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Soil organic carbon pools and its dynamics in the managed teak plantations of Kerala Western Ghats

(Final Report of the project KFRI 645/2012)

S. Sandeep

Kerala Forest Research Institute
(An Institution of Kerala State Council for Science, Technology and Environment)
Peechi – 680 653, Kerala, India

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ABSTRACT OF THE PROJECT PROPOSAL

1. Project Number : KFRI 645/2012

2. Title of the Project : **Soil organic carbon pools and its dynamics in the managed teak plantations of Kerala Western Ghats**

3. Objectives

   1. To study soil organic carbon partitioning in the teak plantations of Kerala Western Ghats

   2. To analyse the mineral - organic interactions and thermal stability of soil organic carbon in these teak plantations

   3. To evaluate the effects of predicted rise in temperature on the soil organic carbon reserves of teak plantations

4. Date of commencement : August 2012

5. Duration : 3 years

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7. Investigators : S. Sandeep

CONTENTS

	Page No.
Abstract	1
Introduction	3
Review of literature	5
Materials and Methods	8
Results	22
Discussion	61
Summary	71
References	74

List of tables

No.	Title	Page
1	Description of different zones with teak plantations in the Western Ghats	10
2	Basic physico - chemical parameters of soil (0 – 20 cm) used in the CENTURY model	20
3	Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – A in Kerala Western Ghats	23
4	Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – B in Kerala Western Ghats	26
5	Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – C in Kerala Western Ghats	26
6	Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – D in Kerala Western Ghats	27
7	Active organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats	27
8	Slow organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats	28
9	Passive organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats	28
10	Correlation between different carbon fractions in teak planted soils of Kerala	29
11	Effect of site qualities on Walkley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – A in Kerala Western Ghats	30
12	Effect of site qualities on Walkeley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – B in Kerala Western Ghats	30

13 Effect of site qualities on Walkeley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – C in Kerala Western Ghats 31

14 Effect of site qualities on Walkeley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – D in Kerala Western Ghats 31

15 Walkeley and Black carbon concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats 32

16 Microbial biomass carbon concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats 32

17 Total polysaccharide concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats 33

18 Chemical composition of humic acids extracted from teak planted soils in Kerala Western Ghats 34

19 Adsorption maxima (Qmax) and binding coefficient (k) for DOC adsorption on soil minerals as derived from Langmuir isotherm in different teak growing zones 50

20 Changes in activation energy (KJ mole-1) of soil organic carbon decomposition with site quality in teak plantations of Kerala Western Ghats 53

21 Changes in temperature coefficient (Q10) of soil organic carbon decomposition with site quality in teak plantations of Kerala Western Ghats 53

22 Correlation matrix of activation energy and Q10 with different soil physico – chemical parameters 54

List of figures

No.	Title	Page
1	Map showing the sampling locations of teak plantations in Kerala Western Ghats	9
2	Carbon pools and flows as envisaged in the CENTURY model. The diagram shows the major factors which control the flow.	18
3	The century model environment showing the relationship between the programmes and the file structure	19
4a - d	Carbon stocks (kg m^{-2}) in (a)zone A (b)zone B (c)zone C (d)zone D	24
5	Average carbon stocks (kg m-2) in different zones	24
6a -d	Variation in carbon content (kg m-2) with depth in (a) zone A (b) zone B (c) zone C (d) zone D	25
7	Humic acid from classified according to Kumada's method (all zones)	35
8a - h	Representative FTIR spectra of humic acids in (a)zone A – site quality I (b) zone A – site quality IV (c)zone B – site quality I (d) zone B – site quality IV (e)zone C – site quality I (f) zone C – site quality IV (g) zone D – site quality II (h) zone D – site quality IV	36-39
9	Representative scanning electron microscopy images of humic acids from site quality I in (a) zone A (b) zone B (c) zone C (d) zone D	41
10	Representative transmission electron microscopy images of humic acids (zone A - site quality I)	42
11a – d	X-ray diffraction spectra of clay minerals in (a) zone A (b) zone B (c) zone C (d) zone D	44-45
12a - o	Langmuir adsorption isotherm fits of carbon in teak soils of (a -d) zone A (e - h) zone B (i - l) zone C (m - o) zone D	46-49
13a-d	Effect of ions on carbon adsorption in teak soils of (a) zone A (b) zone B (c) zone C (d) zone D	51-52
14	a. Mean monthly rainfall distribution in zone – B (2000 -12) b. Mean monthly maximum and minimum air temperatures in zone - B (2000 -12)	56

15 Changes in soil carbon pools with continuous teak rotations in Zone B as predicted by CENTURY soil carbon model. 57

16 Changes in total organic carbon in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios 59

17 Changes in active organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios 59

18 Changes in slow organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios 60

19 Changes in passive organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios 60

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Abstract

Soil organic carbon plays a major role in sustaining ecosystems and maintaining environmental quality as it acts as a major source and sink of atmospheric carbon. The present study aims to assess the soil carbon stocks and pools in the teak systems, their interactions with soil colloids and assess its turnover under different projected climate change scenarios. Soil samples were collected from plantations of 40 - 50 years of age. A stratified random sampling method was adopted where the agro - ecological units was used as the main strata and site qualities (I, II, III and IV) as substrata.

The results show that the mean carbon stocks in teak plantations of Kerala Western Ghats varied from 7.38 - 12.10 kg m^{-2} and the Southern High Hills (Zone D) with a much cooler climate (mean annual temperature 21.6 °C; rainfall 3602 mm) was found to store a significantly higher amount of carbon in the 1 meter soil depth than all the other teak growing zones.

The carbon fractions in these teak plantations were found to vary between zones. Active and slow carbon pools were found significantly higher in site quality I and II. In contrast, there was no significant difference in the passive SOC concentration among different zones or site qualities. Even though the studied teak plantations exhibited a wide range of soil types, the presence of almost equal amounts of passive carbon in them show that the recalcitrance of carbon in these soils is mainly by way of their chemical structure rather than soil enabled protection against decomposition.

The elemental composition of the extracted humic acids showed that their carbon and nitrogen contents ranged from 26.2 - 44.4% and 4.1 - 6.3% respectively. Though site quality IV had comparatively higher C/N ratio than the other sites this was found to be well within the critical limits of 10:1 required to sustain carbon and nitrogen mineralization. The E4/ E6 ratio values, Kumada's classification system and spectroscopic analyses by way of FTIR analyses indicated that the humic substances in these systems were a polymeric mixture of many molecules predominantly aromatic with phenolic and amine substituents linked together. The scanning electron microscope (SEM) and transmission electron microscope (TEM) images establish that these humic acids are also poly crystalline and shapeless with particle sizes in the micro ranges.

Mineral organic interactions and carbon retaining capacity was also assessed in these teak planted soils. Site deterioration was found to increase the Fe and Al sesquioxide contents in these soils and co-flocculation of carbon by these sesquioxides was found to promote higher carbon storage in the degraded teak sites (site quality IV). However, Langmuir isotherm fits show low binding coefficient values for soils from lower site qualities indicating weak carbon retention by these soils which can be easily lost by decomposition. Among the different ions, anions were found more efficient in improving the carbon adsorption than cations. In general, the adsorption of carbon varied in the presence of anions as $PO_4^{3-} > SO_4^{2-} > NO_3^-$ and for cations as $Ca^{2+} > Mg^{2+} > Al^{3+} > Fe^{3+}$. Activation energies (Ea) were found to be positively affected by Q_{10} values and ionic balances in the soil. Fe, Ca and CEC were found to have negative influence on Q_{10} values of carbon decomposition in soils of teak plantations. The results suggest that improving the net ionic equilibrium in soils may serve to enhance the Ea values of carbon decomposition.

The model simulations using CENTURY soil carbon model showed that residue burning process after deforestation/ clear felling adds plant residues from the native vegetation thereby initially increasing the active and slow carbon fractions. However, the decline in TOC and other pools of carbon with rotation age indicates that the initial residue addition is lost and a degradation trend sets in the teak planted soil. Active carbon maintained at a high level during the first rotation showed a rapid decline in the second rotation. During the clear felling of first rotation, there is an intense soil disturbance and subsequent burning causes the plant material to be lost as CO_2. Active carbon being the most sensitive fraction among the different pools gets depleted rapidly under such management strategies.

The different predicted temperature scenarios showed a similar trend and there was a rapid conversion of slow to active pool during warming. The decline in total carbon along with this conversion points to the fact that the reaction is a forward one with the final product being CO_2. Thus warming can have an adverse effect on teak ecosystem health by way of depleting its carbon content and effectively converting it into a carbon source rather than a sink.

INTRODUCTION

Carbon dioxide is the most potent greenhouse gas contributing to radiative forcing and global climate change. The concentration of CO_2 has increased from 280 ppmv in 1750 to 367 ppmv in 1999 and is currently increasing at the rate of 1.5 ppmv/year. The 1997 Kyoto Protocol is framed on the principle that CO_2 from the air can be sequestered in the soil and biomass and is a practical way of mitigating climate change. Land use/ land management change and forestry activities that are shown to reduce atmospheric carbon dioxide levels are included in the Kyoto emission reduction targets (Article 3.3 of the Kyoto protocol) (Van Vliet *et al.,* 2003).

The world's soils contain about 1550 Pg of organic carbon, which is more than twice the amount in the atmosphere (IPCC, 2007). The soil organic carbon is a complex system consisting of several pools of varying turnover times. Soil organic matter has a dual role in the ecosystem. On the one hand it positively regulates aggregate stability, cation exchange capacity, nutrient release rate (through mineralization) and water holding capacity. The other role of SOM is to store carbon safely for several years. The roles defined for SOM are controlled by two pools – active and passive - and analysing these pools will give a true sense of the ecosystem sustainability and storage potential.

Different factors prevent the organic matter from biodegradation in soils. The physical and chemical environment have an effect on the stability of the organic carbon in soil. The chemical structure of soil organic matter and its physical accessibility to microbes and enzymes are important factors. The formation of associations of organic matter and mineral surfaces is considered to be another important process in the soil carbon cycle, as it stabilizes the organic matter in soils against microbial mineralization. Analysing these interactions will provide insight into the ability of soil to store organic carbon and to prevent it from mineralization to $CO_{2.}$ This will in turn open up vistas for better carbon management in these systems.

Devising alternatives/ strategies for long term carbon management is a very difficult task due to the high vulnerability of the carbon stored in the various systems. To undertake such an activity one has to have a fair idea about the turnover of organic carbon in the various systems over a period of time. Recently, simulation models are used worldwide to predict carbon dynamics through centuries and millennia. However no such attempt has been made to predict the carbon turnovers in the managed forest systems of Kerala or the Western Ghats.

Forests worldwide contain about 45% of the global carbon stock. In the context of climate change, forests are unique in that they are both a source and a sink of carbon dioxide, the most abundant greenhouse gas. The studies on soil and vegetation carbon pools and soil biological processes controlling soil carbon dynamics have implications for natural resource management and soil carbon sequestration.

Kerala is endowed with a rich forest ecosystem and 29% of the landscape is clothed with forests. The natural forests remain largely undisturbed and provide great potential for carbon sequestration. On the other hand, managed forest systems are man-made and besides their natural potential, provides management opportunities to sustain or even improve their carbon capturing and storage potentials.

The managed forest systems in Kerala constitute 1056.02 km^2 (10% of total forest area) and nearly 70% of these are occupied by plantations of teak. The studies conducted so far are mainly concentrated on total organic carbon content of the soils. Mere quantification of the total organic carbon does not indicate the real carbon storage potential of these systems, as only a fraction (passive pools) of this contributes to the actual storage for longer periods. Also there is a need to generate a more comprehensive knowledge about carbon pools, thermal sensitivities and future turnover rates in order to decide on the choice of species and management options. Hence the project has been designed with the following objectives:

1. To study soil organic carbon partitioning in the teak plantations of Kerala Western Ghats.

2. To analyse the mineral - organic interactions and thermal stability of soil organic carbon in these teak plantations.

3. To evaluate the effects of predicted rise in temperature on the soil organic carbon reserves of teak plantations

REVIEW OF LITERATURE

Soil organic carbon content is a balance between addition and decomposition rates and, as such, changes in ecosystems can bring about marked changes in both pool size and turnover rate of soil organic carbon (SOC) and therefore nutrients. Small changes in total soil organic carbon are difficult to detect because of the high background levels and natural soil variability. For this reason several attempts have been made to use sub - pools as sensitive indicators of changes in soil organic carbon (Jenkinson and Rayner, 1977).

CO_2 efflux from soil to atmosphere is a major component of greenhouse gas emission and is a crucial pathway of the C cycle. Based on a five-decade record of chamber measurements, Bond-Lamberty and Thomson (2010) estimated that the global soil CO_2 efflux, widely referred to as soil respiration, was about 98 PgC y^{-1} in 2008, which is more than 13 times the rate of fossil fuel combustion (IPCC, 2007), indicating that 20–40% of the atmospheric CO_2 circulates through soils annually. The CO_2 evolution from soil is highly sensitive to temperature and global changes may have a great influence on the magnitude of CO_2 efflux. Knorr *et al.* (2005) concluded from their soil incubation studies that the decomposition of stable soil organic matter is even more sensitive to increases in temperature than that of labile pools, thereby exerting an even stronger positive feedback to global warming than assumed by current carbon cycle models. A significant positive correlation between the activation energy (Ea) and the log-transformed apparent turnover time of the sample was observed in many studies.

Clay minerals strongly influence the major physical and chemical properties of soil as well as soil organic matter and its chemical nature. Clay mineralogy varies spatially as a function of climate and parent material, and temporally as a function of soil development (Jenny, 1941). Several studies have indicated that the large changes in the quantity and turnover of soil organic carbon across landscapes and over long time spans may be due to clay mineral enabled variation in passive (mineral-stabilized) carbon in the soil (Laird, 2001; Torn *et al.*, 1997).

The Inter-Governmental Panel on Climate Change has projected that the global mean surface temperature is predicted to rise by 1.1–6.4°C by 2100 (IPCC 2007). Increasing atmospheric temperatures and carbon dioxide along with uncertainties in annual precipitation will have an adverse affect on ecosystem sustainability and productivity.

Hence it will be imperative to assess the future trends in soil organic carbon in different ecosystems.

International scenario

Of the 130 million ha of forest plantations in the world (Allan and Lanly, 1991), just over half are located in the tropics (FAO, 1995). The total carbon storage that can be credited to global forest plantations today is an estimated 11.8 Pg C (Winjum and Schroeder, 1997), and about 10% of it is lost every year through land conversion, since industrialization. Forestry activity designed to store carbon is often proposed for the tropics, as tropical climates support rapid vegetation growth (Schroeder and Ladd, 1991). Marland (1998) estimated that based on higher potential growth rates, the area required to capture annual carbon emissions could be reduced by 25% if afforestation efforts were centred in the tropics. Grainger (1988) calculated that the tropics contain 758 million ha of depleted or degraded lands which were once forested. Reforestation of these areas would capture significant amounts of atmospheric carbon, and would be expected to contribute to soil quality and conservation (Schroeder, 1992). Although there are several estimates of carbon storage in various forest types (Brown, 1993; Lugo and Brown, 1992; Vogt, 1991), few estimates of individual species carbon storage potential have been published. To allow informed choices between species when establishing carbon storage projects, it is important to characterize various traits which influence carbon storage on a per species basis. Such information would also be useful for inclusion in global carbon storage/cycling models (Kraenzela *et al.,* 2003).

There is general consensus that the increasing concentration of greenhouse gases (e.g. CO_2, CH_4, N_2O, O_3) has led to changes in the earth's climate. Furthermore, there is agreement that human activities such as fossil fuel combustion, land-use change and agricultural practices have contributed substantially to the rise in atmospheric greenhouse gas concentrations (IPCC, 1997). Forestry, and afforestation in particular, is regarded as an important activity that can offset the effects of greenhouse gas emissions. Projects that increase the area of plantations have been suggested for inclusion under the Clean Development Mechanism (CDM) as defined in Article 12 of the Kyoto Protocol (Van Vliet *et al*., 2003). However, significant uncertainties in the reliability of carbon pool and flux measurements make it difficult to determine the (net) carbon benefits of afforestation or forestry management practices. As a result, further investment in, and development of, the plantation industry is threatened (Van Vliet *et* *al.,* 2003). There is a growing need for computer simulation models that can assist in the estimation of carbon budgets (Mosier, 1998; Landsberg, 2003;Van Vliet *et a*l., 2003; Battaglia *et al.*, 2004).

Indian scenario

The first comprehensive study of SOC in Indian soils was conducted using data from different cultivated fields and forests with variable rainfall and temperature patterns (Jenny and Raychaudhuri, 1960). The study confirmed the effects of climate on C reserves in the soil. Using ecosystem areas from different sources and representative global average C densities, organic carbon (OC) in Indian soils was estimated as 23.4–27.1 Pg (Dadhwal and Nayak, 1993). Chhabra *et al.* (2003) estimated the organic C pool of Indian forest soils as 6.8 Pg C in top 1 m, using estimated SOC densities and Remote Sensing based area of forest types. Another attempt to estimate SOC stock by Gupta and Rao (1994) using a database with 48 soil series reported an SOC stock of 24.3 Pg for soil depths ranging from surface to an average depth of 44–186 cm in Indian soils. However, the first comprehensive report of SOC stock in India was carried out by Bhattacharyya *et al.* (2000) who estimated 9.5 Pg SOC at a depth of 0–0.3 m.

The forestry sector can not only sustain its carbon but also has the potential to absorb carbon from the atmosphere. The rate of afforestation in India is one of the highest among the tropical countries, currently estimated to be 2 Mha per annum. The annual productivity has increased from 0.7 m^3 per hectare in 1985 to 1.37 m^3 per hectare in 1995. Increase in annual productivity directly indicates an increase in forest biomass and hence higher carbon sequestration potential. The carbon pool for the Indian forests is estimated to be 2026.72 Mt for the year 1995. Estimates of annual carbon uptake increment suggest that our forests and plantations have been able to remove at least 0.125 Gt of CO_2 from the atmosphere in the year 1995. Assuming that the present forest cover in India will sustain itself with a marginal annual increase by 0.5 Mha in area of plantations, we can expect our forests to continue to act as a net carbon sink in future (Lal and Singh, 2000).

Forested systems are recognized worldwide as a good sink of atmospheric carbon and features in all global initiatives to mitigate climate change. Kerala lying in the South Western corner of India has a rich forest cover. But being a landscape in the humid tropics, the terrestrial pools of carbon in this region is amenable to decomposition and it is highly pertinent to analyze the carbon and their dynamics in these systems.

MATERIALS AND METHODS

The experimental methodology related to the study on "Soil organic carbon pools and its dynamics in the managed teak plantations of Kerala Western Ghats" comprising of the assembles for both field studies and laboratory analysis are presented below.

I. Site selection

Teak plantations constitute approximately 75000 ha in the Kerala part of Western Ghats, which account for nearly 70 percent of the managed forest systems in the state. Data on teak plantations of Kerala Western Ghats waiting final felling (40 – 50 years age) was compiled from Kerala Forest Department and KFRI statistics Department. The plantations in 40 - 50 year age were selected as silvicultural operations in teak are over by 30 years and the carbon is more or less stabilized within the next 10 years. A stratified random sampling method was adopted where the agro - ecological units (Kerala State Planning Board, 2013) was used as the main strata and site qualities (I, II, III and IV) as substrata. The information on agro-ecological units developed by Kerala State Planning Board in collaboration with NBSS & LUP, Nagpur served as basic input for determining the first stratum of sampling.

Six agroecological units were found to have more than 75% of the teak plantations. The six units were Northern Foot Hills, Northern High Hills, North Central Laterites, South Central Laterites, Southern and Central foothills and Southern High Hills. Based on the similarity in climate and properties of teak growing soils, these were further combined to form 4 broad zones (Zone A to D; Table 1). The site quality classification (site quality I to IV) of teak plantations of Kerala by KFRI statistics department was used as the substarta (Jayaraman and Shivaraju, 2012). Site quality I plantations awaiting final felling was found absent in zone D. Hence sampling in this zone was restricted to site qualities II, III and IV.

In each zone, plantations were selected in such a way so as to accommodate all the 4 site quality classes. Stratified sampling with probability proportional to size (PPS) scheme was used to identify plantations in each zone. Enough number of samples were collected to adequately represent the heterogeneity of each zone and site quality. The sampling locations are depicted in Figure 1.

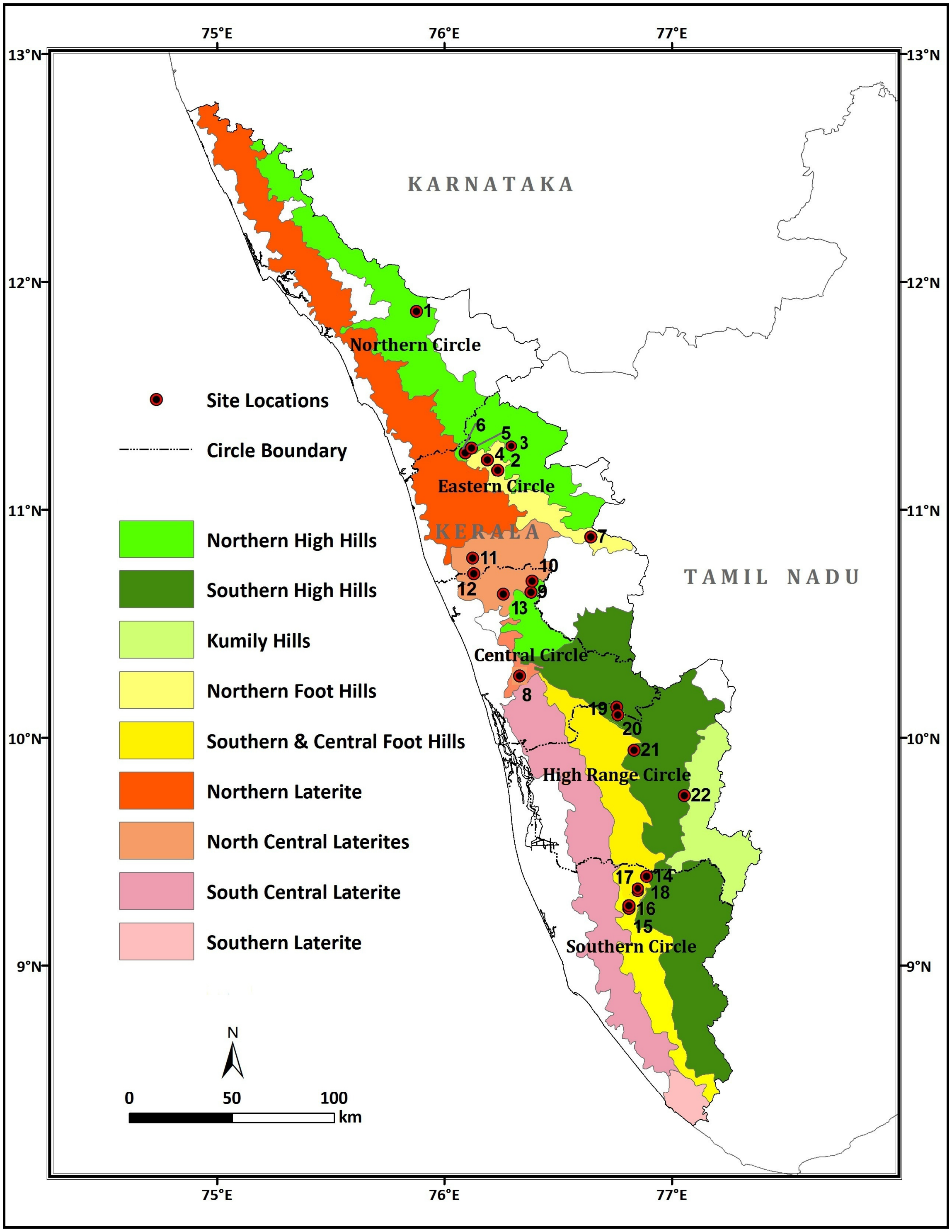


Figure 1. Map showing the sampling locations of teak plantations in Kerala Western Ghats

Table 1. Description of different zones with teak plantations in the Western Ghats

Zone	**Particulars**
Zone -A	It includes the agroecological units Northern Foothills and Northern High Hills <u>Northern Foot Hills</u>: The climate is tropical humid monsoon type (mean annual temperature 27.5 °C; rainfall 3462 mm) with dry period of around four months. The strongly acid, gravelly, lateritic, low-activity, clay soils are rich in organic matter. The narrow valleys have similar, but non-gravelly, soils with impeded drainage conditions. Shorter dry period, absence of plinthite layer in soil and enhanced levels of organic matter distinguish the foothill soils from north central and northern midland laterites. <u>Northern High Hills</u>: The climate is tropical humid monsoon type (mean annual temperature 26.2 °C; rainfall 3460 mm) with dry period of nearly four months, much longer than in the southern counterpart. The hilly terrain has deep, well drained, strongly acid, organic-matter-rich, clay soils. The valleys have deep, imperfectly drained, acid clay soils.
Zone – B	It includes the agroecological units North Central Laterites and South Central Laterites. <u>North Central Laterites</u>: The climate is tropical humid monsoon type (mean annual temperature 27.6 °C; rainfall 2795 mm) with dry period of around four and half months. The uplands have strongly acid, gravelly, lateritic, low-activity, clay soils, often underlain by plinthite. The lowlands have strongly acid, non-gravelly clay soils with impeded drainage. <u>South Central Laterites</u>: The climate is tropical humid monsoon type (mean annual temperature 26.5 °C; rainfall 2827 mm) with dry period around three and half months. The soils are strongly acid, lateritic clay soils herein are gravelly and often underlain by plinthite. The lowlands have strongly acid, low-activity, non-gravelly clay soils with impeded drainage conditions.

Zone – C	It includes the agroecological units Southern and Central foothills. The climate is tropical humid monsoon type (mean annual temperature 27.5 °C; rainfall 3462 mm) with dry period of around two and a half months. The strongly acid, gravelly, lateritic, low-activity, lateritic clay soils are rich in organic matter. The narrow valleys have similar but non-gravelly soils with impeded drainage conditions. Shorter dry period, absence of plinthite layer in soil and higher soil organic matter distinguish the foothills from midland laterites.
Zone – D	It includes the agroecological units Southern High Hills. Altitude more than 600 metres. Besides elevation, the steep slopes of the terrain and lower temperatures distinguish the high hills from the foothills and midlands. The climate is tropical humid monsoon type, but lower temperatures than in coastal plain and midlands (mean annual temperature 21.6 °C; rainfall 3602 mm). Length of dry period is only two months. The steeply sloping hilly terrain has deep, well drained, strongly acid, organic-matter-rich clay soils.

II. Soil sample collection

Soil pits were taken in toposequence to a depth of 100 cm in each of the selected sites and samples were separated into depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. The pits were taken in the upper, middle and lower slope. Enough number of such pits were taken depending on site factors such as gradient, aspect etc. From each site, additional surface samples were drawn from randomly selected spots and composited to account for the probable variability in biotic and abiotic factors within a site quality. The soil analysis protocols for the set objectives are detailed below.

Soil samples from surface (0 - 20 cm depth) were also drawn from selected teak plantations (different age groups) in zone B for generating input data for carbon modeling studies.

III. Laboratory analysis

The soil samples were air dried, sieved and stored in plastic containers. The stored soils were characterized for their general physico-chemical properties such as pH, electrical conductivity, texture etc., using standard protocols.

1. Soil organic carbon partitioning

Soil carbon partitioning was studied with respect to different carbon fractions in the processed soil. The detailed methodology is as follows.

a. Total organic carbon (TOC)

Total organic carbon in soil (depth wise) was determined by CHNS analyzer (EURO EA3000). 5 - 10 mg of well pulverized samples were used for the estimation. The instrument settings used are as follows:

Carrier flow (ml/min) : 120 ± 5

Carrier (kPa) : 80

Purge (ml/min) : 80

Oxygen (ml) for 5 x 9 mm tin caps : 20

ΔPO_2 (kPa) : 35

Oxidation time (sec) : ≈8

Sampling delay (sec) : ≈6

Run time (sec) : 320

Front furnace temperature (°C) : 980

GC oven temperature (°C) : 115

Detector : TCD

b. Walkley and Black Organic Carbon (WBC)

WBC represents easily oxidisable fraction of total organic carbon. This fraction was determined in soil samples passed through 0.2 mm sieve by wet digestion method of Walkley and Black (1934).

c. Polysaccharides

The soil carbohydrate pool is composed of polysaccharides derived from various sources, i.e. plant and animal tissues, plant mucilage, cellular tissues and extracellular products of soil microbes. Polysaccharides content in the soil samples were analyzed with the technique modified from Whistler *et al*. (1962) by Lowe (1994). The polysaccharides were extracted with H_2SO_4 and the absorbance values read at 490 nm in a spectrophotometer to determine the total polysaccharides.

d. Microbial biomass carbon (MBC)

Microbial biomass carbon gives the carbon immobilized in the microbial cells. It has a turnover time of less than 1 year and indirectly indicates the microbial activity of the soil. Microbial biomass carbon (MBC) was determined by fumigation–extraction method (Jenkinson and Powlson, 1976).

e. Active carbon

Active or labile carbon represents the bio – available form of organic carbon that has a low turnover time (< 5 yrs). Active SOC was determined using the $KMnO_4$ oxidation method, in which soil samples containing about 15 mg SOC were put into 333 mmol L^{-1} KMnO4 solution (25 ml), oscillated for 1 h to oxidize active SOC. The amount of active SOC was quantified by the amount of KMnO4 consumption determined spectrophotometrically (Blair *et al.,* 2005).

f. Passive carbon

Passive SOC represents the recalcitrant form of organic carbon with mean residence time of 200 -1500 years. This fraction was measured by using acid hydrolysis (Leavitt *et al.*, 1996), taking more than 5 g of soils into a test tube containing 6 N HCl and boiling them for 16 hours. The samples were washed to pH=7.0 with distilled water, dried in an oven of 60 °C and the carbon of these samples was quantified as passive SOC by CHNS analyzer (EURO EA3000).

g. Slow carbon

Slow SOC is considered as intermediate between active and passive carbon fractions with a mean residence time of about 20 - 40 years. Slow SOC was taken as the difference between the TOC and the sum of active and passive SOC.

h. Humic acid

The humic acids were extracted by classical alkali extraction procedure. The extracted humic acids were characterized with respect to carbon, nitrogen, functional groups and E4/E6 ratio (Stevenson, 1994). Carbon and nitrogen estimations were done using CHNS analyzer (EURO EA3000), functional goups using FT - IR and E4/E6 ratio using uv - vis spectrophotometer.

i. Soil carbon stocks

Soil carbon stocks were estimated upto 1m depth to have a better understanding of the terrestrial reservoir of soil organic carbon in the teak plantations of Kerala. Soil pits were taken in a toposequence to a depth of 100 cm in each of the selected sites and samples were separated into depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Core samples were also taken from these depth intervals for bulk density estimations. Total carbon in the soils collected from different depths were estimated (CHNS EURO EA 3000) and used for carbon stocks calculations using the following formula by Batjes (1996):

$$\mathrm{Cm} = \sum_{i=1}^{n} \mathrm{BD} * \mathrm{TC} * \mathrm{d} * (1 - \mathrm{Si})$$

where C_m = Carbon stocks (Mg m^{-2})., Tc_i = Total carbon of i^{th} layer (g C/ g), B_i = Bulk density of i^{th} layer (Mg m^{-3}), d_i = Depth of i^{th} layer (m), Si = volume proportion of fragments > 2mm .

2. Mineral - organic interactions and thermal stability of soil organic carbon

a. Mineral – organic interaction studies

Soil samples collected from the mineral horizon (A - horizon) of different site qualities in the teak growing zones were used for the present investigation. Soils were passed through a 2 mm sieve, air-dried and stored. Dissolved organic carbon (DOC) was extracted from weed composts prepared at KFRI central nursery. The compost was soaked in deionized water for 5 days and the suspension was filtered with 0.45 µm glass fiber filters and stored at 4 °C. This initial DOC extract solution had a concentration of ~200 mg C L^{-1}. From this concentrated leachate solution, ten solutions ranging in DOC concentration from 0 to ~120 mg L^{-1} was prepared by dilution with a 0.01 mg L^{-1} $CaCl_2$ solution.

Batch incubations were performed by adding 0.03 L of the initial DOC solutions to 3 g of soil in a 0.05 L centrifuge vial. Vials were hand shaken to ensure that soil and solution was in a slurry, and laid flat on a horizontal shaker for 24 h at 4 °C, at a speed of 60 rpm. The tubes were placed upright to settle for ~30 min prior to filtration with a 0.45 µm glass fiber filter.

The initial mass (IM) isotherm (Eq. (1)) establishes a linear relationship between the mass of the absorbent (DOC) removed from or released into the solution phase (RE), normalized for soil mass (mg kg^{-1}), and the concentration of the initial solution (Xi), also normalized for soil mass (mg kg−1). The RE was calculated as the difference in DOC concentrations found within the initial and final solution phases. The amount of adsorbent desorbed into solution at a starting concentration of 0 mg kg^{-1} (y-intercept) is defined as the desorption term (b), expressed in units of mg kg^{-1}. The slope of the regression (m) is the partition coefficient, and is unitless.

$$\mathbf{RE = m\ .\ Xi - b} \qquad \mathbf{Eq.\ (1)}$$

Past studies have shown that DOC sorption onto mineral soils can best be described by the Langmuir isotherm (Gu *et al.,* 1994; Kothawala *et al.,* 2008). The Langmuir isotherm was modified to correct for native adsorbed solute on the soil surface of mineral soils by adding the desorption term, b. The amount of DOC adsorbed (mg DOC kg^{-1} soil) or desorbed (RE) is a function of the final measured equilibrium solution concentration (X_f) (mg DOC L^{-1} solution), the maximum sorption capacity (Qmax) (mg DOC kg^{-1} soil), and the binding affinity (k) (L mg^{-1}) according to the following model

$$\mathbf{RE = \frac{(k.\ Qmax.\ X_f)}{(1+k.\ X_f)} - b} \qquad \mathbf{Eq.\ (2)}$$

The isotherms were subsequently fitted using the R statistical package (R version 3.2.3) to obtain k and Qmax.

b. Effect of ions on the adsorption of organic carbon in soil minerals

To analyse the effect of ions on the adsorption of organic carbon on soil minerals, three different anions (NO_3^-, SO_4^{2-} and PO_4^{3-}) and four cations (Ca^{2+}, Mg^{2+}, Al^{3+} and Fe^{3+}) were used. The anions and cations were added as their sodium salts and chloride salts, respectively. The mineral soils were shaken in an end to end shaker at room temperature for 24 hours with 100 Mg L^{-1} DOC solution and 0.01M salt solution. The soil: solution ratio was maintained as 1: 2. At the end of shaking, the supernatant solution was collected by centrifugation. Amount of DOC adsorbed on soil minerals was found out by difference of initial and final values.

c. Thermal stability studies

Soil samples collected from the mineral horizon (A - horizon) of different site qualities in the teak growing zones were passed through a 2 mm sieve, air-dried and used for the thermal stability of SOC. The decomposition rate and activation energies of soil carbon were investigated by an incubation experiment of 150 days' duration. Soil samples (5g) were incubated in wide mouth bottles after estimating the initial organic carbon (%) and moistening it to field capacity. Four incubation temperatures *viz.,* 25°C, 30°C, 35°C and 40°C were used for the study. The organic carbon in the incubated soil was estimated at regular intervals (0, 3, 6, 9, 12, 15, 18, 30, 45, 60, 90, 120, and 150 days). The organic carbon lost during the period was estimated by subtracting the amount lost during the period from the initial organic carbon content (at 0th day) and was used for determining the first order rate kinetics using the equation:

$$\mathbf{A_t = A_0 e^{-kt}} \qquad \textbf{Eq. (3)}$$

where, k is the decomposition rate constant; A_0 and A_t are the amount of organic carbon at zero and 't' time.

The activation energy (Ea) was calculated using Arrhenius equation:

$$\mathbf{k = A \exp(-Ea/ RT)} \qquad \textbf{Eq. (4)}$$

where, k is the decomposition rate constant; A is the frequency factor; Ea is the required activation energy in joules per mole; R= 8.314 J K^{-1} mol^{-1} and T is the temperature (K). Ea was calculated from the slope (Ea/R) obtained by plotting ln k against 1/T (Knorr *et al.,* 2005).

Q_{10} indicates the responses of biological processes with temperature. Q_{10} values were calculated as a function:

$$\mathbf{Q_{10} = (k_2/ k_1)^{(10/T_2 - T_1)}} \qquad \textbf{Eq. (5)}$$

where k_2 and k_1 are the reaction rates at temperatures T_2 and T_1 respectively (T_1=298 K and T_2=308 K) (Kirschbaum, 1995).

3. Modelling soil organic carbon reserves in teak plantations of Kerala Western Ghats

Modelling exercises were performed to understand the soil carbon turnover in these teak ecosystems of Western Ghats and realizing future soil organic carbon under projected climate change scenarios. CENTURY Agroecosystem Version 4.0 was used in the present study to analyze the carbon dynamics with continuous teak rotations as well as projected climate change scenarios.

The Century ecosystem model is described by Parton *et al.* (1987). In brief, it is a general ecosystem model that simulates the dynamics of C, N, P and S in different plant/soil systems through an annual cycle over centuries to millennia. Century was originally developed for grasslands (Parton *et al.* 1987) but has since been extended to agricultural crops, forests, savanna systems and temperate and tropical forest systems (Paustian *et al.* 1992; Carter *et al.* 1993; Parton, 1996; Gijsman *et al.* 1996).

(a) Structure of the model

The model comprises of two forms of litter, viz. metabolic and structural and three SOM compartments, viz. active, slow and passive, which differ in their potential rates of SOM decomposition (Figure 2). The active pool represents soil microbes and microbial products (total active pool is ~2 to 3 times the live microbial biomass level) and has a turnover time of months to a few years depending on the environment and sand content. The soil texture influences the turnover rate of the active soil SOM (higher rates for sandy soils) and the efficiency of stabilizing active SOM into slow SOM (higher stabilization rates for clay soils). The surface microbial pool turnover rate is independent of soil texture, and it transfers material directly into the slow SOM pool. The slow pool includes resistant plant material derived from the structural pool and soil-stabilized microbial products derived from the active and surface microbial pools. It has a turnover time of 20 to 50 years. The passive pool is very resistant to decomposition and includes physically and chemically stabilized SOM and has a turnover time of 400 to 2000 years. The proportions of the decomposition products which enter the passive pool from the slow and active pools increase with increasing soil clay content. On the other hand, carbon leaving the active organic matter component is either released as CO_2 or goes into the 'slow' organic C pool with the split determined by soil texture. Soil texture also regulates the rate of transfer between slow and passive forms (Figure 2).

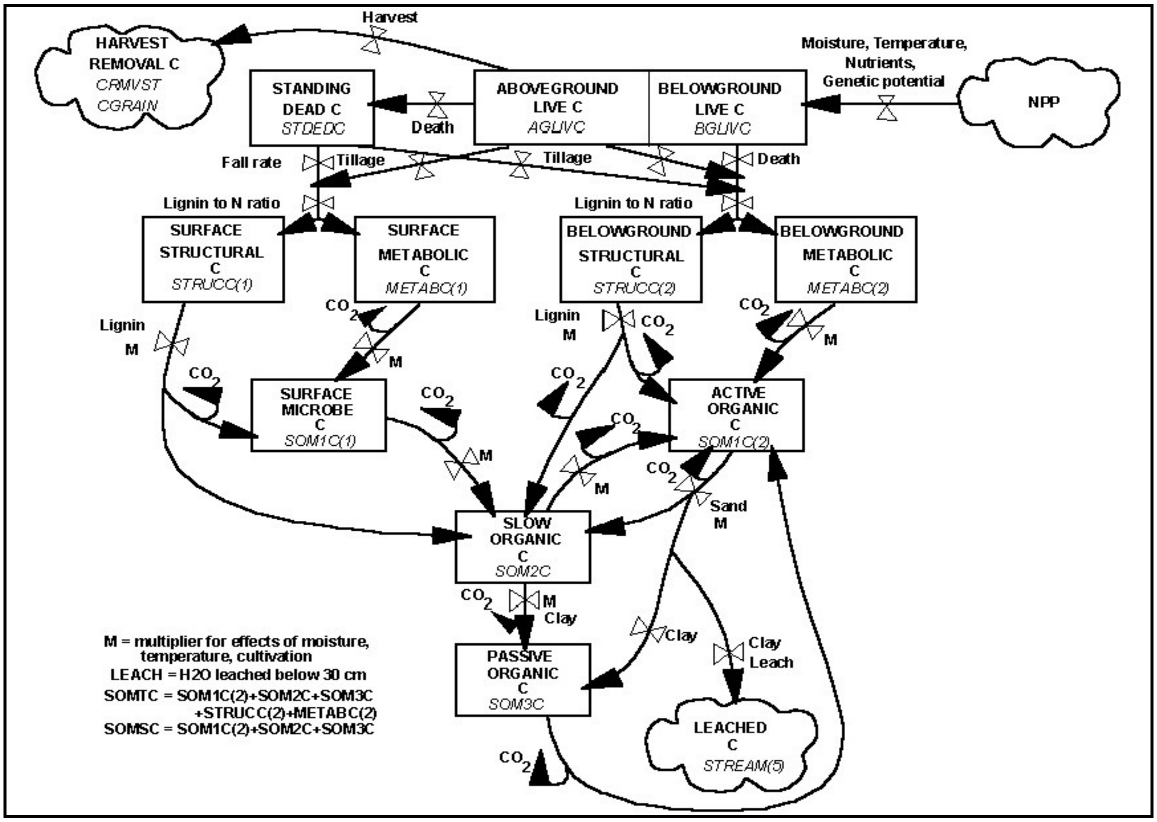


Figure 2. Carbon pools and flows as envisaged in the CENTURY model. The diagram shows the major factors which control the flow.

(b) Data requirement

The CENTURY model requires weather parameters such as monthly maximum and minimum temperature and monthly rainfall. In addition to that, it requires twelve data files (Figure 3). Each file contains a certain subset of variables. 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 or sweep tillage, thinning operations etc. 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.

Data sets needed for the simulation analysis were collected from published sources and from on-field experiments. Total organic carbon was estimated from the samples using CHNS analyzer and these estimates supplemented and sufficed input data requirement for model calibration and validation and subsequent analysis.

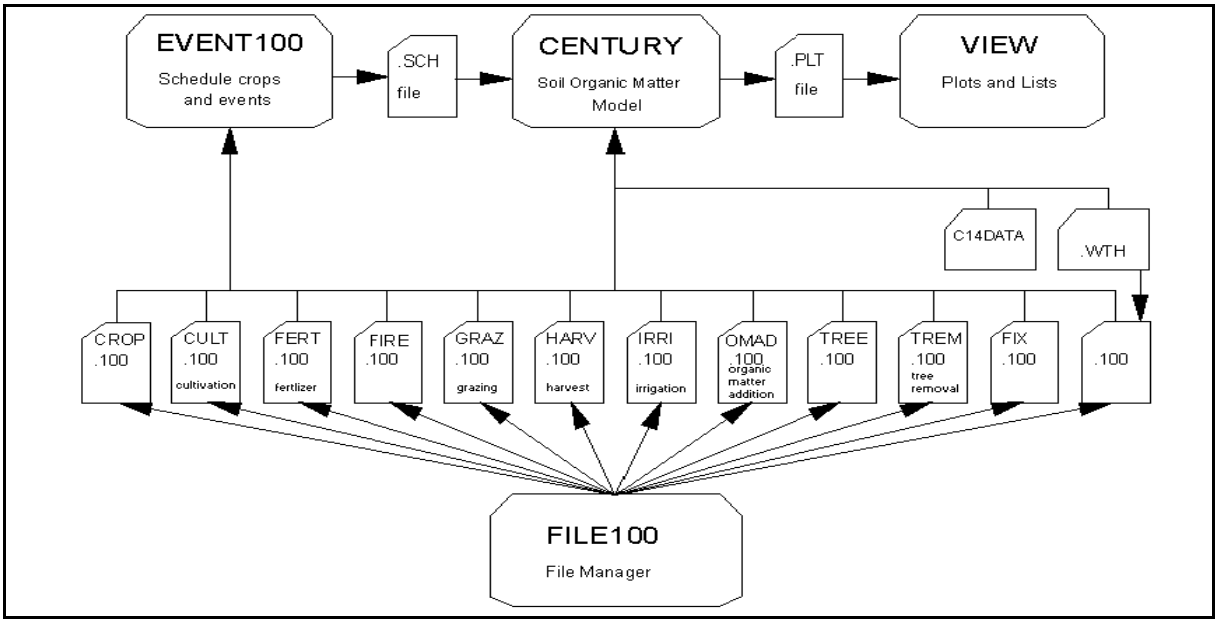


Figure 3. The century model environment showing the relationship between the programmes and the file structure

Description of major files used in CENTURY model (as shown in Figure 3)	
.100 Files	**Description**
fix.100	Fixed parameters related to SOM decomposition
site.100	Site-specific parameters - precipitation, soil texture, initial conditions for SOM
crop.100	Crop options file
cult.100	Cultivation options file
fert.100	Fertilization options file
fire.100	Fire options file
graz.100	Grazing options file
harv.100	Harvest options file
irri.100	Irrigation options file
omad.100	Organic matter addition options file
tree.100	Tree options file
trem.100	Tree removal options file

(c) Parameterisation of the CENTURY model

The ability of the Century model to predict changes in SOC turnover depends largely on the plant productivity submodels, which determine plant production and returns to the soil. Though century has plant sub-models, these files have associated management practices (sowing/ planting time, irrigation, addition of fertilizer and FYM, yield and method of harvesting) that are very different from those used in the teak plantations. In order to address this, we gathered data on teak management information and was then used to create teak files in CENTURY that are specific to Kerala Western Ghats (Table 2).

Table 2. Basic physico - chemical parameters of soil (0 – 20 cm) used in the CENTURY model

Site and soil variables		Teak
SITLAT	Latitude of model site (deg)	10.31
SITLNG	Longitude of model site (deg)	76.13
SAND	Fraction of sand in soil	0.70
SILT	Fraction of silt in soil	0.18
CLAY	Fraction of clay in soil	0.12
BULKD	Bulk density of soil	1.42
NLAYER	Total soil layers in column	3.0
NLAYPG	Total soil layers available for plant growth	3.0
pH	Soil pH	5.80
DRAIN	Drainage	Well drained

(d) Model evaluation

The Century model was run to simulate changes in soil C contents in the 0–20 cm depth (of soils) of the teak plantations in zone B. The output from the model was then compared with available field data to evaluate model performance. This was done both qualitatively (by visual examination of graphed output) and quantitatively using the statistical parameters: the sample correlation coefficient (r), the root mean square error

(RMSE) which is a measure of coincidence between measured and modelled values and EF which is modelling efficiency (Smith *et al.,* 1996).

$$r = \frac{(\sum_{i=1}^{n}(Oi - \bar{O}) - (\sum_{i=1}^{n}(Pi - \bar{P})}{((\sum_{i=1}^{n}(Oi - \bar{O}))^{0.5}\,(\sum_{i=1}^{n}(Pi - \bar{P}))^{0.5}} \qquad \textbf{Eq. (6)}$$

$$\mathrm{RMSE} = \frac{100}{\bar{O}} \sqrt{\sum_{i=1}^{n}(P_i - O)^2/n} \qquad \textbf{Eq. (7)}$$

$$\mathrm{EF} = \frac{(\sum_{i=1}^{n}(Oi - \bar{O})^2 - (\sum_{i=1}^{n}(Pi - \bar{P})^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2} \qquad \textbf{Eq. (8)}$$

where Oi is the observed (measured) value, Pi is the predicted (simulated) value, $\bar{O}$ is the mean of the observed (measured) data, $\bar{P}$ is the mean of the predicted (simulated) data, and n is the number of paired values.

(e) Soil organic carbon turnover due to predicted climate change scenarios

The climate change projections in the form of Represented Concentartion Pathways (RCP 2.6, 4.5, 6.0, and 8.5) were downloaded from runs of the DSSAT weather generator model archived by the IPCC Data Distribution Center, developed in Fifth Assessment Report. The weather parametes such as maximum temperature, minimum temperature and rainfall was collected for Thrissur over a period from 2015 to 2050 and were given as inputs to the model. The model was run without changing other parameters that had already been calibrated.

4. Statistical analysis

Site quality comparisons of parameter means within a zone were performed using one-way ANOVA procedures in SPSS version 20.0. Parameter means and site qualities were the main effects of the ANOVA. Zone wise variations were analyzed using two – way anova where zones and site qualities were the main effects of the ANOVA. Pair-wise treatment comparison was made using Tukey’s HSD test. All the treatment effects were compared at $p < 0.05$ level.

RESULTS

The results of the study on "Soil organic carbon pools and its dynamics in the managed teak plantations of Kerala Western Ghats" is as follows:

General soil characters

The soils of teak plantations in Kerala were found to be acidic with a sandy loam texture. The clay content in the soils varied from 4.47 - 16.27 % and CEC from 2.11 - 8.49 cmols (p+) kg^{-1}. In general, site qualities I and II had a mixture of hydroxy interstratified vermiculites, micas and kaolinites, whereas site quality IV had a predominance of kaolinite, Fe and Al oxides, gibbsite and quartz.

1. Soil carbon stocks and pools

a. Carbon stocks

The carbon stocks varied from 6.74 – 11.98 kg m^{-2} in zone A, 5.49 – 8.94 kg m^{-2} in zone B, 6.68 – 11.98 kg m^{-2} in zone C and 10.11 – 14.85 kg m^{-2} in zone D in the top 1m of soil covered by teak plants (Figure 4a - d). There was no significant variation among zones A to C with respect to the carbon stocks. In general, the mean carbon stocks in different zones varied from 7.38 - 12.10 kg m^{-2} (Figure 5). Zone D, lying in a much cooler climate (mean annual temperature 21.6 °C; rainfall 3602 mm) than the other zones of teak plantations was found to store a significantly higher amount of carbon than all the teak growing zones. There was not much variation among zone- A (9.34 kg m^{-2}) and C (9.39 kg m^{-2}) in their capacity to store carbon in the 100cm soil layer. Irrespective of the zones, site qualities I and II had the highest storage capacity of carbon and site quality IV the lowest. The surface layer (0 – 20 cm) had the highest concentration of carbon content (2.93 – 4.59 kg m^{-2}) and the values decreased with depth (Figure 6a -d).

The carbon distribution with depth within the soil profiles in different zones is given in Figure 6a - d. Irrespective of the zones, it was found that 70 - 75% of the total carbon stocks in the teak plantations of Kerala Western Ghats are distributed in the 0 - 60 cm depth. The upper 0 - 30 cm layer contains only 35 - 40% of the total carbon stocks. The subsurface layers with active root concentration i.e., 30 - 60 cm stores approximately 50 % of the total stocks in these teak plantations. Beyond 60 cm carbon is added mainly by way of translocation from the surface and was found to have 10 -15 % of the total stocks. However, the amount of carbon stored in any of these layers was found to be influenced by the site quality in all the zones.

Most of the studies assessing carbon stocks of forest systems considers only the 0 - 30 cm depth for soil carbon stock assessment and this study establishes that calculation of soil carbon stocks upto this depth alone will grossly under represent the actual carbon storage potential of our tropical forest systems.

b. Soil organic carbon pools

Different site qualities influenced the turnover of carbon in soil. Active and slow fractions with comparatively lesser turnover times (0 -5 years and 20 – 40 years respectively) are essential for the ecosystem sustainability compared to the passive recalcitrant forms with turnover times of 200 to thousands of years. In zone A, the teak planted soils were found to contain 0.35%, 0.33% and 0.82% of active, slow and passive carbon respectively (Table 3). In site quality 1, the active and slow carbon pools were found to be nearly double that of the passive fraction whereas site deterioration was found to substantially reduce the former fractions with respect to the latter. In site quality IV, active + slow carbon fractions were only one - fourth of that of the passive fraction, thereby seriously impairing the ecosystem health.

Table 3. Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – A in Kerala Western Ghats

Site Quality	Active carbon (%)	Slow carbon (%)	Passive carbon (%)
I	0.65^{a}	0.75^{a}	0.60^{b}
II	0.37^{b}	0.35^{b}	$0.84a^{b}$
III	0.24^{c}	$0.18b^{c}$	0.96^{a}
IV	0.14^{c}	0.05^{c}	0.88^{a}
Mean	0.35	0.33	0.82

Same lowercase x stands for no significant difference of carbon fraction at P<0.05 level in different site qualities.

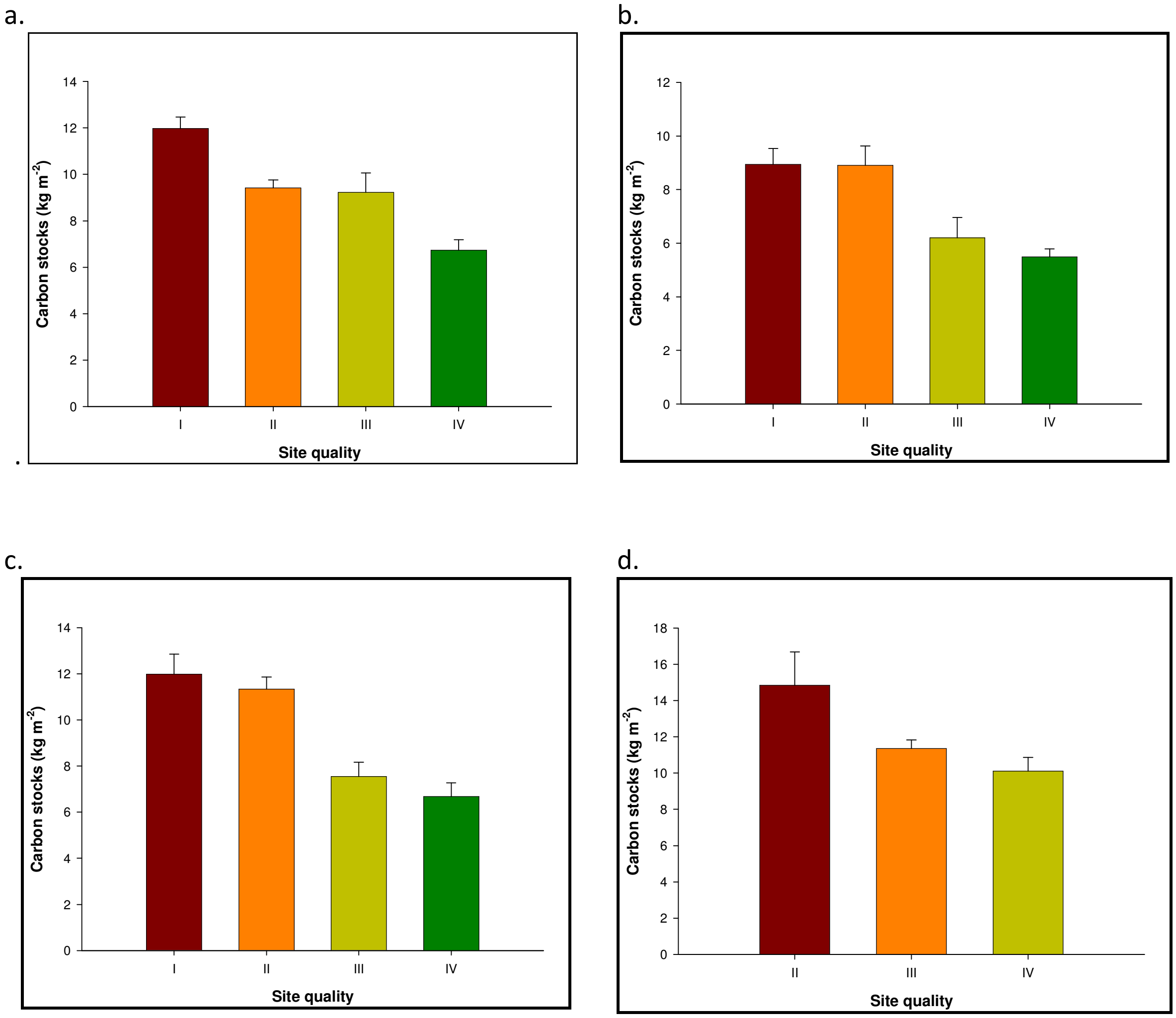


Figure 4a - d. Carbon stocks (kg m^{-2}) in (a) zone A (b) zone B (c) zone C (d) zone D

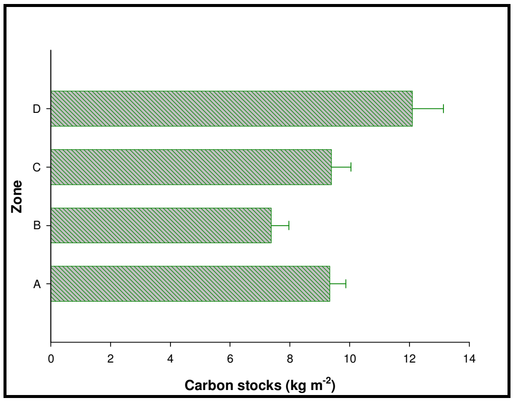


Figure 5. Average carbon stocks (kg m^{-2}) in different zones

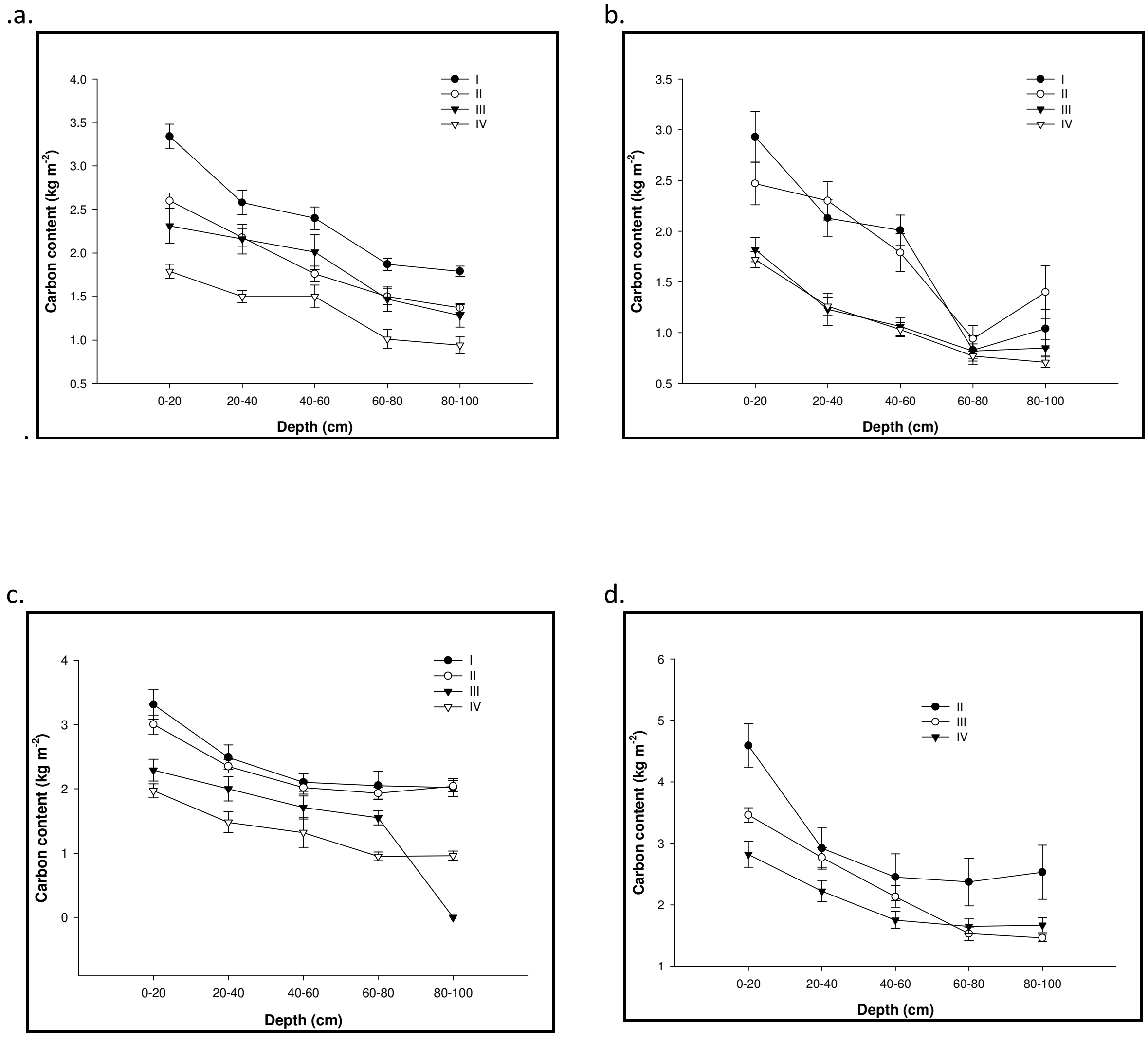


Figure 6a - d . Variation in carbon content (kg m^{-2}) with depth in (a) zone A (b) zone B (c) zone C (d) zone D

In zone B, passive carbon was found to be the dominant fraction accounting for nearly 50 percent of the total organic carbon in soil (Table 4). In site quality I of this zone,the active carbon was about 3 times higher than that present in site quality IV. Site quality I was also found to have significantly higher slow carbon than all the other sites in this zone. The most dominant fraction in this zone was the passive fraction which was found to be on par at all the sites.

Table 4. Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – B in Kerala Western Ghats

Site Quality	Active carbon (%)	Slow carbon (%)	Passive carbon (%)
I	0.30^{a}	0.51^{a}	0.95^{a}
II	0.24^{a}	0.22^{b}	1.01^{a}
III	0.17^{ab}	0.21^{b}	0.82^{a}
IV	0.10^{b}	0.08^{b}	0.85^{a}
Mean	0.20	0.25	0.91

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Active carbon fractions in site qualities I and II of zone C was found to be significantly higher than that of site qualities III and IV which had similar contents (Table 5). Slow carbon was found to be highly influenced by site quality in this zone and the values ranged from 0.14 – 0.71%. The slow carbon concentration in site quality - I (0.71%) was about 5 times higher than that of the content in soils of site quality – IV (0.14%). Passive carbon concentration showed no significant variation among the soils with different site qualities.

Table 5 . Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – C in Kerala Western Ghats

Site Quality	Active carbon (%)	Slow carbon (%)	Passive carbon (%)
I	0.44^{a}	0.71^{a}	0.83^{a}
II	0.43^{a}	0.38^{b}	0.98^{a}
III	0.26^{b}	0.29^{bc}	0.82^{a}
IV	0.20^{b}	0.14^{d}	0.84^{a}
Mean	0.33	0.38	0.87

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

In zone – D, highest amount of active carbon concentration was found in site quality – II (0.79%), which was significantly higher than the concentration of this fraction in other site qualities (Table 6). In general, 0.74% slow carbon fractions were found in the teak grown soils of this zone and the passive carbon contents ranged from 0.68% in site quality – III to 1.12% in site quality – IV.

Table 6 . Changes in active, slow and passive soil carbon pools with site quality in teak plantations of zone – D in Kerala Western Ghats

Site Quality	Active carbon (%)	Slow carbon (%)	Passive carbon (%)
II	0.79^{a}	1.05^{a}	0.90^{a}
III	0.50^{b}	0.89^{b}	0.68^{ab}
IV	0.29^{c}	0.28^{c}	1.12^{a}
Mean	0.53	0.74	0.90

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Different zones also influenced the C fractions in teak planted soil (Tables 7 to 9). Active carbon fractions in zones A, C and D were on par and were 40% to 70% higher than that of zone – B. Active and slow carbon concentration were found to decrease with site quality in all the zones. In contrast, no significant difference was found in the passive SOC concentration associated with different zones or site qualities confirming that zone and site quality variations affects significantly active + slow pools and it is this fraction that determines ecosystem health and functions rather than the recalcitrant passive pool.

Table 7 .Active organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone - A	Zone – B	Zone - C	Zone - D	Mean
I	0.65	0.30	0.44	--	0.46^{a}
II	0.37	0.24	0.44	0.79	0.46^{a}
III	0.24	0.18	0.26	0.50	0.29^{b}
IV	0.14	0.10	0.20	0.29	0.18^{c}
Mean	0.35^{A}	0.20^{B}	0.33^{A}	0.53^{A}	

Same capital letter X indicates no significant difference of carbon fraction at $P<0.05$ level in the different zones; same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 8 .Slow organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone - A	Zone - B	Zone - C	Zone - D	Mean
I	0.75	0.51	0.71	0.00	0.66^{a}
II	0.35	0.22	0.38	1.05	0.50^{b}
III	0.18	0.21	0.29	0.89	0.39^{b}
IV	0.06	0.08	0.14	0.28	0.14^{c}
Mean	0.33^{B}	0.25^{C}	0.38^{B}	0.74^{A}	

Same capital letter X indicates no significant difference of carbon fraction at $P<0.05$ level in the different zones; same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 9.Passive organic carbon concentration (%) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone - A	Zone - B	Zone - C	Zone - D	Mean
I	0.60	0.95	0.83	--	0.79^{a}
II	0.84	1.01	0.98	0.90	0.93^{a}
III	0.96	0.82	0.82	0.68	0.82^{a}
IV	0.87	0.85	0.84	1.12	0.92^{a}
Mean	0.82^{A}	0.91^{A}	0.87^{A}	0.90^{A}	

Same capital letter X indicates no significant difference of carbon fraction at $P<0.05$ level in the different zones; same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Total organic carbon was found to be directly related to active carbon, slow C and passive C (Table 10). A significant positive correlation was found between active and slow carbon pools, but the recalcitrant passive pool was found to have no positive or negative tradeoffs with either of the two pools. This means that input additions, tree harvest, rotation duration etc., will influence only the active and slow pools and passive carbon remains more or less undisturbed. The changes in total organic carbon should hence be a reflection of slow and active pools rather than the passive pool.

Table 10. Correlation between different carbon fractions in teak planted soils of Kerala

	TC	**AC**	**SC**	**PC**
TC	1			
AC	.827**	1		
SC	.792**	.756**	1	
PC	.398**	.003	-.158	1

**. Correlation is significant at the 0.01 level (2-tailed)

TC – Total organic carbon; AC – Active carbon; SC – Slow carbon; PC – Passive carbon

On an average, Walkley and Black carbon (WBC) ranged from 6.82 to 16.52 g kg^{-1} soil under different site qualities (Table 11). Site quality - I increased WBC significantly over other teak planted soilsin zone - A. Microbial biomass carbon (MBC), i.e., organic carbon associated with microbial cells varied from 0.35 to 0.70 g kg^{-1} soil and constituted 3 - 4% of WBC (Table 11). The results show that site qualities - II, III and IV were inferior to site quality - I in maintaining the MBC content of soils, indicating that even slight variations in site quality will seriously impair the MBC status of soils. Total polysaccharide (TP) content ranged from 2.57 g kg^{-1} soil in site quality - IV to 7.51 g kg^{-1} soil in site quality - I. Although site qualities - II and III showed significantly higher values of TC content when compared with soil site quality - IV, these two were inferior to site quality - I.

The WBC content in soil was significantly affected by site quality in zone - B (Table 12). Site quality - III could not change the WBC status of soil significantly compared to the lowest site quality - IV. Like WBC, microbial biomass carbon was also affected significantly by decline of site quality and site quality - I was found to have 83% higher MBC content than site quality IV. Site quality - II and III could maintain similar levels of MBC contents. Zone - B was found to contain an average of 4.94 g total polysaccharides per kg soil.

Table 11. Effect of site qualities on Walkley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – A in Kerala Western Ghats

Site Quality	Walkeley and Black carbon	Microbial biomass carbon	Total polysaccharides
	(g kg^{-1} soil)		
I	16.52^{a}	0.70^{a}	7.51^{a}
II	8.27^{b}	0.25^{b}	5.72^{b}
III	9.52^{b}	0.43^{ab}	5.17^{b}
IV	6.82^{b}	0.35^{b}	2.57^{c}
Mean	10.28	0.43	5.24

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 12. Effect of site qualities on Walkley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – B in Kerala Western Ghats

Site Quality	Walkeley and Black carbon	Microbial biomass carbon	Total polysaccharides
	(g kg^{-1} soil)		
I	14.64^{a}	0.66^{a}	9.42^{a}
II	11.26^{b}	0.36^{b}	5.32^{b}
III	6.44^{c}	0.40^{b}	2.05^{c}
IV	6.87^{c}	0.11^{c}	2.98^{c}
Mean	9.80	0.38	4.94

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

In zone - C, WBC and TP were significantly affected by site qualities but there was no effect of site quality deterioration on MBC (Table 13). The soils were found to contain 11.28 g kg^{-1} soil, 0.29 g kg^{-1} soil and 4.08 g kg^{-1} soil WBC, MBC and TP respectively. Walkley and Black carbon and total polysaccharides in site quality - IV in zone - C was only 50% of that found in site quality – I, thereby posing a serious concern of sustaining soil health in such low quality sites.

Compared to other zones, WBC and TP contents were very high and MBC content low in the teak planted soils of zone – 4 (Table 14). The WBC contents ranged from 8.24 g kg^{-1} in site quality - IV soil to 21.67 g kg^{-1} soil in site quality - II. Likewise, TP contents varied from 3.43 g kg^{-1} in site quality - IV soil to 8.34 g kg^{-1} soil in site quality - III. The reduction in quality from III to IV drastically reduces the WBC, MBC and TP contents by 50% which can seriously hamper teak soil health and productivity in this zone.

Table 13. Effect of site qualities on Walkeley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – C in Kerala Western Ghats

Site Quality	Walkeley and Black carbon	Microbial biomass carbon	Total polysaccharides
	(g kg^{-1} soil)		
I	15.13^{a}	0.37^{a}	5.41^{a}
II	12.36^{ab}	0.27^{a}	4.41^{ab}
III	11.42^{b}	0.33^{a}	3.88^{b}
IV	8.29^{c}	0.20^{a}	2.61^{c}
Mean	11.80	0.29	4.08

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 14. Effect of site qualities on Walkeley and Black carbon, microbial biomass carbon and total polysaccharide content in teak plantations of zone – D in Kerala Western Ghats

Site Quality	Walkeley and Black carbon	Microbial biomass carbon	Total polysaccharides
	(g kg^{-1} soil)		
II	21.67^{a}	0.24^{a}	8.07^{a}
III	17.02^{b}	0.25^{a}	8.34^{a}
IV	8.24^{c}	0.11^{b}	3.43^{b}
Mean	15.65	0.20	6.61

Same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

The Walkley and Black carbon concentration was found to be highest in zone - D which retained substantially higher amounts than teak growing soils in other zones (Tables 15 to 17). The WBC content varied among the zones as zone - D > zone - C > zone - A = zone - B and among the site qualities as site quality - I > site quality - II > site quality - III > site quality - IV. The degradation from site quality III to the lowest quality IV was found to substantially reduce the WBC content of soils. The MBC content showed a reverse trend than that of WBC among the zones with zone - A having a significantly higher amount followed by zone - B, zone - C and zone – D when the mean values are compared. Zone - D with a comparatively cooler climate would have negatively influenced the growth and multiplication of microbes, hence lower MBC. Among the site qualities, site quality - I had significantly higher MBC content than site quality - II and III, which were on par. Site quality - IV had the lowest MBC content and hence can be considered limiting for soil microbial growth and activity. Total polysaccharide content didn’t show a definite trend between the zones with zone - D giving significantly higher values than zones - B and C. Site quality was found to influence the total polysaccharide content significantly in all the zones.

Table 15 .Walkley and Black carbon concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone – A	Zone - B	Zone - C	Zone - D	Mean
I	16.50	14.63	15.13	--	15.42^a
II	8.28	11.26	12.36	21.67	13.39^b
III	9.53	6.45	11.42	17.02	11.10^c
IV	6.80	6.87	8.28	8.25	7.55^d
Mean	10.28^C	9.80^C	11.80^B	15.65^A	

Same capital letter X indicates no significant difference of carbon fraction at $P<0.05$ level in the different zones; same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 16.Microbial biomass carbon concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone - A	Zone - B	Zone - C	Zone - D	Mean
I	0.70	0.66	0.37	--	0.57^a
II	0.25	0.36	0.27	0.24	0.28^b
III	0.43	0.40	0.33	0.25	0.35^b
IV	0.35	0.11	0.20	0.11	0.19^d
Mean	0.43^A	0.38^B	0.29^C	0.20^D	

Same capital letter X indicates no significant difference of carbon fraction at $P<0.05$ level in the different zones; same lowercase x stands for no significant difference of carbon fraction at $P<0.05$ level in different site qualities.

Table 17 .Total polysaccharide concentration (g kg^{-1} soil) in different zones and site qualities of teak planted soils in Kerala Western Ghats

	Zone - A	Zone - B	Zone - C	Zone - D	Mean
I	7.51	9.42	5.41	--	7.44^{a}
II	5.72	5.32	4.41	8.08	5.88^{b}
III	5.17	2.05	3.88	8.34	4.86^{c}
IV	2.57	2.98	2.61	3.43	2.90^{d}
Mean	5.24^{A}	4.94^{B}	4.08^{B}	6.62^{A}	

Same capital letter X indicates no significant difference of carbon fraction at P<0.05 level in the different zones; same lowercase x stands for no significant difference of carbon fraction at P<0.05 level in different site qualities.

c. Humic acid characterization

The elemental composition of the extracted humic acids show that their carbon and nitrogen contents ranged from 26.2 - 44.4% and 4.1 - 6.3% respectively (Table 18). The carbon content of humic acids was found to be lowest in zone - C. The results indicate tendencies in better site qualities (I and II) for the carbon and C/N ratio to remain unchanged and the nitrogen content to increase. In the degraded sites (IV) it was observed that the carbon and C/N ratio increased while the nitrogen content decreased. Though site quality IV had comparatively higher C/N ratio than the other sites this was found to be well within critical limits of 10:1 required to sustain carbon and nitrogen mineralization. The total acidity or exchange capacity of humic acids due to the presence of dissociable protons or H^+ ions in aromatic, carboxylic or phenolic hydroxyl groups were found to vary from 8.5 - 11 meq/g in the different zones. The contribution to the total acidity was mainly from phenolic acidity which varied from 71 - 92% of the total acidity.

The E4/ E6 ratio values for the humic acids was found to be between 2.8 - 4.9 indicating compounds with high molecular weights and higher degrees of humification. Measured values of optical density from site qualities - I and II were characterized by comparatively higher values at 465 nm and higher E4/E6 ratios than the humic acids from site quality - IV. The lowest E4/ E6 ratio (2.8) was observed in site quality - IV of zone - A and zone - B and highest (4.9) in site quality - II of zone - D. Figure 7 shows that the humic acids determined in this study from different teak growing zones of

Kerala Western Ghats were similar to type A in Kumada's classification system which is characterized by high stability, high degree of aromatic condensation and a relatively low concentration of functional groups. This further confirms the SOM distribution shown by the E4/E6 ratio which pointed to the presence of highly humified soil organic matter in these planatations.

Table 18. Chemical composition of humic acids extracted from teak planted soils in Kerala Western Ghats

	C (%)	N (%)	H (%)	O (%)	S (%)	C:N	Total acidity (meq/g)	Carboxylic acidity (meq/g)	Phenolic acidity (meq/g)	E4/ E6
Zone – A										
I	35.4	5.0	4.2	55.4	nd	7.1	9.5	2.0	7.5	4.3
II	37.8	5.3	3.8	53.2	nd	7.2	10.5	2.6	7.9	3.3
III	41.2	5.3	3.9	49.6	nd	7.8	10	2.6	7.4	3.1
IV	36.7	4.4	2.8	56.1	nd	8.4	10	2.7	7.3	2.8
Zone – B										
I	31.2	4.6	3.4	60.8	nd	6.7	8.5	2.0	6.5	3.3
II	33.5	5.9	3.2	57.4	nd	5.6	11	2.5	8.5	3.4
III	37.5	5.0	3.0	54.6	nd	7.6	10.5	3.0	7.5	3.2
IV	44.4	5.4	4.0	46.2	nd	8.2	10	1.9	8.1	2. 8
Zone – C										
I	26.2	6.3	2.4	65.1	nd	4.2	10	2.0	8.0	4.4
II	29.7	4.2	3.0	63.2	nd	7.1	10	1.7	8.3	4.4
III	36.3	5.0	3.1	55.6	nd	7.2	11	2.5	8.5	4.4
IV	28.8	4.1	2.7	64.4	nd	7.1	11	2.8	8.2	3.9
Zone – D										
II	35.4	5.7	3.3	55.6	nd	6.2	10.5	2.1	8.4	4.9
III	28.8	5.1	2.8	63.3	nd	5.7	10.5	1.8	8.7	4.3
IV	41.0	4.6	3.0	51.4	nd	9.0	11	0.88	10.1	4.0

nd - non detectable

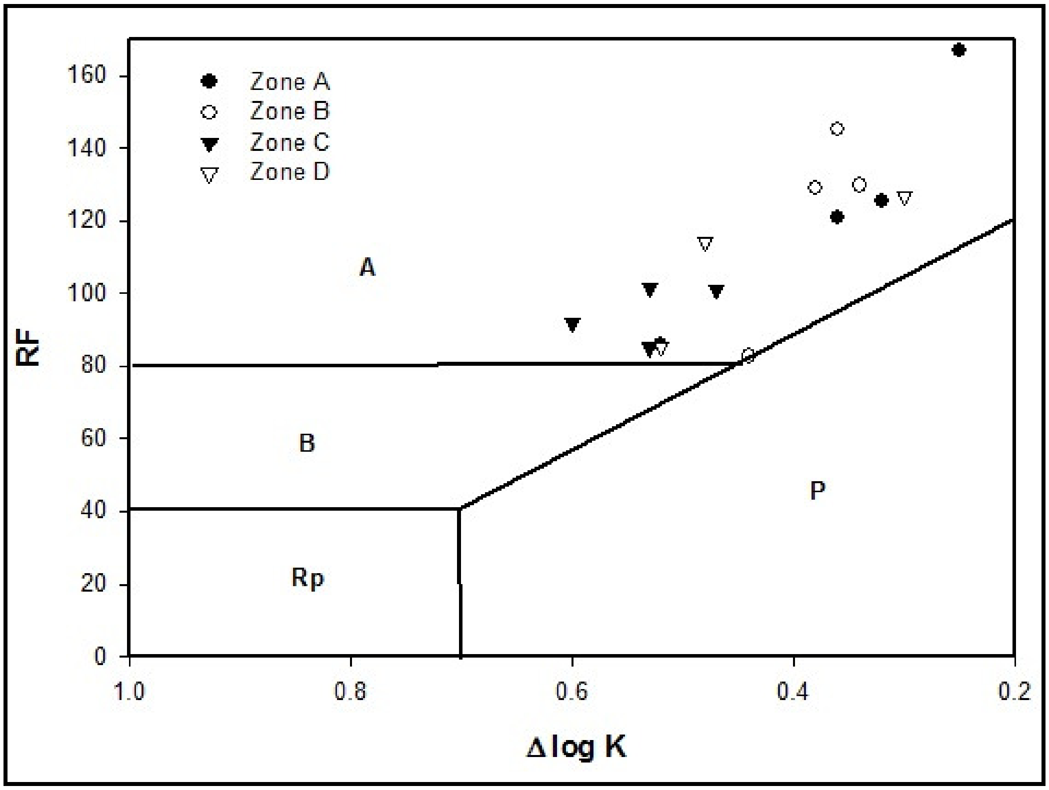
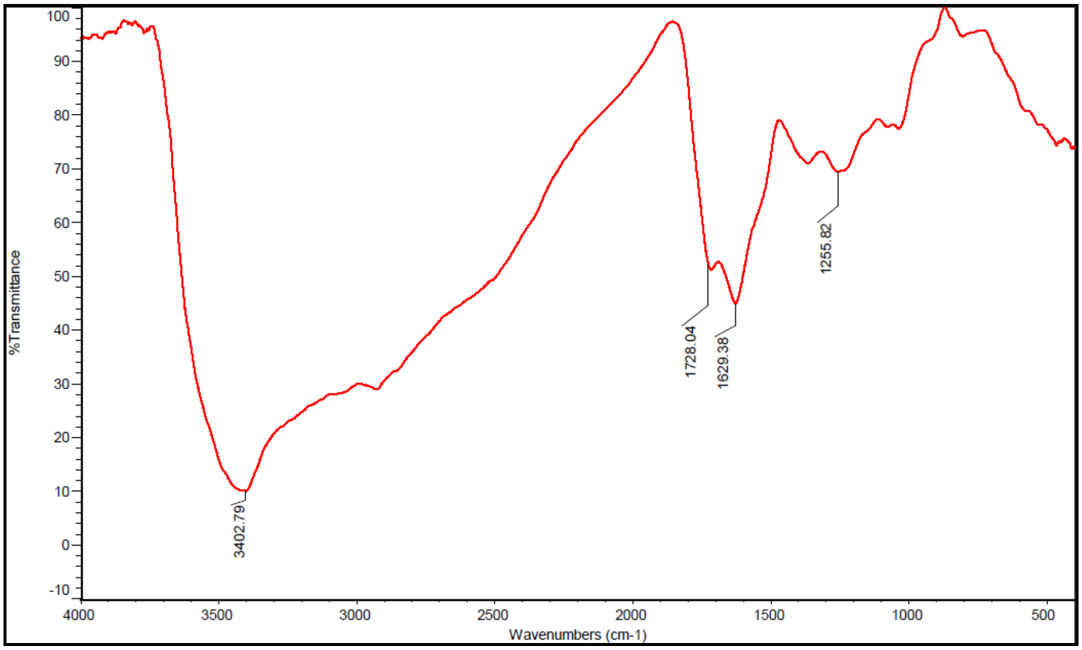


Figure 7. Humic acid classified according to Kumada's method (all zones)

The FTIR spectra of humic acids from different site qualities and zones indicated a similar pattern (Figures 8a – h). As the main absorption band was above 3000 cm^{-1} the humic acid is likely to be unsaturated (contains C = C) or aromatic rings. Two set of bands in the region 1615 - 1495 cm^{-1}, with one set around 1600 cm^{-1} (aromatic ring stretch) and the other around 1500 cm^{-1} (aromatic ring stretch) confirms that the structures are indeed aromatic. Moreover, medium-to-strong absorptions, sometimes more than one, between 850 and 670 cm^{-1}, can be assigned to C-H out-of-plane bending on an aromatic ring. Hydrogen bonding by these groups would have influenced the band broadening and lowered the mean absorption frequency in this spectral range. Weak adsorption bands in the 2500 - 2000 cm^{-1} region in humic acids extracted from zone - A and C points to a possibility of triple bonded carbon (stretching) in the skeletal structure.

a.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20
10
0
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%Transmittance
4000
3500
3000
2500
2000
1500
1000
500
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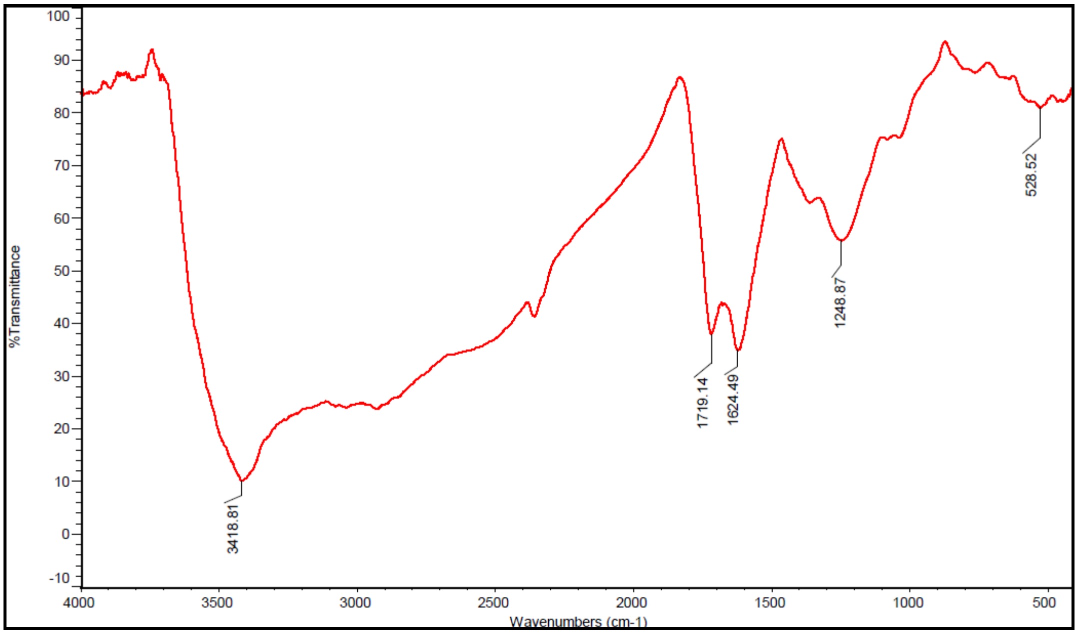
1629.38
1255.82

b.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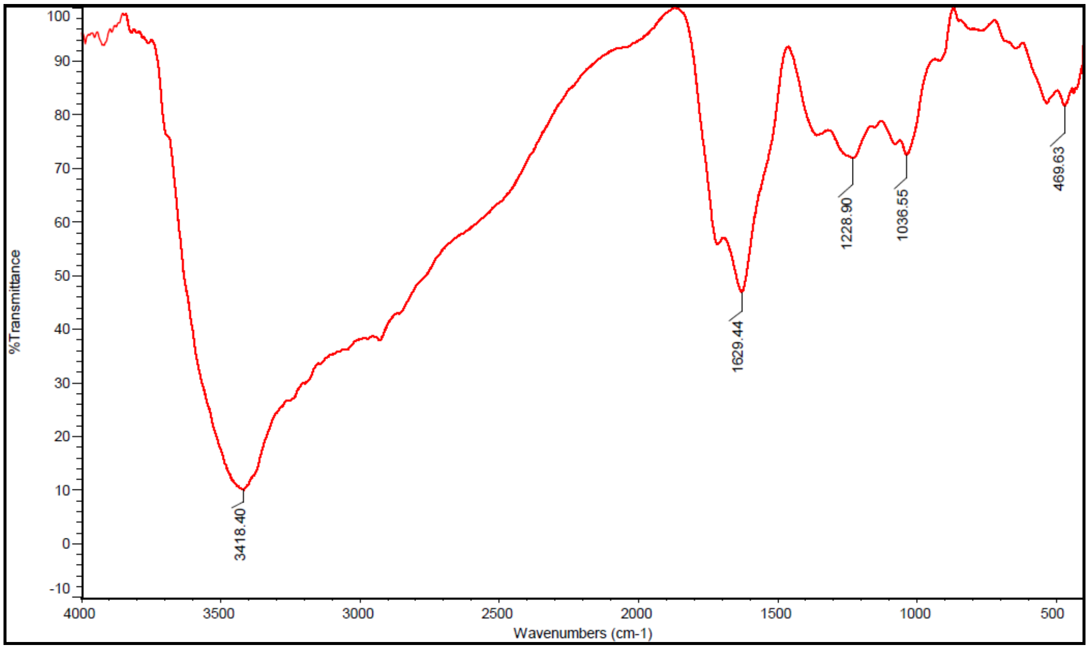
c.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1000
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Wavenumbers (cm-1)
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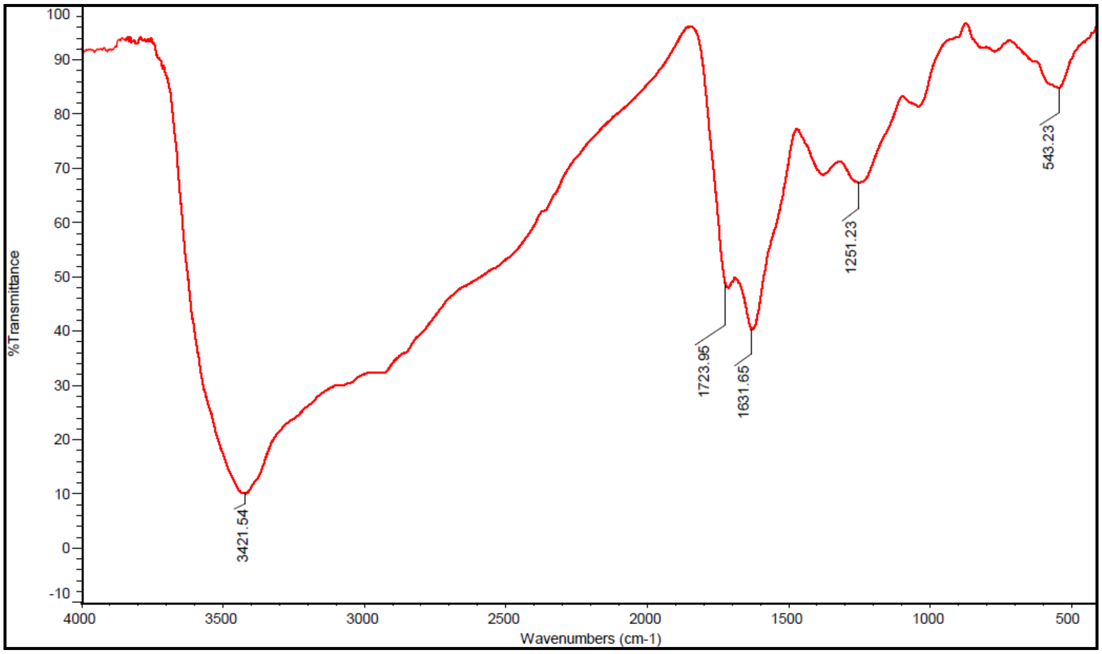
1036.55
469.63

d.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Wavenumbers (cm-1)
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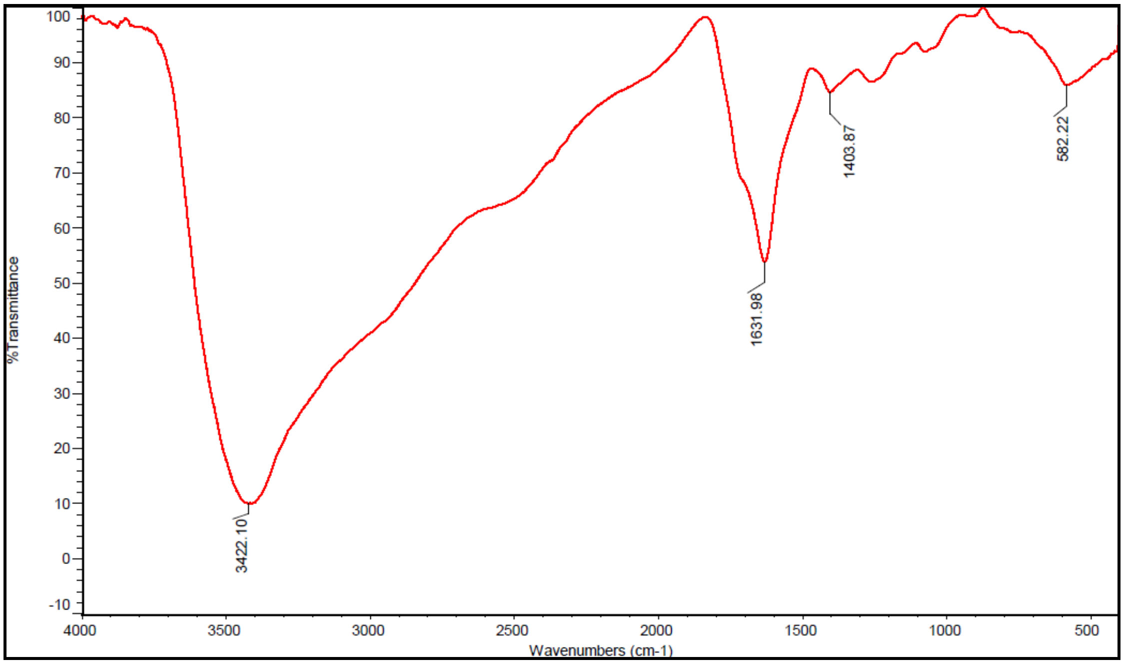
1251.23
543.23

e.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%Transmittance
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1500
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500
Wavenumbers (cm-1)
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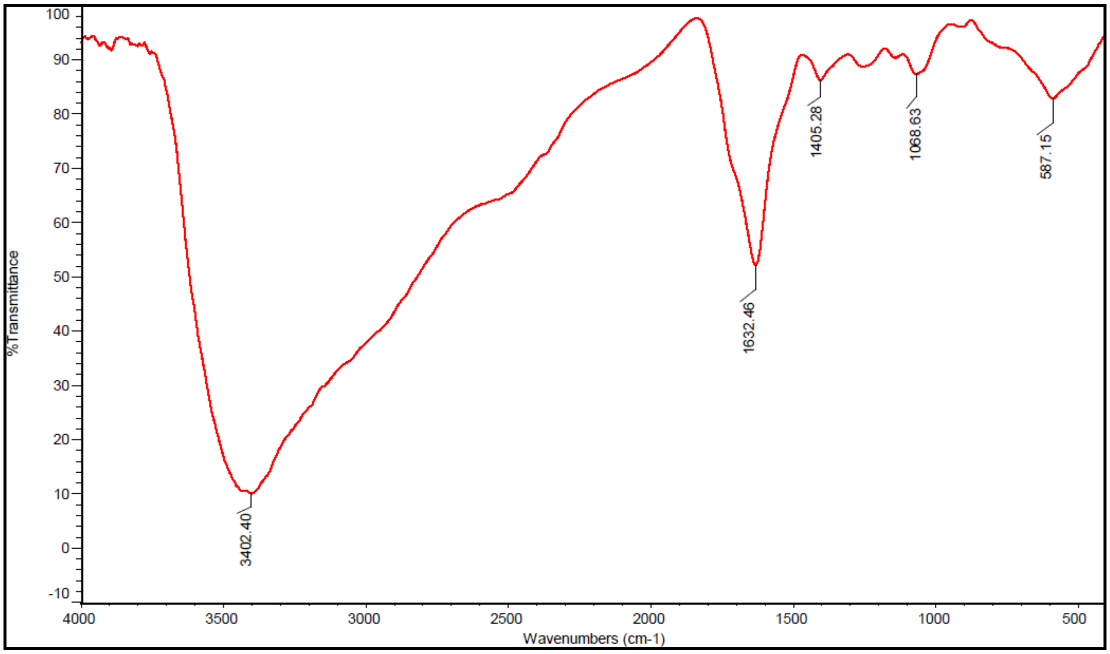
582.22

f.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%Transmittance
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1000
500
Wavenumbers (cm-1)
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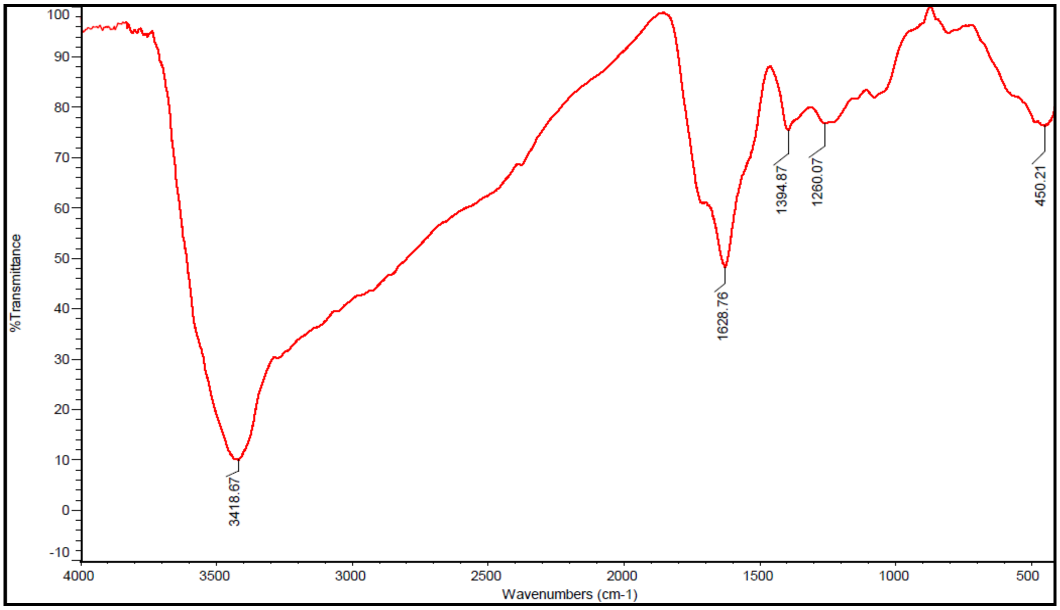
1068.63
587.15

g.



h.

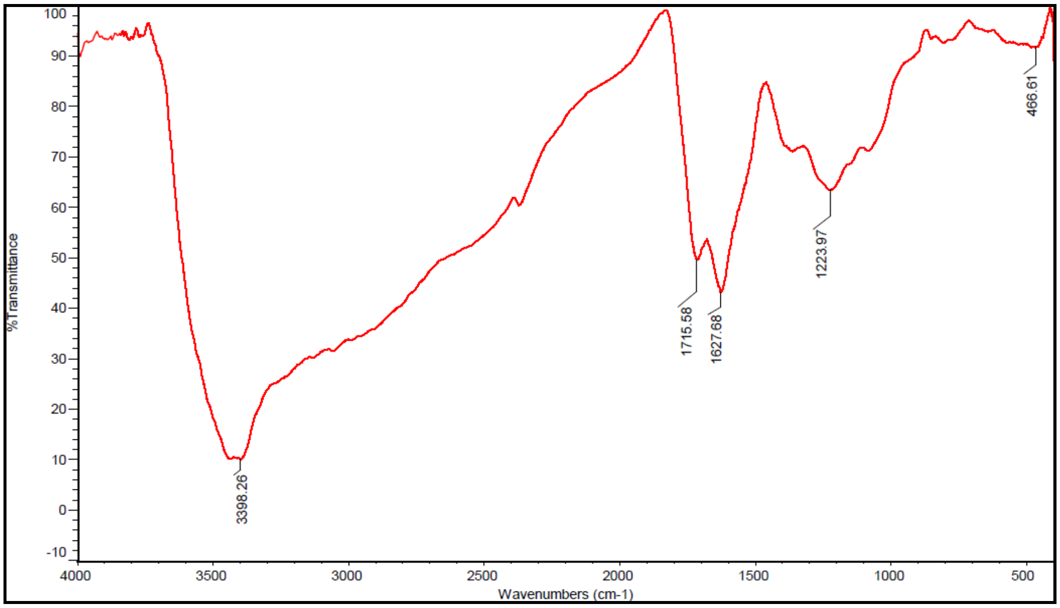


Figure 8a – h. Representative FTIR spectra of humic acids in (a) zone A – site quality I (b) zone A – site quality IV (c) zone B – site quality I (d) zone B – site quality IV (e) zone C – site quality I (f) zone C – site quality IV (g) zone D – site quality II (h) zone D – site quality IV

With respect to the functional groups, a relatively sharp and common band found at 3415 - 3380 cm^{-1} in all the analysed samples can be assigned to non-hydrogen-bonded hydroxy group which can be an alcohol or phenol with a sterically hindered OH group. In spectra of humic acids from zone - A and B the absorption bands at 2935 and 2860 cm^{-1} are attributed to aliphatic methylene groups and assigned to fats and lipids. This confirms the presence of some long linear aliphatic chain along with the aromatic rings in the polymeric HA structures in these zones.

The prominent bands at 1740 - 1690 cm^{-1} in all the analyzed humic acids is most relevant, since in this region rarely other functional groups than C=O show intense absorption bands and they are not affected by water content of the samples. The intensity of the C=O band was relatively more in humic acids from site quality - IV than site quality - I. The absorbance in the FT-IR spectra of humic acids in the region 1170–950 cm^{-1} is assigned to C–O stretching of polysaccharides or polysaccharide-like substances, Si–O of silicate impurities, and clay minerals possibly in a complex with humic materials. Humic materials showed a decrease in intensity at 1080–1030 cm^{-1} in zones - A, B and D with site quality indicating the loss of polysaccharides with site degradation in these zones. However, a no change in the intensity at 1038 cm^{-1} in Zone - C is more possibly due to silicate impurities rather than polysaccharide content.

The FTIR results indicate that the humic substances from soils of teak plantations in the Kerala Western Ghats may be considered polymeric mixture of organic molecules predominantly aromatic with phenolic and amine substituents, linked together.

Scanning electron microscopy (SEM) was used to assess the morphological characterization of the extracted humic acids. SEM images revealed the appearance of well aggregated microstructures of humic acids which is usually associated with its stabilization process.

With its very high spatial resolution the transmission electron microscope (TEM) allows the determination of colloidal size, structure and shape of humic substances. TEM images establish that these humic acids are laminated (shapeless), poly crystalline with particle size in micro range (Figure 9 and 10). Irrespective of the studied zones, SEM and TEM images gave a similar pattern for humic acids extracted.

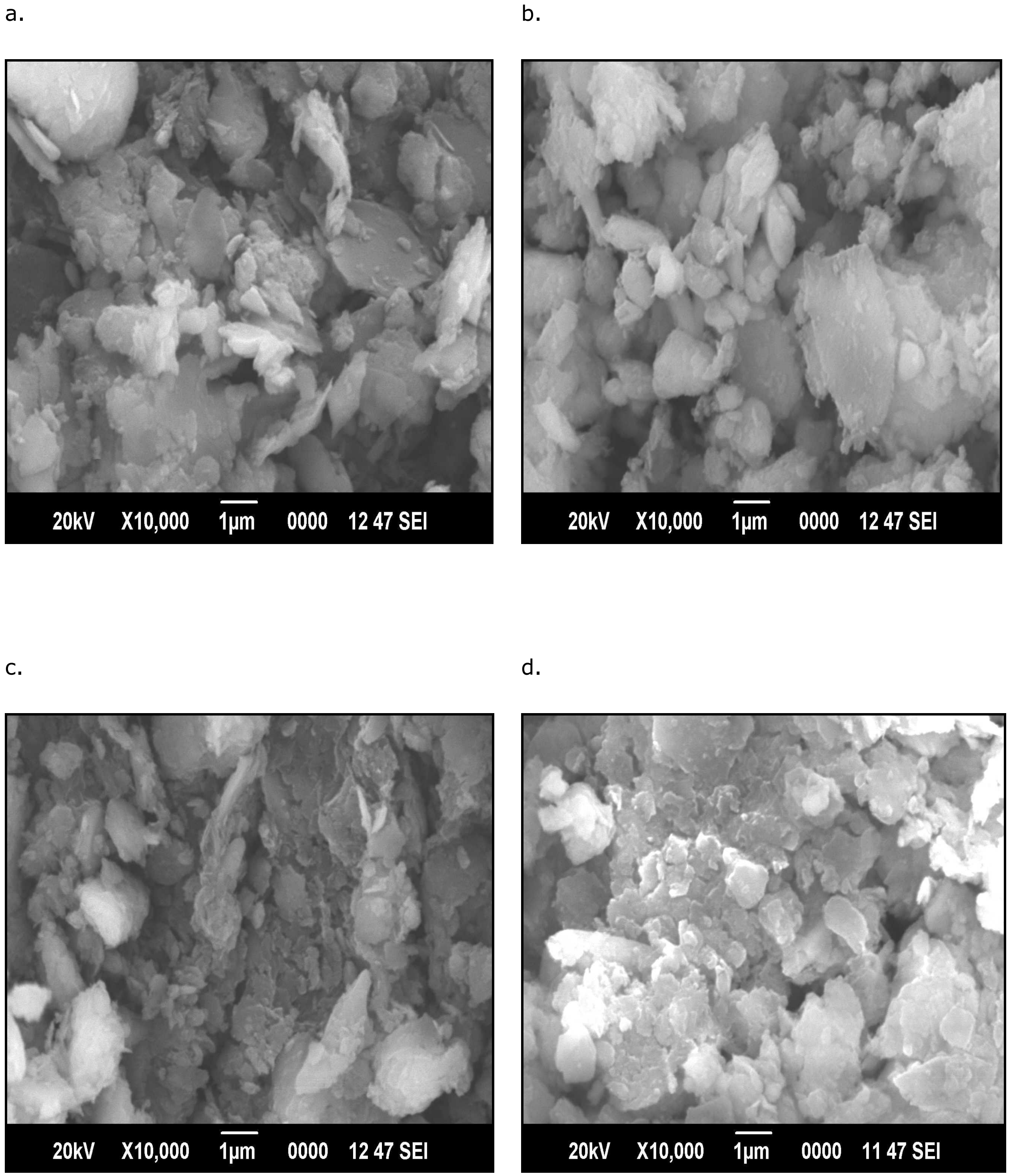


Figure 9. Representative scanning electron microscopy images of humic acids from site quality I in (a) zone A (b) zone B (c) zone C (d) zone D

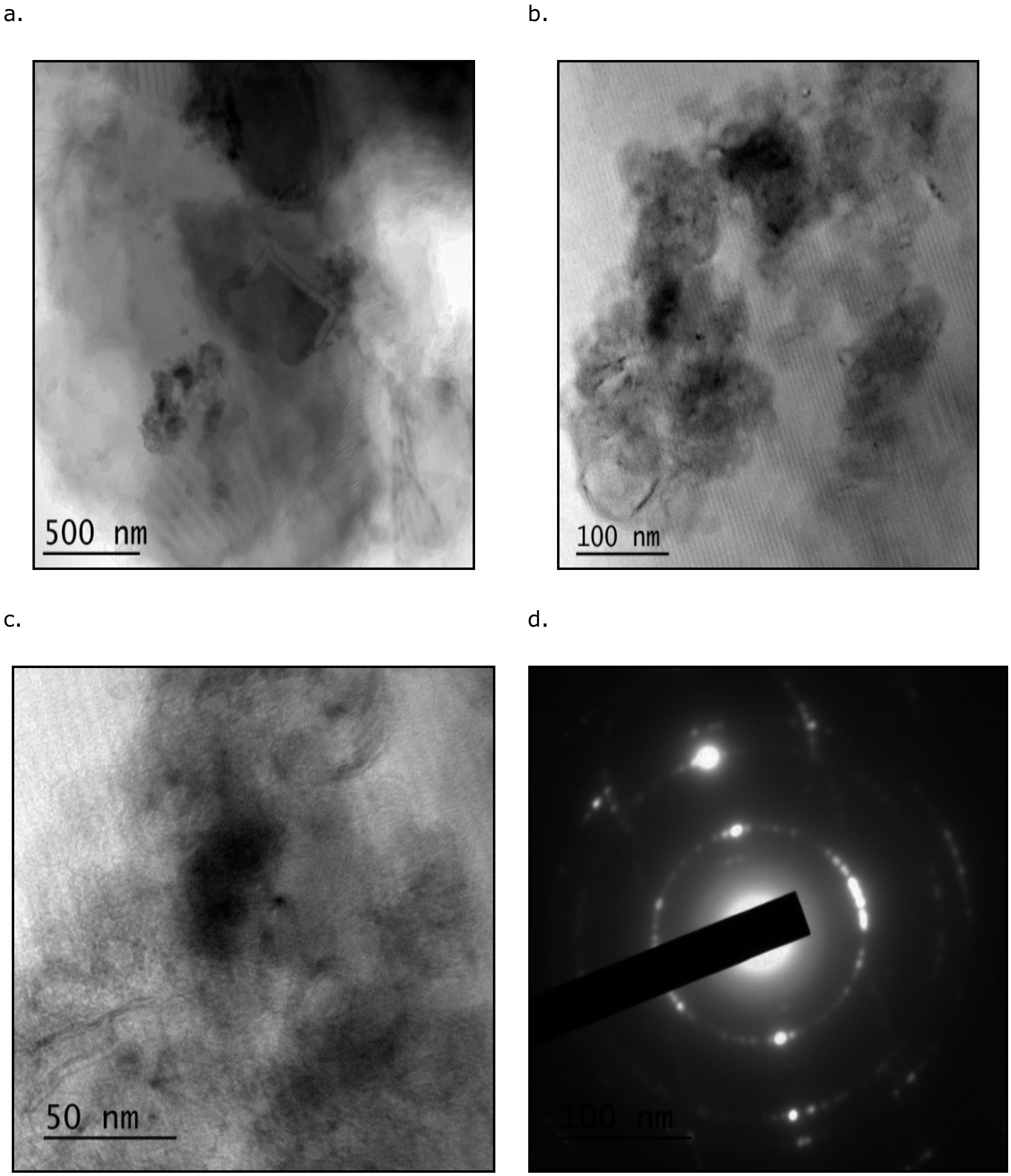


Figure 10. Representative transmission electron microscopy images of humic acids (zone A - site quality I)

2. Mineral - organic interactions and thermal stability of soil organic carbon

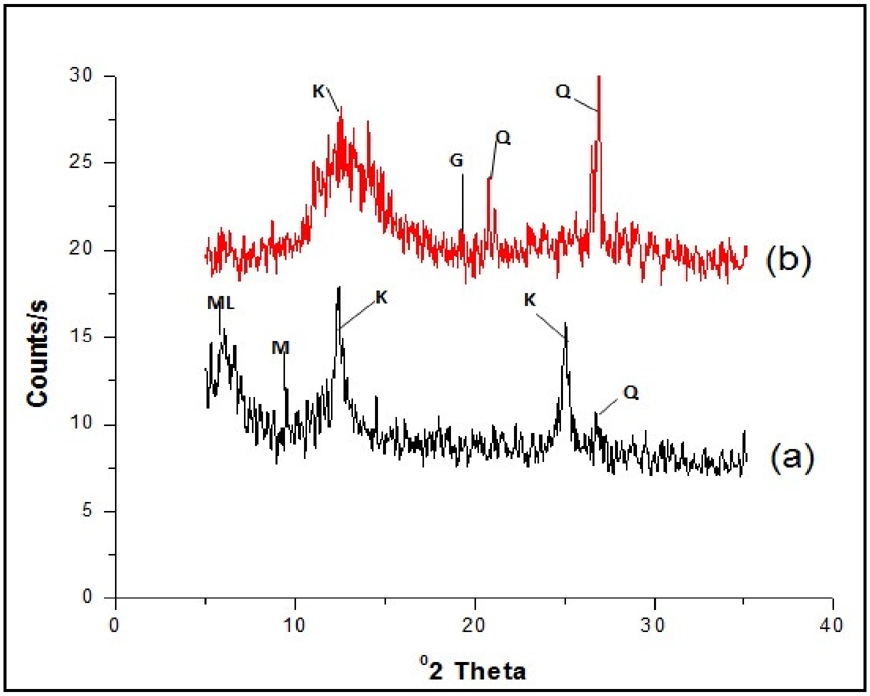
a. Mineral – organic interaction studies

The adsorption of DOC on soils depends greatly on its mineralogical make up. X - ray diffraction analyses indicate that the teak planted soils in site quality 1 and II in zones A and B is a mixture of mixed layer minerals, micas and kaolinites. In these zones, as the soils degrade to site quality IV, 2:1 minerals with higher surface areas and charge densities were found almost completely weathered to form a kaolinite, gibbsite and quartz dominated soil (Figures 11a - d). In zones C and D, no significant difference was observed in the soil minerals with changes in site quality.

The binding coefficient k derived from Langmuir isotherm is a measurement of the shape of an isotherm, where higher k values indicate increasingly nonlinear isotherms. In all the zones, k values in site quality I was higher and exhibited a wider range of variation than in site quality IV (Table 19; Figures 12a - o). The k values varied from 0.01 L mg^{-1} to 0.04 L mg^{-1} in zones A and B, 0.03 L mg^{-1} to 0.05 L mg^{-1} in zone C and from 0.01 L mg^{-1} to 0.02 L mg^{-1} in Zone D. The highest variation was observed in zones A and B and lowest in zone D. Zone C had the maximum k value of 0.05 L mg^{-1} in site quality I. The higher k values reflect the fact that sorption isotherms are more nonlinear in site qualities I and II and more linear in site quality IV. Curvature in the isotherm (high k) indicates sorption to high-affinity sites at low DOC concentrations, and the decrease in slope observed at higher DOC concentrations may indicate progression to lower affinity chemical and physical adsorption sites. Irrespective of the zones, Qmax for DOC absorption was found to be more in site quality IV compared to site quality I. For example, in zone A the Qmax values for site quality I and IV were found to be 1397 mg kg^{-1} and 3427 mg kg^{-1} respectively (approximately twice than that of site quality I). However, increases in Qmax of site quality IV over site quality 1/II was not that pronounced in zones C and D.

The changes in DOC adsorption pattern in the presence of anions (NO_3^-, SO_4^{2-}, PO_4^{3-}) and cations (Ca^{2+}, Mg^{2+}, Fe^{3+} and Al^{3+}) were evaluated (Figures 13a - d). The results indicate that anions were more efficient in improving the DOC adsorption in these soils than cations. In general, the adsorption of DOC varied in the presence of anions as $PO_4^{3-} > SO_4^{2-} > NO_3^-$ and for cations as $Ca^{2+} > Mg^{2+} > Al^{3+} > Fe^{3+}$. The results show that anions exert less competition for DOC adsorption in these soils.

a.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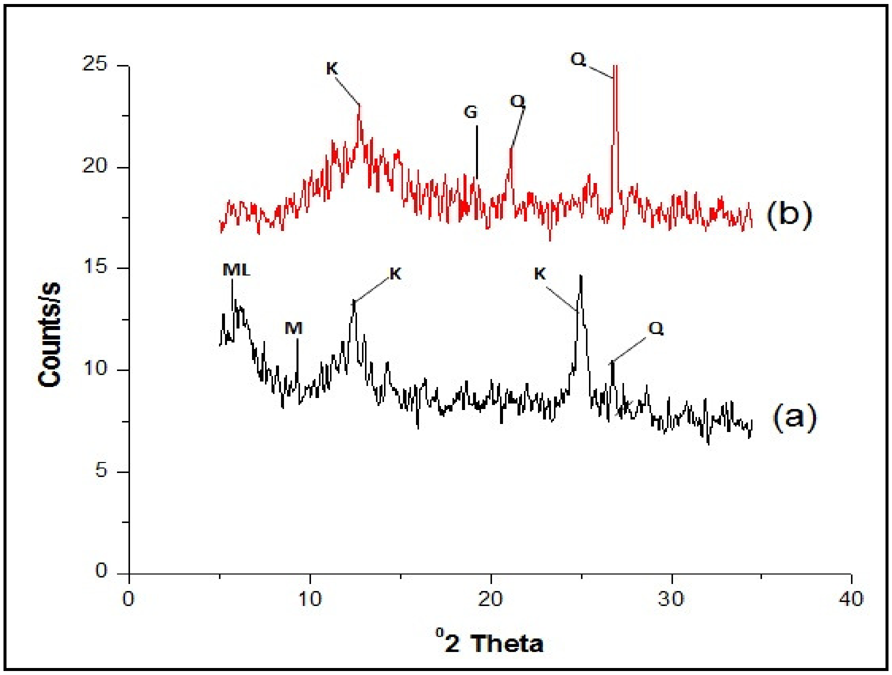
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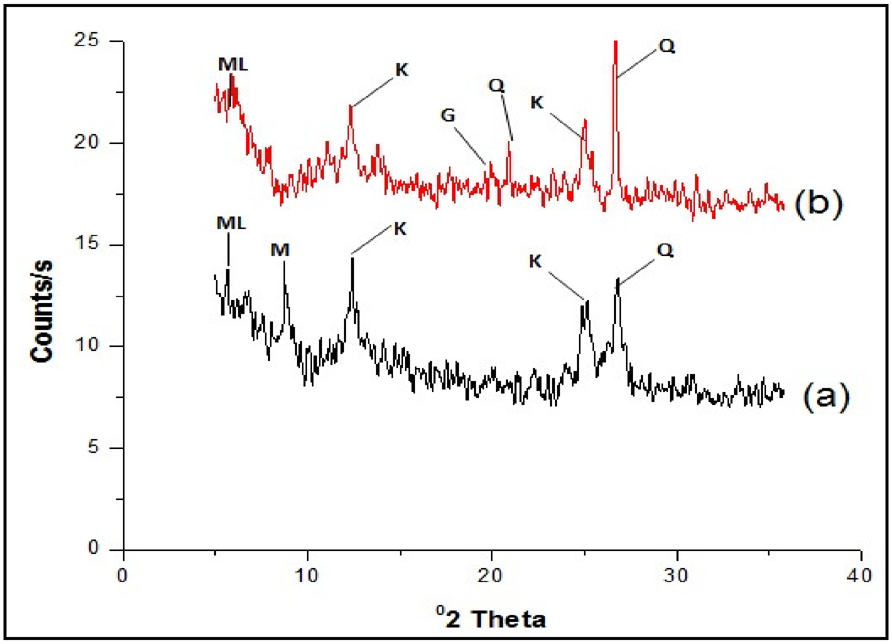
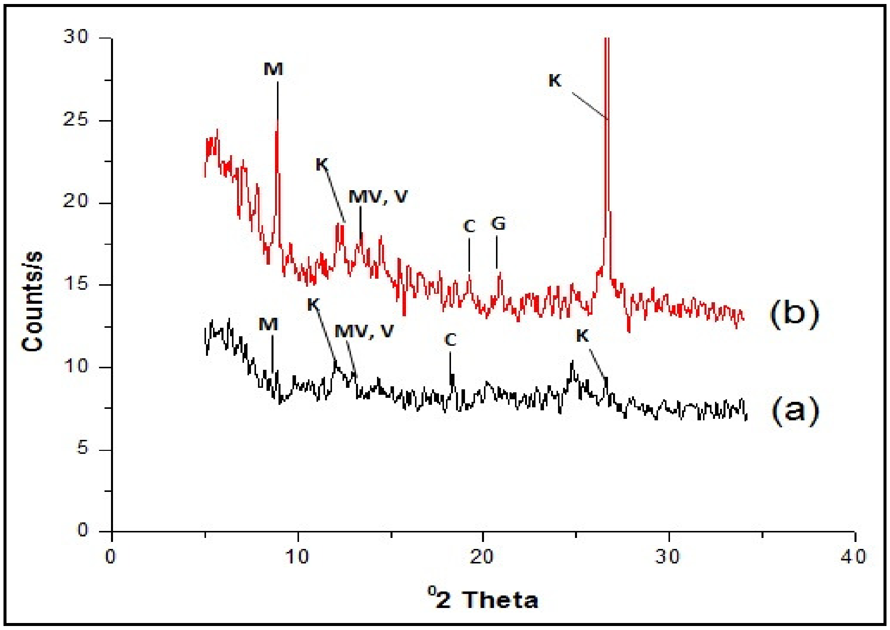
c.

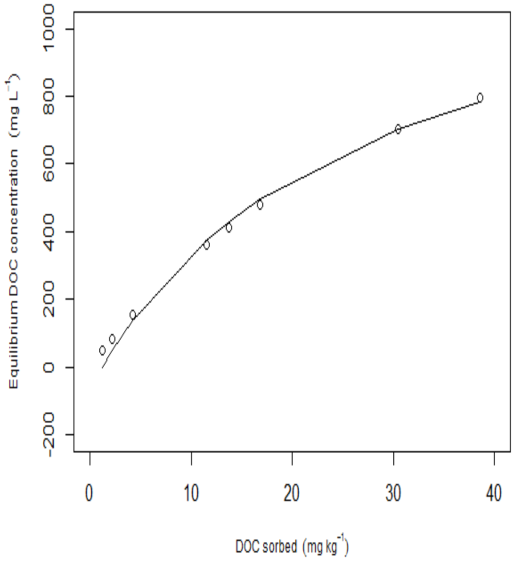


d.

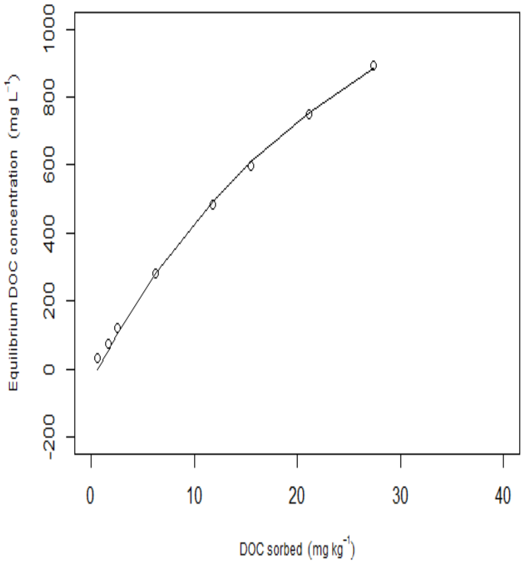


Figures 11a – d. X-ray diffraction spectra of clay minerals in (a) zone A (b) zone B (c) zone C (d) zone D

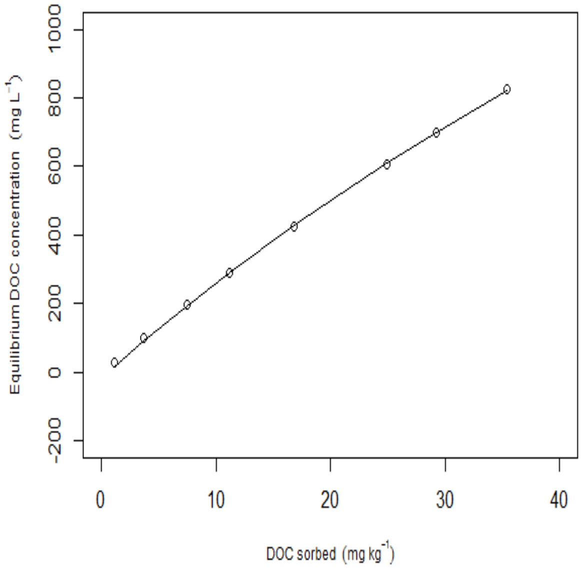
a. Zone A: Site quality I



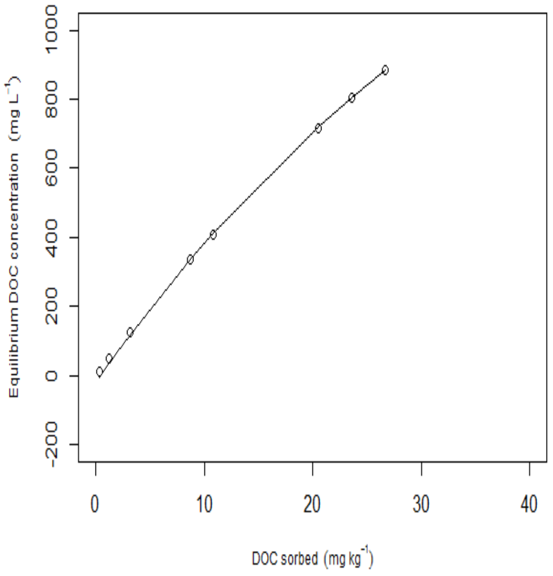
b. Zone A: Site quality II



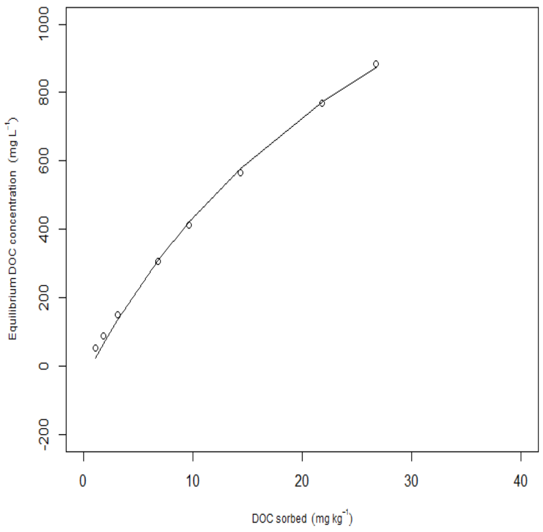
c. Zone A: Site quality III



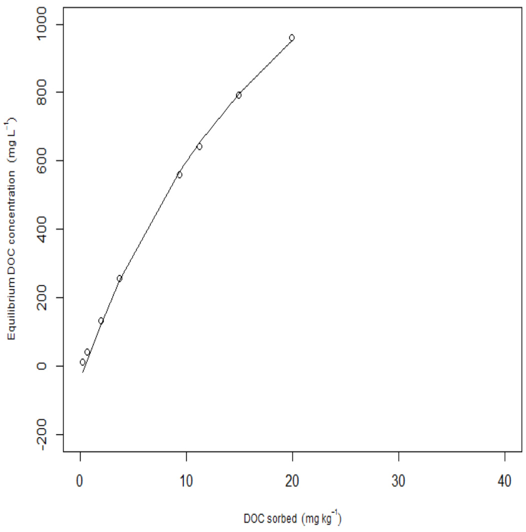
d. Zone A: Site quality IV



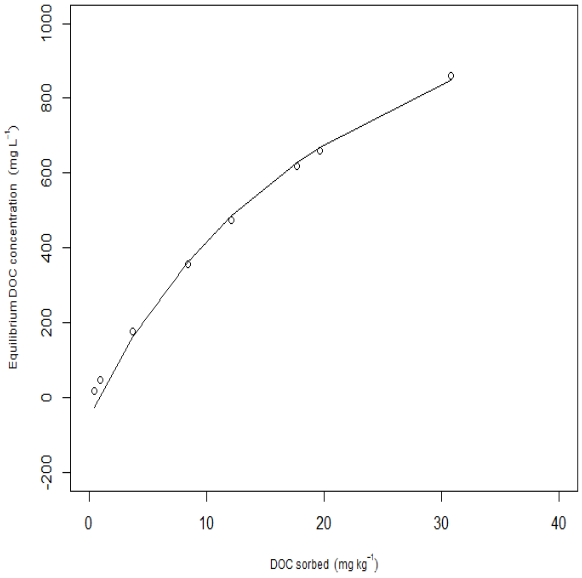
e. Zone B: Site quality I



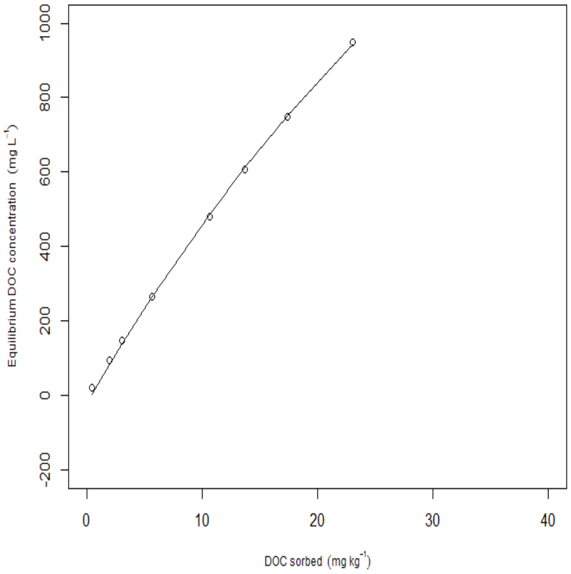
f. Zone B: Site quality II



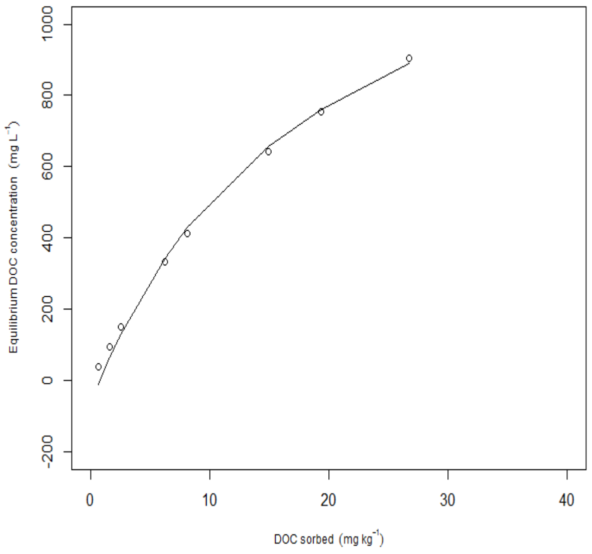
g. Zone B: Site quality III



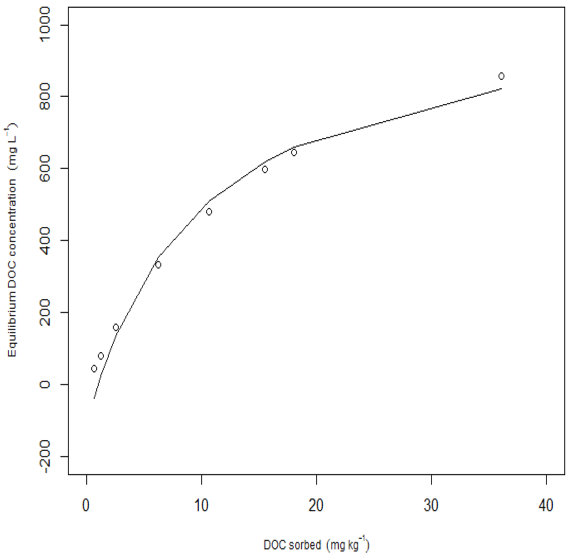
h. Zone B: Site quality IV



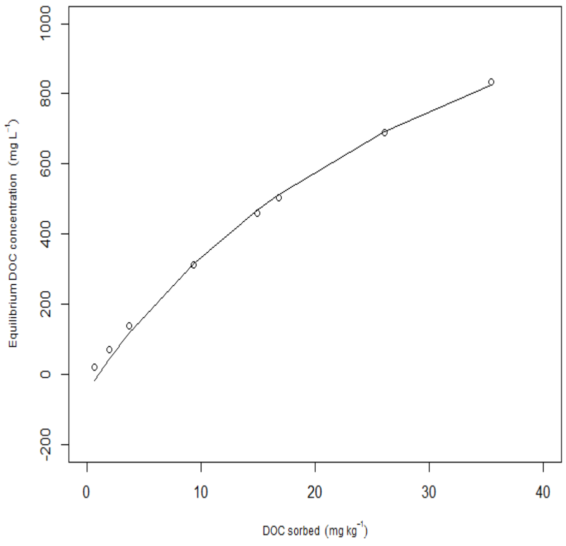
i. Zone C: Site quality I



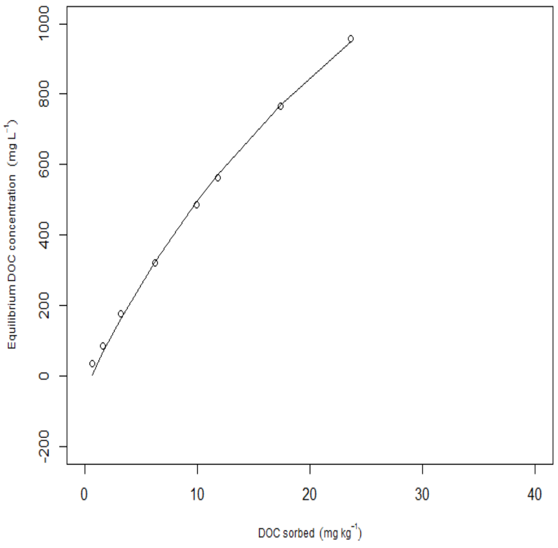
j. Zone C: Site quality II

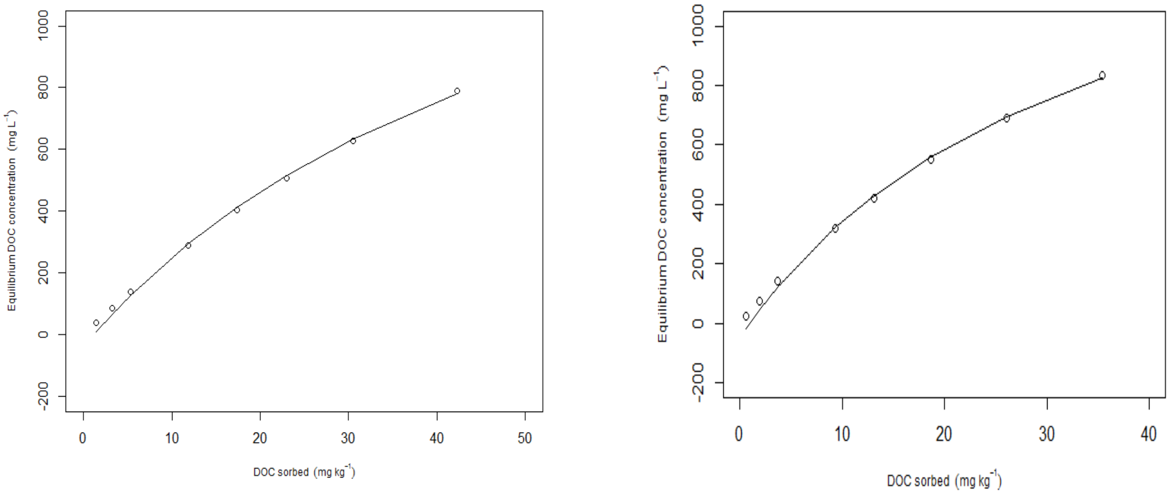


k. Zone C: Site quality III



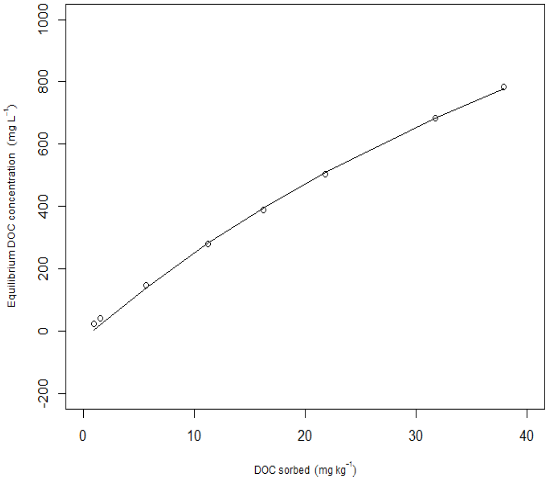
l. Zone C: Site quality IV





m. Zone D: Site quality II

n. Zone D: Site quality III



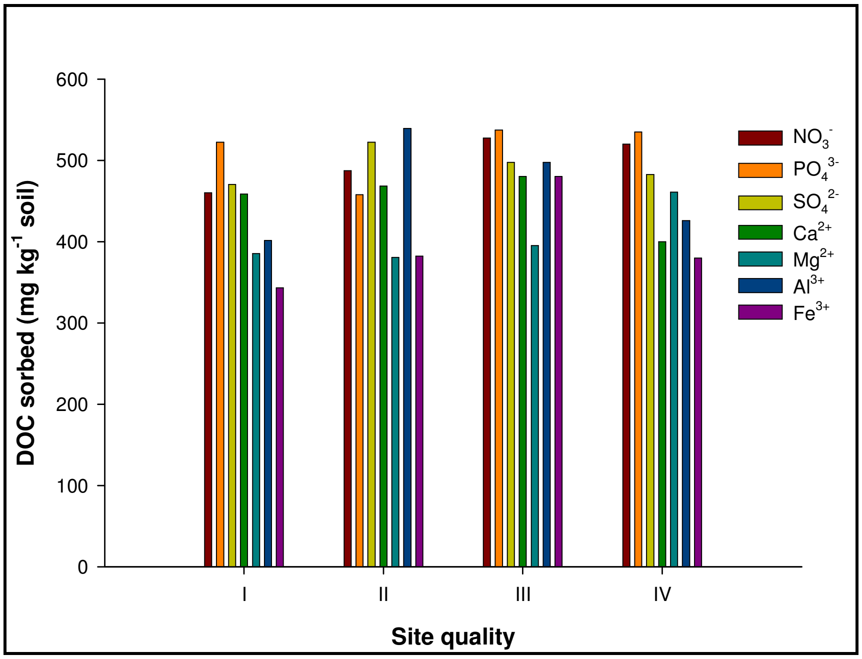
o. Zone D: Site quality IV

Figure 12a - o. Langmuir adsorption isotherm fits of carbon in teak soils of (a -d) zone A (e - h) zone B (i - l) zone C (m - o) zone D

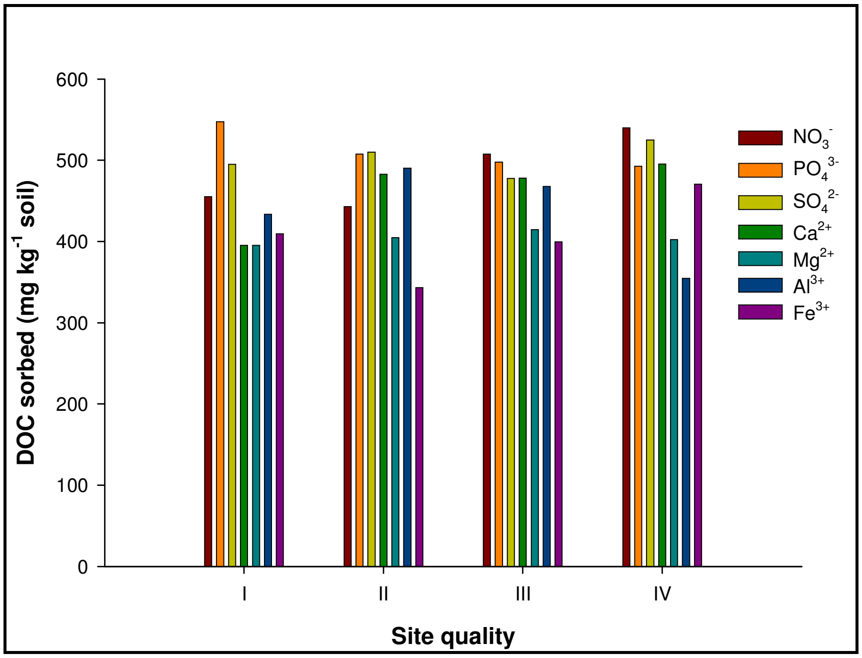
Table 19. Adsorption maxima (Qmax) and binding coefficient (k) for DOC adsorption on soil minerals as derived from Langmuir isotherm in different teak growing zones

Site quality	Qmax ($mg\ kg^{-1}$)	k ($L\ mg^{-1}$)
Zone - A		
I	1397	0.04
II	2077	0.03
III	4218	0.01
IV	3427	0.01
Zone - B		
I	1998	0.03
II	2229	0.04
III	1597	0.04
IV	4166	0.01
Zone - C		
I	1603	0.05
II	1174	0.10
III	1735	0.03
IV	2561	0.03
Zone - D		
II	1911	0.02
III	1684	0.03
IV	2524	0.01

a.


DOC sorbed (mg kg^{-1} soil)
600
500
400
300
200
100
0
I
II
III
IV
Site quality
NO_3^-
PO_4^{3-}
SO_4^{2-}
Ca^{2+}
Mg^{2+}
Al^{3+}
Fe^{3+}

b.


DOC sorbed (mg kg^{-1} soil)
600
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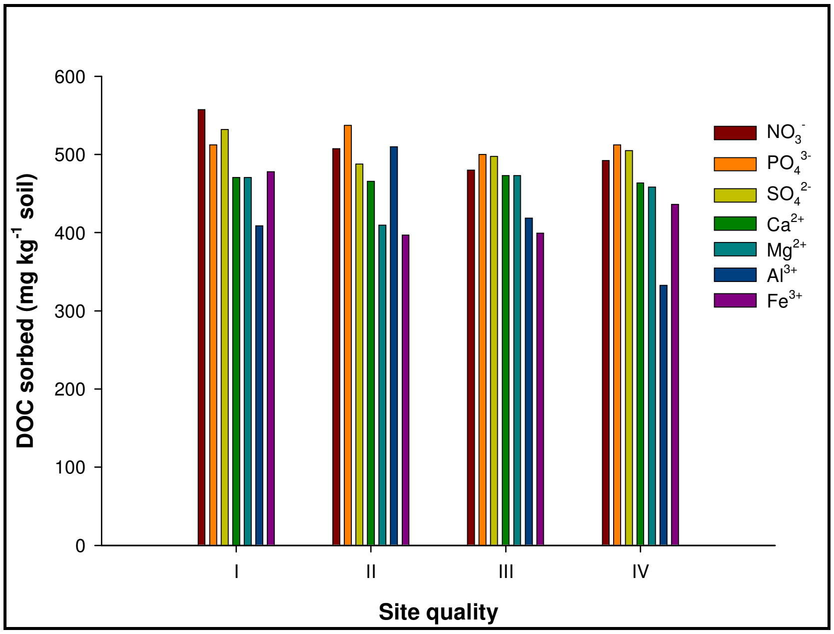
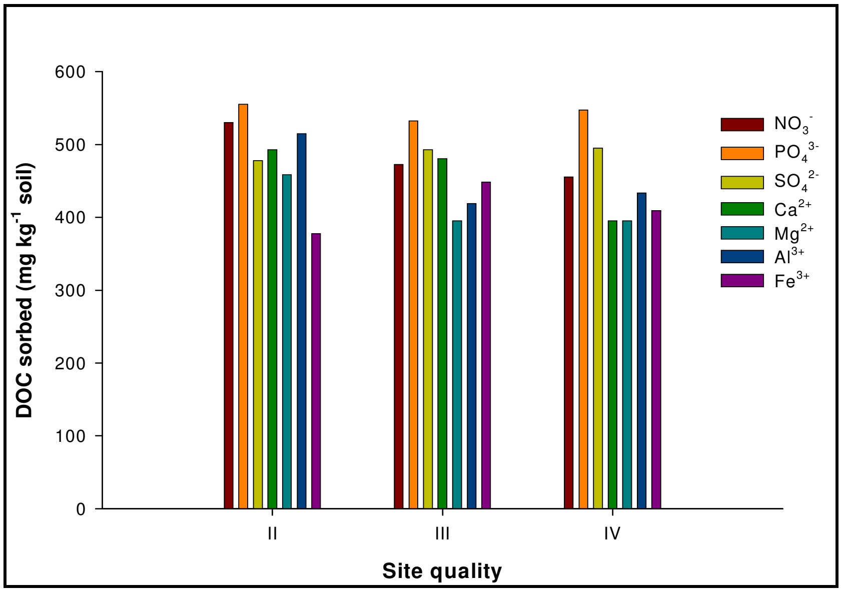
200
100
0
I
II
III
IV
Site quality
NO_3^-
PO_4^{3-}
SO_4^{2-}
Ca^{2+}
Mg^{2+}
Al^{3+}
Fe^{3+}

c.



d.



Figures 13a – d. Effect of ions on carbon adsorption in teak soils of (a) zone A (b) zone B (c) zone C (d) zone D

b. Thermal stability of SOC in teak plantations

The Ea of soil carbon decomposition was effectively modified by zones and site qualities (Table 20). In zone A and B, site quality IV had an edge over other site qualities in improving the Ea of SOC. The Ea values varied between 13.01 - 85.67 kJ mole^{-1} in different site qualities and between 36.10 - 73.19 kJ mole^{-1} in different zones. Results indicate that teak planted soils with higher passive carbon fractions generate a temperature insensitive process that enhance Ea and reduce the decomposition rate. Interaction of zone and site quality factors show that site quality IV in zone D maintained the highest Ea values of carbon decomposition. The correlation of soil parameters with Ea indicates a significant negative correlation of Ea with activity ratios of different ions in soil solution.

Table 20. Changes in activation energy (KJ mole^{-1}) of soil organic carbon decomposition with site quality in teak plantations of Kerala Western Ghats

Site Quality	Zone A	Zone B	Zone C	Zone D	Mean
I	13.85	9.75	15.43	--	13.01^{d}
II	32.43	27.78	30.40	30.15	30.19^{c}
III	43.94	19.50	62.83	80.22	51.62^{b}
IV	70.05	87.35	76.08	109.20	85.67^{a}
Mean	40.07^{C}	36.10^{C}	46.18^{B}	73.19^{A}	

Same capital letter X indicates no significant difference of carbon fraction at P<0.05 level in the different zones; same lowercase x stands for no significant difference of carbon fraction at P<0.05 level in different site qualities.

Table 21. Changes in temperature coefficient (Q_{10}) of soil organic carbon decomposition with site quality in teak plantations of Kerala Western Ghats

Site Quality	Zone A	Zone B	Zone C	Zone D	Mean
I	1.22	1.82	1.91	--	1.65^{b}
II	1.15	1.22	1.42	1.48	1.31^{c}
III	1.30	1.32	2.76	1.36	1.68^{b}
IV	1.29	2.44	4.15	1.61	2.36^{a}
Mean	1.23^{D}	1.70^{B}	2.56^{A}	1.48^{C}	

Same capital letter X indicates no significant difference of carbon fraction at P<0.05 level in the different zones; same lowercase x stands for no significant difference of carbon fraction at P<0.05 level in different site qualities.

Table 22. Correlation matrix of activation energy and Q_{10} with different soil physico – chemical parameters

	Ea	**Q_{10}**	**Clay**	**Silt**	**Sand**	**Fe**	**Mn**	**Mg**	**Ca**	**K**	**Na**	**Al**	**CEC**	**AR1**	**AR2**
Ea	1														
Q_{10}	.366*	1													
Clay	0.136	0.111	1												
Silt	-0.064	0.053	-0.144	1											
Sand	-0.066	-0.128	-.72**	-.58**	1										
Fe	-0.191	-.503**	-0.097	0.213	-0.06	1									
Mn	0.287	-0.069	-0.028	0.223	-0.13	0.085	1								
Mg	-0.213	-0.12	.471**	-0.198	-0.249	0.008	-0.152	1							
Ca	-0.242	-.401**	.378*	-0.221	-0.157	0.285	-0.066	.583**	1						
K	0.251	-0.19	0.132	-0.018	-0.096	-0.047	0.02	-0.154	-0.195	1					
Na	-0.17	-0.07	0.066	0.048	-0.088	.350*	.314*	0.127	.417**	-.417**	1				
Al	0.009	0.289	-0.029	-0.081	0.081	0.088	0.169	-0.196	0.002	-.357*	.619**	1			
CEC	-0.211	-.444**	.414**	-0.215	-0.19	.317*	-0.041	.593**	.984**	-0.033	.403**	-0.032	1		
AR1	.415**	0.163	-0.24	0.101	0.127	-0.153	-0.032	-.569**	-.733**	.645**	-.511**	-0.212	-.647**	1	
AR2	.409**	0.126	-0.201	0.087	0.104	-0.171	-0.075	-.523**	-.690**	.715**	-.569**	-0.293	-.594**	.984**	1

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

AR1 = $(Na^+ + K^+)/ (Ca^{2+} + Mg^{2+})^{0.5}$

AR2 = $(Na^+ + K^+)/ (Ca^{2+} + Mg^{2+})^{0.5} + (Fe^{3+} + Al^{3+})^{0.33}$

Equation 5 depicts that if rate of the reaction is completely temperature independent, the resulting Q_{10} will be 1.0 and the value increases with increasing thermal dependency of the reaction.Here we used Q_{10} as an indicator of temperature dependencies of carbon decomposition in soil and also to infer the reaction rate changes over a 10^{o}C range of temperature rise (Table 21). Q_{10} values were affected by site qualities with site quality IV (Q_{10} = 2.36) having a significantly higher sensitivity to temperature than site quality I (Q_{10} = 1.65).

Ea was found to be positively affected by Q_{10} values and ionic balances in soil (AR1 and AR2). Fe, Ca and CEC were found to have a negative influence on Q10 values of carbon decomposition in soils of teak plantations (Table 22). The results suggest that improving the net ionic equilibrium in soils may serve to enhance the Ea values of carbon decomposition. However, to counteract the effects of warming on carbon decomposition and subsequent loss, Ca management may serve as a good option. Though Fe can also counteract the thermal effects on decomposition, its concentration rise in the soils may lead to iron toxicity in plants at least in the early stages. The positive correlation between Ea and $Q_{10,}$ shows that even recalcitrant or passive carbon fractions in the soils of teak plantations can be highly thermal sensitive and undergo faster decomposition under conditions of warming.

3. Modelling soil organic carbon reserves in teak plantations of Kerala Western Ghats

a. Weather parameters

The study sites have March as the hottest month with an average monthly temperature of 29.76°C. The study area receives approximately 2779 mm rainfall, most of which is received during the south - west monsoon period June – August (Figures 14 a -b). The soils of the study site were sandy loam in texture.

b. Dynamics of soil organic carbon in teak ecosystem

Results of the Century modelling for soil organic carbon in teak is shown in Figure 15. It shows the trajectory of SOC through time for continuous teak cultivations in Kerala. The model efficiency was found to be 0.80 with RMSE values of 3.14. The R^2 values of 0.82 shows a reasonably good association between the observed and simulated values.

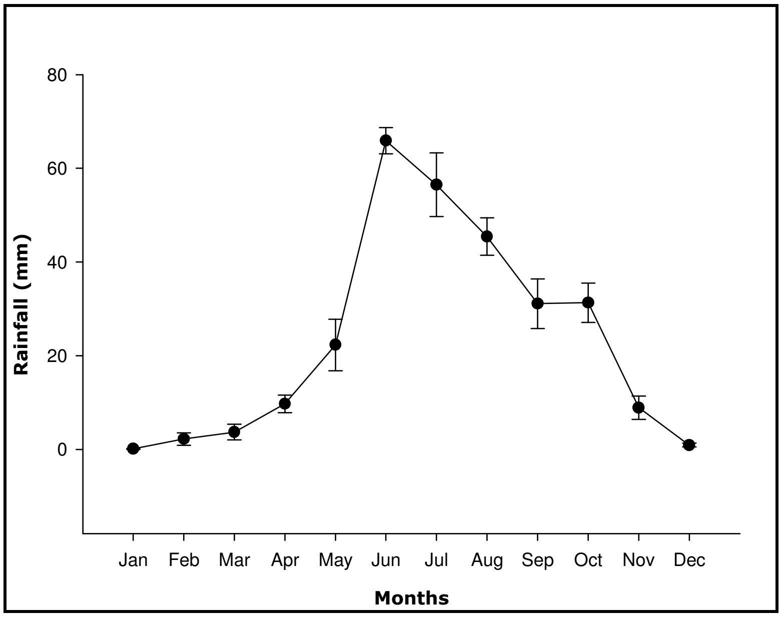


Figure 14 a. Mean monthly rainfall distribution in zone - B (2000 -12)

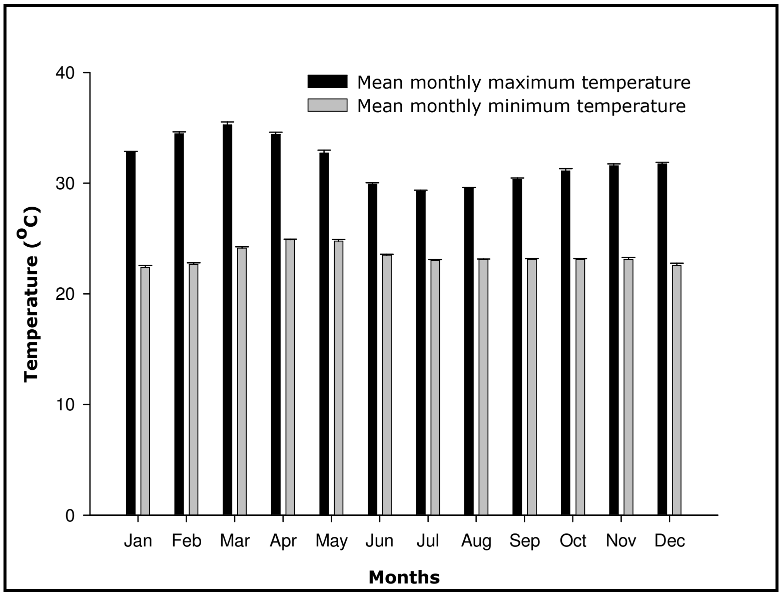


Figure 14 b. Mean monthly maximum and minimum air temperatures in zone - B (2000 -12)

Teak plantations are in general planted after clear felling existing forest stands and burning the residues. The model predicts a 50% reduction in SOC with each rotation. The values decreased from 60Mg/ha to 30 Mg/ ha at the end of the first rotation. At the start of the second rotation (age = 50 yrs), a further burning was induced to clear the land. The burning adds new organic carbon to the soil, especially in the slow pool, which however gets reduced within the first 5 -6 years.

The simulation experiment results are for zone - B wherein the surface layers of site quality I and IV were found to store nearly 51 Mg/ha and 32 Mg/ha of SOC, respectively. The simulation trends show that the carbon content of teak rotation nearly follows this trend. SOC being an indicator of land degradation, we can expect that the current practice of continuous teak rotation without adequate soil management will deplete the SOC by 50% with every subsequent rotation.

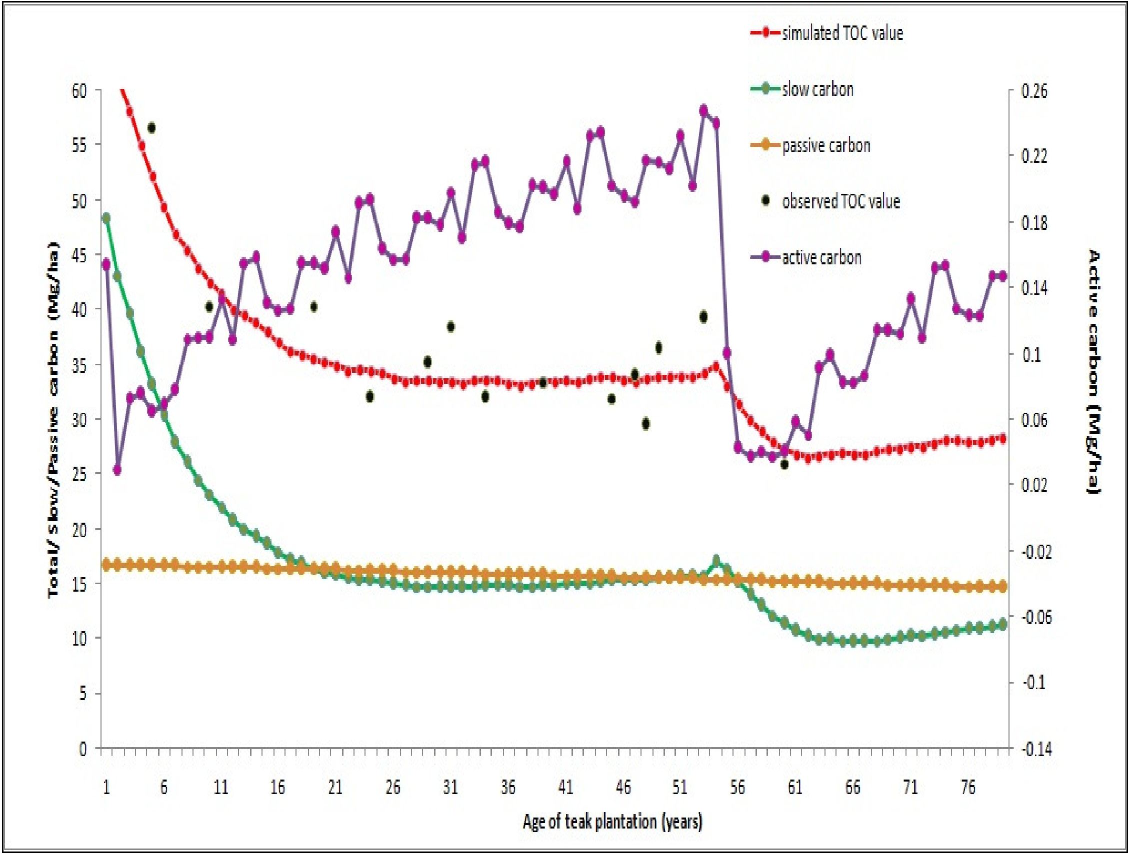


Figure 15. Changes in soil carbon pools with continuous teak rotations in Zone B as predicted by CENTURY soil carbon model.

The CENTURY model depicts a direct link between below ground structural, active carbon pool and slow carbon pool in soils. The slow and active pools in due course of time supplements the passive pool. Further, these linkages have a multiplier effects of temperature, moisture and cultivation practices (Figure 2).

Active carbon was found to show an increasing trend during the first 50 years (1st rotation) with the values improving from 45 kg/ ha to nearly 60kg/ha. There was a good tradeoff between active and slow carbon pool. As the passive carbon remained almost unaltered throughout the experiment (15 Mg/ha at start of the rotation and 14.5 Mg/ha after 2 rotations) and litter additions remain unchanged, the enhancements in active carbon pool can be attributed entirely to the conversions from slow pool.

The different projected temperature scenarios ranging from 2.5 to 6.5 ^{O}C (centennial projections) were used to evaluate the SOC turnover in teak plantations of Kerala. The year 1990 was considered as the base year and projections were done upto 2050 (Figures 16 - 19.). The results show that all scenarios predict on par SOC turnover. Scenario with a centennial increase of even 2.5 ^{O}C will lead to a SOC decline of 15 Mg/ha (33%) than the normal within 30 yrs (here: year 2020). The slope indicates that the carbon decomposition proceeds with an increasing trend till it stabilizes after 50 years at 20 Mg/ha after 50 years (here: 2040).

Active carbon was found to start at a much higher range (650 kg/ha) than the normal (14 kg/ha) under all temperature rise scenarios during the initial years (Figure 16 - 19). Figure 2 shows that active carbon pool is supplemented either by the belowground structural and metaboloic carbon or by the slow pools. Considering the structural and metabolic pools to remain unaltered, rapid increases in active pools can be attributed primarily to the conversion of slow carbon to active pool.

The slow to active conversion was found to occur only for a finite period (initial 25 - 30 years) and thereafter shows a sharp decline. The passive carbon pools were found more or less unaffected by warming indicating a balance between conversions and loss to these pools. The results indicate a situation wherein the slow pools are converted to active pools which are subsequently lost as carbondioxide. Moreover, the decreasing trend with an increasing slope for total organic carbon indicates that the rises in temperature may convert the plantations to a source of CO_2 feeding to the atmosphere.

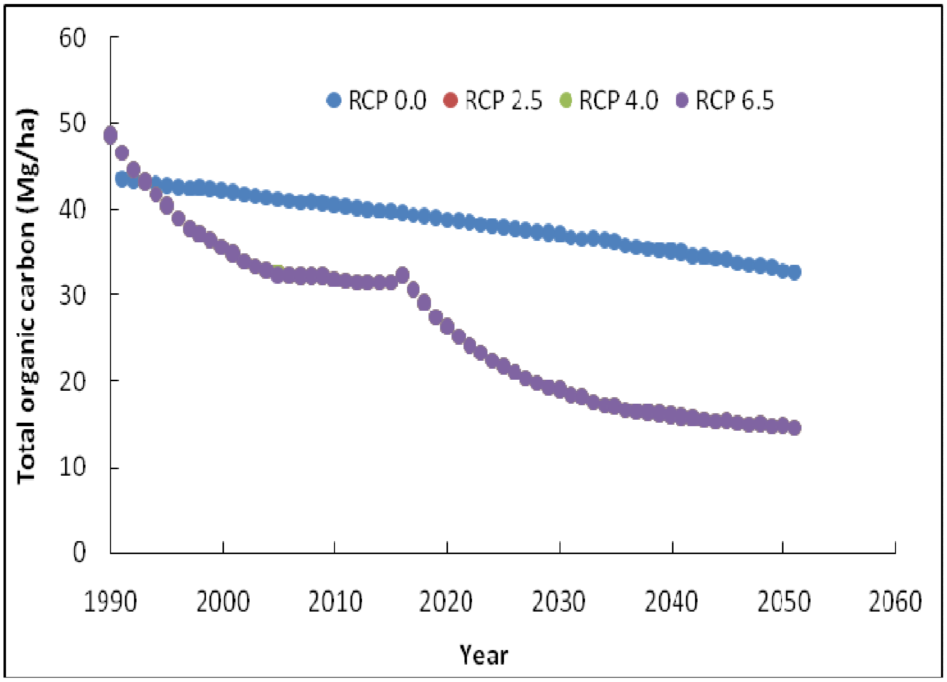


Figure 16. Changes in total organic carbon in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios

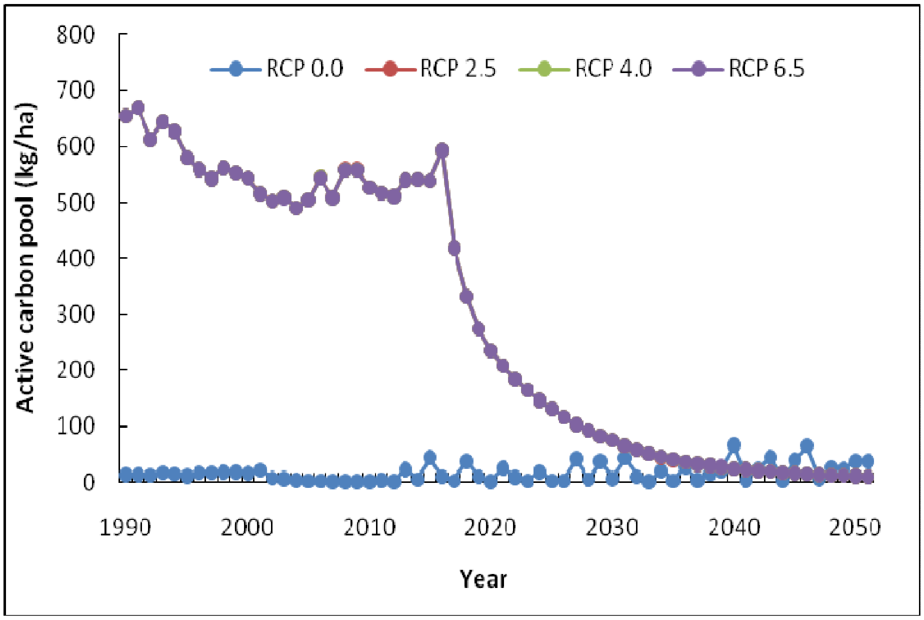


Figure 17. Changes in active organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios

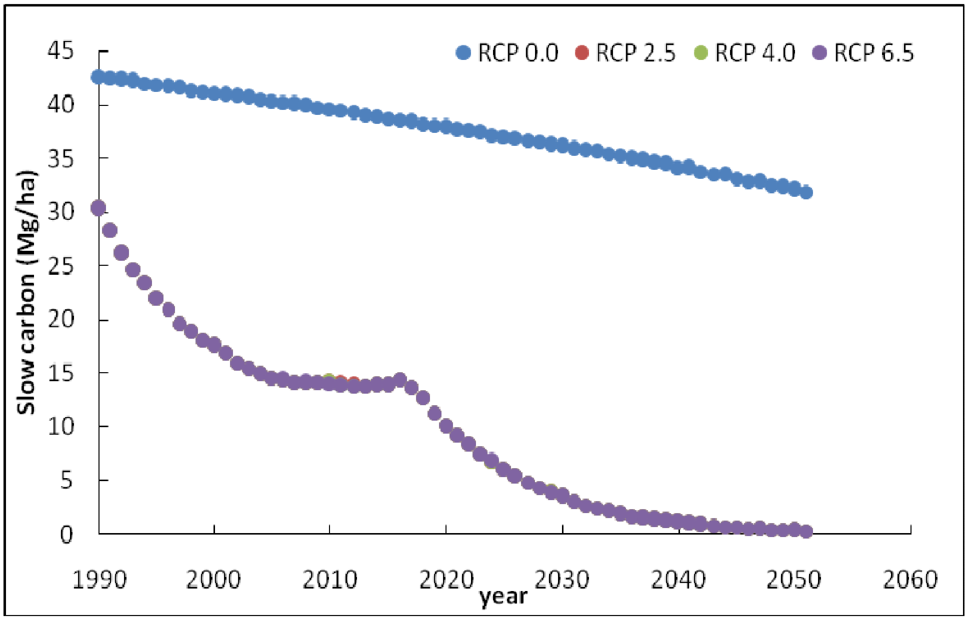


Figure 18. Changes in slow organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios

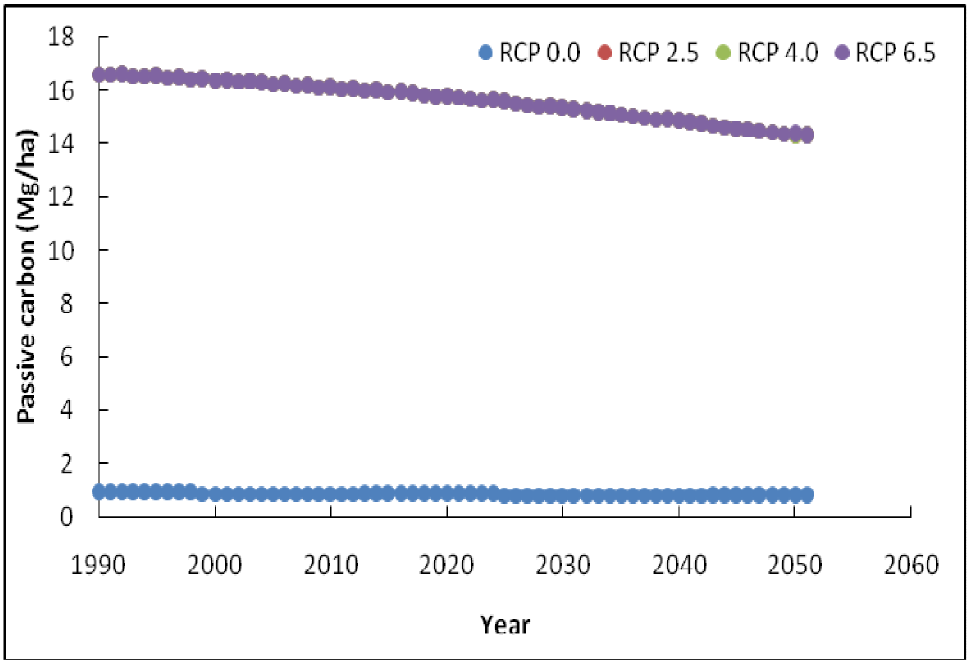


Figure 19. Changes in passive organic carbon pools in teak soils as predicted by CENTURY soil carbon model under different climate change scenarios

DISCUSSION

1. Soil carbon stocks and pools

A very high zone to zone variation in the carbon stocks was observed in the teak planted soils of Kerala Western Ghats. This variation could be due to the differences in soil, terrain and degradation effects. The selected zones represent an altitudinal gradient and accumulation of SOC along this gradient could also be attributed to the temperature/rainfall variations and pedogenic processes specific to each zone. Several earlier studies have reported that soil C stocks result from the balance of opposite C fluxes that are influenced by historical and anthropogenic factors such as past and present land use, natural or anthropogenic perturbations and biophysical factors such as temperature, precipitation, vegetation type and bedrock (Wardle, 1997; Bhatti *et al.,* 2002; Wardle *et al.,* 2003; Lal, 2005). The highest amount of carbon stocks was found in zone - D (12.10 kg m^{-2}) and lowest in Zone B. Zone - D, lying in the higher altitudes experiences a relatively lesser mean annual temperature and thereby effectively resist carbon decomposition and loss. On the other hand, Zone - B comprises of central midland laterites and experiences a hot humid tropical climate. The low activity clays along with conducive climate for carbon decomposition effectively reduces the carbon stocks in these soils. The negative correlation of C stocks with mean annual temperatures have also been reported by Kane and Vogel (2009) and Follett *et al.* (2012).

There was higher proportion of C storage in subsurface layers with active root growth. Higher carbon stocks in the subsoil horizons might result from both higher carbon inputs to the subsoil and higher residence time of SOM. The major sources of organic carbon input into subsoils are thought to be plant roots, root exudates, bioturbation and dissolved organic matter leached from upper horizons (Rumpel and Kögel-Knabner, 2011). Besides, recent studies have provided evidence that stabilization of C in the soil was driven by its accessibility rather than by its chemical nature (Fontaine *et al.,* 2007; Dungait *et al.,* 2012; Rumpel and Kögel-Knabner, 2011). As a consequence, variables that lead to accumulation of C deeper in the soil profile, where physicochemical conditions are prone to C stabilization, might also have a positive impact on its residence time in the soil. This study thus proves that that superficial sampling depths might lead to soil carbon stock underestimations in the managed teak plantations of Western Ghats.

Mean residence time (MRT) of active, slow, and passive SOC is about 1–5, 20–40, and 200–1500 years, respectively (Parton *et al.,* 1987), indicating the increasing stability from active to passive SOC. Site qualities - 1 and II were found to have significantly higher active and slow carbon than site quality - IV. The active fractions of soil organic matter generally consist of cellular biopolymers such as soluble sugars, carbohydrates, amino acids, peptides, amino sugars and lipids which has rapid turnover rates and are sensitive to alterations in landuse (Belay-Tedla *et al.,* 2009). On oxidation, this pool of SOC adds to the loading of CO_2 to the atmosphere to accentuate global warming. At the same time, this pool of SOC fuels the soil food web and therefore greatly influences nutrient cycling that helps in maintaining soil quality and its productivity (Chan *et al.* 2001; Verma *et al.,* 2010; Sandeep *et al.,* 2016). On the other hand, passive soil organic carbon fraction is composed of organic materials that are highly resistant to microbial decomposition and hardly serves as a good indicator for assessing soil quality and productivity (Weil *et al.,* 2003; Sherrod *et al.,* 2005; Majumder *et al.,* 2008).

Site deterioration in teak plantations, especially under continuous rotation, have been attributed to the lack of understorey vegetation that leaves the soil exposed and vulnerable to erosion (Champion, 1932; Pandey and Brown, 2000), allelopathic properties of teak leaves that reduce understorey growth and microbial diversity (Healey and Gara, 2003) and frequent fires that reduce regeneration, leaf cover (Laurie and Griffith, 1942; Bell, 1973) and organic carbon (Balagopalan and Alexander, 1985). In site quality - I and II, the adverse factors affecting soil quality are at a minimum and hence a diverse mix in the quality and complexity of organic matter input to soils detritus originating from leaf, root and mycorrhizal biomass (Hagen-Thorn *et al.,* 2004; Lai *et al.,* 2015) was observed. Such sites also have a rich diversity of soil invertebrate and microbial populations (Hobbie *et al*., 2006; Lynch *et al*., 2012). The highly complex and heterogeneous organic residues found in the SOM of better site qualities along with the microbial population help maintain high level of active and slow carbon pools in these soils (Sollins *et al*., 1996). In deteriorated sites (site quality III and IV) teak leaf litter and root residues remain the only major organic detritus and earlier reports have indicated that teak leaves add less SOM to soil compared with other broad leaved species (Sankaran, 1993).

No significant difference was found in the passive SOC concentration associated with different zones or site qualities. Also in the present study, significant positive correlation was found between active and slow carbon pools whereas these pools were not found to influence the recalcitrant passive pool. This shows that the recalcitrant pool acts more or less independently in the teak plantations of humid tropics and comprises of only resistant carbon components and no decomposable fraction. This is contrary to the previous studies wherein a strong relationship is observed between the non-labile and labile carbon and suggests that the passive soil carbon fractions comprise of both decomposable and resistant components (Lowe, 1978; Conteh, 1998; Zhao *et al*., 2012). It has been established that the breakdown of added residues and of SOM are affected by their physical and chemical characteristics, as well as by temperature, moisture, nutrition, and other factors that affect biological activity directly. Soil organic carbon can be physically protected by its inherent physical integrity or by soil agreggates by way of providing a barrier to the decomposing enzymes (Oades, 1995; Craswell and Lefroy, 2001: Dungait *et al*., 2012; Kellner *et al*., 2014) Studies by Kiem *et al*. (2000) compared the chemical structure of fertile and C-depleted soils to prove that structural stability is one of the major reasons for recalcitrance of SOM in soil. The structural stability may be on account of molecular recalcitrance to decomposition or by way of high levels of organomineral associations (Zou *et al*., 2005). Even though the studied teak plantations exhibited a wide range of soil types, the presence of almost equal amounts of passive carbon in them show that the recalcitrance of carbon in these soils is mainly by way of their chemical structure rather than soil enabled protection against decomposition. The high condensation of the humic acid substances from teak plantations of Kerala Western Ghats was further supported by the E4/E6 values and A type humic categorization in Kumada’s classification scheme. Being grown in different soils and microclimatic zones, it is the chemical structure promoted recalcitrance which remains common as evidenced from the above results. As there was no significant difference in the passive SOC concentration associated with different zones or site qualities, it should be concluded that a major reason for almost similar high amounts of recalcitrant carbon in the teak growing soils of Kerala Western Ghats is due to the inherent chemical structure of the humic acids formed in the humid tropical conditions.

Zone - D with a mean annual temperature less than the other zones had the minimum decomposition and maximum WBC. On the other hand, Zone - A and B experiences the typical humid tropical climate, favours rapid decomposition and subsequent carbon loss. Climatic influences on WBC has been established in a number of studies (Lal, 2005; Kane and Vogel, 2009; Follett *et al*., 2012).

Soil microbial activity can be greatly affected by many factors such as soil moisture (Wan *et al*., 2007), initial soil nutrient conditions (Xu *et al*., 2010), labile organic carbon, nitrogen pools (Schimel *et al*., 2007) and plant communities (Bai *et al*., 2010). Most experiments have shown that warming can increase soil microbial activities (Luo, 2007; Bardgett *et al*., 2008), but a few studies report that warming can decrease or have no effect on microbial activities (Zhang *et al*., 2005; Allison and Treseder, 2008; Liu *et al*., 2009). The significantly higher MBC content in zone - A and B with hot humid climate (MAT ~ > 27°C and mean precipitation ~ 2500 mm) than in zone - C and D with lesser MAT supports the former hypotheses that warming promotes microbial activities in the teak plantations of Kerala Western Ghats. Warming reportedly increase the soil labile organic C and microbial biomass in forested ecosystems (Belay-Tedla *et al*., 2009). As labile organic C and N pools are accessible to soil microorganisms, they can function as an important short-term reservoir of nutrients for microbes and plants, hence supports a healthy microbial population in warmer climate with adequate soil moisture. As soil microorganisms mediate C and N cycling, microbial activities are responsible for decomposition of soil organic C (Conant *et al*., 2008; Davidson and Janssens, 2006). The relatively high microbial activity and subsequent C decomposition in zone - A and B can be placed responsible for the lower amounts of WBC in these soils. With respect to polysaccharides, zones didn’t have any significant influence whereas it was found to vary with site qualities. The FTIR spectra also indicates that humic acids produced in the teak planted soils have varying degrees of polysaccharide side chains in the basic structure.

The chemical composition of the humic acids was obtained through FT-IR analysis. The FTIR spectra show that humic acids from teak plantations are a mixture of many molecules predominantly aromatic with phenolic, polysaccharide like compounds and amine substituents, linked together. The existence of one or more aromatic rings in the humic acid structure was confirmed from the C - H and C=C-C ring-related vibrations (above 3000 cm^{-1}). The results were similar to the observations of Anderson and Schoenau (1993) who reported that HA fraction is a biologically resistant fraction of soil organic matter with a core of strongly condensed aromatic structures surrounded by aliphatic side chain components. A prominent absorption band found at 3415 - 3380 cm^{-1} in all the analysed humic acid samples was assigned to non-hydrogen-bonded hydroxyl group. Hydroxyl group is usually isolated – either because of steric hindrance effects or because the sample is in the vapour state or in a dilute solution of a nonpolar solvent – the band is characteristically narrow, and is observed at the natural, higher frequency. Humic acids from zones A and B gave absorption bands at 2935 and 2860 cm^{-1} attributed to aliphatic methylene groups. Earlier studies have reported that aliphatic peaks are characterstic of humic acids and presence of these functional groups effectively keeps the SOM in a labile state (Kaiser and Ellerbrock, 2005; Simon 2007). A higher content of C=O groups (high intensity spectral bands at 1740 - 1690 cm^{-1}) was obtained in humic acids from all the zones and the intensity of the C=O band was relatively more in humic acids from site quality - IV than site quality - I. Though humic acids from site quality - I also produced bands in this region, they were of a broad nature. That could be explained by the fact that the composition of the organic inputs varies in different site qualities with site quality - IV receiving only teak litter and root residues as primary organic matter (Gunzler and Bock, 1990; Ellerbrock *et al.*, 1999, 2001; Kaiser and Ellerbro, 2005). Since content of carboxylic groups is an indication of intensity of the humification process, the higher amounts of C=O contents in site quality - IV indicates that OM in these soils has undergone a rigorous humification process (Stott and Martin, 1990; Zsolnay, 1996). Also the higher C=O content would be expected to enhance the interaction of SOM with predominant polyvalent cations such as Fe^{3+} and Mn^{4+} in soils leading to the formation of organo-mineral complexes (Stevenson, 1994) that render them recalcitrant.

The FTIR spectra indicate the presence of large amounts of polysaccharides in the humic acids extracted from all zones and a decrease in intensity was observed with site quality. The polysaccharides in the humic acid moiety is primarly of microbial and plant origin which can be either structural polysaccharides such as cellulose or storage polysaccharides like starch (Leifeld *et al*. 2002). The maintenance of higher amounts of polysaccharides in site quality -I can have multitude of effects on soil health by way of forming soil agreggates and reduced SOM decomposition, non-nutritive OM carryover effects by enhancing soil-water retention as polysaccharides are strongly hydrophilic in nature and enhance nutrient bioavailability by micronutrient complexing or microbial stimulation (Lowe 1978; Ros *et al*. 2006).

2. Mineral - organic interactions and thermal stability of soil organic carbon

a. Mineral – organic interaction studies

The mineralogical make up of the soil plays a major role in determining the carbon adsorption in soil. This is because different types of clay (i.e. 1:1 and 2:1 clays) have substantial differences in CEC and specific surface (Greenland, 1965) and should, consequently, have different capacities to adsorb organic materials. The higher temperature and moisture regimes in tropical regions induce faster decomposition and usually contribute to the lower stabilization of C by the 1:1 clays. Mineralogical analysis of soils from different site qualities show that as the soils degrade from site quality I to site quality IV, 2:1 minerals are almost completely weathered to form kaolinite, Fe and Al-oxides, gibbsite and quartz dominated soil. Though the 1: 1 minerals have lesser number of active DOC adsorption sites than 2:1 minerals, the Fe and Al oxides can co-flocculate SOM and consequently stabilize it. The higher concentration of sesquioxides in site quality IV soils would be responsible for higher Qmax values in these sites when compared to site quality I. Site quality I with its predominance of 2:1 clays provides large surface area and active sites for strong DOC adsorption as indicated by higher k values in these soils.

Recent studies have proposed a saturation limit for SOC due to silt + clay protection (Hassink, 1996.,1997), soil structure (physical protection within aggregates), and the biochemical complexity of the organic compounds (Baldock and Skjemstad, 2000). Six *et al*. (2002) proposed a whole-soil C saturation limit with respect to soil C input and found that an asymptotic curve fit the SOC content and C input level data better than a linear relationship. Accordingly, it was suggested that the smaller increase in SOC content with increased C input level was due to the decreased capacity of a high C soil to store added C. This conceptual model implies that the farther a soil is from saturation (i.e., the greater the saturation deficit), the greater its capacity and efficiency to sequester added C, whereas a soil approaching saturation will accumulate a smaller amount of SOC at a slower rate and efficiency (Hassink and Whitmore, 1997). Site quality IV being lower in carbon content (farther from saturation level) have a greater capacity to sequester added C than the soils of site quality I that is near to saturation. In short, the higher Qmax values in site quality IV soils than site quality I can be attributed to co-flocculation of SOM by Fe and Al sesquioxides and lower inherent carbon content farther away from its saturation capacity. However, the low binding coefficient values for these soils indicate that carbon is retained very weakly by these soils and can be lost by decomposition.

Addition of DOC to acidic soils results in mobilization of Al and Fe. Presumably, DOC extracted from organic material is under saturated with respect to Al and Fe. Thus, when added to soil material, DOC may form soluble complexes with these metals and lead to increasing solubilization (Dahlgren and Marrett, 1991). The increasing concentration of Fe and Al in the soil solution effectively precipitates a portion of the added PO_4^{3-} making them unavailable to block the active DOC adsorption sites in colloids. SO_4^{2-} and NO_3^- don't have such complexation mechanisms and hence block the active adsorption sites thereby reducing DOC retention in soil colloids.

Among the cations, Ca^{2+} was found to be most effective in improving DOC concentration in soil. In acidic soils, divalent cations are physically adsorbed into the interface as counter ions to form an outer-sphere complex $=SiO^-$ ……M^{2+} (Tadros and Lyklema, 1969). This process helps divalent cations to form a bridge between the negative charge sites on silica surfaces and the negative charge of organic molecules (Goyne *et al*., 2005; Pils and Laird, 2007). However Ca^{2+} addition will increase the soil pH which may negatively influence the adsorption of DOC on colloids. Studies by Feng *et al.* (2005) have shown that the primary mechanism for DOC sorption onto clays is through pH-dependent, electrostatic interactions involving anion exchange. As the pH increases, clays and variably charged mineral surfaces (Fe and Al oxides) become less positive and aqueous species become more negative, both of which tend to minimize sorption via ligand and anion exchange (Jardine *et al*., 1989; Gu *et al*., 1994). This may be a reason for lower adsorption potential of Ca^{2+} with respect to the studied anions.

b. Thermal stability of SOC in teak plantations

$Q_{10,}$ which explains the change in reaction rate over a 10° C temperature rise, was used along with activation energy to explain the intrinsic temperature sensitivity of SOC decomposition in teak systems. Both Ea and Q_{10} values were significantly higher in site quality IV thereby giving a clear indication of temperature sensitivity of recalcitrant C pools in teak soils. In site quality I, the activation energy being low, reaction occurs faster even at lower temperatures leaving relatively lesser fraction of molecules with sufficient energy to react at higher temperatures, and consequently, the Q_{10} value decreases. Similar were the observations of Davidson *et al*. (2006) and Sandeep and

Manjaiah (2014) that relative rate of decomposition of soil organic matter with low activation energy may be less sensitive to temperature.

Q_{10} values had a significant negative correlation with Ca, CEC and Fe. Q_{10} values decrease when there is an effective shielding of SOC from decomposition forces. Calcium promotes soil aggregation and thereby offers a physical barrier to carbon decomposition. Calcium content being comparatively higher in site qualities I to III restricts decomposition even at higher temperatures, hence the lower Q_{10} values. Minerals with larger CEC provide larger SSAs and usually bind carbon more strongly against decomposition. Such minerals were found to be less in site quality IV, hence incapable of arresting SOC decomposition at higher temperatures. Fe and Al oxides abundant in acidic soils are inhabited by single coordinated hydroxyl groups (Kögel-Knabner *et al*., 2008) and provide abundant reactive surface sites onto which OC can be adsorbed. The soil chemical analyses show that Fe content and CEC were at par in site qualities 1 and IV. Hence these factors cannot be considered as major parameters in determining Q_{10} in these soils. In other words improving the Ca content in soils will be one of the viable carbon management options in teak growing soils of Kerala Western Ghats. In general, though site quality IV maintains a higher Ea of SOC decomposition, their Q_{10} values indicate that they are highly vulnerable to decomposition at higher temperatures.

Moreover, Fe and Al oxides are suggested to be stronger stabilizers for SOC than smectites and kaolinites in most acid soils (Chorover and Amistadi, 2001). The significance of Fe and Al oxides in the persistence of SOC has partly been attributed to their physicochemical properties: (1) such minerals provide dense hydroxyl sites that allow organic acids to be strongly and efficiently adsorbed by mineral surfaces to form associations via co-precipitation (Lalonde *et al*. 2012) or ligand exchange, which has been proposed as one of the energetically strongest associations between SOC and mineral surfaces (Eusterhues *et al*., 2005, Kleber *et al*., 2005, Mikutta *et al*., 2006, Kang and Xing, 2007; Kang and Xing, 2008), (2) micropores (<2 nm) and small mesopores (2–10 nm) of Fe and Al oxides can offer extra sorptive sites for SOC and increase reactivity (Kaiser and Guggenberger, 2003). The above mentioned mechanisms of Fe/Al in the given mineral matrix shield OC against microbial attack and prevent carbon decomposition with temperature rise.

3. Modelling soil organic carbon reserves in teak plantations of Kerala Western Ghats

Soil organic carbon comprise approximately 2/3rd of terrestrial carbon storage. It has recently been suggested that soil carbon may play important roles as source (Houghton *et al*., 1989; Schimel *et al*., 1990; Townsend *et al*., 1992] or sink (Tans *et al*., 1990; Harrison *et al*., 1993) of carbon in response to changing climate and atmospheric CO_2. Soil organic matter simulation in areas under long term use provides an important tool to test future scenarios, enabling the adoption of more impressive management of environment. The purposes of the present objective were: a) to simulate, with the Century model, the impacts of long rotation continuous rotations on soil organic matter, b) to validate the Century model for teak soils of humid tropical regions by comparing the simulated values with those measured in the field and c) to analyze the carbon turnover in these plantations under projected climate change scenarios.

The evaluation of the Century model using the values from zone B gives an indication of the performance of the Century model. Zone B soil has a sandy loam texture and drain freely. Century appeared to model changes in SOC successfully in the teak planted soils as indicated by a model efficiency of 0.80, RMSE values of 3.14 and R^2 values of 0.82. These results strengthen faith in the capacity of Century model to properly simulate the TOC stocks in tropical soils, corroborating with the results of other projects that were also done in the tropical region (Liang *et al*., 1996; Leite *et al*., 2004a; 2004b).

From the values obtained by the simulation in the managed teak plantations, the total organic carbon and their respective pools (active, slow and passive) may be seen in Figure 15. Due to the deforestation and subsequent burning just before raising a fresh teak plantation, the TOC and their respective pools (active and slow) increased considerably during the initial stages, however, after a few years these stocks declined rapidly. It is an expected behavior (Stevenson, 1994), because the burning process after deforestation/ clear felling leaves much plant material from the native vegetation thereby increasing mainly the active and slow compartment of the TOC. However, the decline in TOC and other pools of carbon with rotation age indicates a degradation trend for the soil. Active carbon maintained at a high level during the first rotation showed a rapid decline in the second rotation. During the clear felling of first rotation, there is an intense soil disturbance and subsequent burning causes the plant material to be lost as

CO_2. Active carbon being the most sensitive fraction among the different pools gets depleted rapidly under such management strategies (Parton *et al*., 1987).

The different predicted temperature scenarios project a similar trend for carbon turnover. The trends show that there is rapid conversion of slow to active pool during warming. The decline in TOC along with this conversion points to the fact that the reaction is a forward one with the final product being CO_2. Thus warming can have an adverse effect on teak ecosystem health by way of depleting its carbon content and effectively converting it into a carbon source rather than a sink. The increased conversion of slow to active pool to gaseous CO_2 with temperature indicates that the microflora can enzymatically acclimatize to decompose slow SOC at higher temperatures in these soils (Boddy *et al*., 2008; Allison *et al*., 2010). Such increased depolymerization of complex organic molecules in the slow pool with warming can also be due to higher activity of existing enzymes or greater production of enzymes responsible for decomposition reactions. The results are in confirmation with earlier works (Luo *et al.,* 2001; Allison *et al.,* 2010; Sihi *et al.,* 2016) using microbial enzyme models where microbial acclimatization and increases in microbial biomass and degradative enzyme activity were attributed as key reasons for ephemeral increases in soil respiration with warming. However, the discontinuance of the trend after 25 – 30 years indicates that this conversion gets reverted once the slow carbon pool reaches a critical minimum. The low activity clayey conditions (1:1 clays) along with high sesquioxide contents (Fe- and Al-oxides being strong flocculants) present in the humid tropical soils can reduce further the available surface for adsorption of SOM and enhance carbon losses with warming (Six *et al.,* 2002). Further, the low activation energies of the active carbon make decomposition easy, keeping this pool at low levels (Stevenson, 1994; Six *et al.,* 2002).

Passive carbon was found to be unaffected by the rotation age. With temperature rise, two definite trends were obtained for this fraction of carbon: there was 14 -15 times higher concentration of this pool and it was found to follow a steady trend throughout the simulation period. The higher concentration of passive carbon with warming can be attributed to the enhanced recalcitrance of carbon. Six *et al.* (2002) have also reported a higher aromatization through the condensation and complexation of decomposition residues with warming, rendering them more resistant to subsequent decomposition. This large C proportion in the passive pool occurs at the expense of accelerated microbial decomposition of the materials in the active and slow pool (Stevenson, 1994).

SUMMARY

The mean carbon stocks in the teak plantations of Kerala Western Ghats varied from 7.38 - 12.10 kg m^{-2}. Teak planted areas in the Southern High Hills (Zone D) with a much cooler climate (mean annual temperature 21.6 °C; rainfall 3602 mm) was found to store a significantly higher amount of carbon in the 1 meter soil depth than all the teak growing zones. The carbon fractions in these teak plantations were found to vary between zones. Active carbon fractions in zones A, B and D were on par and were 40% to 70% higher than that of zone – B. Active and slow carbon concentrations were found to decrease with site quality in all the zones. In contrast, no significant difference was found in the passive SOC concentration associated with different zones or site qualities confirming that zone and site quality variations affects only the active + slow pools and it is this fraction that determines the ecosystem health and functions rather than the recalcitrant passive pool.

A significant positive correlation was found between active and slow carbon pools in these soils. The recalcitrant passive pool was found to have no tradeoffs with either of the two pools. This means that input additions, tree harvest, rotation duration etc. have a profound influence only on the active and slow pools and passive carbon remains more or less undisturbed. The changes in TOC should hence be a reflection of slow and active pools rather than the passive pool. Even though the studied teak plantations exhibited a wide range of soil types, the presence of almost equal amounts of passive carbon in them show that the recalcitrance of carbon in these soils is mainly by way of their chemical structure rather than soil enabled protection against decomposition. In other systems of the region, mineral organic interactions and soil aggregation were attributed as major factors for recalcitrance of passive pools of soil carbon which is not so in the teak planted soils.

The elemental composition of the extracted humic acids show that their carbon and nitrogen contents ranges from 26.2 - 44.4% and 4.1 - 6.3% respectively. Though site quality IV had comparatively higher C/N ratio than the other sites this was found to be well within critical limits of 10:1 required to sustain carbon and nitrogen mineralization. The total acidity or exchange capacity of humic acids due to the presence of dissociable protons or H^+ ions in aromatic, carboxylic or phenolic hydroxyl groups was mainly from phenolic acidity. The E4/ E6 ratio values for the humic acids was found to be between 2.8 - 4.9 indicating compounds with high molecular weights and higher degrees of humification. The humic acids from different teak growing zones of Kerala Western Ghats were similar to type A in Kumada's classification system which is characterized by high stability, high degree of aromatic condensation and a relatively low concentration of functional groups. The results were further confirmed by FTIR analyses which indicated that the humic substances from soils of teak plantations in the Kerala Western Ghats may be considered a polymeric mixture of many molecules predominantly aromatic with phenolic and amine substituents, linked together. The SEM and TEM images establish that these humic acids are also poly crystalline and shapeless with particle sizes in the micro ranges.

Site deterioration was found to increase the Fe and Al sesquioxide contents in these soils. Co-Flocculation of carbon by these Fe and Al oxides would help higher carbon storage in the degraded teak sites (site quality IV). Moreover, present lower inherent carbon contents farther away from its saturation capacity also presents a promising scenario for more terrestrial carbon accumulation in these soils. However, the low binding coefficient values for these soils indicate that carbon is retained very weakly by these soils and can be easily lost by decomposition. Among the different ions, anions were found more efficient in improving the carbon adsorption than cations. In general, the adsorption of carbon varied in the presence of anions as $PO_4^{3-} > SO_4^{2-} > NO_3^-$ and for cations as $Ca^{2+} > Mg^{2+} > Al^{3+} > Fe^{3+}$.

Ea was found to be positively affected by Q_{10} values and ionic balances in soil (AR1 and AR2). Fe, Ca and CEC were found to have a negative influence on Q_{10} values of carbon decomposition in soils of teak plantations. The results suggest that improving the net ionic equilibrium in soils may serve to enhance the Ea values of carbon decomposition. To counteract the effects of warming on carbon decomposition and subsequent loss, Ca management may serve as a good option. Though Fe can also counteract the thermal effects on decomposition, its concentration rise in the soils may lead to iron toxicity in plants at least in the early stages. The positive correlation between Ea and $Q_{10,}$ shows that even recalcitrant or passive carbon fractions in the soils of teak plantations can be highly thermal sensitive and undergo faster decomposition under conditions of warming.

The model simulations using CENTURY soil carbon model showed that residue burning process after deforestation/ clear felling adds plant residues from the native vegetation thereby initially increasing the active and slow carbon fractions. Active carbon maintained at a high level during the first rotation showed a rapid decline in the second rotation. During the clear felling of first rotation, there is an intense soil disturbance and subsequent burning causes the plant material to be lost as CO_2. Active carbon being the most sensitive fraction among the different pools gets depleted rapidly under such management strategies.

The different predicted temperature scenarios projects a similar trend for carbon turnover. The trends show that a there is a rapid conversion of slow to active pool during warming. The decline in TOC along with this conversion points to the fact that the reaction is a forward one with the final product being CO_2. Thus warming can have an adverse effect on teak ecosystem health by way of depleting its carbon content and effectively converting it into a carbon source rather than a sink.

The changing climate scenarios can convert the terrestrial sinks to sources in the humid tropics. This will lead to a positive feedback to atmospheric greenhouse gas concentrations and rapidly deplete the ecosystem of its carbon reserves. Hence future works should focus on developing management strategies that can help conserve the stored terrestrial carbon in these managed forest systems. Research works should also explore strategies for improving organo - mineral complexes in these soils by way of options such as artificially enhanced weathering facilitating carbon capture and storage in these ecosystems.

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