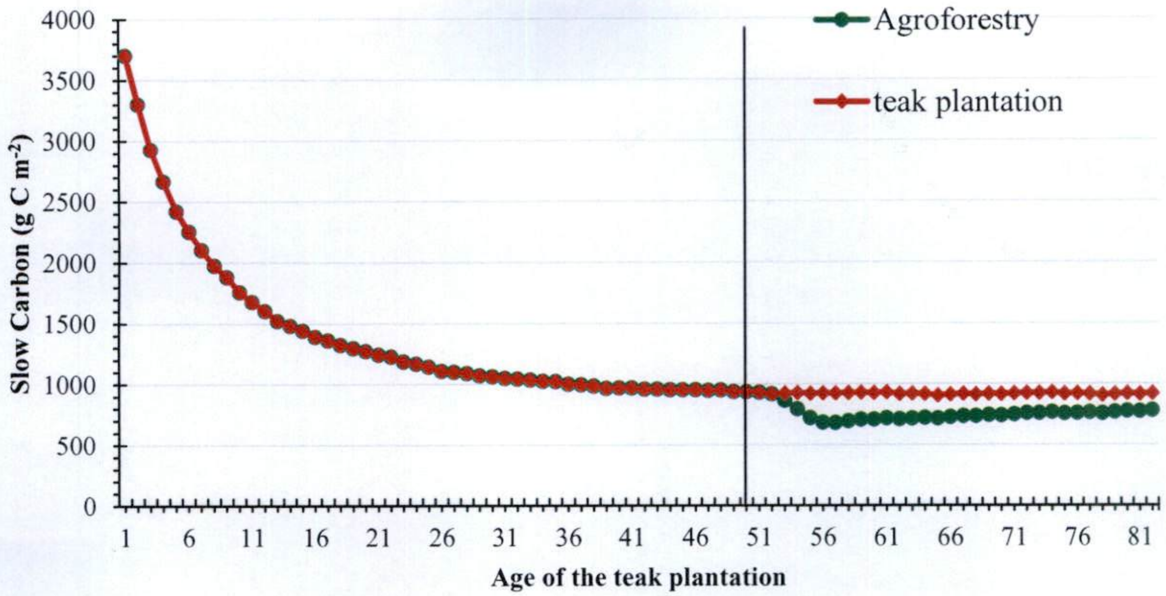


Figure 25. Simulation results of slow carbon pool under the teak plantation converted to agroforestry practices scenario (teak and ginger cultivation).

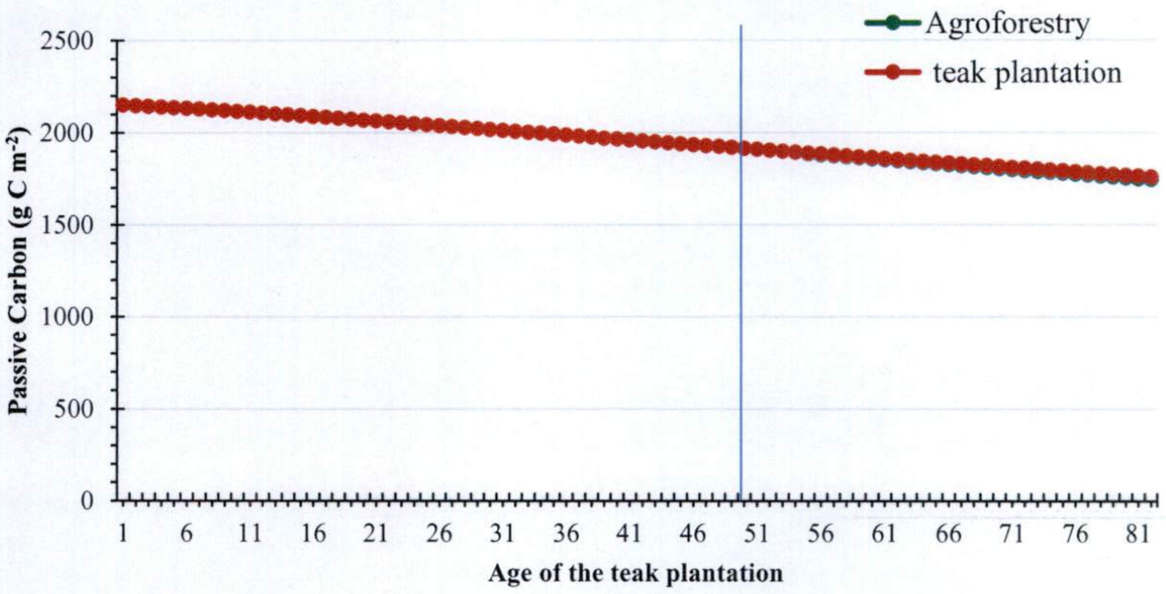


Figure 26. Simulation results of passive carbon pool under the teak plantation converted to agroforestry practices scenario (teak and ginger cultivation).

4.10. Scenario 6. Teak plantation with silvicultural practices: conversion to Ginger cultivation.

This scenario assumes a teak plantation that is being converted to cultivation of ginger. The total SOC observed at initial period of conversion was 2864.40 g Cm^2, which then declined to 1747.65 g C m^{-2} after a 30 year period of simulation (Fig 27 & Table 22). A considerable difference of 954.43 g C m^{-2} was noticed due to conversion of teak plantation to ginger cultivation.

The active carbon observed in the initial period was 11.86 g C m^{-2} which then decreased to 2.69 g C m^{-2} (Fig 28 & Table 22) in a 4 year period of time. There was a slight increase to 4.45 g C m^{-2} at the 5th year and then declined to 0.034 g C m^{-2} by the end of the 30th year. In short, the active carbon showed a decrease of 12.91 g C m^{-2} in ginger cultivation as compared to that of the teak plantation.

Slow carbon pool decreased from 931.94 to 32.69 g C m^{-2} for the entire simulation period (Fig 29 &Table 22). A difference of 866.32 g C m^{-2} was observed for slow carbon in ginger cultivation as compared to that of the teak plantations.

Passive carbon pool decreased from 1907.3 to 1706.28 g C m^{-2} (Fig 30 &Table 22) during the simulation period. A difference of 50.71 g C m^{-2} was noticed in the passive carbon pool of ginger cultivation when compared to the teak plantation.

Table 22. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in teak converted to ginger cultivation areas

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Ginger cultivation	Teak plantation	Ginger cultivation	Teak plantation	Ginger cultivation	Teak plantation	Ginger cultivation
1	2864.41	2864.41	11.87	11.87	931.94	931.94	1907.31	1907.31
2	2843.81	2843.81	11.08	11.08	917.02	917.02	1901.80	1901.80
3	2845.39	2734.62	12.66	3.65	923.55	819.67	1896.97	1891.79
4	2843.69	2675.52	12.54	2.70	926.64	767.14	1892.02	1886.34
5	2831.57	2633.96	11.87	4.45	919.59	733.45	1886.90	1880.55
6	2831.54	2560.68	12.52	2.28	924.24	669.04	1882.11	1874.40
7	2823.61	2492.68	11.78	1.64	921.74	608.76	1876.81	1868.82
8	2822.40	2423.49	12.69	1.27	924.99	547.61	1872.19	1862.86
9	2819.80	2357.80	12.58	1.03	927.22	489.56	1867.32	1856.89
10	2812.91	2299.76	12.39	0.86	925.20	438.85	1862.57	1851.03
11	2813.19	2237.97	12.87	0.71	930.08	385.26	1858.00	1844.15
12	2795.57	2185.22	11.40	0.60	918.16	340.12	1852.59	1837.63
13	2792.18	2137.67	12.23	0.50	920.05	300.00	1847.51	1831.10
14	2784.78	2092.15	12.07	0.43	917.59	262.23	1842.45	1824.15
15	2766.41	2055.92	11.29	0.37	904.64	232.81	1837.16	1817.98
16	2769.70	2021.67	12.87	0.32	912.65	205.60	1832.51	1811.53
17	2769.66	1989.84	12.75	0.27	917.18	180.89	1827.76	1804.91
18	2759.20	1962.84	12.08	0.24	911.55	160.52	1822.84	1798.69
19	2760.61	1936.01	12.73	0.20	917.41	140.87	1818.25	1791.91
20	2754.19	1913.98	12.00	0.18	916.19	125.21	1813.16	1785.84
21	2754.22	1892.86	12.90	0.15	920.46	110.76	1808.73	1779.45
22	2752.86	1873.53	12.80	0.13	923.69	97.96	1804.07	1773.17
23	2747.11	1856.38	12.60	0.11	922.60	87.13	1799.52	1767.05
24	2748.44	1838.14	13.09	0.10	928.31	76.17	1795.14	1759.99
25	2731.98	1822.27	11.61	0.08	917.29	67.10	1789.96	1753.35
26	2729.61	1807.63	12.44	0.07	919.97	59.19	1785.10	1746.77
27	2723.19	1793.22	12.29	0.06	918.25	51.87	1780.25	1739.82
28	2705.75	1781.33	11.50	0.05	905.98	46.23	1775.19	1733.68
29	2709.85	1769.71	13.09	0.05	914.59	41.09	1770.75	1727.29
30	2710.60	1758.49	12.96	0.04	919.68	36.46	1766.20	1720.77

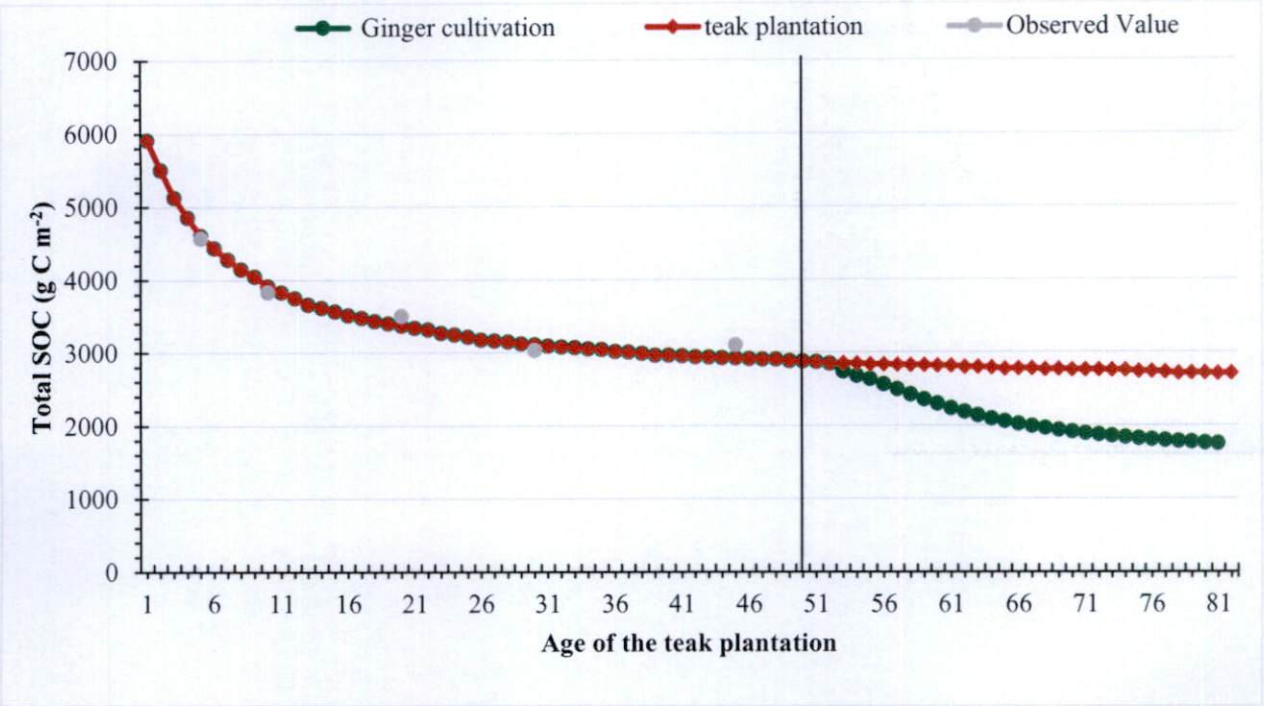


Figure 27. Simulation results of total soil organic carbon in conversion of teak plantation to ginger cultivation scenario (*Zingiber officinale*)

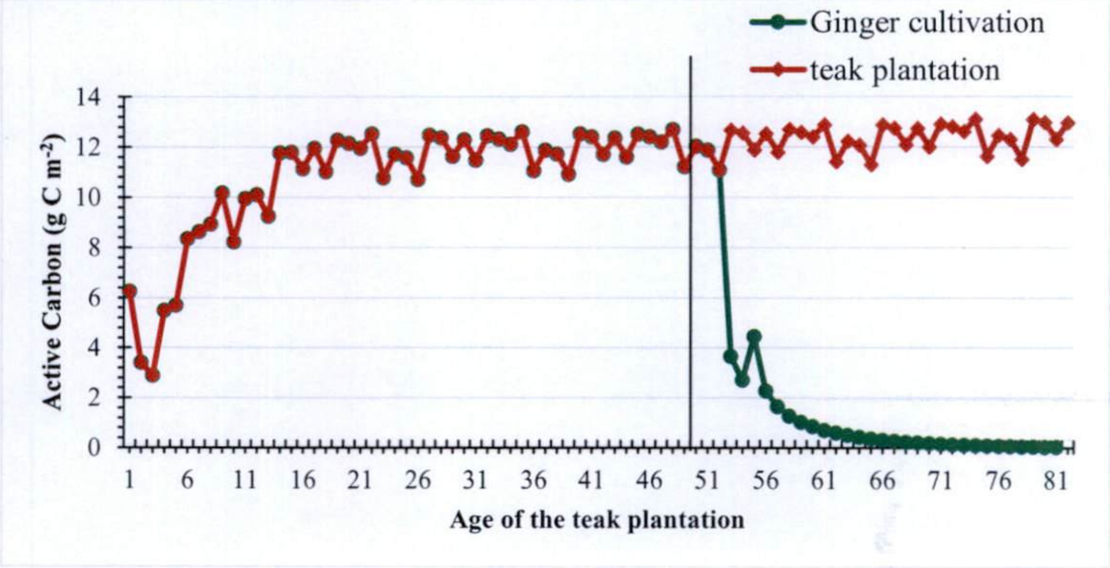


Figure 28. Simulation results of active carbon pool under the teak plantation converted to ginger cultivation scenario (*Zingiber officinale*).

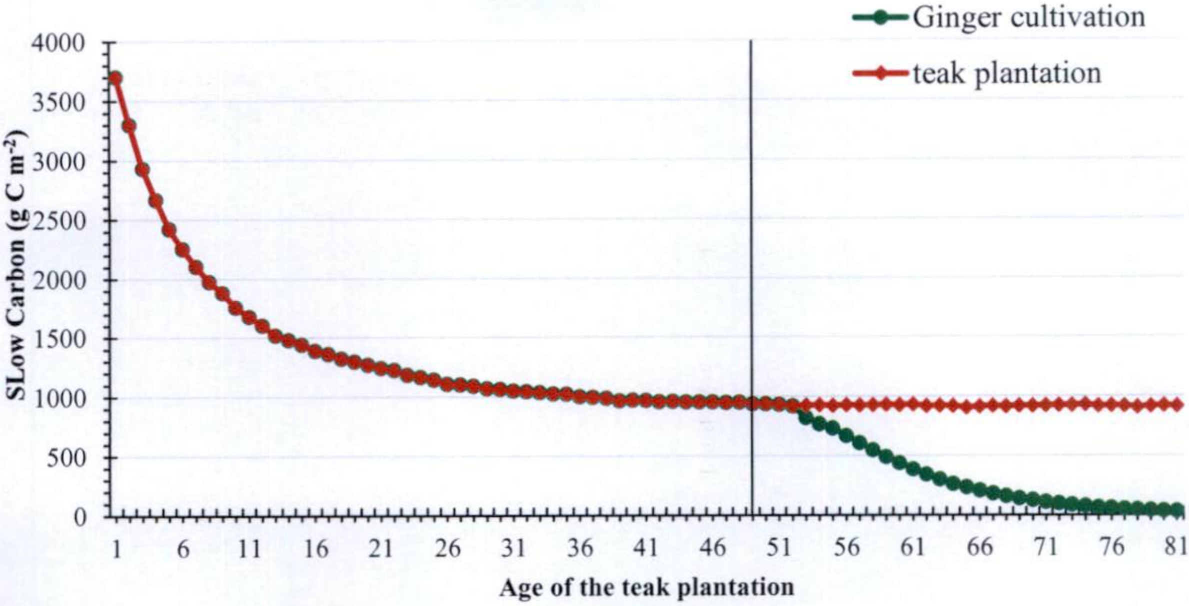


Figure 29. Simulation results of slow carbon pool under the teak plantation converted to ginger cultivation scenario (*Zingiber officinale*).

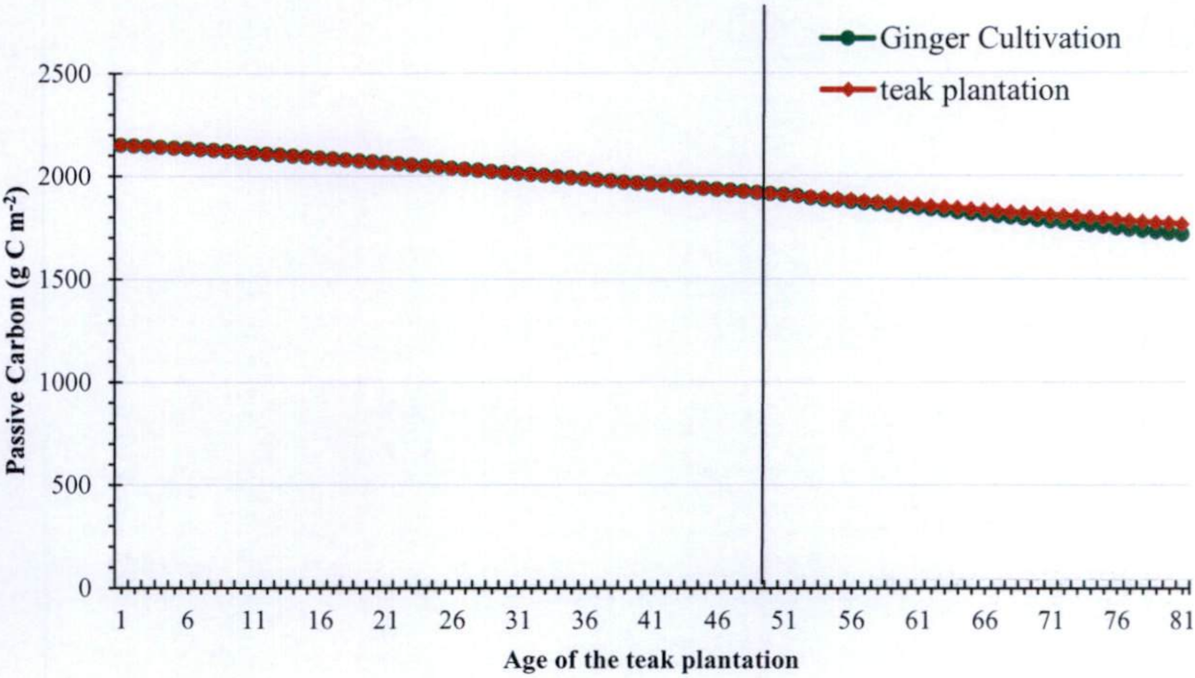


Figure 30. Simulation results of passive carbon pool under the teak plantation converted to ginger cultivation scenario (*Zingiber officinale*).

4.11. Scenario 7. Teak plantation with silvicultural practices: conversion to agricultural practices (upland rice cultivation + root vegetables (tuber crops) + pulses).

This scenario depicts a teak plantation that is being converted for agricultural practices. The total SOC observed in the first year was 2864.40 g C m^{-2} (Fig 31 &Table 23) which then started to increase to 3260.02 g C m^{-2} at 6 years. It showed a declining trend and reached 1856.84 g C m^{-2} after 30 years of simulation. The final difference noted for agricultural practices was 846.74 g C m^{-2} as compare to that of the teak plantation.

The active carbon pool increased from 11.86 to 40.36 g C m^{-2} (Fig 32) within 3 year period, and then decreased to 31.70 g C m^{-2} by the next year. An increase to 35.09 g C m^{-2} was noticed during 5th year. After that, a declining trend from 35.09 to 0.543 g C m^{-2} at the end of the simulation period was observed. The difference of 12.40 g C m^{-2} was observed in the agriculture practices as compared to that of the teak plantations.

The slow carbon pool increased from 931.94 to 1345.49 g C m^{-2} (Fig 33 &Table 23) within the initial six year period. After that the values decreased from 1345.49 to 124.50 g C m^{-2} till the end of the simulation period. The difference of 796.41 g C m^{-2} was noticed for the slow carbon content in the agricultural practices compared to teak plantation. The passive carbon content for 30 years marginally decreased from 1907.30 to 1729.60 g C m^{-2} (Fig 34). A difference of 27 g C m^{-2} was found for agricultural practices as compared to that of the teak plantation.

Table 23. Simulated total soil organic carbon and different carbon pools (gCm^{-2}) in teak converted to agriculture practices

Year	Total carbon		Active carbon pool		Slow carbon pool		Passive carbon pool	
	Teak Plantations	Agriculture	Teak plantation	Agriculture	Teak plantation	Agriculture	Teak plantation	Agriculture
1	2864.41	2864.41	11.87	11.87	931.94	931.94	1907.31	1907.31
2	2843.81	2843.81	11.08	11.08	917.02	917.02	1901.80	1901.80
3	2845.39	3073.48	12.66	40.36	923.55	1147.17	1896.97	1897.29
4	2843.69	3182.02	12.54	31.70	926.64	1264.39	1892.02	1892.07
5	2831.57	3250.51	11.87	35.10	919.59	1328.88	1886.90	1886.95
6	2831.54	3260.50	12.52	28.44	924.24	1345.50	1882.11	1882.37
7	2823.61	3228.80	11.78	23.14	921.74	1321.39	1876.81	1877.26
8	2822.40	3177.46	12.69	19.61	924.99	1276.78	1872.19	1872.66
9	2819.80	3107.74	12.58	16.53	927.22	1214.58	1867.32	1867.47
10	2812.91	3030.03	12.39	14.12	925.20	1143.95	1862.57	1862.43
11	2813.19	2951.49	12.87	12.16	930.08	1072.47	1858.00	1857.35
12	2795.57	2860.00	11.40	10.26	918.16	988.93	1852.59	1851.41
13	2792.18	2774.07	12.23	8.78	920.05	910.47	1847.51	1845.73
14	2784.78	2690.21	12.07	7.53	917.59	834.06	1842.45	1839.95
15	2766.41	2605.27	11.29	6.41	904.64	756.91	1837.16	1833.75
16	2769.70	2533.71	12.87	5.57	912.65	692.28	1832.51	1828.15
17	2769.66	2462.72	12.75	4.80	917.18	628.54	1827.76	1822.17
18	2759.20	2395.61	12.08	4.13	911.55	568.66	1822.84	1816.09
19	2760.61	2338.11	12.73	3.60	917.41	517.78	1818.25	1810.45
20	2754.19	2279.60	12.00	3.10	916.19	466.46	1813.16	1804.24
21	2754.22	2230.02	12.90	2.71	920.46	423.34	1808.73	1798.57
22	2752.86	2180.84	12.80	2.34	923.69	381.12	1804.07	1792.41
23	2747.11	2136.52	12.60	2.03	922.60	343.42	1799.52	1786.47
24	2748.44	2096.82	13.09	1.78	928.31	310.18	1795.14	1780.62
25	2731.98	2054.97	11.61	1.51	917.29	275.70	1789.96	1773.86
26	2729.61	2018.67	12.44	1.30	919.97	246.30	1785.10	1767.49
27	2723.19	1985.28	12.29	1.12	918.25	219.78	1780.25	1761.10
28	2705.75	1953.00	11.50	0.96	905.98	194.68	1775.19	1754.36
29	2709.85	1926.30	13.09	0.84	914.59	174.44	1770.75	1748.26
30	2710.60	1900.75	12.96	0.72	919.68	155.58	1766.20	1741.90

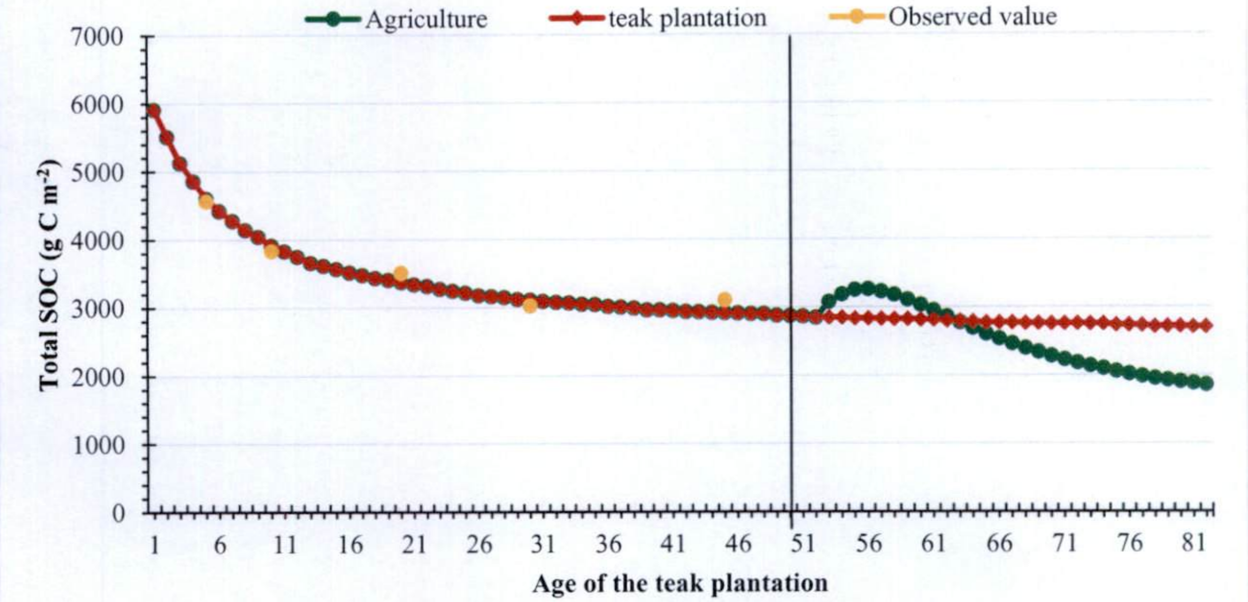


Figure 31. Simulation results of total soil organic carbon in conversion of Teak plantation to agricultural practices scenario (tuber crops and pulses).

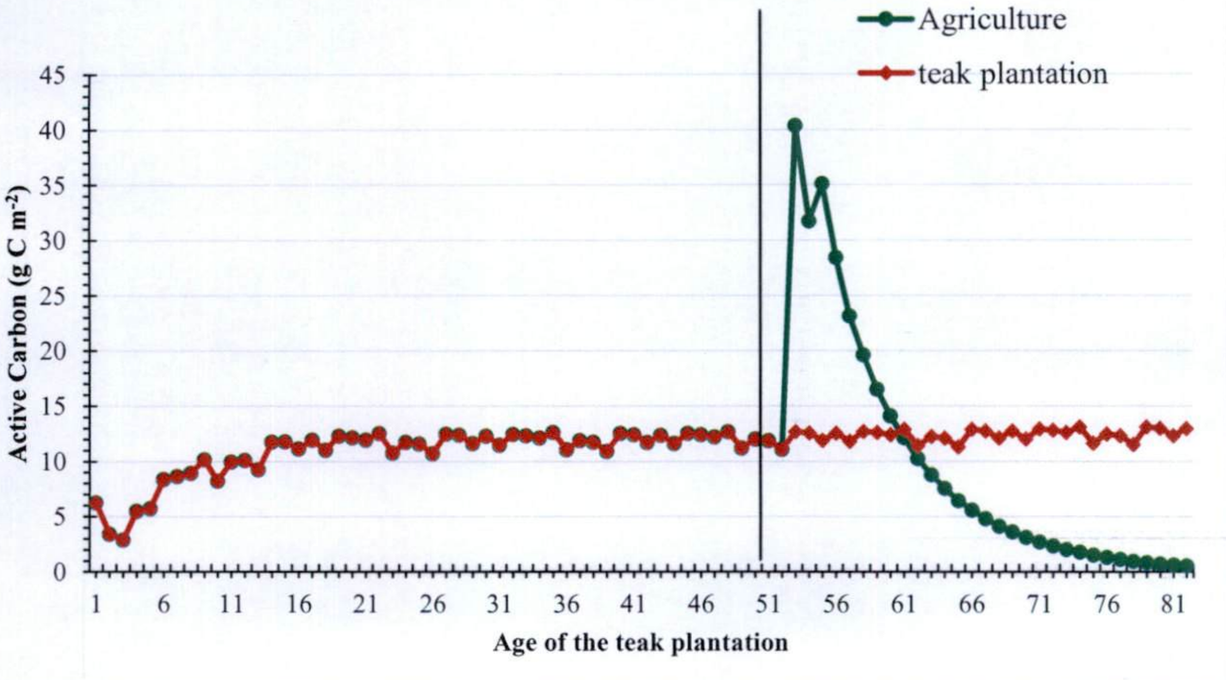


Figure 32. Simulation results of active carbon pool under the teak plantation converted to an agricultural practice scenario (tuber crops and pulses)

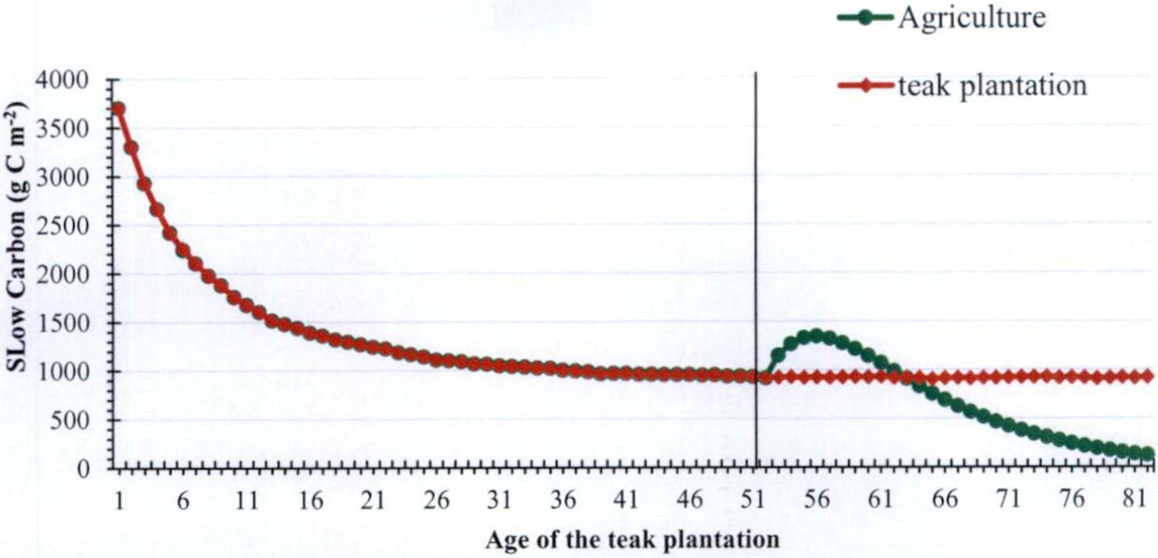


Figure 33. Simulation results of slow carbon pool under the teak plantation converted to an agricultural practice scenario (tuber crops and pulses).

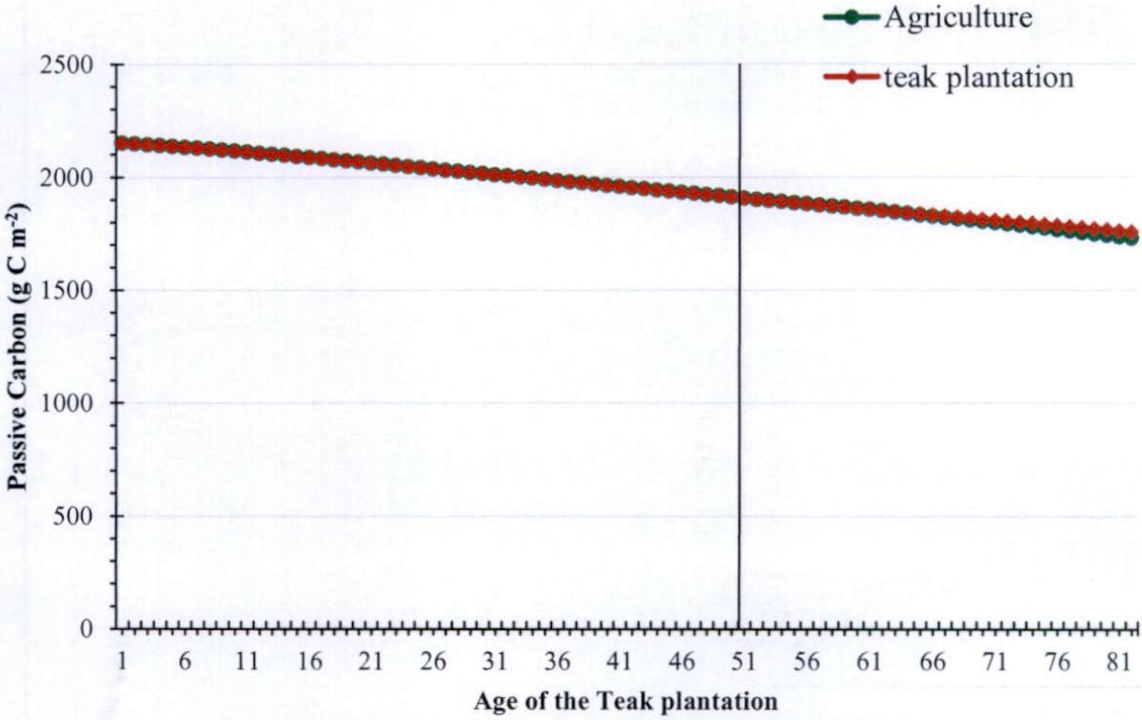


Figure 34. Simulation results of passive carbon pools under the teak plantation converted to an agricultural practice scenario (tuber crops and pulses).

4.12 STELLA process Model

The age classes of 1 to 5, 6 to 10, 11 to 20, 21 to 30 and more than 30 years showed an average SOC value of 4563.7 g C m^{-2}, 3829.58 g C m^{-2}, 3502.82 g C m^{-2}, 3194.10 g C m^{-2} and 3103.12 g C m^{-2} respectively (Table 24 & Fig 36). Whereas the STELLA model simulated average values were found to be 4441.2 g C m^{-2}, 4216.74 g C m^{-2}, 3896.24 g C m^{-2}, 3245.41 g C m^{-2} and 3278.32 g C m^{-2} respectively.

A strong and linear relationship (r^2=0.927) was seen between measured and simulated total SOC values suggests (Fig 36) that the STELLA model is reliable in simulating the carbon dynamics in teak plantations.

The CENTURY and STELLA model were verified by comparing with measured as well as the simulated data (Table 24). It was found that CENTURY model simulates much better when compared to that of STELLA process Model. The model efficiency was also found to be very high in CENTURY model (0.922) whereas, it was found comparatively less with STELLA process model (0.694).

STELLA® automatically defines the differential equation system and solves it. In STELLA® language the following equations are generated (Fig 35).

```
ACTIVE_CARBON (T) = ACTIVE_CARBON (T - DT) + (POOL1 + FLOW_4 -
FLOW_2 - FLOW_6 - FLOW_7) * DT
INIT ACTIVE_CARBON = 6.5
INFLOWS:
POOL1 = 1*FLOW_2*FLOW_1
FLOW_4 = 1.1
OUTFLOWS:
PASSIVE_CARBO(T) = PASSIVE_CARBO(T - DT) + (POOL3 + FLOW_5 +
FLOW_6 - FLOW_3 - FLOW_9) * DT
INIT PASSIVE_CARBO = 3700
INFLOWS:
FLOW_5 = 0.25*POOL3
FLOW_6 = 0.25*POOL1
```

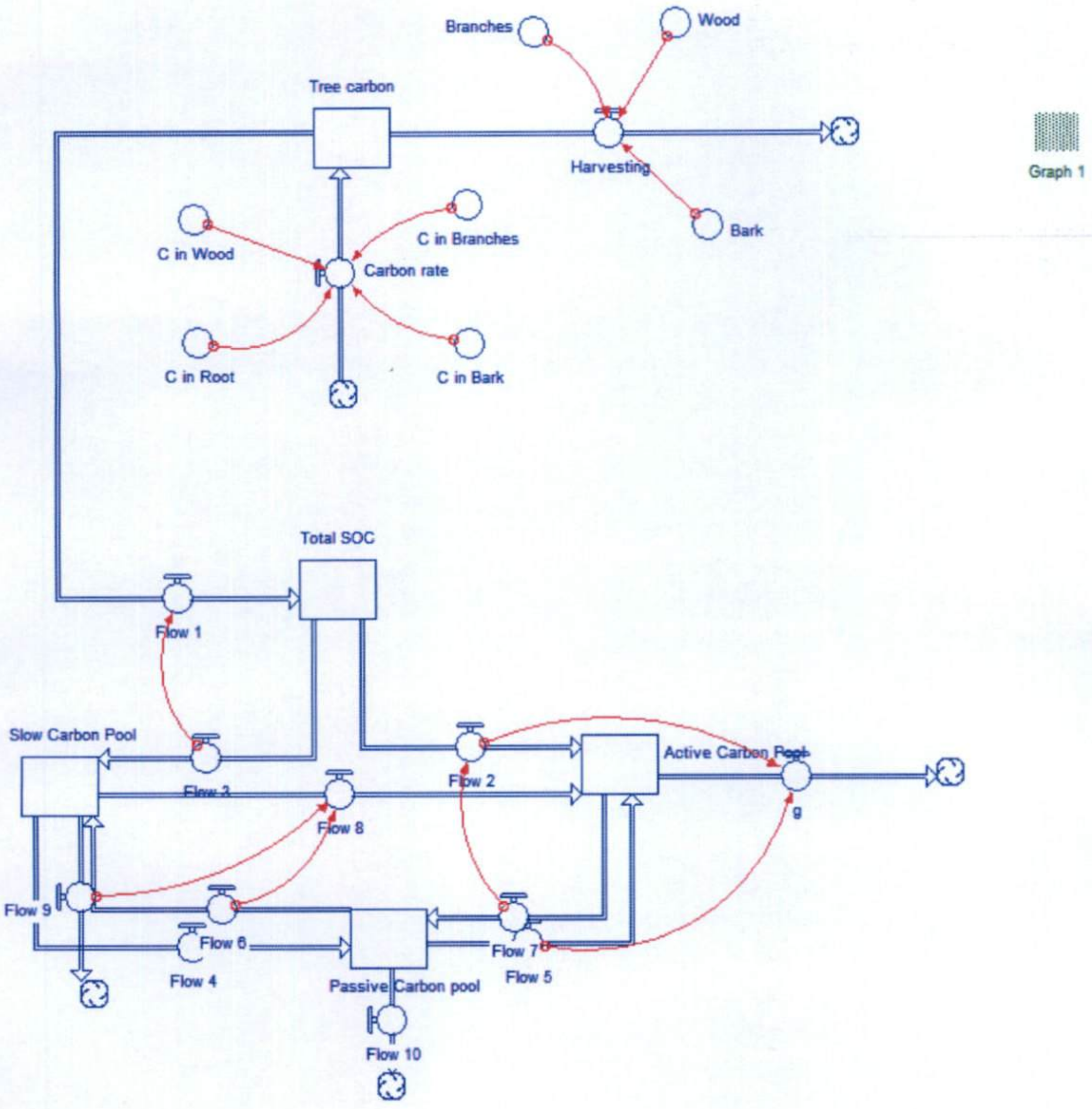


Figure 35. Carbon dynamics in teak plantations of Kerala using STELLA Model.

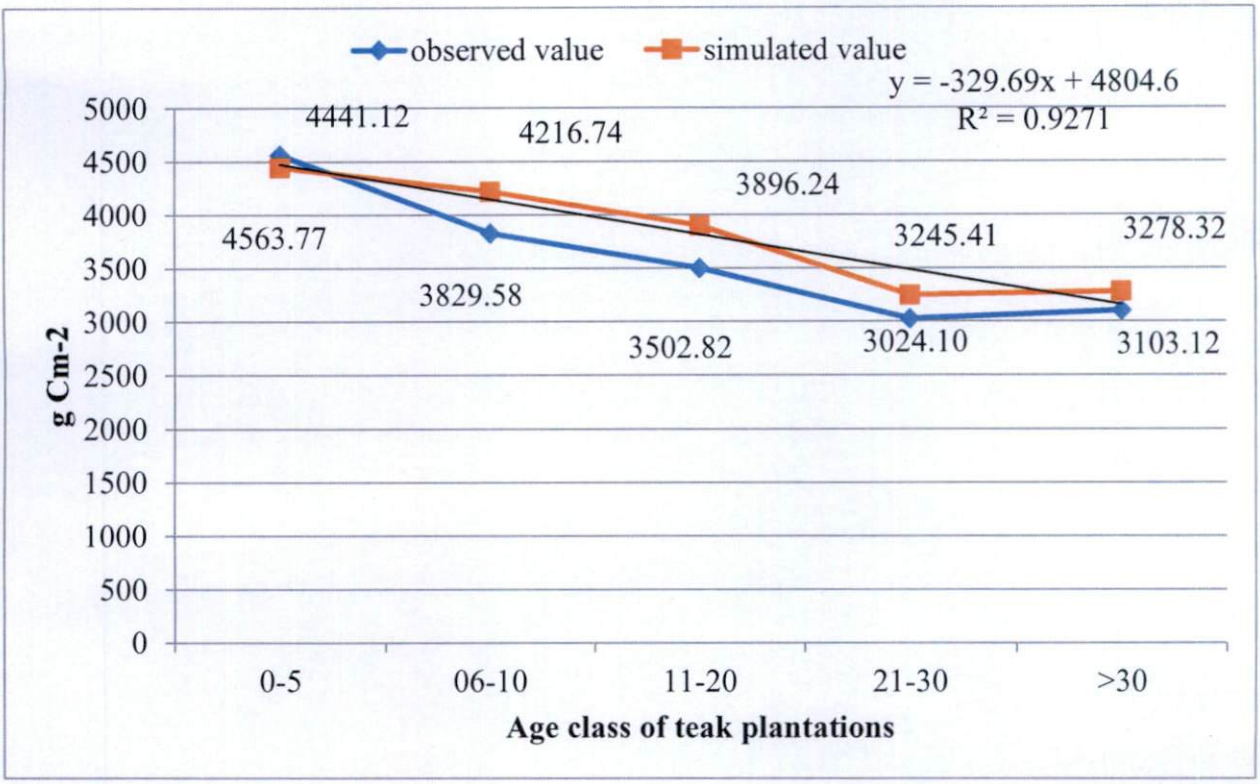


Figure 36. Measured and STELLA simulated soil organic carbon stocks in teak plantations of Kerala

```
SLOW_CARBON(T) = SLOW_CARBON(T - DT) + (POOL2 + FLOW_2 +
FLOW_3 - FLOW_4 - FLOW_5 - FLOW_8) * DT
INIT SLOW_CARBON = 2564
OUTFLOWS:
FLOW_5 = 0.25*POOL3
SOIL_ORGANIC_CARBON(T) = SOIL_ORGANIC_CARBON(T - DT) +
(FLOW_1 - POOL1 - POOL2 - POOL3 - FLOW_10) * DT
INIT SOIL_ORGANIC_CARBON = 6168
POOL1 = 1*FLOW_2*FLOW_1
TREE_CARBON(T) = TREE_CARBON(T - DT) + (CARBON_INPUT -
HARVESTING - FLOW_1) * DT
INIT TREE_CARBON = 35
INFLOWS:
CARBON_INPUT = WOOD*BRANCHES*BARK*ROOT
OUTFLOWS:
HARVESTING =
WOOD_CARBON*BRANCH_CARBON*BARK_CARBON*ROOT_CARBON
```

Discussion

5. DISCUSSION

Present results of the investigation was on "Modeling carbon dynamics in teak *(Tectona grandis)* plantations of Kerala" are discussed here under

5.1 Climate

The Kerala State falls in the region of tropical climate. The coastal location of the State and a high variation in relief from the coast to the Western Ghats influence the climatic characteristics to a large extent. While most of the areas are under tropical dry and wet conditions with high maritime influence, certain areas in the eastern parts experience subtropical type of climate.

5.1.1 Temperature: Five attributes of temperature variations, namely, the highest temperature, mean maximum, mean monthly, mean minimum and the lowest temperature are shown in figure 6. The period, March - May, is the hottest when temperature reaches a maximum (>32°). From June, it gradually comes down due to heavy monsoon. Again, an increasing trend is noticed in October and November, followed by lower temperatures (<25°) in the months of December and January.

5.1.2 Rainfall: Kerala receives the highest annual rainfall among the different states of India – about 300 cm in a year which is three times the average rainfall of India. The State receives rainfall for almost ten months in a year from both monsoons and local systems though most of the rainfall occurs during the southwest monsoon period (Fig 7).

5.2 Soil studies

5.2.1 Physical properties of soil

Table 5 shows that soils in the selected teak plantations were mainly sandy loam in texture. It was also noticed that the soil texture did not vary with depth among different age class of teak. After clear felling and during the initial years of establishment of plantations, the soils were exposed in the absence of any soil conservation measures and this would lead to soil erosion (Balagopalan, 1987.). In the younger plantations with periodical thinning, both mechanical and silvicultural, these might have led to the loss of surface layer, exposing the subsurface layer. As both depths of 0-20 cm and 20-40 cm were of the same textural class, no apparent difference in the texture was immediately noticed, though an increase in gravel was observed. In older teak plantations, even though erosion continues, it is not as intense as in the beginning due to partial canopy closure, presence of litter, undergrowth etc. As a result, rather than the complete loss of topsoil, continuous loss of liner particles was noted in older plantations. This incessant loss of liner particles results in the change of textural class from sandy clay loam to loamy sand in older plantations. This finding is at variance from the conclusions of Okoro *et al.* (1999) who observed that the texture of the soils was not affected by the respective plantation species but agrees with the findings of Balagopalan (1995).

Table 6 shows the water holding capacity, which shows no difference between the plantations of different age class in the depth of 0-20 cm, but in the depth of 20-40cm, the water holding capacity in 0-5Y (37.82%) was significantly different from other age classes. As the water holding capacity of soils is controlled to a greater extent by organic matter. The more the organic matter in soils, higher the water holding capacity (Ghosh and Bhardwaj, 2002). It was also observed that in deeper layers, the organic matter was found to decrease due to low incorporation of litter when compared to the surface layer. This decrease in organic carbon with depth also explains for the decrease of water holding capacity. These studies were limited to a single plantation of teak and as such provide no information about variation of water holding capacity with age. There were no significant differences with respect to soil porosity between the different age class of the plantation as well as depth.

The table 7 shows that the bulk density values were generally higher in deeper layer of the soil. The mean bulk density values were in the range 1.0 to 1.36 g/cm^3. Mechanical compaction of the soils during clear felling of natural forest and also during the initial stages of plantation establishment may be responsible for higher compaction in plantation soils. It was also noticed that difference between the bulk density values of natural forest and plantations was most pronounced in the surface. This could be due to the loss of loose surface soil due to plantation activities. Enhanced bulk density values in a teak plantation in Nigeria were reported by Aborisade and Aweto (1990). A similar finding was reported by Balagopalan (1995) from Kerala. Amponsah and Meyer (2000) and Rathod and Devar (2003) found soils of both teak and eucalypt plantations to be more compacted to natural forest.

5.2.2 Chemical properties of soil

Soils of teak plantations were acidic in nature. Soil test results showed soil pH records ranged from 5.0 to 6.0 (Table 6) indicating moderate acidicity these are suitable for cultivation of teak (Asubonteng, *et al.*, 1995). The same was noted by Okoro *et al.* (2000) and Chamshama *et al.* (2000) in different age classes teak plantations and adjacent natural forest. Within teak plantations, pH values were found to increase with age in all depths. Lower pH values in soils of different age teak plantations compared to natural forest was also observed by Nath *et al.* (1988) and Balagopalan and Jose (1997).

The total nitrogen content in teak plantations varied from 0.07 % to 0.34% and in natural forests, the variation was from 0.43 % to 1.23 % (Table 9). The total nitrogen in soils was highest in the surface and decreased with the depth in both teak plantation and natural forest. In teak plantations, total nitrogen was observed to increase with age though the difference was not significant. This trend is clearly visible in the two upper layers. Due to the plantation activities in the initial year of its establishment, loss of top soil and accompanying nitrogen behind a soil that is low in nitrogen content. As the plantation ages, addition of litter, its mineralization and incorporation into the soil enhances the nitrogen content of soil. Total nitrogen is significantly and positively correlated to organic carbon and mirrors the variation of organic carbon in soil (Lal, 2008).

The mean values of available phosphorus in the teak plantations and natural forest varied from 1.0 to 4.81 g kg^{-1} and 3.16 to 4.82 g kg^{-1} respectively (Table 10). Balagopalan (1995) observed slightly higher available phosphorus values in teak plantations compared to natural forest, though the difference was not significant. Similar observations were also made by Chavan *et al.* (1995). On the other hand, Aborisade and Aweto (1990) observed that the concentrations of available phosphorus were similar in plantations of teak and natural forest, while Mongia and Bandyopadhyay (1992) and Okoro *et al.* (2000) reported lower phosphorus values in teak soils compared to natural forest. In the present study, we could not find any significant difference in available P values of teak plantation and natural forest.

Soil carbon is considered the single most important indicator of soil quality and a major component in the assessment of soil quality (Sikora *et al.,* 1996). In this study the soil carbon was highest in the surface and decreased with the depth in both teak plantation as well as natural forest (Table 12). Organic carbon in teak plantations varied from 0.76 to 2.07 per cent and in natural forest, it varied from 1.35 to 2.88 per cent. In both natural forest and plantations of teak, organic carbon decreased with depth. The sharp decrease from surface to subsurface is due to the accumulation of organic matter through leaf litter in the upper layer. Similar findings were reported by Salifu and Meyer (1998), and also Amponsah and Meyer (2000). Conversely, no significant difference between organic carbon values of a teak plantations and natural forest in Nigeria was reported by Okoro *et al.* (1999). The occurrence of more organic matter content in natural forest is due to a number of factors including diversity of vegetation cover (Lundgren, 1978). In natural forest, greater diversity of species results in diversity of litter substrate and faster mineralization leading to enhanced organic carbon content compared to teak. Moreover lower erosion in natural forest results in greater conversion of organic matter (Maro *et al.,* 1993). For the establishment of teak plantations, the natural forest was clear felled and slashes burned. In the beginning, the soil is exposed to the environment and erosion is wide spread. This results in loss of top soil along with the organic carbon in it. However, as the plantations mature addition of litter to soil and its decomposition increases soil organic matter. As teak grows, it provides cover to the soil. However, plantations of teak are subjected to mechanical and silvicultural thinning. The disturbance to the soil during the above processes and decrease of soil cover leads to loss of soil organic carbon. Litter production at this stage appears to be inadequate to balance the loss of organic carbon. The net result is progressive loss of soil organic carbon. The exposures of the soil also exacerbate losses due to soil erosion, and leaching of dissolved organic carbon (Kalbitz *et al.,* 2000). A few field experiments by previous authors indicated low or moderate erosion rates in teak plantations; although, some discrepancies are found between different studies, probably not only due to the use of different methodologies, but also due to differences in soils, climates and plantation management. However, a general trend can be observed as many of the studies reporting high erosion rates were conducted in places where prescription fires are a common management practice (Maeght *et al.,* 2011; Hamilton, 1991; Maeght *et al.,* 2011; Tangtham, 1992). The mechanical thinning is carried out at the age of five to ten years and the silvicultural thinning occurs at an interval of 10 years starting from the age of 15 and ends by 45. It is probably that at this stage, the rate of nutrient return to the soil through the fall and break down of litter is greater than its loss from soil. Thus an increase in soil organic carbon occurs. In the older age class plantations, the values approach those of natural forest.

5.3 Modeling soil carbon pool under teak plantation of Kerala

Results of the modelling using Century for Soil Organic Carbon (SOC) pool for teak plantation in Kerala is presented in figure 10. As per simulation, the total SOC in teak plantation declined to about 50 per cent from the initial value of 6168 g C m^{-2} to 3371 g C m^{-2} in 30 years (Fig 10). There after SOC pool declined at a slower rate (43 g C m^{-2} yr^{-1}) till 45 years of age (2717 g C m^{-2}) and reached a stable level by 80 years (2710 g C m^{-2}). From the results it is clear that the conversion of natural forest to teak plantation resulted in significant loss of SOC.

About half of SOC was lost by conversion of natural forest to teak plantation. The loss of SOC can be attributed to many reasons. The most important among these would be the lower rate addition of organic matter in the soil. Raising of teak plantation is preceded by clearing of natural vegetation in an area. Generally all vegetation including herbs and shrubs are removed and cleared. Teak saplings are then planted at 2 X 2 m spacing. Weeding is recommended during the first three years after establishment. Teak being an early fast grower, canopy generally closes in about four years. Subsequently, thinning is under taken in order to prevent crowding (Koegh, 1987 and Kadambi 1992). While weeding keeps ground vegetation under check in initial years (Boley *et al.,* 2009), the closed canopy prevents it in later stages. In short, the miscellaneous vegetation under teak plantation is controlled to a very low level through management intervention. This reduction in understory vegetation could also be due to excessive light reduction and or allelopathic effect of teak leaf and root exudates on the germination of plants. Healey and Gara (2003), reported considerable concentrations of phenolic acids in teak foliage. Phenolics have been implicated in regeneration failure in many forest types (de Moral *et al.,* 1978; Li *et al.,* 1993). Teak plantations have cover litter production compared to natural forests (Janson *et al.,* 1992). Disruption of organic matter addition in the soil due to these reasons could be a major reason for lowering of SOC under the teak plantation.

In Kerala, teak plantations are raised in well drained soil with topography characterized by gentle to moderate slopes. Kerala is a high humid tropic with rainfall exceeding 3000 mm per annum (Fig 7). Mountain sides of Kerala face severe soil erosion (Kumar *et al.*, 2003) due to high intensity rainfall and steepness of slope (Jose *et al.*, 2011). High erosion observed in teak plantations (Champion, 1932 in White, 1991) hampers even recruitment. Despite the threat of erosion, little soil and water conservation measures are generally undertaken in teak plantation. Teak plantations have been reported to increase soil hydraulic conductivity and macroporosity in comparison to grazed lands (Mapa, 1995). They generally show a high erosion rate, in which most of the top soil is lost and the subsurface layer is exposed. Low levels of litter production have also been linked to the high rates of erosion under teak plantations. It was also seen that gravel was left behind and fine particles lost from the surface leading to coarsening of texture (Balagopalan and Geetha, 2006).The large leaves of teak trees are associated with an increase in raindrop erosivity, as drops falling from teak vegetation will have several times greater kinetic energy than those falling from other species (Calder, 2001). Studies have shown that the major portion of Kerala (51.98%) falls in 0-5 tones ha^{-1} year^{-1} soil loss category (Jose *et al.*, 2011). Olson (1949) concluded that in teak plantation with slight sheet erosion, up to 25% top soil gets lost, and with moderate erosion, 25-75% of top soil may be carried away. In the case of severe erosion, more than 75 % of top soil gets lost. On slopes of length 10 m, annual loss of soil was 327 and 199 tons ha^{-1} for gradients of 43% and 21% respectively (Suarez De Castro, 1951).

Forest fires are common in teak plantations. Just prior to plantations establishment, slash burning is under taken. Fire burns organic matter, heats up the top soil and changes the physiochemical properties of soils and causes erosion. Harmon *et al.*, 2008; Mitchell, 2009 found that soil organic matter did not increase with stand age of teak plantations in Myanmar due to frequent combustion of organic layer. Hence, fire can be a major practice of burning that can lead to destruction of 70 per cent organic matter in the surface 7.5 cm of the soil (Youngberg 1953). Vukicevic and Melosevic (1960) found that after fires in teak plantations, organic matter decreases and also they observed that burning causes marked decrease in C: N ratio and initial organic matter level is reached only 55 years after fire incidence.

Kerala is characterized by very hot summer during the period from February to May. The maximum temperature 35^0C in the absence of proper soil cover, soil temperature can rise to 37^0C. This increases the chances of soil respiration through microbes (Hashimoto *et al.*, 2004).

Takahashi *et al.* (2009) reported that the carbon dynamics in the soil under teak plantations the temperature did not significantly influence soil respiration due to small variation. Soil respiration in teak plantations had no clear difference between different stand ages. The CO_2 efflux fluctuated probably due to changes in soil moisture controlled by rainfall events.

5.3.1 Carbon pools

Soil organic carbon is considered to be one of the most important pools. Its amount and nature plays a key role in soil quality (Larson and Pierce, 1992). Organic carbon (OC) although not a plant nutrient, its low amount can have deleterious effect on soil health and crop productivity (Stevenson, 1982). Therefore, maintenance or improvement in the OC content of the soil is of utmost importance. Details of the carbon pools are as follows.

5.3.1.1 Active carbon

Active soil organic carbon is a sensitive indicator for changes in soil organic carbon following the land-use change than the total amount of carbon mineralized. A higher amount of active pool of C indicates the existence of carbon readily mineralizable by the microbes. The active pools of C are considered as the most labile, mobile and readily available source of energy for micro-organisms and contribute to soil quality through their role in the formation and stabilization of soil structure (Mc Gill *et al.,* 1981). Labile soil organic carbon consists of rapidly mineralized components with turnover rates ranging from a few days to a few years. The most labile components are cellular contents, such as carbohydrates, amino-acids, peptides, amino-sugars and lipids. Labile soil organic carbon also includes less readily metabolized structural materials, including waxes, fats, and resins (Jenkinson and Rayner, 1977; Jenkinson and Ladd, 1981). The active fraction of soil organic carbon consists mainly of microbial biomass and its metabolites (Paul and Voroney 1980). Microbial biomass is of particular importance, acting alternatively as a source or sink for nutrients (Duxbury *et al.,* 1989; Singh *et al.,* 1989). The soil microbial biomass forms a labile pool of organic carbon comprising 1-3% of total soil organic carbon (Jenkinson and Ladd, 1981).

Labile soil organic carbon plays a key role in the maintenance of soil fertility as a source of plant nutrients due to its chemical composition and rapid turnover rate. The macroclimate, principally soil temperature and moisture, regulates the rates of decomposition of labile soil organic carbon (Jenkinson and Ayanaba, 1977) and the equilibrium in soil microbial biomass (Insam *et al.,* 1989). In the humid tropics, isothermic and isohyperthermic temperatures and uniform soil moisture availability maintain high rates of microbial metabolism and increase the turnover of the labile components of soil organic matter (Duxbury *et al.,* 1989).

The disturbance to the soil during the plantation establishment processes and decrease of soil cover leads to loss of soil organic carbon. Litter addition at this stage appears to be inadequate to balance for the loss of organic carbon. The net result is progressive loss of active / labile soil organic carbon. In present study the active carbon pool decreased from 6.25 g C m^{-2} to 2.88 g C m^{-2} by the end of 3rd year and slowly increased to 10.17 g C m^{-2} by 9th year. By the end of 80th year, the active pool stabilized around 12 g C m^{-2} (Fig 10). In effect, the active carbon doubled by 80 from the year of establishment of plantation. During first two years, the above and belowground biomass is low, resulting is decreased the active carbon pool. Because for the beginning of establishment of teak plantations, the soil is exposed to the environment and erosion is wide spread. This would result in loss of top soil along with the organic carbon in it. However, as the plantations mature addition of litter to soil and its decomposition increases soil organic matter. As teak grows, it provides cover to the soil. Hence the active carbon pool increased in the 3rd year when the canopy starts closing and litter deposition increases. In India, average litter fall in teak plantations ranges from 3.3 to 4.5 Mg ha^{-1} (Pande *et al.*, 2002). The annual teak leaf litter production in the present study was found to be 3.6 t ha^{-1} (Fig 8). After 5th year, the active carbon pool increases gradually, with increased biomass returned to the soil. Rapid decomposition is often reported for teak leaves, usually more than 90 % in a year (e.g. Sankaran, 1993; Maharudrappa *et al.,* 2000; Pande, 2005). Soil carbon stock usually increases over time after planting trees (Sakai *et al.*, 2010), due to carbon input from litter fall and the turnover of dead roots (Richter *et al.,* 1999). Large soil respiration rates in the teak plantation might also be explained by high belowground biomass production which leads to high root respiration rates (Trumbore *et al.,* 1995).

At the end of simulation period, the active carbon got stabilized as the actual teak plantation. The increase in the active carbon is a good predictor of soil respiration. Thus, active soil organic carbon is a sensitive indicator for the changes in soil organic carbon following land use changes (Chang *et al.,* 2012).

5.3.1.2 Slow carbon

The slow pool contains physically-protected forms of plant material and soil stabilized microbial products; these pools have an intermediate turnover time of 20-50 years. In the present study, slow carbon reduced from 3700 g C m^{-2} to 1224 g C m^{-2} (Fig 10) at the age of 22, and finally stabilized at 920 g C m^{-2} at an age of 80 years. Hence, the simulations indicate substantial loss of slow carbon pool from the system. Soil aggregation is considered to be one of the important processes of stabilizing soil organic matter (SOC) pools; therefore, characterization of water stable aggregate carbon, also known as slow pool of SOM, is important in maintenance of soil fertility. Soil organic matter is the major binding agent and aggregation is hierarchical in which primary particles and clay domains are cemented into micro-aggregates and later into macro aggregates. The most recalcitrant components of soil organic matter are highly polymerized humic substances, resulting from decomposition of plant debris (lignin-like substances) or condensation of soluble organic compounds released through the decomposition of sugars, amino-acids, polyphenols and lignin (Duchaufour, 1977; Stevenson, 1982). Humic acid represents a significant part of this fraction as a recalcitrant end-product of microbial activities transformed from plant and animal detritus (Stout *et al.,* 1981).

5.3.1.3 Passive Carbon

Passive pools comprise the fraction of SOM, which is most resistant to mineralization and decomposition. It includes physically and chemically stabilized SOC with a turnover time of 400-2000 years. Hence, this forms an important part of sequestered carbon in soils. Passive carbons more or less remain stable. It decreased from 2150 g C m^{-2} to 1912 g C m^{-2} at the age of 50 years (Fig 10) and marginally declining to 1757 g C m^{-2} at the end of 80 years. The initial rapid decline in soil carbon over a few weeks represents the rapid decomposition of the active fraction and fine roots (Hendriksen and Robinson 1984). Then the rate decreases, reflecting carbon losses from the slow fraction, and becomes asymptotic to the residual carbon in passive SOM. Stevenson, (1982) lists seven studies in tropical forests where carbon losses (which will include fine root mass) range from 7- 54% in one to three years.

The study attempted to simulate different scenarios to explain the nature of SOC under different land use systems.

5.4 Scenario 1: Replanted teak plantations

This scenario assumes that teak plantations were replanted after harvesting the previous crop with a rotation of 50 years adopting normal silvicultural practices that are in vogue. The present study showed that the total SOC decreased by about 8 per cent when the initial value dropped from 2865 g C m^{-2} to 2665 g C m^{-2} in the first 12 years (Fig 11). The SOC then returned to the initial levels and kept increasing for the next 24 years. Thus, the replanted teak shows a significant increase in the total SOC. Soil carbon stock usually increased during the initial period after re-planting (Sakai *et al.,* 2010) due to carbon input from litter fall and the turnover of dead roots (Richter *et al.,* 1999). In some studies where the initial soil carbon stock was found to be very low (2000–3000 g C m^{-2}), SOC was found to linearly increase with time after afforestation (Foote and Grogan, 2010). The decrease of SOC in the young plantation during the first few years may be due to the higher soil carbon decomposition rates due to land preparation and planting (Jandl *et al.,* 2007). This indicates that decrease of soil disturbance could be helpful to conserve carbon release in re-planted teak plantations. In this study, the average rates of carbon accumulation during the study period (i.e., 30 yr) ranged from 1.5 to 9 per cent yr^{-1} in the upper 20 cm of soil.

The present study demonstrate that the active carbon pool in replanted area was 11.86 g C m^{-2} at the first year of planting, which increased to 17.17 g C m^{-2} by the end of 3rd year, Then it declined to 6.03 g C m^{-2} at age of 7th year, and the trend further proceeded in a fluctuating manner from 10.64 g C m^{-2} to 12.47 g C m^{-2} at an age of 30 year (Fig 12). Usually in teak plantations, weeding operation takes place from the period of 1-3 years after establishment. Being an early fast grower, the canopy closure of teak occurs in about four years after which shaded conditions prevail underneath. This leads to quicker decomposition of what is left after weeding which gradually modify the soil conditions leading to a bare and exposed surface.

The slow carbon in the initial period started to increase at 50.36 g C m^{-2} from an age of three years, which then declined to 30 per cent (Fig 13) at an age of 12th year. The slow carbon then increased to 1016 g C m^{-2} at an age of 30 year of simulation period and a slight increase to 1757 g C m^{-2} in the passive carbon was noticed in replanting of teak plants as compared to that of the old teak plantation (Fig 14). Boley *et al.* (2009) indicates that faster rates of change over short time periods are possible as a result of changes in environmental conditions.

5.5 Scenario 2: Forest fire damages (in different intervals)

Forest fire, whether controlled or uncontrolled, have profound impacts on the physical environment including land cover/land use, biodiversity, climate change and forest ecosystem. They also have serious implications on environment, human health and on the socio-economic system of the affected regions. Occurrence of fire is frequent in almost all teak plantations in Kerala. The deleterious effect of fire on teak plantation growth and wood quality is well known as it could wipe out a very young plantation (Ansep, 1925). In older plantations it could eliminate the undergrowth, burn up the organic matter in the soil and reduce the number of soil organisms. Blanford (1933) reported that epicormic shoots develop in the teak trees following a fire.

Fire is a major disturbance that can have an impact on the soil C stock in a forest ecosystem, and may also have a particularly long-term impact on the C stock in soils of the teak plantations. The most intuitive changes the soils experience during burning is the loss of organic matter. Depending on fire severity, the impact on the organic matter consists of volatilization of minor constituents, charring or complete oxidation. Substantial consumption of organic matter begins in the 200–250^{0}C range to complete at around 460^{0}C (Giovannini *et al.,* 1988). Combustion causes reduction or total removal of the forest floor (Simard *et al.,* 2001).

This scenario relates to the teak plantations that are affected by forest fire and the model simulated the occurrence of fire every three years. The simulated values of total SOC in fire damaged teak plantation is found to be lesser as compared to that without fire. In the study we found a 20 per cent decline in the total SOC by the 22nd year of plantation (Fig 15). The SOC stabilized at 2343 g C m^{-2} at the age of 30 years after replanting, the final simulated age.

A substantial decrease in the SOC concentration was observed in the present study even though an increase in the percentage of total SOC mineralized was observed immediately after the fire. In contrast, Johnson and Curtis (2001) reported that fire resulted in no significant effects on either C or N stocks, but a significant effect of time has been observed on these stocks after the occurrence of fire. Thus, it may be derived that the effects of fire on SOC stocks or concentration are not always instantaneous or negative.

The SOC pool is the balance between the C input from aboveground litterfall and belowground rhizo-deposition, and release by decomposition (Jandl *et al.,* 2007). Immediately after fire, the site is colonized by broadleaf tree species, shrubs, and herbs whose litter decomposes easily and contributes SOC to the mineral soil. In the 73-year-old stands, litter incorporation to SOC would be slow (Brassard *et al.,* 2008).

Fine roots contribute substantially more to the soil SOC pool than aboveground litter (Ruess *et al.,* 1996, 2003; Steele *et al.,* 1997; Yuan and Chen, 2010). The lower SOC pool in 203-year-old stands is also attributable to the result of lower production and slower turnover rates of coniferous fine roots (Finér *et al.,* 1997; Yuan and Chen, 2010). The impact of fire on SOC stocks depends on fire temperature and duration, SOC stock and its distribution in the soil profile, and change in the decomposition rate of SOC following the fire event (Page-Dumroese *et al.,* 2003). Ferna′ndez *et al.* (1999) found that the long-term fire-induced increase in SOC due to the decline of the mineralization rate lasted up to at least 2 years. Kauffman *et al.* (1995) reported similar results in a multi-site study in the Brazilian Amazon. Ewel *et al.* (1981) also reported carefully controlled slash-and-burn experiment in Woomer *et al.* (1997) following *chitemene* in Northern Zambia. Carbon in soils is physically protected from massive loss during felling and burning and may increase due to entry of incompletely combusted particulates depending on the intensity of the burn (Andriesse and Schelhaas, 1987). They reported soil carbon losses from slash-and-burn to a depth of 75 cm as great as 2100 g C m^{-2} in Thailand and 1500 g C m^{-2} in Sri Lanka. Woomer *et al.* (1997) report soil carbon losses of 8000 g ha^{-1} yr^{-1} due to slash-and-burn of coastal sand dune forests in Mozambique. Ramakrishnan and Toky (1981) reported that the soil organic carbon contents were greater in 30 year fallows than in five year *jhum* cycles of north-east India and that the soil carbon in the longer fallows was more subject to loss during land clearing and cultivation. These and other reports (Palm *et al.,* 1996) of soil organic matter stability during slash and burn illustrate that it is difficult to generalize about its fate, and may be further complicated by erosion subsequent to land clearing (Nye and Greenland, 1964).

Although carbon storage is often favoured by climate mitigation efforts, fire hazard reduction often seeks to reduce fuel accumulation by lowering forest carbon density. Both climate mitigation and fire hazard reduction may be achieved by favouring recalcitrant carbon storage pools and minimizing storage in labile or fine fuels. As noted earlier, recalcitrant pools include large diameter trees, snags, coarse wood, and soil. Labile or fine fuels include understorey, fine wood, and duff.

Reducing C storage in labile or fine fuels may be achieved by controlling understorey C that burns readily. In this scenario, the contribution of SOC pools is relatively low compared to without fire affected areas of teak carbon storage, so loss of the understorey would have little effect on carbon sequestration. Therefore recommend thinning understorey C as a means to reduce labile fuel loading while maximizing C storage. Fire strategies favouring recalcitrant carbon may reduce fuels that contribute to increased fire risk and do not contribute a large proportion of C to long term storage. Recalcitrant C is also favoured by reducing soil disturbance (Lal, 2004; Page-Dumroese and Jurgensen, 2006).

While this scenario provides management opportunities to balance carbon sequestration efforts with fire, these opportunities should consider management implications besides fire hazard and carbon sequestration. Fire salvage should consider the effects on ecosystem function in terms of vegetation regeneration, animal and plant diversity, hydrology, erosion, and nutrient cycling (Serrano-Ortiz, 2011; Donato, 2006; Castro, 2010).

5.6 Scenario 3: Conversion to Natural forests

Land conversion to natural forests is generally regarded as the one of most efficient systems for soil carbon sequestration (Stockman *et al.,* 2013), although there are other reports of positive or no effects at all (Davis *et al.,* 2007; Laganiere *et al.*, 2010; Wiesmeier *et al.,* 2012). Conversion from teak plantation to natural forest resulted in an increase of SOC pools. There was an initial decline in total SOC by 18 per cent by the age of 13 years (Fig 19). After that the soil carbon increased with age upto 30th year. By the end of simulation period, there was an annual increase in the simulated total SOC values of natural forest by 162.97 g C m^{-2} as compared to that of the actual teak plantation. The SOC pools normally changes in response to the changes in land use or land management practices and hence conversion to natural forests provide an opportunity to increase SOC sequestration (Singh and Lal, 2005). In the present study, all the carbon pools increased which resulted in an increase in SOC when land is converted to natural forest.

Younger organic material, from recently added roots, litter residues, dead organisms or waste products is the most biologically "active" fraction which supports the living soil biological community. This fraction is more readily decomposed and has been shown to have a strong response to management practices, such as tillage, residue handling and crop rotations (Carter, 2002). Changes between forest types involves change in species composition and tree density (Khanna, 1987) resulting in changes in the vegetation carbon pool. In the present study, there was an initial decrease in the active carbon pool by 47 per cent at the end of 7th year, after which it returned to steady-state. The total SOC and their respective pools (active, slow and passive) decreased in the first 13 years which then gradually returned to the preliminary values. This is an expected behaviuor (Stevenson, 1994); since most plant material from the teak vegetation remained in the area even after the conversion which is incorporated and thereby increasing the slow and passive pools, in turn increasing the total stocks. The present study shows the importance of natural vegetation on soil carbon pools. Similar observations were noticed for the different carbon pools considered in this study: active, slow and passive pools.

5.7 Scenario 4: Conversion to agroforestry system (Teak trees with Ginger cultivation).

A series of 30 year projections were generated using the Century model to evaluate the effect of agroforestry (teak and ginger) on levels of SOC in Kerala. The total SOC on conversion of teak plantation to agroforestry system declined by about

10 per cent by seven years (Fig 23). Then the values increased and stabilized at 2546 g C m^{-2} at the age of 30 years. No significant difference was observed for the total SOC in agroforestry system when compared to that of the teak plantation. In teak based agroforestry system canopy of teak hinders ginger plant from adequate light intensity in the forest floor, while ginger requires good light intensity of about 25% for optimum photosynthesis, (Valenzuela, 2011). Also, the interaction between the root of teak and ginger predisposes ginger to soil nutrient competition. Sasikumar *et al,* (2008) and Lujiu *et al,* (2010), found that ginger is an exhausting crop and requires large amounts of nutrients, especially potassium (K) and nitrogen. Availability of these nutrients in teak plantation soil will influence tiller formation in ginger. Teak has been reported to possess allelopathic character by secretion of certain hormones that suppress the development of other plants around it (Macias *et al.,* 2004; Siddiqui *et al.,* 2009; Macias *et al.,* 2010). Walker *et al.* (2007) used WaNuLCAS, a model SOM dynamics on that of the Century model, to simulate organic matter inputs in agroforestry multistrata coffee (*Coffea arabica*) systems compared to sole crop coffee. They noted that organic matter input from the agroforestry system was 25% greater than that of the sole crop system, and they suggested that this might have contributed to an increase in the long-term SOC stock in the system.

Initially the active carbon pool decreased 82 per cent within a five year period, and then slowly increased to 11.05 g C m^{-2} by the 30th year (Fig 24) of simulation and slow carbon also decreased 25 per cent at the age of eight years, after which it proceeded to increase slowly to 780.97 g C m^{-2} at the end of 30 years (Fig 25). In this study, the different C pools modeled by Century for agroforestry and teak plantation were similar to those reported by others. Woomer (1993) reported that the establishment of an agroforestry alley cropping system with *Leucaena leucocephala* and an annual C input of 200 g m^{-2}, increased the active and slow fractions, but the passive fraction showed little change. This was attributed to the conservation tillage in use prior to the introduction of no-till cultivation practices. Several earlier reports also suggest that soil disturbance by ploughing favors a greater rate of SOM mineralization and humification and thereby increase the passive C fraction in the tropical alley cropping system. Carvalho-Leite *et al.* (2004) also noted similar results and observed an increase in the passive C fraction in cultivated soil (disc plow, harrow, and harrow-disc plow combination) compared to soil under no-till. This finding is consistent with results of Ogunkunle and Awotoye (2011) that soil under the sole cropping of teak was impoverished due to the high rate of nutrient uptake of the teak. Soils of teak plantation decline in carbon, nitrogen and organic matter due to annual burning (Oseni *et al.* 2009), this scenario of loss of vital nutrients affect ginger stands and invariably reduce rhizome yield under the plantation. Kumar (2011) reported that nutrient immobilization and/or leaching may be important in stopping the fertilizer response in teak plantation, also increased rate of nutrient recycling reduce the use efficiency of inorganic nutrients such as NPK, and lead to their reduced retention especially under low soil organic matter levels.

5.8 Scenario 5: Conversion to Ginger cultivation

The present study indicates a significant decrease in the SOC concentration with increasing duration of ginger cultivation under intensive management. The initial total SOC declined by 39 per cent towards the end of simulation (Fig 27). The possible mechanisms that may be involved in the decrease of SOC concentration are (1) annual application of inorganic fertilizer intensively that may have increased the decomposition rate of SOM which in turn reduced the SOC pools (Mancinelli *et al.*, 2010); (2) intensive tillage operations that improves the aeration of soil profile and thereby enhancing the exposure to SOC decomposers (Sainju *et al.*, 2008); and (3) removal of understorey that reduces the C input, (Wang *et al.*, 2011). In addition to these, removal of understory vegetation increases the soil temperature and enhances the mineralization of SOM (Wang *et al.*, 2011). It has been reported that inorganic fertilizer application or tillage practices have positive or negative effects on SOC stock or labile organic C pools (Mancinelli *et al.*, 2010; Gong *et al.*, 2012).

Li *et al.* (2010) recorded the highest soil loss in ginger growing plots (22.68 t/ha/yr), which was statistically similar with that of turmeric plots (16.52 t/ha/yr) followed by aroid plots (12.02 t/ha/yr). The highest soil loss is reported in ginger and turmeric cultivation since they require soil loosening for growth which results in immense disturbance to the soil profile. Possible reasons for the decrease of labile organic C pools in the soil with increasing duration under intensive management would be the same as that for the decrease of SOC stock. Some studies showed that the labile organic C pools responded to management practices in different ways (Li *et al.*, 2010; Wang and Wang, 2011). This might be because of nutrient depletion due to erosion of top soil of the experimental plots. These results are in agreement with the findings of many other studies (Muhr, 1965; World Bank, 1991; Khisa *et al.*, 2002 and Gafur *et al.*, 2000). Thus, soil erosion along with nutrients depletion is considered as one of the most serious problems on the slopes. Greer *et al.* (1996) reported that a decline in SOM (biological oxidation or erosion) significantly reduced the N supply and resulted in deterioration of soil physical condition, leading to crop yield reduction.

5.9 Scenario 6: Conversion to Agriculture (Root vegetables (tuber crops) + pulses)

The present study found significant difference in soil organic carbon in all the carbon pools between teak plantations and the agricultural land converted from teak. The initial total SOC increased by 14 per cent in six years time which later on showed a declining trend and got reduced by 43 per cent after 30 years of simulation (Fig 31).

Earlier studies revealed a similar estimate of SOC losses after conversion of forests to agriculture; Machado and Brum (1978) reported 38 per cent SOC reduction after woodland clearing and 14 years of intensive soil management for annual grain crops in a very clayey Oxisol similar to the one in this study (Skjemstad *et al.,* 2000; Dieckow *et al.,* 2007).

Land use change in the form of conversion from native vegetation to agriculture is usually associated with loss of SOC. Davidson and Ackerman (1993) reported a 20–30 per cent global mean reduction of SOC stock with introduction of agriculture. Van Den Bygaart *et al.* (2003) established a mean reduction of 24 per cent of native SOC of Canada when forests were converted to agriculture. Veldkamp (1994) found a 50 per cent decrease in SOC native stocks within five years of agriculture in tropical soils in Costa Rica. Conversion of forest land to agriculture in Southern Brazil, lead to 30–50% reduction in SOC (Machado, 1976; Pottker, 1977). In the farming period, soil management by deep tilling generally leads to loss of SOC. Assuming equal soil management and cropping systems, differences in C dynamics in these soils during the initial years under agriculture could primarily be attributed to soil texture, with greater C losses taking place in the coarser texture soils (Feller and Beare, 1997).

Century maintains the initial soil mass of the 0–20 cm simulation layer by transferring soil from a subsurface layer in a quantity equal to the soil lost by erosion (Pennock and Frick, 2001). The present study shows that the active carbon pool primarily increased by 24 per cent within three year period, and then decreased by 21 per cent the next year (Fig 32). This was followed by a declining trend which exhibited a 98 per cent reduction till the end of the simulation period. In practical terms, a considerable fraction of soil C lost in erosion is replaced by more recalcitrant subsurface C.

The slow carbon initially increased by 44 per cent (Fig 33) within a six year period it then decreased slowly by 90 per cent by the end of the simulation. The passive carbon content for the initial 30 years shows a decrease by 17 per cent (Fig 34). Singh (2012) reported an increase in phenolic content particularly the humic acid fraction, with the increased period of agricultural interference which in turn attributed to the slower decomposition of lignin under anaerobic conditions. He pointed out that the increased phenolic character of the SOM was probably affecting N cycling. The Century Model in the study of C dynamics provided a reasonable assessment of overall changes in SOC stocks in teak plantations converted to agriculture crops in Kerala.

Summary

6. SUMMARY

The study on "Modeling carbon dynamics in teak plantations of Kerala" was carried out in teak plantations of Kerala during 2011-2015. This chapter presents a summary of the findings of the study as well as some suggestions on areas of further research. The main objective of this study was to estimate the carbon stocks in teak plantations of Kerala. The study also estimated the long term trends in carbon sequestration; this was carried out using a CENTURY model by simulating carbon pools in teak plantations. The study also aims at development of a system dynamic model for carbon prediction for teak plantations.

Teak plantations were divided into five age classes for sampling. The age classes were 0-5, 6-10, 11-20, 21-30 and above 30 years. Thirty samples were selected at random for each stratum. Quadrants of 50m x 50m size were established in each plot. Out of the 150 plots thus made, 50 plots were used for the validation of the model which was developed. Out of the plots selected, 10 plantations from each age class were selected at random for soil collection and thus a total of 50 soil samples were taken. Soil pits of 1m x 1m x 1 m were dug in each sample plot and soil sample were collected from 0-20, 20-40, 40-60 and 60-100cm depths.

Salient findings of the study are summarised below,

1. The average annual temperature was 24 ^{0}C. The average monthly temperature in summer (February to May) was 32 ^{0}C. March was the hottest month with an average monthly temperature of 35 ^{0}C. With average temperatures of 25 ^{0}C, December to January was the coolest months. In between higher temperature were seen in October to November.

2. The study areas experienced rainfall during winter: there was very little or no rainfall during summer. Maximum monthly precipitation occurs in June (up to 69 cm) and the rainfall reduced to 9 cm in the month of November.

3. The soil texture was sandy loam in all the sites and at different depth of soils in teak plantations of Kerala.

4. The study on water holding capacity varied from 38.35 % to 39.87 % at a depth of 0-20 cm, while at 20-40 cm depth, varied from 37.82 % to 41.39 %.

5. The bulk density values were generally higher in deeper layer of the soil. The mean bulk density values were in the range 1.0 to 1.36 g/cm^3.

6. Soil pH of teak plantations ranged from 5.0 to 6.0 indicating moderate acidity in teak plantations.

7. The total nitrogen content in teak plantations varied from 0.07 to 0.34 % and in natural forests, the variation was from 0.43 to 1.23 %. The total nitrogen in soils was highest in the surface and decreased with the depth in both teak plantation and natural forest.

8. The mean values of available phosphorus in the teak plantations and natural forest varied from 1.0 to 4.81 g/kg and 3.16 to 4.82 g/kg.

9. The sulphur varied from 0.23 to 0.09 % in teak plantations but in natural forests sulphur was negligible to be noticed in the analysis. The analysis of variance showed that there was no significant difference in the age class of teak plantations with respect to the soil sulphur.

10. The soil carbon in soils was highest in the surface and decreased with the depth in both teak plantation as well as natural forest. The analysis of variance for soil carbon in different age class and depths showed no significant difference of soil carbon between the age classes of plantations.

11. The simulated results of CENTURY model, the total SOC in teak plantation declined to about 50 per cent from the initial value of 6168 g C m^{-2} to 3371 g C m^{-2} in 30 years. There after SOC pool declined at a slower rate (43 g C m^{-2} yr^{-1}) till 45 years of age (2717 g C m^{-2}) and reached a stable level by 80 years (2710 g C m^{-2}). From the results it is clear that the conversion of natural forest to teak plantation resulted in significant loss of SOC. About half of SOC was lost by conversion of natural forest to teak plantation.

12. Active carbon pool in teak plantations rapidly decreased from 6.25 g C m^{-2} to 2.88 g C m^{-2} by the end of 3rd year and slowly increased to 10.17 g C m^{-2} by 9th year. By the end of 80th year, the active pool stabilized around 12 g C m^{-2}. In effect, the active carbon doubled by 80 in the year of establishment of plantation.

13. Slow carbon pool in teak plantations reduced from 3700 g C m^{-2} to 1224 g C m^{-2} at the age of 22, and finally it reaches at 920 g C m^{-2} at an age of 80 years. Hence, the simulations indicate substantial loss of slow carbon pool from the system. Soil aggregation is considered to be one of the important processes of stabilizing soil organic matter (SOC) pools; therefore, characterization of water stable aggregate carbon, also known as slow pool of SOM, is important in maintenance of soil fertility.

14. Passive carbon pools in teak plantations more or less remain stable. It decreased from 2150 g C m^{-2} to 1912 g C m^{-2} at the age of 50 years and then marginally declined to 1757 g C m^{-2} at the end of 80 years.

15. In a scenario of replanting teak plantations after harvest at 50 years, and the model indicated that the total SOC decreased by about 8 per cent in the first 12 years. The SOC then returned to the initial levels and kept increasing for the next 24 years. Thus, the replanted teak shows a significant increase in the total SOC, compared to the first rotation teak.

16. This scenario relates to replanted teak plantations and the model simulated the slow carbon initial period started to increase at 50.36 g C m^{-2} an age of three years, which then declined to 30 per cent at an age of 12th year. The slow carbon then increased to 1016 g C m^{-2} at an age of 30th year of simulation period and a slight increase in the passive carbon was noticed in replanting of teak plants as compared to that of the old teak plantation (1757 g C m^{-2}).

17. In teak plantations that are affected by forest fire and every three years since initiation. The simulated values of total SOC in fire damaged teak plantation is found to be lesser as compared to that without fire. The study found a 20 per cent decline in the total SOC by the 22nd year of plantation. The SOC stabilized at 2343 g C m^{-2} at the age of 30 year of teak plantation. A substantial decrease in the SOC concentration was observed due to forest fire.

18. Converting teak plantation to natural forest resulted in an increase of SOC pools. There was an initial decline in total SOC by 18 per cent by the age of 13 years. After that the soil carbon increased with age up to 30th year. By the end of simulation period, there was an annual increase in the simulated total

SOC values of natural forest by 162.97 g C m^{-2} as compared to that of the actual teak plantation.

19. Converting teak plantation to natural forest, there was an initial decreased in the active carbon pool by 47 per cent at the end of 7th year, after which it returned. The total SOC and their respective pools (active, slow and passive) had a considerable decrease in the first 13 years which then gradually returned to the initial values.

20. Conversion of teak plantation to agroforestry system, resulted in declined SOC by about 10 per cent after a period of seven years. Then the values increased and stabilized at 2546 g C m^{-2} at the age of 30 years. No significant difference was observed for the total SOC in agroforestry system when compared to that of the teak plantation.

21. By converting of teak plantation to agroforestry system. The active carbon pool decreased by 82 per cent at a five year period, and then slowly increased to 11.05 g C m^{-2} at the 30th year of simulation. Slow carbon also decreased 25 per cent at the age of eight years, after which it proceeded to increase slowly to 780.97 g C m^{-2} at the end of 30 years.

22. By converting of teak plantation to ginger cultivation, resulted in decrease in total SOC with increasing duration of ginger cultivation under intensive management. The initial total SOC declined by 39 per cent towards the end of simulation.

23. Converting teak plantations to agriculture were observed in significant difference in soil organic carbon in all the carbon pools between teak

plantations and the agricultural land converted from teak. The initial total SOC increased by 14 per cent in six years time which later on showed a declining trend and reduced by 43 per cent after 30 years of simulation.

24. Active carbon pool in converted agriculture (tubers and Pulses) primarily increased by 24 per cent within a 3 year period, and then decreased by 21 per cent the next year. This was followed by a declining trend which exhibited a 98 per cent reduction till the end of the simulation period.

25. The slow carbon initially increased in the agriculture scenario by 44 per cent within a period of six years, which then decreased by 90 per cent by the end of the simulation. The passive carbon pool in the meanwhile shows a decreased by 17 per cent.

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Appendices

APPENDIX I

Crop 100 - Crop parameters (Ginger cultivation)

Parameters	Description	Values
prdx(1)	potential aboveground monthly production for crops (gC/m^2)	400.0
pltmrf	planting month reduction factor to limit seedling growth; set to 1.0 for grass	1.0
fulcan	value of aglivc at full canopy cover, above which potential production is not reduced	150.0
frtc(1)	initial fraction of C allocated to roots; for Great Plains equation based on precipitation, set to 0	0.50
frtc(2)	final fraction of C allocated to roots	0.50
frtc(3)	time after planting (months with soil temperature greater than rtdtmp) at which the final value is reached	1.0
biomax	biomass level (g biomass/m2) above which the minimum and maximum C/E ratios of new shoot increments equal pramn(*,2) and pramx(*,2) respectively	800.0
prbmn(3,2)	parameters for computing minimum C/N ratio for belowground matter as a linear function of annual precipitation	24.0
prbmx(3,2)	parameters for computing maximum C/N ratio for belowground matter as a linear function of annual precipitation	420.0
fligni(1,1)	intercept for equation to predict lignin content fraction based on annual rainfall for aboveground material	0.06
fligni(2,1)	slope for equation to predict lignin content fraction based on annual rainfall for aboveground material. For crops, set to 0.	0.0
fligni(1,2)	intercept for equation to predict lignin content fraction based on annual rainfall for belowground material	0.06
fligni(2,2)	slope for equation to predict lignin content fraction based on annual rainfall for belowground material. For crops, set to 0.	0.0
himax	harvest index maximum (fraction of aboveground live C in grain)	0.90
himon(1)	number of months prior to harvest in which to begin accumulating water stress effect on harvest index	1.0
himon(2)	number of months prior to harvest in which to stop accumulating water stress effect on harvest index	0.0
efrgrn(3)	fraction of the aboveground E which goes to grain	0.6
vlossp	fraction of aboveground plant N which is volatilized (occurs only at harvest)	0.04
fsdeth(1)	maximum shoot death rate at very dry soil conditions (fraction/month); for getting the monthly shoot death rate, this fraction is multiplied times a reduction factor depending on the soil water status	0.0
fsdeth(2)	fraction of shoots which die during senescence month; must be greater than or equal to 0.4	0.0
fsdeth(3)	additional fraction of shoots which die when aboveground live C is greater than fsdeth(4)	0.0
fsdeth(4)	the level of aboveground C above which shading occurs and shoot senescence increases	500.0
fallrt	fall rate (fraction of standing dead which falls each month)	0.4
rdr	maximum root death rate at very dry soil conditions (fraction/month); for getting the monthly root death rate, this fraction is multiplied times a reduction factor depending on the soil water status	0.05
rtdtmp	physiological shutdown temperature for root death and change in shoot/root ratio	2.0
crprtf(3)	fraction of E retranslocated from grass/crop leaves at death	0.0
snfxmx(1)	symbiotic N fixation maximum for grass/crop (Gn fixed/Gc new growth)	0.0

APPENDIX II

Fire 100 - Fire parameters

Parameters	Description.	Values	References
FLFREM	fraction of live shoots removed by a fire event	0.7	Default values
FDFREM (1)	fraction of standing dead plant material removed by a fire event	0.7	Default values
FDFREM (2)	fraction of surface litter removed by a fire event	0.3	Default values
FRET (1)	fraction of burned aboveground material removed by a fire event (N)	0.2	Balagopalan, and Alexander 1987; Jeremy, *et al.*, 2009; Suzuki *et al.*, 2007
FRET (2)	fraction of burned aboveground material removed by a fire event (P)	1.0	
FRET (3)	fraction of burned aboveground material removed by a fire event (S)	0.1	
FRTSH	additive effect of burning on root/shoot ratio	1.0	
FNUE(1)	effect of fire on increase in maximum C/N ratio of shoots	10.0	
FNUE(2)	effect of fire on increase in maximum C/N ratio of roots	30.0	Haripriya, 2003

APPENDIX III

Site 100 – Site parameters

Name	Description	Value	References
Climate parameters			
PRECIP (1-12)			Sample Tested
TMN2M (1-12)			Sample Tested
TMX2M (1-12)			Sample Tested
Site and soil variables			
SITLAT	Site latitude (degrees) latitude of model site (deg)	12.47	Sample Tested
SITLNG	Longitude of model site (deg)	76.42	Sample Tested
SAND	Fraction of sand in soil	0.73	Sample Tested
SILT	Fraction of silt in soil	0.13	Sample Tested
CLAY	Fraction of clay in soil	0.14	Sample Tested
BULKD	Bulk density of soil	1.11	Sample Tested
NLAYER	Total soil layers in column	4	Sample Tested
AWILT(10)	The wilting point of soil layer X	0.31	**Default value**
AFIEL(10)	The field capacity of soil layer X	0.432	**Default value**
pH	Soil pH	6.20	Sample Tested
External N input			
EPNFA(1)	Average annual dry N deposition (g N/m^2/yr)	0.21	**Default value**
EPNFA(2)	Slope for determining the effect of annual precipitation on atmospheric N deposition	0.0028	**Default value**
Initial soil carbon pools			
SOM1CI(1,1)	Initial value for C in forest system leaf component (g C/m^2)	53.75	Sample Tested
SOM1CI(2,1)	Initial value for N in a forest system leaf component (g N/m^2)	278.4	Sample Tested
SOM2CI(1)	Initial value for C in forest system fine branch component (g C/m^2)	4837.20	Sample Tested
SOM3CI(1)	Initial value for C in SOM with slow turnover (g C/m^2)	1535.84	Sample Tested
CLITTR(1,1)	Initial value for C in plant residue (g C/m^2)	45.09	Sample Tested
Organic matter initial values			
RCES1(1,1)	Initial C:N ratio in surface organic matter with fast turnover (active SOM)	20.29	Sample Tested
RCES1(1,2)	Initial C:P ratio in surface organic matter with fast turnover (active SOM)	74.29	Kumar *et al.*, 2009
RCES1(1,3)	Initial C:S ratio in surface organic matter with fast turnover (active SOM)	810.76	
RCES1(2,1)	Initial C:N ratio in SOM with fast turnover (active SOM)	4.76	Sample Tested
RCES1(2,2)	Initial C:P ratio in SOM with fast turnover (active SOM)	77.95	
RCES1(2,3)	Initial C:S ratio in SOM with fast turnover (active SOM)	357.29	
RCES2(1)	Initial C:N ratio in SOM with intermediate turnover (slow SOM)	63.97	Sample Tested
RCES2(2)	Initial C:P ratio in SOM with intermediate turnover (slow SOM)	350.93	
RCES2(3)	Initial C:S ratio in SOM with intermediate turnover (slow SOM)	2878.12	
RCES3(1)	Initial C:N ratio in SOM with slow turnover (passive SOM)	33.17	Sample Tested
RCES3(2)	Initial C:P ratio in SOM with slow turnover (passive SOM)	181.96	
RCES3(3)	Initial C:S ratio in SOM with slow turnover (passive SOM)	1492.36	
RCELIT(1,1)	Initial C:N ratio for surface litter	121.75	Sample Tested
RCELIT(1,2)	Initial C:P ratio for surface litter	445.76	
RCELIT(1,3)	Initial C:S ratio for surface litter	4864.57	
RCELIT(2,1)	Initial C:N ratio for soil litter	121.75	Sample Tested
RCELIT(2,2)	Initial C:P ratio for soil litter	445.76	

RCELIT(2,3)	Initial C:S ratio for soil litter	4864.76	
AGLIVE(1)	Aboveground N initial value (gN/m^2)	16.54	Takahashi *et al*., 2012; Tiwari and singh, 2013
AGLIVE(2)	Aboveground P initial value (gP/m^2)	2.094	Kumar *et al*., 2009
AGLIVE(3)	Aboveground S initial value (gS/m^2)	0.406	Kumar *et al*., 2009
BGLCIS(1)	Initial value for belowground live C (gC/m^2)	252.23	Sreejesh *et al*., 2013
BGLIVE(1)	Initial value for belowground live N (gN/m^2)	21.03	
BGLIVE(2)	Initial value for belowground live P (gP/m^2)	6.09	
BGLIVE(3)	Initial value for belowground live S (gS/m^2)	0.681	Sreejesh *et al*., 2013
STDCIS(1)	Initial value for standing dead C (gC/m^2)	168.2	
STDEDE(1)	Initial value for N in standing dead (gN /m^2)	12.36	Chandrashekara, 1996;
STDEDE(2)	Initial value for P in standing dead (gP/m^2)	1.58	
STDEDE(3)	Initial value for S in standing dead (gS/m^2)	0.148	
Forest organic matter initial parameters			
RLVCIS(1)	Initial value for C in forest system leaf component (g C/m^2)	164.5	Swarnalatha and Reddy, 2011
RLEAVE(1)	Initial value for N in a forest system leaf component (g N/m^2)	4.32	
FBRCIS(1)	Initial value for C in forest system fine branch component (g C/m^2)	17.0	Thamos *et al*., 2013
FBRCHE(1)	Initial value for N in a forest system fine branch component (g N/m^2)	0.657	Kumar *et al*., 2009
RLWCIS(1)	Initial value for C in forest system large wood component (g C/m^2)	6311	Thamos *et al*., 2013
RLWODE(1)	Initial value for N in a forest system large wood component (g N/m^2)	50.73	Kumar *et al*., 2009
FRTCIS(1)	Initial value for C in forest system fine root component (g C/m^2)	312.0	Thamos *et al*., 2013
FROOTE(1)	Initial value for N in a forest system fine root component (g N/m^2)	5.804	
CRTCIS(1)	Initial value for C in forest system coarse root component (g C/m^2)	1102.5	
CROOTE(1)	Initial value for N in a forest system coarse root component (g N/m^2)	18.36	
WD1CIS(1)	Initial C values for forest system dead fine branch material (g/m^2)	111.5	
WD2CIS(1)	Initial C values for forest system dead large wood material (g/m^2)	1265	
WD3CIS(1)	Initial C values for forest system dead coarse root material (g/m^2)	272	
CLITTR(2)	Initial C values for forest system dead fine root material (g/m^2)	38.9	

APPENDIX IV

Tree.100 – Tree parameters

Forest production and control						
prdx (3)	Gross primary production (g biomass/m^2/month)				9999.9	Metherell *et al.*, 1993
prdx (4)	Net primary production (g biomass/m^2/month)				100.0	Metherell *et al.*, 1993
ppdf(1)	Optimum temperature for production (^{0}C)				22.07	Sample tested
ppdf(2)	Maximum temperature for production (^{0}C)				35.50	Sample tested
Biomass chemistry						
	Minimum					
Variables	**Plant Parts**	C/N	C/P	C/S		N in leaves; Sample tested.
cerfor(1,1,i)	for leaf	18.16	300	300		
cerfor(1,2,i)	for fine root	32.26	250	250		
cerfor(1,3,i)	for fine branch	24.48	1100	1100		
cerfor(1,4,i)	for large wood	58.34	4000	4000		
cerfor(1,5,i)	for coarse root	38.50	4000	4000		
	Maximum					
cerfor(2,1,i)	for leaf	30.14	300	300		
cerfor(2,2,i)	for fine root	40.13	250	250		
cerfor(2,3,i)	for fine branch	68.42	1100	1100		Rathod and Devar, 2002; Thomas *et al.*, 2013; Metherell *et al.*, 1993; Balagopalan and Chacko, 1996
cerfor(2,4,i)	for large wood	496.36	4000	4000		
cerfor(2,5,i)	for coarse root	105.30	4000	4000		
	Initial					
cerfor(3,1,i)	for leaf	23.98	300	300		Thamos et al., 2013
cerfor(3,2,i)	for fine root	48.72	250	250		
cerfor(3,3,i)	for fine branch	58.18	1100	1100		
cerfor(3,4,i)	for large wood	79.49	4000	4000		
cerfor(3,5,i)	for coarse root	98.41	4000	4000		
Production allocation pattern						Kaul *et al.*, 2010; Kumar *et al.*,2009; Chandrashekara,1996; Thamos *et al.*, 2013
fcfrac(1,1)	C allocation fraction of new production for leaf (Range 0-1)				0.101	
fcfrac(2,1)	C allocation fraction of new production for fine root (Range 0-1)				0.033	
fcfrac(3,1)	C allocation fraction of new production for fine branch (Range 0-1)				0.113	
fcfrac(4,1)	C allocation fraction of new production for large wood (Range 0-1)				0.232	
fcfrac(5,1)	C allocation fraction of new production for coarse root (Range 0-1)				0.033	
fcfrac(1,2)	C allocation fraction of old leaves for mature (Range 0-1)				0.202	
fcfrac(2,2)	C allocation fraction of old fine roots for mature forest (Range 0-1)				0.576	
fcfrac(3,2)	C allocation fraction of old fine branch for mature forest (Range 0-1)				0.310	
fcfrac(4,2)	C allocation fraction of old large wood for mature forest (Range 0-1)				0.990	
fcfrac(5,2)	C allocation fraction of old coarse roots for mature forest (Range 0-1)				0.576	
Biomass turnover rates						
leafdr (12)	Monthly death rate fractions for leaves for each month 1-12				0.180	Sample tested
wooddr(1)	Monthly death rate fraction for leaf (Range 0-1)				0.090	Sample tested
wooddr(2)	Monthly death rate fraction for fine root				0.267	

wooddr(3)	Monthly death rate fraction for fine branch	0.067	
wooddr(4)	Monthly death rate fraction for large wood	0.039	
wooddr(5)	Monthly death rate fraction for coarse root	0.391	
Lignin fraction of tree components			
wdlig(1)	Lignin fraction for forest leaf	0.26	Sample tested
wdlig(2)	Lignin fraction for forest fine root	0.21	
wdlig(3)	Lignin fraction for forest fine branch	0.20	
wdlig(4)	Lignin fraction for forest large wood	0.25	
wdlig(5)	Lignin fraction for forest coarse root	0.029	

APPENDIX V

Trem.100 – Tree removal

Parameters	Description	Values	References
evntyp	event type flag		
	= 0 for cutting,	0	
	= 1 for fire		
remf(5)	fractions of material component removed from pools		
	(1) = live leaves	0.9	Thamos *et al.*, 2013
	(2) = live fine branches	0.9	Sreejesh *et al.*, 2014
	(3) = live large wood	0.9	Thamos *et al.*, 2013
	(4) = dead fine branches	0.9	Kumar *et al.*, 2010
	(5) = dead large wood	0.5	Kumar *et al.*, 2010
fd(2)	fractions of live root components that die		
	(1) = fine root	0.0	
	(2) = coarse root	0.5	
retf (1,4)	fraction of E in killed live leaves that is returned to the system (ash or litter)		
	(1,1) = C	1	Sample Tested
	(1,2) = N	1	Moya *et al.*, 2015; Kumar *et al.*, 2010; Rathod and Devar, 2004; Sreejesh *et al.*, 2013
	(1,3) = P	1	Moya *et al.*, 2015;Kumar *et al.*, 2010; Rathod and Devar, 2004; Sreejesh *et al.*, 2013
	(1,4) = S	1	Moya *et al.*, 2015; Kumar *et al.*, 2010; Swarnalatha, 2000.
retf(2,4)	fraction of E in killed fine branches that is returned to the system (ash or dead fine branches)		
	(2,1) = C	1	Kumar *et al.*, 2010; Thamos *et al.*, 2013
	(2,2) = N	1	Rathod and Devar, 2010; Moya *et al.*, 2014; Rugmini *et al.*, 2013; Kumar *et al.*, 2014
	(2,3) = P	1	Rathod and Devar, 2010; Moya *et al.*, 2015; Rugmini *et al.*, 2007; Kumar *et al.*, 2014
	(2,4) = S	1	
retf(3,4)	fraction of E in killed large wood that is returned to the system (ash or dead large wood)		
	(3,1) = C	0.1	Kumar *et al.*, 2010; Thamos *et al.*, 2013
	(3,2) = N	0.1	Rathod and Devar, 2010; Moya *et al.*, 2014; Rugmini *et al.*, 2013; Kumar *et al.*, 2014
	(3,3) = P	0.1	Rathod and Devar, 2010; Moya *et al.*, 2015; Rugmini *et al.*, 2007; Kumar *et al.*, 2014
	(3,4) = S	0.1	

APPENDIX VI
STELL model - equations

ACTIVE_CARBON(T) = ACTIVE_CARBON(T - DT) + (POOL1 + FLOW_4 - FLOW_2 - FLOW_6 - FLOW_7) * DT
INIT ACTIVE_CARBON = 6.5
INFLOWS:
POOL1 = 1*FLOW_2*FLOW_1
FLOW_4 = 1.1
OUTFLOWS:
PASSIVE_CARBO(T) = PASSIVE_CARBO(T - DT) + (POOL3 + FLOW_5 + FLOW_6 - FLOW_3 - FLOW_9) * DT
INIT PASSIVE_CARBO = 3700
INFLOWS:
FLOW_5 = 0.25*POOL3
FLOW_6 = 0.25*POOL1
OUTFLOWS:
FLOW_3 = 6
FLOW_9 = 26
SLOW_CARBON(T) = SLOW_CARBON(T - DT) + (POOL2 + FLOW_2 + FLOW_3 - FLOW_4 - FLOW_5 - FLOW_8) * DT
INIT SLOW_CARBON = 2564
INFLOWS:
POOL2 = 5
FLOW_2 = 0.25
FLOW_3 = 6
OUTFLOWS:
FLOW_4 = 1.1
FLOW_5 = 0.25*POOL3
FLOW_8 = 25
SOIL_ORGANIC_CARBON(T) = SOIL_ORGANIC_CARBON(T - DT) + (FLOW_1 - POOL1 - POOL2 - POOL3 - FLOW_10) * DT
INIT SOIL_ORGANIC_CARBON = 6168
INFLOWS:
FLOW_1 = 0.5
OUTFLOWS:
POOL1 = 1*FLOW_2*FLOW_1
TREE_CARBON(T) = TREE_CARBON(T - DT) + (CARBON_INPUT - HARVESTING - FLOW_1) * DT
INIT TREE_CARBON = 35
INFLOWS:
CARBON_INPUT = WOOD*BRANCHES*BARK*ROOT
OUTFLOWS:
HARVESTING = WOOD_CARBON*BRANCH_CARBON*BARK_CARBON*ROOT_CARBON
FLOW_1 = 0.5
BARK = 2.86
BARK_CARBON = 2.86
BRANCHES = 1.86

BRANCH_CARBON = 1.86
ROOT = 3.33
ROOT_CARBON = 3.33
WOOD = 23.26
WOOD_CARBON = 23.26

APPENDIX VII

GPS coordinates of sample sites

Sl No.	Study sites	LATITUDE	LONGITUDE
1	Kannavam	11^0 52’ 86.00”	75^0 84’ 99.90”
2	Kottiyur	11^0 88’ 14.45”	75^0 05’ 9^{0}9.94”
3	Begur	11^0 50’ 57.33”	76^0 05’ 30.89”
4	Periya	11^0 50’ 20.00”	75^0 51’ 18.26”
5	Mananthavady	11^0 49’ 16.57”	76^0 01’ 14.71”
6	Kalpetta	11^0 34’ 58.00”	76^0 03’ 49.41”
7	Meppady	11^0 32’ 39.80”	76^0 07’ 7.06”
8	Chadleth	11^0 35’ 55.10”	75^0 27’ 32.20”
9	Nilambur	11^0 16’ 24.65”	76^0 20’ 12.74”
10	Edavanna	11^0 16’ 21.34”	76^0 12’ 13.05”
11	Vazhikadavu	11^0 23’ 11.00”	76^0 20’ 49.21”
12	Karulai	11^0 17’ 10.02”	76^0 19’ 66.42”
13	Kalikavu	11^0 10’ 48.00”	76^0 18’ 45.80”
14	Attappadi	11^0 04’ 21.25”	76^0 33’ 53.41”
15	Agali	11^0 05’ 52.17”	76^0 38’ 37.61”
16	Mannarkad	11^0 01’.23.43”	76^0 27’ 15.52”
17	Olavakkode	10^0 47’ 24.72”	76^0 37’ 4.52”
18	Walayar	10^0 50’ 51.02”	76^0 50’ 30.45”
19	Ottapalam	10^0 47’ 50.40”	76^0 25’ 7.54”
20	Nelliyampathi	10^0 32’ 18.26”	76^0 37’ 19.54”
21	Alathur	10^0 37’ 20.05”	76^0 32’ 44.5”
22	Vadakkancherry	10^0 40’ 3.05”	76^0 16’ 33.4”
23	Pattikad	10^0 37” 49.07”	76^0 15’ 29.15”
24	Machad	10^0 38’ 33.62”	76^0 22’ 52.62”
25	Periyaram	12^0 04’ 16.23”	75^0 17’ 49.11”
26	Palappilly	10^0 26’ 0.73”	76^0 22’ 46.01”
27	Vellikulangara	10^0 20’ 56.14”	76^0 24’ 75.17”
28	Charpa	10^0 18’ 17.93”	76^0 36’ 7.45”
29	Sholayar	10^0 21’ 05.92”	76^0 33’ 28.03”
30	Kollathirumedu	10^0 15’ 19.34”	76^{0}28’ 17.50”
31	Athirapally	10^0 18’ 11.78”	76^0 35’ 24.26”
32	Kalady	10^0 10’ 53.10”	76^0 30’ 49.70”
33	Kodanadu	10^0 10’ 14.60”	76^0 35’ 39.10”
34	Thundathil	10^0 09’ 17.80”	76^0 39’ 59.80”
35	Kuttampuzha	10^0 09’ 6.04”	10^0 09’ 6.04”
36	Ranni	9^0 24’ 10.07”	76^0 47’ 22.00”
37	Konni	9^0 13’ 32.08”	76^0 50’ 44.24”
38	Naduvathumuzhi	9^0 12’ 10.4”	76^0 50’ 1.2”
39	Mannarppara	9^0 13’ 6.3”	76^0 49’ 39.3”
40	Achenkovil	9^0 05’ 49.00”	77^0 07’ 23.36”
41	Kallar	9^0 05’ 31.65”	77^0 06’ 57.31”
42	Pathanapuram	9^0 05’ 31.98”	76^0 51’ 56.81”
43	Thanmela	8^0 57’ 47.95”	77^0 04’ 50.27”
44	Arienkavu	8^0 58’ 58.69”	77^0 09’ 6.75”
45	Kothamangalam	10^0 6’ 29.40”	76^0 40’ 29.50”
43	Thodupuzha	9^0 55’ 2.70”	76^0 50’ 7.80”
47	Mullaringodu	10^0 01’ 14.50”	76^0 45’ 5.30”
48	Erimeli	9^0 28’ 30.98”	76^0 46’ 53.59”
49	Nerimangalam	10^0 02’ 58.29”	76^0 46’ 53.59”
50	Kulathupuzha	8^0 54’ 38.14”	77^0 03’ 28.27”

MODELING CARBON DYNAMICS OF TEAK PLANTATION IN KERALA

By

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(2011-27-101)

ABSTRACT

Submitted in partial fulfillment of the
requirement for the degree of

DOCTOR OF PHILOSOPHY IN FORESTRY

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2015

ABSTRACT

The study on “Modeling carbon dynamics in teak (*Tectona grandis* Linn. F) plantations of Kerala” was carried out in teak plantations of Kerala Forest Department during 2011-2015. The study attempted to estimate the carbon stocks in teak plantations and model the soil carbon using ‘Century’ soil carbon modelling tool. The modelling tool was used to analyze the soil carbon under different scenarios. The study also developed of a system dynamic model for carbon prediction for teak plantations.

Teak plantations were divided into five strata based on age (0-5, 6-10, 11-20, 21-30 and >30 years). Thirty samples were selected at random for each stratum. Quadrants of 50 m x 50 m size were established in each sample for vegetation analysis. Fifty samples among the 150 samples so selected were used for the validation of the developed model. Ten plantations each from each age class (50 samples) were selected at random for soil studies. Pits of 1m x 1m x 1 m were dug in each sample plot and soils were collected at 0-20, 20-40, 40-60 and 60-100 cm depths. The total litter was collected from each plot at an interval of three months to estimate diurnal litter fall. Soil C, N, S was estimated along with the N, P, K and lignin of litter. Biomass of the study site was estimated using allometric equations. Secondary data on weather parameters were collected from appropriate sources.

Significant differences were not observed among the different age classes and soil depths in case of sand and silt content of soil. However, clay content varied between the different age classes and soil depths. Although water holding capacity did not vary among the plantations of different age class in the surface layer (0-20 cm), it varied among the age classes at 20-40 cm. The bulk density did not differ between age classes, while it was higher in deeper layer of the soil (1.1 to 1.36 g/cm^3). Soil pH was moderately acidic (5.1 to 6.0).

The soil N varied from 0.07 to 0.34 % in plantations, while the values ranged from 0.43 to 1.23 % in natural forests. Nitrogen content was highest in the surface and decreased with the depth in both teak plantation and natural forest. The mean values of available P in the teak plantations and natural forest varied from 1.0 to 4.81 g/kg and 3.16 to 4.82 g/kg respectively. Significant differences in soil C was noticed between plantation and natural forest. While the soil C did not vary between various age classes, it was higher in surface layers compared to deeper layers.

Simulation by CENTURY model in teak plantation indicated decline in total SOC up to 50 per cent by 30th year from the initial value of 6168 g Cm^{-2}. There after SOC pool declined at a slower rate till 45 years and reached 2702 g C m^{-2} by 80 years. There was rapid decrease in active carbon pool in teak plantations from 6.25 g C m^{-2} to 2.88 g C m^{-2} initially (up to 3rd year) and slow increase to 10.17 g C m^{-2} by 9th year. By the end of 80th year, the active pool almost doubled to 12 g C m^{-2}. Slow carbon pool in teak plantations reduced from 3700 g C m^{-2} to 1224 g C m^{-2} by 22 years and reached 920 g C m^{-2} at an age of 80 years. Passive carbon pools in teak plantations more or less remained stable (2150.84 to 1912 g C m^{-2}). Analysis indicated that the model was able to predict the values with high efficiency (0.922) and accuracy ($R^2 = 0.9156$)

Fire reduced total SOC in teak plantation. The study found a 20 per cent decline in the total SOC by the 22nd year of plantation establishment. The SOC reached at 2343 g C m^{-2} at the age of 30year of teak plantation compared to 2702 g C m^{-2} in a normal plantation. Teak plantation converted to natural forest resulted in an increase of SOC pools by 163 g C m^{-2} compared to that of the teak plantation. Conversion of teak plantation to agroforestry system resulted in marginal decline of 156 g C m^{-2} in SOC by 30 years. The SOC in teak plantation converted to ginger cultivation declined by 39 per cent at 30 years after ginger cultivation. Conversion of teak plantation to agriculture (pulses and tuber) resulted in significant reduction all the carbon pools. The SOC declined to 43 per cent at 30 years.

A system dynamic model of soil carbon dynamics was developed using STELLA software. It was observed that the model was able to predict the total SOC with high precision (ME=0.69). The present study indicated that modelling is suitable for studying C dynamics in soils under teak plantations. Present results highlight the potential of using these tools for reliable evaluation the carbon sequestration potential of management interventions at plantation as well as landscape level.