COMPARATIVE ANALYSIS OF CARBON AND NUTRIENT POOLS IN SOILS OF SELECTED WOODY ECOSYSTEMS OF CENTRAL KERALA, INDIA

By

VEENA PRASAD

2011-20-106

THESIS

Submitted in partial fulfilment of the
requirements for the degree of

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DECLARATION

I, hereby declare that this thesis entitled "**COMPARATIVE ANALYSIS OF CARBON AND NUTRIENT POOLS IN SOILS OF SELECTED WOODY ECOSYSTEMS OF CENTRAL KERALA, INDIA**" is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

Place: Vellanikkara
Date: 26-04-2017

VEENA PRASAD
(2011-20-106)

CERTIFICATE

Certified that this thesis entitled "**COMPARATIVE ANALYSIS OF CARBON AND NUTRIENT POOLS IN SOILS OF SELECTED WOODY ECOSYSTEMS OF CENTRAL KERALA, INDIA**" is a record of research work done independently by **Ms. Veena Prasad (2011-20-106)** under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Place: Vellanikkara
Date: 26-04-2017

Dr. Kunhamu T. K.
(Chairman, Advisory Committee)
Professor and Head,
Department of Silviculture and
Agroforestry,
College of Forestry, KAU.

CERTIFICATE

We, the undersigned members of the advisory committee of **Ms. Veena Prasad (2011-20-106)**, a candidate for the degree of BSc- MSc (Integrated) Climate Change Adaptation, agree that the thesis entitled "**COMPARATIVE ANALYSIS OF CARBON AND NUTRIENT POOLS IN SOILS OF SELECTED WOODY ECOSYSTEMS OF CENTRAL KERALA, INDIA**" may be submitted by **Ms. Veena Prasad (2011-20-106),** in partial fulfilment of the requirement for the degree.

Dr. Kunhamu T. K.
(Chairman, Advisory Committee)
Professor and Head,
Department of Silviculture and
Agroforestry,
College of Forestry, KAU.

Dr. P. Indira Devi
(Member, Advisory Committee)
Professor (Agricultural Economics)
Special Officer
ACCER, K.A.U.,
Vellanikara

Dr. Beena V. I
(Member, Advisory Committee)
Assistant Professor, AICRP on STCR
College of Horticulture, KAU.

Dr. Jamaludheen V.
(Member, Advisory Committee)
Associate Professor,
Department of Silviculture and
Agroforestry,
College Of Forestry, KAU

(External Examiner)

Dr. Sandeep.S
Scientist - B
Soil Science
Kerala Forest Research Institute
Peechi - 680 653, Thrissur

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VEENA PRASAD

DEDICATED TO

ALL MY LOVING TEACHERS, MY AMMA,
ACHAN, AND BROTHER

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ABBREVIATIONS

ANOVA	Analysis of Variance
C	Carbon
CH_4	Methane
cm	Centimeter
CO_2	Carbondioxide
$CuSO_4$	Copper Sulfate
EU	European union
g, gm	Gram
GHG	Greenhouse gas
Gt	Gigaton
Gt eq yr^{-1}	Gigaton equivalent per year
ha	Hectare
k	Potassium
KFD	Kerala Forest Department
kg	Kilogram
Mg	Mega gram
mg	Milli gram

N	Nitrogen
Na_2SO_4	Sodium Sulfate
N_2O	Nitrogen Oxide
P	Phosphorous
Pg	Petagram
REDD+	Reduced Emission From Forest Degradation And Deforestation
S	Sulfur
SOC	Soil Organic Carbon
TOF	Trees Outside Forests
UNEP	United Nations Environmental Programme

INTRODUCTION

Woody perennials are integral part of Kerala which have significant potential for protective functions in terms of regulation of physical and chemical fluxes in ecosystems, carbon sequestration and mitigation of environmental pollution along with productive functions by providing food, fuel, fodder, green manure and timber. Woody trees are incorporated in agro forestry systems, homegardens, silvopastural systems, and as monoculture plantations. These contribute to the timber and wood requirement of the society along with fuel wood requirement of households in Kerala. According to FSI (2011) total quantity of timber used in household is around 18.5 million cubic meters and fuel wood used per year is 14.543 million tones which is building pressure on the forestry sector. Establishing woody ecosystem on the degraded lands as well as with agroforestry systems will thus enhance as a carbon sink and in time will reduce the pressure on existing forest there by reducing emission from forest degradation.

Economic and population growth has driven anthropogenic greenhouse gas emission increase since the pre-industrial era which led to increased atmospheric concentrations of carbon dioxide (CO_2), methane and nitrous oxide higher than ever. Carbon dioxide is the principal cause of global warming and the current greenhouse gas (GHG) concentrations are 30 percent more than the pre-industrial level. Anthropogenic GHG emissions in 2010 have reached 49 ± 4.5 Gt CO_2 eq yr^{-1} which is the major reason for more than half of the observed increase in global average surface temperature from 1951 to 2010 (IPCC, 2014). Terrestrial ecosystems functions as a sink of atmospheric carbon and also limiting the GHG emission from land through carbon sequestration, carbon conservation and carbon substitution. Hence expanding the size of the global terrestrial sink is one strategy to extenuate CO_2 build-up in the atmosphere. Tree plantations are advocated as a carbon sink and establishment of tree plantations has been proposed as an effective method for sequestering CO_2 and mitigating atmospheric CO_2 levels. Carbon sequestration occurs in aboveground growing biomass and in belowground soil. Soil is the largest terrestrial pool of organic carbon. Total soil C pool is 2300 Pg (1 petagram=10^{15} g = 1 billion ton) while atmospheric and vegetation pools are 770 Pg and 610 Pg respectively which shows soil pool is 3 times than that of atmospheric and 3.8 times the vegetation pool. The soil C pool comprises soil organic carbon (SOC) estimated at 1550 Pg) and soil inorganic C approximately 750 Pg both to 1 m depth (Nair *et al.*, 2009). Reduced inputs of roots and biomass residues will trigger SOC pool depletion and also will increase carbon output from soil. For each Pg of carbon reduction from soil 0.47 ppmv of C will be released back to atmosphere (Lal, 2001).

Trees play a major role in nutrient recycling and further reduce nutrient removal through reducing surface runoff and soil erosion. The network of root system further acts as a barrier for nutrient leaching through soil. Tree litter improve soil fertility, however, it depends on the quality and quantity of tree litter, soil type, and climatic conditions of the area. The role of trees and plantation in stabilizing CO_2 levels and increasing carbon sink potential of soils have taken considerable scientific attention by the recent years and has been manifested in a number of international and national agreements and policies, such as the Kyoto Protocol, the Paris Agreement, REDD+ and the European Union (EU) climate policy. Slight changes in the soil organic carbon stock (SOC) could cause significant impacts on the atmospheric carbon concentration. SOC pool may greatly change or largely dependent quantity and variability of above ground biomass, litter fall and the land use pattern under the system. Hence it is important to know what kind of plantation is suited as a climate change mitigation option. Quantitative information on the carbon and nutrient contribution to the soil by various woody ecosystems would help to understand their potential to enrich the soil attributes and productivity there by helping to assess their role in mitigating climate change.

There is also a chance that the land under these systems will act as a source of GHGs thus exacerbates global warming with faulty land use practices. Degraded soils have lower SOC and nutrient stock than their potential capacity. In addition to GHG emission, the changing land use patterns trigger surface runoff and erosion and intensive cultivation causes removal of nutrients from soil. Woody ecosystems offer nutrient enrichment through litter fall and fine root turnover.

Many woody ecosystems are prevalent in Kerala but little has been known about the comparative potential of these systems to sequester carbon and nutrients. Homegardens and plantations of mahogany, teak, acacia and mango are widely seen woody ecosystems in Kerala. Homegardens are distinguishing traits of the state which plays a fundamental role in providing food security to the farmer and have high potential for carbon (C) sequestration, especially due to its rich agro biodiversity. Plantation systems are the next important woody ecosystems seen in Kerala. The social forestry wing has been raising plantations on various land categories *viz*. land along the sides of highways, railway lands, and land at the disposal of government so on. *Acacia auriculiformis* was widely planted along vast stretch of state under social forestry projects. Social forestry wing has planted an area of about 4000 ha with acacia (KFRI, 1993). Teak and mahogany are two principal forest plantations in Kerala and are promising source of income generation. Mango is considered to be an inevitable part of homegardens and also, commercial orchards are well established in the state of Kerala. These woody systems hence can be further incorporated with the degraded lands as well as fallow lands of Kerala. Though these are well suited plantations in Kerala their adaptability as well as ecological services varies considerably.

In this backdrop the study was undertaken in five major woody ecosystems of Central Kerala *viz.* homegarden, and mature plantations of *Tectona grandis*, *Acacia auriculiformis*, *Swietenia macrophylla* and *Mangifera indica* with the following objective:

i. To assess and compare the soil carbon stocks in selected woody ecosystems *viz.* teak, mahogany, acacia, mango and typical homegarden

ii. To analyze the nutrient stocks in these woody ecosystems.

REVIEW OF LITERATURE

2.1. GLOBAL WARMING AND GHG EMISSION

Warming of the climate system is obvious and is unprecedented over decades. Of the last 1400 years, the period from 1983 to 2012 was likely the warmest 30-year period in the Northern hemisphere. A warming of 0.85°C is observed over the period, 1880 to 2012. There is 95 percent certainty among scientists that global warming is caused by anthropogenic activities mainly increasing concentrations of GHGs, especially CO_2. Cumulative anthropogenic CO_2, emissions to the atmosphere were 2040 ± 310 Gt CO_2 between 1750 and 2011. While about 60 percent of these emissions have been removed from atmosphere and stored on land (in plant and soils) and in the ocean, the rest remained in the atmosphere (880 ± 35 Gt CO_2). Oceanic uptake of CO_2 over past decades has resulted in acidification of ocean (26% increase in acidity). About half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the period, 1970 to 2010 with larger absolute increases in last 15 years, despite a growing number of climate change mitigation policies. It was found that global anthropogenic emissions have reached 49 ± 4.5 Gt CO_2 eq yr^{-1} in 2010. The global mean surface temperature change for the period, 2016–2035 relative to 1986–2005 is expected to be in the range of 0.3°C to 0.7°C, which depends on committed warming caused by past, as well as future anthropogenic emissions (IPCC, 2014). As per the report of IEA (2007), India will become one of the top three emitters of the world by 2030. Net emission from India has already gone beyond 1727.71 million tons of CO_2 equivalent (GOHP, 2014) and is already experiencing a warming climate with projections of high temperature regimes over southern India (World Bank, 2013). Studies have shown that Kerala has become more vulnerable to climate change (Brenkert and Malone, 2005)

2.2. MITIGATION STRATEGIES FOR REDUCING AND MANAGING THE RISKS OF CLIMATE CHANGE

The IPCC (Intergovernmental Panel on Climate Change) defines mitigation as ''an anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases'' (IPCC, 2007). The intervention can be a complex plan or a simple improvement that mitigates climate change (UNEP, 2016). Carbon capture and storage facilities are regarded as the most discussed climate change mitigation options. Most of them are complex carbon capture technologies with high cost and technical uncertainties owing to the slow and narrowed implementation in India (Kapila and Haszeldine, 2008). The Bali action plan had put forward the proposal that forests in developing countries must be considered as a primary climate change mitigation option (FAO, 2007). Locking atmospheric carbon through trees provide an ideal mitigation strategy which is environmentally sound and cost effective. According to United Nations Framework Convention on Climate Change, mitigation is crucial in stabilizing GHG concentration in atmosphere (UNFCCC, 2016a).

Integrative approaches on the economic as well as environmental constraints need to be studied to examine the role of plantations as carbon sinks (Montagmini and Porras, 1998). The total global carbon storage potential from afforestation and reforestation activities for the period, 1995–2050 is estimated to be between 1.1 and 1.6 Pg C (1 Pg=Peta gram, 10^{15}g) per year, of which 70 percent could occur in the tropics (IPCC, 2007). Substantial emissions reductions over the next few decades can reduce climate risks while delaying mitigation shoots up the burdens beyond curb. Climate mitigation would require substantial emissions reductions and near zero emissions of CO_2 and other long-lived greenhouse gases. Land use, land use change and forestry particularly deforestation contribute to greenhouse gas emission (UNFCCC, 2016a) and livelihoods play major role in driving deforestation and forest degradation. It is unique to country's national circumstances, capacities and capabilities (UNFCCC, 2016b). On an average, about 28 percent of anthropogenic CO_2 emissions were collected and stored by the land based sinks between 2002 and 2011 (Peters *et al.*, 2012). Carbon dioxide removal by increasing tree cover is recommended as a cost-effective method and plays a major role in many mitigation scenarios where it reduces net emissions and enhances carbon sinks in land-based sectors (IPCC, 2014).

2.3. CARBON SEQUESTRATION IN WOODY ECOSYSTEMS

According to IPCC (2007), carbon sequestration can be defined as "the uptake of carbon containing substances and, in particular, CO_2 into another reservoir with a longer residence time". Usually these reservoirs include oceans, soils, vegetation and geologic formations. Nair *et al.* (2010) has given an agroforestry perspective to carbon sequestration as "the locked storage of atmospheric CO_2, in vegetation, detritus and soil pools as fixed carbon, after being taken up for photosynthesis". Carbon sequestration occurs directly and indirectly. Directly, inorganic chemical reactions convert carbon dioxide into soil inorganic carbon compounds and indirectly through photosynthesizing atmospheric carbon dioxide into plant biomass. The plant biomass is sequestered as SOC while decomposing (SSSA, 2001). Carbon can either remain stored in soils for long period or be quickly released back into the atmosphere with respect to the climatic conditions, natural vegetation, soil texture, and drainage (ESA, 2000).

The incorporation of trees in a treeless land improves soil properties and can result in greater net carbon sequestration (Young, 1997). In a woody ecosystem, carbon sequestration occurs in the aboveground and belowground segments. In aboveground, it is stored in specific plant parts (stem, leaves, etc. of trees and herbaceous components), and belowground includes living biomass such as roots and other belowground plant parts, soil organisms and carbon stored in various soil horizons. Type of system (and the nature of components and age of perennials), site quality, and previous land-use has significant effect on the total amount sequestered in each part (Nair, 2011). In order to consider woody ecosystem as a climate change mitigation option, the carbon captured should be stored and stabilized in the sink

(Krna and Rapson, 2013; Mackey *et al.*, 2013) which is carried out by the extensive root system. Up to 2.2 Pg C may be sequestered above and belowground over 50 years in agroforestry systems (Lorenz and Lal, 2014). In addition, carbon that gets locked in the wood products is complementary to that of the permanent stock in standing trees. This kind of storage gives relaxation time to implement cleaner technologies (FAO, 2003).

Plantations are forests of introduced species and in some cases native species, established through planting or seeding, with few species, even spacing and/or even-aged stands. Along with forest plantations, homegardens, agroforestry and silvopastoral systems and individual trees grown as wind breaks are also important in providing ecosystem foods and services (Peyre *et al.*, 2006; Beer *et al.*, 2000). Sink capacity of soil is enhanced when degraded ecosystems are restored with perennial vegetation. Studies have shown that reforesting with appropriate stand density could even improve the soil organic carbon of SOC rich systems like grasslands (Chen *et al.*, 2016). Better silvicultural practices resulted in considerably high carbon stock in the above ground biomass in plantation of Sal (406.4 Mg ha^{-1}) than that of natural forest (324 Mg ha^{-1}) (Baishya *et al.*, 2009). Likewise establishing plantations in degraded land provide an alternative way to solve the issues resulting from forest degradation and deforestation and to also enhance the carbon sequestration in soil via litter decomposition and root turnover (Tom-Dery *et al.*, 2015), which is otherwise slow or absent in fallow lands. Globally there are millions of trees in urban areas, on farms, along roads, homegardens and so on, that does not come under the definition of forest, widely recognized as trees outside forest (TOF). These relatively little recognized forms of trees are now receiving greater attention (Long and Nair, 1999) as they play extensive role in contributing national biomass and carbon stocks as well as the livelihood of people (Schnell *et al.*, 2015). In tropics, TOF are a major source of food (Bergeret and Ribot, 1990). In addition, the ecological functions regulated by trees in terms of soil and water conservation by preventing erosion and maintaining soil fertility, boosted the recognition of TOF (Carle *et al.*, 2002; FAO, 2001).

Trees outside forest (TOF) in India mainly growing on private land are the main source of wood in the country for industry and domestic wood fuel (Pandey, 2008) and is therefore an important natural resource (Schnell *et al.*, 2015). In Kerala about 90% of fuelwood requirement is met from trees outside forests (FSI, 1998), which further reduce the pressure on existing forests.

2.4. BELOW GROUND SOIL ORGANIC CARBON AND CARBON DYNAMICS

Soil organic carbon (SOC) plays a very significant role in the global carbon cycle as it is the largest terrestrial carbon pool (Lal, 1999). Restoration of existing 2 billion ha of land could reverse annual atmospheric CO_2 increase (Lal, 2000). According to Batjes and Sombroek (1997), soils contained 1550 Pg of organic carbon upto 1m depth. Of the five major carbon pools, *viz.* oceanic pool, geologic pool, soil organic carbon pool, biotic pool and atmospheric pool (Lal, 2003a), sequestering carbon in SOC pool is the cost effective mitigation method. Lal (2001) reported that converting degraded soils under agriculture and other land uses into forests and perennial land use can enhance the SOC pool. The severely depleted and degraded soils of tropics hold large potential to sequester carbon (Lal, 2004a). The restoration of degraded soils and ecosystems could sequester about 7 to 10 Tg C yr^{-1} in India (Lal, 2004b).

Vertical distribution of SOC is influenced by root distribution and turnover rates of corresponding vegetation and diverse set of organisms present in soil (Paton, 1995; Bronick and Lal, 2005; Schmidt *et al.*, 2011; Schrumpf *et al.*, 2011), since litter and rhizodeposition are the first and foremost way through which carbon enters soil pool (Rasse *et al.*, 2005; Guo *et al.*, 2008). Introducing deeply rooted vegetation into shallow rooted systems hence store carbon deep in the soil (Fisher *et al.*, 1994; Jobbagy and Jackson, 2000) while the physiochemical interactions with soil particles stabilize root derived carbon input in deeper horizons (Rasse *et al.*, 2005; Kell, 2012) making deep soil a carbon reservoir. As such the stability of carbon in soil depends on the root carbon incorporated into the soil through root turnover (Rasse *et al.*, 2005). Furthermore, elevated surface input of SOM preferentially increases dissolved organic carbon which is transported and stabilized in deeper soil horizons in due course (Lorenz and Lal, 2005).

Carbon and nutrient stocks in deep layers have significant influence on site quality parameters like biomass production and total carbon stock (Callesan *et al.*, 2016). Assessment of SOC storage gives an idea about the sequestration potential and losses of soil carbon (Davidson and Janssen, 2006) as well as the carbon cycle and climate change which allows the formulation of future policies (Sreenivas *et al.*, 2016; Dorji *et al.*, 2014).

2.5. SOIL CARBON SEQUESTRATION; IMPACTS ON GLOBAL CLIMATE CHANGE AND FOOD SECURITY

Increasing population and urbanization drives the need for increasing food security and at the same time maintenance of environmental quality (Bronik and Lal, 2005). Soil carbon sequestration is a win-win strategy. Enhancing SOC pool could substantially offset fossil fuel emissions (Kauppi *et al.*, 2001) concurrently leading to sustainable management of soil and water resources and ensuring food security. Carbon sequestration enhances food security by improving crop yield. For example, Lal in his study has shown that an increase in carbon pool by 1 ton per hectare in a degraded cropland will increase crop yield by 20 to 40 kilograms per hectare (kg ha^{-1}) for wheat (Lal, 2004a).

Decline in soil organic carbon pool will adversely affect soil structure, thereby enhancing erodibility (Lal, 2004a). Lower density and vicinity to surface aggravates removal of soil organic carbon during erosion. Depletion of SOC has contributed to 78 Pg carbon to the atmosphere (Lal, 2005) and at the same time restoration of same could offset 5 to 15% of fossil fuel emission per year (Lal, 2004b). The land conversions for intensive agriculture in response to increasing demand for food will adversely affect soil carbon stocks.

2.6. RELEVANCE OF WOODY ECOSYSTEMS IN KERALA: ENVIRONMENTAL AND ECONOMIC SERVICES OF WOODY ECOSYSTEMS

Woody perennial based system has the property to restore degraded ecosystems and improve site productivity (Kumar, 2006). Forest plantations are important in terms of its economic, social, and environmental benefits. Environmental benefits include combating desertification, absorbing carbon to offset carbon emissions, protecting soil and water, rehabilitating lands exhausted from other land uses and providing rural employment (Carle *et al.*, 2002). Teak and mahogany are two prominent forest plantation species in Kerala. Both are slow-growing and valuable hardwood species easier to grow under tropical ecological conditions (FAO, 2001). Kerala forest department alone have above 56510 ha under teak plantation (Prabhu, 2005). *Acacia auriculiformis* is suitable for social and farm forestry programmes since it has the ability to adapt well to various soil and climatic conditions along with features like fast growth, nitrogen fixing ability, and evergreen nature (Narendra, 2011). Auriculiformis is well adapted to acidic soils as well. Also their densely matted root system protects the top soil from erosion (NAS, 1983).

The horticultural systems have more SOC sequestration potential than agricultural systems (Naitam and Bhattacharya, 2004) due to its greater canopy cover, leaf litter, and favorable micro environment (Singh *et al.*, 2009). Mango is the most prominent horticultural plantation in India with highest area of 2516 thousand ha (NHB, 2015). Commercial orchards are now established in Kerala comprising a total area of 75911 hectares under mango cultivation (Cocohol, 2016). Carbon sequestration through horticultural system is a better option if forestry is not feasible. The average carbon stock sequestered per tree was found to be highest in *Mangifera* *indica* (1.73 t/tree against 0.12 ± 0.24 t/tree.) in the forest reserves of Eastern Ghats (Pragasan, 2014).

Homegardens are centuries old productive systems (Schroth *et al*., 2001). The woodfuel collected from homegardens is an alternative for fossil fuel (Kumar and Nair, 2004). The state is estimated to have 4.32 million homegarden covering 1.4 M ha of land (Kumar,r 2006), making homegardens the most important agroforestry system. Of the total annual wood production, 83 percent was from the homegardens (house compounds and farmlands) (FSI, 1998). Homegardens are diverse in nature in terms of species composition, size, and age (Mohan *et al.,* 2007). According to Saha *et al.* (2009) soil carbon content in homegardens ranged from 101.5 to 127.4 Mg ha^{-1} within the 1m profile and is found to be a function of species richness and tree density especially in the top 50cm. Knowledge on carbon and nutrient flux in homegardens is crucial for further management of system for efficient use of resources, energy and increased production (Benjamin *et al.,* 2001).

2.7. INFLUENCE OF PLANTATION ON SOIL NUTRIENT POOL

Soil nutrient distribution in different depths is influenced by weathering, atmospheric deposition, leaching, and biological cycling (Trudgill, 1988) of which plant cycling is a major contributor. Enhancing the diversity and quantity of soil flora and fauna are important in improving soil structure which further improves ability of soil to hold carbon and nutrients (Kay, 1998). Also, the soil carbon storage is influenced by the presence of nutrients (Rastetter, 1992) especially nitrogen, phosphorous and sulphur in organic matter (Kirschbaum *et al*., 2001). To sequester 10,000 kg of C in humus, 833 kg of N, 200 kg of P and 143 kg of S are needed assuming C: N ratio of 12:1, C: P ratio of 50:1 and C: S ratio of 70:1 (Himes, 1998).

Unlike monoculture plantations, multispecies agroecosystems are more sustainable in terms of soil nutrients pools (Vandermeer *et al*., 1998), since the deeper and denser rooting system in a multispecies system consumes the soil nutrients sustainably (Ong *et al.*, 2004). Root system plays a vital role in the nutrient enrichment. Nutrient deficient soils generally have shallow root system where substantial part of roots is concentrated on the surface layers (Buresh *et al.*, 2004). Woody trees have the potential to take up nutrients that annuals cannot otherwise from deeper depths (van Noordwijk *et al.*, 1996). Perennials have an ability to retrieve nitrogen from deep soils especially during leaching events. Thus, inter cropping woody trees with annuals ensures sustainable use of nutrients (Buresh *et al.*, 2004). Plant characteristics like tissue stoichiometry, biomass cycling rates, above and belowground allocation, root distributions, and maximum rooting depth may all play an important role in shaping nutrient profiles. Nutrients strongly cycled by plants, such as phosphorous and potassium, were more concentrated in the topsoil (upper 20 cm) (Jobbagy and Jackson, 2001).

2.8. DEPLETION OF CARBON AND NUTRIENT POOLS IN SOIL.

Soils have the property to act as a sink or source of carbon in response to its carbon fluxes (Schrumpf *et al.*, 2011). When humification, aggregation and sedimentation sequester carbon, erosion, decomposition, volatilization and leaching remove soil organic carbon (Batjes, 2004). Despite the opportunities at global, national and local levels to enhance soil carbon, it has disappeared rapidly since the SOC stocks are vulnerable to anthropogenic disturbances (UNEP, 2012). The emission of CO_2 from soil is primarily caused by decomposition of organic matter or soil respiration (Schlesinger and Andrews, 2000; Lal, 2003b). Depletion of SOC is aggravated by soil degradation, land misuse and soil mismanagement (Lal, 2004b) and conversion of natural ecosystems to cultivated or pastoral land (Lal, 2004c). Inadequate planning and inappropriate management of plantations results in environmental degradation (Carle *et al.*, 2002).

Even though SOC pool is three times the vegetation pool, the reduced biomass productivity and low root turnover caused considerable reduction in the SOC pools in soils of India (Lal, 2004a). Ramachandran *et al.* (2000) has shown that the ratio of soil organic carbon to that of vegetation is only 1.3 times in the natural forests of Eastern Ghats. A similar low ratio of 0.8 was obtained in the study of Kaul, (2010) using a dynamic model CO2FIX in teak plantation. Seventy-five percent or more SOC pool is depleted in the tropics due to conversion of natural forests to agricultural ecosystems and some soils have lost as much as 20 to 80 tons C ha^{-1} (West and Post, 2002). Soil erosion is also regarded as a factor for carbon emission as well as CH_4 and N_2O, leading to low carbon pool in eroded land (Lal 2003b; 2005).

Plants produce poor quality litter that decomposes slowly in a nutrient deficient ecosystem since the growth is slow and nutrients are utilized efficiently by the tree itself. This leads to further depletion in soil nutrient pool since nutrient enrichment through litter is low (Hobbie, 1992). Also, fast growing species deplete more nutrients since the nutrients withdrawal during growth and loss through harvest far exceeds the replenishment (Goncalves *et al.*, 1997; Kumar *et al.*, 1998). It is also noted that fast growing exotic trees such as Acacia resulted in marked loss of nutrients from the site (Kumar *et al.*, 1998).

MATERIALS AND METHODS

3.1. STUDY SITE

The study was conducted in five different mature woody ecosystems *viz*. teak, mahogany, acacia, mango and a homegarden located in Central Kerala during May 2016. Acacia plantation and mango orchard were selected from Kerala Agricultural University, Vellanikara. Teak, mahogany plantations and homegarden were selected from Thrissur district.

3.1.1. Climate

The climate is humid tropical with South-West and North-East monsoons. Summer rainfalls are also not uncommon in the region.

3.2. MATERIALS

3.2.1. Woody ecosystems

Mature forest plantations of teak, mahogany, acacia, horticultural plantation of mango and typical homegarden were selected for the study. Mahogany plantation was about 85 years old, teak was 45 years old and acacia was 15 years old.

3.3. METHODS

3.3.1. Design layout

Design: One way ANOVA

Factors: Plantation * Depth

Figure 1. Location map of study area

Plate 1. Mahogany plantation

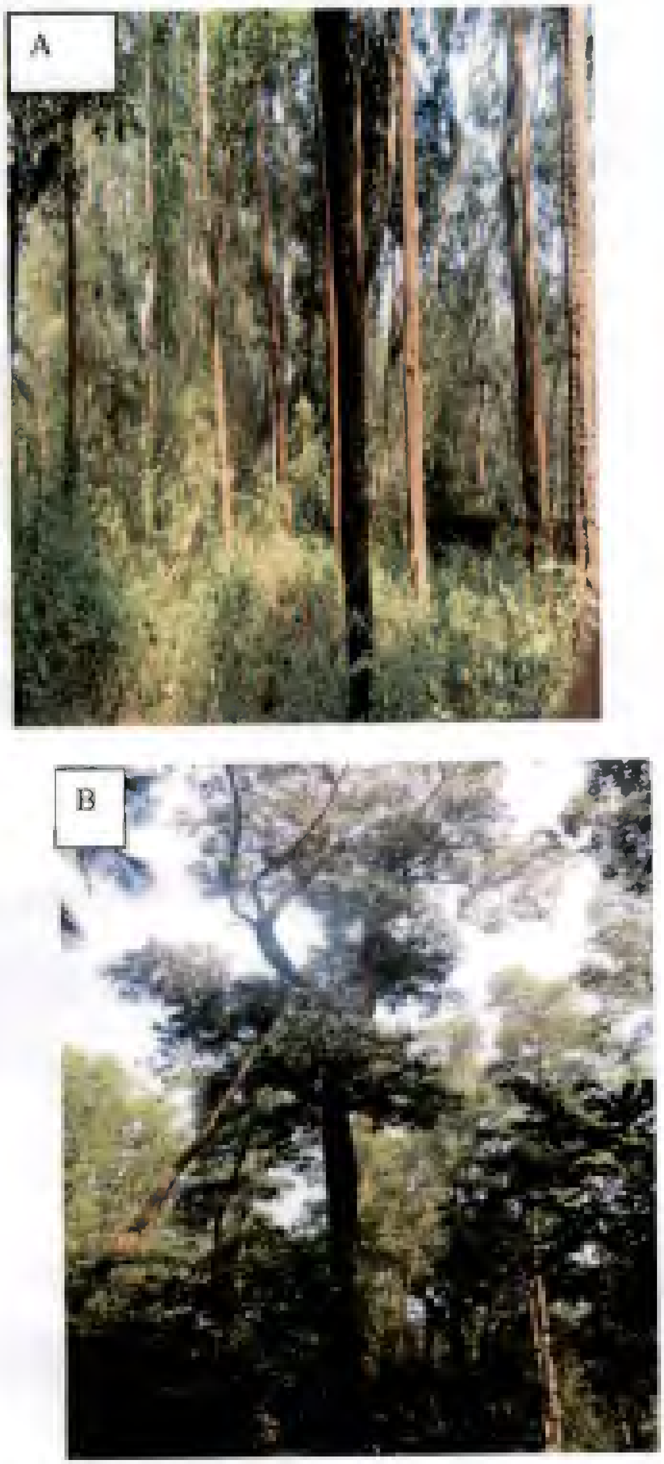

Plate 2. Acacia plantation

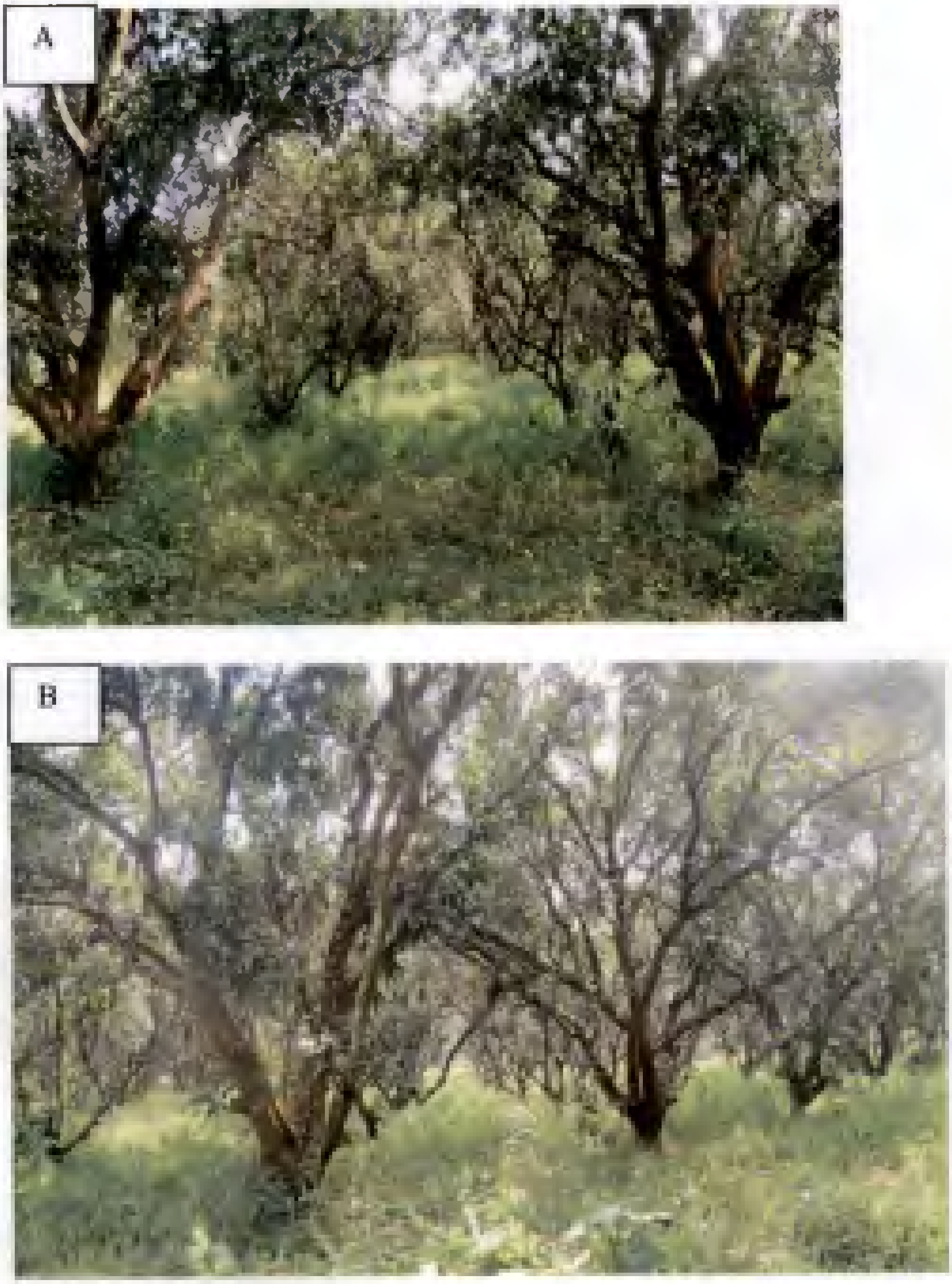

Plate 3. Mango plantation

Plate 4. Teak plantation

Plate 5. homegarden

3.3.2. Above ground parameters

For taking above ground measurements the three plots of size 20m*20m were selected randomly from all the sampling sites. Height (H) and girth at breast height (GBH) of all the trees in the selected plots were taken to calculate tree volume.

Using a measuring tape of 1m GBH was taken, at a height of 1.37m of the tree. Heights of the trees were taken using a Vertex.

3.3.2.1. Tree volume

Using the GBH and height tree volume was calculated using Huber's formula,
Volume = $S_m * L$,
S_m = Sectional area at breast height; L= length of the tree

3.3.3. Soil sampling and preparation

Soil samples were collected in May-June 2016. From each woody ecosystem three sampling points were randomly selected along the slope. The soil was excavated to 1m depth in each sampling point. Soils were collected from five depths *viz*. 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm respectively. Similarly soil samples were collected from a contiguous treeless control plot of each system. Prior to the analysis, samples were air dried and sieved with a 2mm sieve. Undisturbed soil samples were also collected from each depth in a core sampler to calculate bulk density. A 158cm^3 steel cylinder was used to collect soil from each depth which was weighed right away. Soil samples were dried for calculating bulk density, at 105°C for two to three days.

3.3.4. Soil physical properties

3.3.4.1. Bulk density

Soil samples were collected undisturbed from each depth using a core sampler. The core was taken without pressing the cylinder too hard on soil so that the natural bulk density of soil may not be disturbed. Soil was oven dried at 105°C for 48-72 hours and weight was taken. Volume of soil was calculated by measuring volume of cylinder ($\pi r^2 h$). Bulk density was calculated by dividing oven dry weight of soil samples by volume of soil (Jackson 1958).

3.3.5. Soil chemical properties

3.3.5.1. Soil pH

Soil pH was calculated using an aqueous suspension of soil and water in Bray-1-extractant ratio using Elico pH meter (model Li 613).

3.3.5.2. Total nitrogen

The N content in the digest was determined by microkjeldahl method which involves three steps which were:

1.Digestion
2.Distillation
3.Titration

The total nitrogen content in soil was determined by digesting 1g of 2mm sieved soil in 5ml of sulphuric acid in presence of digestion mixture (Na_2SO_4, $CuSO_4$ and selenium). Distillation involved the separation and isolation of the nitrogen from the digestion tube. This was done by raising the pH with NaOH and by doing this ammonium radical was converted to ammonia. On heating, the ammonia was distilled out which was collected in a trapping medium (4% Boric acid). This was then titrated against 0.1N H_2SO_4 in the presence of mixed indicator.

3.3.5.3. Exchangeable potassium

Exchangeable potassium was estimated by flame photometry using 1N neutral ammonium acetate solution as the extractant.

3.3.5.4. Available phosphorous

2.5 g of soil was weighed out into a 100 ml conical flask and added 25 ml of Bray No.1 reagent and shake exactly for 5 minutes. The solution was filtered through Whatman No.42 filter paper. Available phosphorus in the extract was estimated by ascorbic acid method (Watanabe and Olsen, 1965) as per the following procedure:
5 ml of the extract was pipette out into a 25 ml volumetric flask and diluted it to 20 ml. To this 4 ml ascorbic acid was added. Made up the volume with distilled water and shook the contents well. Read the intensity of color after 10 minutes at 660 nm using spectrophotometer. The color was stable for 24 hours and the maximum intensity was developed within 10 minutes. The concentration of P in the sample was computed from the standard curve.

3.3.5.5. Organic carbon

Each sample was air dried for 24hrs and passed through 2mm sieve prior to the analysis. Soil organic carbon was analyzed using wet digestion method (Walkley and Black, 1934).

3.3.6. Below ground carbon and nutrient stocks

Soil carbon and nutrient stock for each soil depth was calculated by multiplying respective carbon and nutrient concentration with its corresponding soil mass (Anderson and Ingram, 1989). Soil mass for each soil layer was calculated using bulk density. Carbon or nutrient stock over 1m depth was calculated by adding respective carbon or nutrient content in each layer up to 1m.

3.3.7. Statistical analysis

Soil physical and chemical properties were analyzed statistically following ANOVA technique (using SPSS). Post hoc analysis (Duncan) was done for each parameter.

RESULTS

The results of the study are presented in this chapter.

4.1 TREE VOLUME

Estimated tree volume shows that mahogany plantation had very high tree volume per hectare when compared with other woody ecosystem. The order of volume for other ecosystem is as follows : homegarden > teak > mango > acacia.

Table 1: Volume of trees in the selected woody ecosystem in Central Kerala

Woody ecosystem	Volume (m^3 ha^{-1})
Homegarden	1889.67
Acacia	957.5
Mango	1321
Teak	1525.42
Mahogany	6061.5

4.2. SOIL STUDIES

Soil samples were analyzed to find bulk density, pH, organic carbon, total nitrogen, available phosphorous and exchangeable potassium.

4.2.1. Soil physical property

4.2.1.1. *Bulk density*

Bulk density of soils of selected woody ecosystems increased with depth though the variation was not significant (Table 2). Bulk density at surface varied from 1.10 kg m^{-3} to 1.41 kg m^{-3} with homegarden having higher bulk density and mango had the least. Bulk density of deeper soils was higher than that at the surface in the selected woody ecosystem except for teak. Homegarden, mango and teak woody ecosystems had higher bulk density at 40-60cm soil layer. Open soils had lower bulk density than corresponding woody ecosystem however not significant, except for mango. As for mango, woody ecosystem soil had lower bulk density than that of contiguous open plot.

Table 2. Bulk density of soils across different depths in selected woody ecosystems in Central Kerala

Depth (cm)	Bulk density (kg m^{-3})									
	Homegarden		Acacia		Mango		Teak		Mahogany	
	Woody system	Open	Woody system	Open	Woody system	Open	Woody system	Open	Woody system	Open
0-20	1.41 (0.01)	1.30	1.19 (0.01)	1.10	1.10 (0.02)	1.06	1.27 (0.02)	1.20	1.24 (0.02)	1.15
20-40	1.29 (0.11)	1.32	1.22 (0.03)	1.18	1.15 (0.05)	1.16	1.23 (0.06)	1.20	1.33 (0.02)	1.09
40-60	1.50 (0.03)	1.42	1.22 (0.03)	1.18	1.26 (0.13)	1.29	1.28 (0.08)	1.13	1.25 (0.05)	1.11
60-80	1.45 (0.05)	1.27	1.21 (0.06)	1.29	1.15 (0.06)	1.42	1.25 (0.11)	1.22	1.33 (0.06)	1.35
80-100	1.42 (0.05)	1.34	1.29 (0.05)	1.27	1.17 (0.13)	1.35	1.27 (0.04)	1.20	1.31 (0.05)	1.31
F test: Non significant										

(Values in parenthesis are standard error of mean)

4.2.2. Soil chemical properties

Each soil sample was analyzed for its chemical properties *viz.* pH, soil organic carbon, total nitrogen, available phosphorous and exchangeable potassium. Depth wise trends as well as woody ecosystem wise variations were studied for each parameter. The chemical properties in soils of each woody ecosystem were compared with chemical properties in soils of contiguous open plots as well.

4.2.2.1. *Soil pH*

Soil pH values of selected woody ecosystems are depicted in Table 3. Soil pH varied from 5.49 to 6.26 within the selected woody ecosystems. Homegarden and mahogany had significantly lower value than contiguous open plot. While other systems had significantly higher value than corresponding treeless control plots. Across woody ecosystems, homegarden had low pH and acacia had high pH although on par.

Table 3. pH of soils across different depths in selected woody ecosystem in Central Kerala

Woody ecosystem	Tree field	Treeless control
Homegarden	5.49^a (0.55)	5.90^b (0.08)
Acacia	6.26^a (0.14)	5.98^b (0.41)
Mango	6.25^a (0.12)	6.09^b (0.59)
Teak	5.66^a (0.33)	5.16^b (0.02)
Mahogany	5.62^a (0.36)	5.88^b (0.43)

(Values in parenthesis are standard error of mean)

(Values with same superscripts do not differ significantly across row)

4.2.2.2. *Organic Carbon*

Soil organic carbon concentration calculated and compared between selected woody ecosystems up to 1m depth is tabulated in Table 4. There was significant variation in soil carbon concentration across selected woody ecosystem and with soil depth. Top 20 cm of soil layer had higher carbon concentration invariably for all the woody ecosystems sampled. The highest carbon content in surface layer (0-20 cm) was observed for the mahogany plantation (1.49%) followed by teak (1.32%) and lowest was for homegarden (0.95%). Mahogany had significantly higher carbon concentration at top 40 cm soil depth compared with other woody systems. Interestingly homegarden had significantly higher carbon concentration at lower soil depth (80-100cm) (0.59%), while acacia had the lowest C concentration (0.36%). The remaining species had moderate concentrations at the lowest soil depths which however were on par.

A general declining trend in soil C concentration had been observed across the soil depths for all the woody ecosystems. The values were significantly different from surface to deeper layers. However, the decline was not prominent at deeper layers (i.e. beyond 60 cm). Despite the higher C concentration for acacia at surface soil there has been sharp reduction across depths as compared to other species.

The SOC was also compared with contiguous treeless open plot (Table 5, Figure 11-15). The SOC in the treeless open soils were considerably lower compared to the corresponding soil in the woody ecosystems. Trends were the same for all the tree species across the soil depths. Among the woody systems, teak and mahogany showed highest improvement in SOC as compared to other species. For instance, at surface soil layer (0-20 cm) teak plantation soils showed 83 percent and mahogany 73 percent increase in SOC as compared to their contiguous open soils. The differences were fairly high for other ecosystems also. Among the species, probably acacia soils had moderate improvement as compared to open especially at deeper soil layers. The differences were more prominent at deeper depths. For instance, there was more than 100 percent increase in SOC at deepest soil layer (80-100 cm) in the mango, teak and mahogany systems as compared with their respective open soils.

Table 4. Soil organic carbon in different soil depths across selected woody ecosystems in Central Kerala.

Depth (cm)	Soil organic carbon (%)				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	0.95_{A}^{c} (0.021)	0.96_{A}^{c} (0.021)	0.96_{A}^{c} (0.121)	1.32_{A}^{b} (0.111)	1.49_{A}^{a} (0.131)
20-40	0.85_{AB}^{bc} (0.011)	0.70_{B}^{d} (0.011)	0.70_{B}^{cd} (0.073)	0.99_{B}^{b} (0.087)	1.25_{B}^{a} (0.032)
40-60	0.73_{BD}^{ba} (0.009)	0.56_{B}^{b} (0.015)	0.61_{BC}^{b} (0.015)	0.80_{C}^{a} (0.116)	0.67_{C}^{ab} (0.022)
60-80	0.63_{D}^{a} (0.008)	0.53_{B}^{a} (0.007)	0.50_{C}^{a} (0.020)	0.51_{D}^{a} (0.049)	0.58_{C}^{a} (0.005)
80-100	$0.59D^{a}$ (0.005)	0.36_{C}^{b} (0.015)	0.51_{C}^{ab} (0.021)	0.50_{D}^{ab} (0.020)	0.51_{C}^{ab} (0.008)
Plantation (F value) =22.05 p value <0.01 Depth (F value) = 113.21 p value<0.01 Interaction (F value) =5.77 p value<0.01					

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 5. Soil organic carbon in selected woody ecosystems and their open plots in Central Kerala

Depth (cm)	Soil organic carbon (%)									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	0.95^{a} (0.021)	0.51^{b} (0.007)	0.97^{a} (0.021)	0.77^{b} (0.024)	0.96^{a} (0.121)	0.70^{b} (0.002)	1.32^{a} (0.111)	0.72^{b} (0.006)	1.49^{a} (0.130)	0.86^{b} (0.006)
20-40	0.85^{a} (0.011)	0.56^{b} (0.005)	0.66^{a} (0.011)	0.65^{a} (0.017)	0.70^{a} (0.073)	0.52^{b} (0.018)	0.99^{a} (0.086)	0.71^{b} (0.007)	1.25^{a} (0.032)	0.56^{b} (0.006)
40-60	0.73^{a} (0.009)	0.40^{b} (0.010)	0.56^{a} (0.015)	0.42^{b} (0.012)	0.61^{a} (0.015)	0.42^{b} (0.013)	0.80^{a} (0.116)	0.40^{b} (0.044)	0.67^{a} (0.022)	0.31^{b} (0.012)
60-80	0.63^{a} (0.008)	0.41^{b} (0.003)	0.53^{a} (0.007)	0.36^{b} (0.010)	0.50^{a} (0.020)	0.34^{b} (0.007)	0.51^{a} (0.049)	0.26^{b} (0.010)	0.58^{a} (0.005)	0.24^{b} (0.000)
80-100	0.53^{a} (0.007)	0.36^{b} (0.004)	0.36^{a} (0.015)	0.26^{b} (0.024)	0.51^{a} (0.021)	0.21^{b} (0.001)	0.50^{a} (0.020)	0.25^{b} (0.015)	0.51^{a} (0.008)	0.23^{b} (0.009)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value = 406.72 p value < 0.01		F value = 169.90 p value < 0.01		F value = 20.41 p value < 0.01		F value = 29.01 p value < 0.01		F value = 94.02 p value < 0.01	

(Values in parenthesis are standard error of means)

4.2.2.3. *Total Nitrogen*

Soils of selected woody ecosystem showed modest variation across woody ecosystem and depth (Table. 6). Mahogany plantation had highest nitrogen concentration in each soil layer up to 1m depth (0.55%, 0.46%, 0.36%, 0.39%, and 0.32%). Differences were not prominent among homegarden, acacia and mango. There was a general declining trend in nitrogen concentration with depth which was significant across soil depths.

Analysis of variance for total nitrogen showed that there was significant increase in total nitrogen concentration in soils of selected woody ecosystem as compared to the nitrogen concentration in the corresponding contiguous open plot for all depth classes except for mango orchard (Table. 7, Figure. 17-21). Among the tree species, the soil nitrogen buildup was highest for Mahogany (112% increase) as compared to nitrogen concentration in the open soil at 0-20 cm soil depth. The second best in terms of nitrogen concentration was teak, which showed as much as 86 percent increase as compared to corresponding open soil. The corresponding values for other tree species were mango (71%), acacia (42%) and homegarden (50%). Reduction across depth was 40 percent for homegarden while 44 percent for open. For mahogany plantation the reduction was 42 percent and for corresponding open soil it was 50 percent.

Table 6. Total nitrogen concentration in different soil depths across selected woody ecosystems in Central Kerala.

Depth (cm)	Total nitrogen concentration (%)				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	0.27_{A}^{c} (0.014)	0.27_{A}^{c} (0.014)	0.36_{A}^{b} (0.010)	0.39_{A}^{b} (0.016)	0.55_{A}^{a} (0.023)
20-40	0.24_{AB}^{c} (0.008)	0.25_{AB}^{c} (0.014)	0.28_{B}^{c} (0.051)	0.35_{A}^{b} (0.025)	0.46_{B}^{a} (0.040)
40-60	0.21_{BC}^{c} (0.008)	0.21_{ABC}^{c} (0.016)	0.22_{BC}^{bc} (0.025)	0.28_{BC}^{b} (0.008)	0.36_{C}^{a} (0.023)
60-80	0.19_{BC}^{c} (0.008)	0.20_{BC}^{c} (0.014)	0.18_{CD}^{c} (0.023)	0.27_{C}^{b} (0.038)	0.39_{C}^{a} (0.003)
80-100	0.16_{C}^{c} (0.008)	0.16_{C}^{c} (0.008)	0.13_{D}^{c} (0.010)	0.24_{C}^{b} (0.016)	0.32_{D}^{a} (0.026)
Plantation (F value) = 79.88 p value < 0.01 Depth (F value) = 44.27 p value < 0.01 Interaction (F value) = 1.41 p value = 0.17					

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 7. Total nitrogen concentration across selected woody ecosystems and their open plots in central Kerala

Depth (cm)	Total nitrogen concentration (%)									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	0.27 (0.014)^a	0.18 (0.008) b	0.27 (0.014)^a	0.19 (0.008)^b	0.36 (0.010)^a	0.21 (0.008) b	0.39 (0.016)^a	0.21 (0.008)^b	0.55 (0.023)^a	0.26 (0.008)^b
20-40	0.24 (0.008)^a	0.15 (0.000) b	0.25 (0.014)^a	0.16 (0.008)^b	0.28 (0.051)^a	0.20 (0.014) b	0.35 (0.025)^a	0.17 (0.014)^b	0.46 (0.040)^a	0.21 (0.008)^b
40-60	0.21 (0.008)^a	0.13 (0.008) b	0.21 (0.016)^a	0.15 (0.000)^b	0.22 (0.025)^a	0.18 (0.008)^a	0.28 (0.008)^a	0.16 (0.008)^b	0.36 (0.023)^a	0.19 (0.008)^b
60-80	0. 19 (0.008)a	0.12 (0.008) b	0.20 (0.014)^a	0.12 (0.000)^b	0.18 (0.023)^a	0.16 (0.008)^a	0.27 (0.038)^a	0.13 (0.008)^b	0.39 (0.003)^a	0.16 (0.008)^b
80-100	0.16 (0.008)^a	0.10 (0.000) b	0.16 (0.008)^a	0.12 (0.000)^b	0.13 (0.010)^a	0.08 (0.000)^a	0.24 (0.016)^a	0.14 (0.008)^b	0.32 (0.026)^a	0.13 (0.008)^b
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value= 43.73 p value< 0.01		F value= 22.67 p value< 0.01		F value= 13.67 p value< 0.01		F value= 24.69 p value< 0.01		F value= 49.34 p value< 0.01	

(Values in parenthesis are standard error of means)

4.2.2.5. *Available Phosphorous*

Table 8 depicts that available phosphorous content in soil across the selected woody ecosystems varied significantly. Woody ecosystems had remarkable effect on available phosphorous concentration in soil. Phosphorous concentration decreased consistently from surface to 1m depth in the selected ecosystems. Homegarden, teak and mango woody ecosystems showed a reduction of 94 percent between surface layer and deeper depth. Mahogany had somewhat similar drop in phosphorous content (90%). Acacia had comparatively less reduction across depth (73%).

Within the top 20cm soil depth, homegarden had highest phosphorous concentration (26.96 mg kg^{-1}), followed by teak (13.08 mg kg^{-1}), mahogany (7.73 mg kg^{-1}), acacia (5.40 mg kg^{-1}). Mango had the least value (3.27 mg kg^{-1}) which was significantly different from each other. Moving on to the deeper layer, the variation got narrowed with no significant difference across selected woody ecosystem, at 80cm depth.

Table 9 and Figure 23-27 depict the variation of phosphorous concentration in woody ecosystems with treeless control plots. All woody ecosystems had significantly higher value than contiguous open plot. At surface, homegarden had higher phosphorous concentration than contiguous open plot (370%), while variation was least for mahogany (67%). Interestingly mahogany plantation had higher variation at 80 cm soil depth (375%) while in homegarden, the increment over open plot reduced to 188 percent. For all other selected woody ecosystems, the variation in phosphorus content from open plot increased with depth though soils of mango and mahogany plantations at 60-80cm layer does not have significantly higher phosphorous concentration than open plots. At 80-100cm soil depth only acacia had significant difference from treeless control while other systems were on par with open plot.

Table 8. Available phosphorous concentration across selected woody ecosystems in Central Kerala

Depth (cm)	Homegarden (mg kg^{-1})	Acacia (mg kg^{-1})	Mango (mg kg^{-1})	Teak (mg kg^{-1})	Mahogany (mg kg^{-1})
0-20	26.93_{A}^{a} (0.657)	5.40_{A}^{d} (0.306)	3.27_{A}^{e} (0.141)	13.08_{A}^{b} (0.999)	7.73_{A}^{c} (0.762)
20-40	20.03_{B}^{a} (0.732)	4.20_{BC}^{c} (0.20)	1.60_{BC}^{d}	6.53_{B}^{d} (0.241)	4.12_{BC}^{c} (0.066)
40-60	4.67_{C}^{a} (0.133)	3.67_{C}^{ab} (0.241)	1.20_{CD}^{c}	3.40_{C}^{b} (0.306)	3.10_{C}^{b} (0.058)
60-80	2.65_{D}^{a} (0.535)	1.47_{DE}^{bc} (0.291)	0.37_{D}^{d} (0.033)	2.20_{D}^{ab} (0.116)	1.07_{DE}^{cd} (0.088)
80-100	1.73_{D}^{a} (0.177)	1.45_{E}^{a} (0.229)	0.21_{D}^{d} (0.013)	0.80_{E}^{ab} (0.116)	0.76_{E}^{ab} (0.014)
Plantation (F value)= 527.66 p value <0.01 Depth (F value)= 693.59 p value<0.01 Interaction (F value)=135.80 p value<0.01					

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 9: Available phosphorous concentration across selected woody ecosystems and contiguous open plots in Central Kerala

Depth (cm)	Available phosphorous concentration (mg kg^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	26.93^a (0.657)	5.73^b (0.145)	5.40^a (0.306)	1.80^b (0.023)	3.27^a (0.141)	1.61^b (0.047)	13.08^a (0.998)	4.03^b (0.175)	7.73^a (0.762)	4.64^a (0.103)
20-40	20.03^a (0.731)	1.47^b (0.033)	4.20^a (0.200)	1.63^b (0.047)	1.60^a (0.000)	1.22^b (0.026)	6.53^a (0.240)	3.16^b (0.068)	4.12^a (0.066)	3.94^a (0.081)
40-60	4.67^a (0.133)	1.80^b (0.100)	3.67^a (0.240)	1.69^b (0.033)	1.20^a (0.000)	0.52^b (0.034)	3.40^a (0.306)	1.30^b (0.047)	3.10^a (0.058)	2.04^b (0.079)
60-80	2.65^a (0.535)	1.05^b (0.040)	2.27^a (0.133)	1.06^b (0.000)	0.37^a (0.033)	0.23^a (0.023)	2.20^a (0.115)	0.56^b (0.026)	1.07^a (0.088)	0.64^a (0.034)
80-100	1.73^a (0.176)	0.60^b (0.058)	1.70^a (0.050)	0.20^b (0.002)	0.21^a (0.013)	0.08^a (0.000)	0.80^a (0.115)	0.21^a (0.026)	0.76^a (0.014)	0.16^a (0.039)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value=626.30 p value < 0.01		F value=115.97 p value < 0.01		F value= 376.39 p value < 0.01		F value= 123.44 p value < 0.01		F value= 89.86 p value < 0.01	

(Values in parenthesis are standard error of means)

4.2.2.6. *Exchangeable Potassium*

There was a general diminution in exchangeable potassium content with depth (Table 10). Highest concentration was observed in the top 20 cm layer. Teak plantation had higher concentration over surface (101.33 mg kg^{-1}) followed by mahogany (99.88 mg kg^{-1}). Homegarden had significantly lower concentration than other plantations (72.65 mg kg^{-1}). Comparing the variation in phosphorous content from surface to 1m depth, mahogany plantation showed lesser reduction over depth with 32 percent reduction from 20cm depth to 1m depth and highest reduction was observed for teak (53%). Homegarden and acacia had similar decrease over depth (46%) while mango had 41 percent reduction in potassium content with depth. At 1m depth, mahogany plantation had highest potassium concentration (67.67 mg kg^{-1}) and teak had the least (37.97 mg kg^{-1}).

Analysis of variance for exchangeable potassium showed that woody ecosystems had significantly higher concentration than contiguous open plots. (Table 11). Mahogany had considerable larger addition than open plots. An increase of 152 percent over open plot was observed for the surface layer which decreased with depth (120%, 116%, 108%, and 97%). A reduction in percent increase over open plot was observed with depth in the selected woody systems. Homegarden had least potassium increment than open plot in all depth groups (32%, 28%, 28%, 4.9%, and 18%). Acacia and teak, despite of the larger increment from treeless plot at surface (20 cm), (66% and 101%), had comparable increment with homegarden at 80 cm depth (16% and 17%) (Figure 29-33).

Table 10. Exchangeable potassium concentration across selected woody ecosystems in Central Kerala

Depth (cm)	Exchangeable potassium concentration (mg kg^{-1})				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	72.65_{A}^{c} (2.13)	82.13_{A}^{b} (0.82)	86.32_{A}^{b} (5.30)	101.33_{A}^{a} (3.45)	99.88_{A}^{a} (2.44)
20-40	68.48_{A}^{b} (2.89)	79.80_{A}^{a} (0.91)	62.03_{B}^{b} (0.69)	81.00_{B}^{a} (3.17)	83.92_{B}^{a} (3.54)
40-60	59.85_{B}^{c} (1.85)	70.75_{B}^{ab} (1.20)	58.20_{BC}^{c} (0.86)	63.81_{C}^{bc} (2.25)	76.72_{C}^{a} (0.38)
60-80	49.07_{C}^{c} (2.59)	52.25_{C}^{bc} (2.64)	54.13_{CD}^{bc} (0.83)	56.55_{D}^{d} (1.52)	71.35_{CD}^{a} (0.23)
80-100	39.15_{D}^{d} (1.76)	44.30_{D}^{cd} (0.91)	50.60_{D}^{bc} (0.33)	37.97_{E}^{d} (6.42)	67.67_{D}^{a} (1.65)

Plantation (F value) = 54.29 p value < 0.01
Depth (F value) = 196.45 p value < 0.01
Interaction (F value) = 6.79 p value < 0.01

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 11. Exchangeable potassium concentration across selected woody ecosystems and their contiguous open plots in Central Kerala

Depth (cm)	Exchangeable potassium concentration (mg kg^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	72.65^{a} (2.13)	55.22^{b} (0.90)	82.13^{a} (0.82)	49.60^{b} (0.95)	86.32^{a} (5.29)	51.70^{b} (0.17)	101.33^{a} (3.45)	50.40^{b} (0.64)	99.88 (2.44)^{a}	39.67^{b} (0.15)^{c}
20-40	68.48^{a} (2.89)	53.48^{b} (1.61)	79.80^{a} (0.91)	42.42^{b} (0.59)	62.03^{a} (0.86)	48.60^{b} (0.60)	81.00^{a} (3.17)	37.07^{b} (0.33)	83.92^{a} (3.54)	38.05^{b} (0.24)
40-60	59.85^{a} (1.85)	46.65^{b} (0.60)	70.75^{a} (1.20)	37.88^{b} (0.26)	58.20^{a} (0.83)	38.47^{b} (0.25)	63.82^{a} (2.25)	32.13^{b} (0.47)	76.72^{a} (0.38)	35.60^{b} (0.31)
60-80	49.07^{a} (2.58)	46.77^{b} (0.32)	52.25^{a} (2.64)	34.92^{b} (0.33)	54.13^{a} (0.33)	35.60^{b} (0.10)	56.55^{a} (1.52)	34.35^{b} (0.22)	71.35^{a} (0.23)	34.30^{b} (0.21)
80-100	39.15^{a} (1.76)	33.28^{b} (0.34)	44.30^{a} (0.90)	38.30^{b} (0.63)	50.60^{a} (0.69)	33.23^{b} (0.61)	37.97^{a} (6.41)	32.13^{a} (0.46)	67.67^{a} (1.65)	34.35^{b} (0.14)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value= 77.04 p value< 0.01		F value= 253.38 p value< 0.01		F value= 50.05 p value< 0.01		F value= 77.09 p value< 0.01		F value= 277.53 p value< 0.01	

(Values in parenthesis are standard error of mean)

4.3.3. Soil carbon and nutrient stocks

4.3.3.1. *Carbon stock*

Woody ecosystems had significant effect on soil carbon sequestration across depth (Table 12). Total carbon stock over 1m was highest for mahogany plantation (116.01 Mg C ha^{-1}) followed by homegarden (105.41 Mg C ha^{-1}) (Figure 3) while Acacia had lowest carbon stock (75.19 Mg C ha^{-1}). Almost half of the total carbon stock was stored in the top 40cm soil depth for all the species. For instance, the top soil (0-40 cm) carbon content for mahogany was almost 60 percent of the total carbon stock in 1m soil depth. Similarly, teak registered about 55 percent of the total soil C stock in the surface 0-40 cm soil depth. Also, there was consistent reduction in carbon content with depth in the selected woody ecosystems. However, fairly good amount of carbon was retained in the deeper depths for all ecosystems. For instance, homegarden soil retained about 16 percent of the total carbon stock in the deepest soil layer (80-100 cm). The corresponding values for other ecosystems were acacia (12.22%), mango (15.47%), teak (12.33%) and mahogany (11.59%).

All the woody ecosystems showed consistently higher soil carbon sequestration compared to their contiguous treeless open soils (Table 13). Interestingly, all the open soils were having uniform carbon stocks that showed a narrow range of 49.78 (mango) to 59.44 Mg C ha^{-1} (homegarden). Among the systems, the overall improvement in C stocks was the highest for mahogany followed by teak, homegarden, mango and acacia. The corresponding increase compared to contiguous open treeless soils was: mahogany (125.26%), teak (85.61%), homegarden (77.33%), mango (52.8%) and the least for acacia (29.17%) (Figure 2).

Homegarden represented the highest improvement in soil carbon stock in the surface soils (0-20 cm) as compared to open soil followed by teak and mahogany. For instance, homegardens showed as much as 100 percent increase (45.97 Mg C ha^{-1}) in soil C content as compared to adjacent open soil in the surface soil layer (0-20 cm). Corresponding values for other systems in the top soil were: 93.5 percent (teak; 47.51 Mg C ha^{-1}), 88.1 percent (mahogany; 64.51 Mg C ha^{-1}), 42 percent (mango; 26.3 Mg C ha^{-1}) and least value of 37.02 percent (16.98Mg C ha^{-1}) for acacia. Fairly high soil carbon buildup was observed for woody systems even at deeper soil depths (80-100 cm). Interestingly mango system showed remarkably high soil carbon at deep soil to the tune of 444 percent increase as compared to the contiguous open soil. Other prominent system that increased C stock at deeper depths compared to open soil were mahogany (120.13%), teak (115%) and homegarden (73.38%) while acacia showed the lowest increase (37.57%) (Figure 2).

4.3.3.2. *Nitrogen stock*

Mahogany plantation had higher stock over all depths with a total stock of 53.61 Mg N ha^{-1} over m depth, against a stock of 22.49 Mg N ha^{-1} in treeless control, followed by teak (38.29 Mg N ha^{-1}). Lowest nitrogen stock was observed in mango orchard (26.72 Mg N ha^{-1}). The variation is not significant for interaction (Table 14).

Total nitrogen stock shows considerable enhancement over treeless control plots (Figure 5). All woody ecosystems had remarkably high nitrogen stock than their contiguous open plot (Table 15). Analysis of variance showed that homegarden, acacia, teak and mahogany had significantly higher nitrogen stock than treeless control at all depths while for mango, the increase was not significant after 40 cm (Table 14). Nitrogen stock in each ecosystem was higher in 0-20cm layers. Nearly half of total nitrogen stock is concentrated in the top 40cm depth, while mahogany had about 61 percent of stock in the top 40cm layer followed by teak (56%), acacia (52%), mango (49%) and homegarden (46%). A similar pattern was seen for open plots as well, where treeless open soils of mahogany and teak had higher allocation in top layer (62%) (Figure 4).

On comparison with treeless plots total stock increment was higher in mahogany plantation. Mahogany had an increment of 31.12 Mg N ha^{-1} (138%) from its contiguous open plot followed by teak (19.11 Mg N ha^{-1}; 99.6%), homegarden (14.01 Mg N ha^{-1}; 87%), acacia (8.92 Mg N ha^{-1}; 50%) and least was observed for mango woody ecosystem (4.88 Mg N ha^{-1}; 22%). At the surface too, mahogany had higher increment of 132 percent over treeless control plot. Similarly remaining woody ecosystems, teak (99%), mango (79%), homegarden (63%) and acacia (55%) showed considerable increase over open soil at surface. At deeper depth (80-100 cm), the increment was not as much prominent as surface in mango and acacia. For instance, mango only had an increase of 6 percent from open plots and acacia had 35 percent increase over treeless, while homegarden, mahogany and teak had higher addition of nitrogen stock than treeless plot even at deeper depth (76%, 145% and 81% respectively) (Figure 4).

Table 12. Soil carbon sequestration across selected woody ecosystems in Central Kerala

Depth (cm)	Soil carbon sequestration (Mg C ha^{-1})				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	26.68_{A}^{d} (0.78)	23.13_{A}^{cd} (0.43)	21.14_{A}^{bc} (3.01)	33.36_{A}^{a} (2.61)	37.17_{A}^{a} (3.65)
20-40	21.95_{BC}^{b} (2.20)	16.25_{BC}^{c} (0.37)	16.14_{B}^{c} (2.42)	24.30_{BC}^{b} (2.47)	33.18_{A}^{a} (0.42)
40-60	21.81_{C}^{a} (0.62)	13.73_{C}^{c} (0.33)	15.42_{BC}^{c} (1.70)	20.12_{C}^{ab} (1.68)	16.73_{B}^{bc} (0.94)
60-80	18.36_{CD}^{a} (0.82)	12.88_{CD}^{b} (0.79)	11.61_{BC}^{b} (1.04)	12.52_{DE}^{b} (0.92)	15.48_{B}^{ab} (0.63)
80-100	16.61_{D}^{a} (0.44)	9.19_{D}^{b} (0.46)	11.77_{C}^{b} (0.86)	12.70_{E}^{ab} (0.40)	13.45_{C}^{ab} (0.39)
Total	105.41 (4.86)	75.19 (2.38)	76.08 (9.03)	103 (8.08)	116.01 (6.03)
Plantation (F value) = 28.89 p value < 0.01 Depth (F value) = 85.90 p value < 0.01 Interaction (F value) = 5.64 p value < 0.01					

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 13: Soil carbon sequestration across selected woody ecosystems and their contiguous open plots in Central Kerala

Depth (cm)	Soil carbon sequestration (Mg C ha^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	26.68^{a} (0.78)	13.33^{b} (0.17)	23.13^{a} (0.43)	16.88^{b} (0.52)	21.14^{a} (3.01)	14.88^{b} (0.18)	33.36^{a} (2.61)	17.24^{b} (0.05)	37.17^{a} (3.65)	19.76^{b} (2.07)
20-40	21.95^{a} (2.20)	14.71^{b} (0.14)	16.25^{a} (0.37)	15.31^{a} (0.40)	16.14^{a} (2.42)	12.12^{a} (0.19)	24.30^{a} (2.47)	16.96^{b} (0.11)	33.18^{a} (0.42)	12.29^{b} (1.38)
40-60	21.81^{a} (0.62)	11.42^{b} (0.27)	13.73^{a} (0.33)	10.01^{b} (0.29)	15.42^{a} (1.70)	10.93^{b}	20.12^{a} (1.68)	9.03^{b} (0.08)	16.73^{a} (0.94)	6.83^{b} (0.61)
60-80	18.36^{a} (0.81)	10.40^{b} (0.07)	12.88^{a} (0.79)	9.33^{b} (0.25)	11.61^{a} (1.04)	9.69^{a}	12.52^{a} (0.92)	6.36^{b}	15.48^{a} (0.63)	6.51^{b} (0.84)
80-100	16.61^{a} (0.44)	9.58^{b} (0.11)	9.19^{a} (0.46)	6.68^{b} (0.60)	11.77^{a} (0.86)	2.16^{b}	12.70^{a} (0.40)	5.90^{b}	13.45^{a} (0.39)	6.11^{b} (1.58)
Total	105.41 (4.86)	59.44 (0.76)	75.19 (2.38)	58.21 (2.06)	76.08 (9.03)	49.78 (0.37)	103 (8.08)	55.49 (0.24)	116.01 (6.03)	51.5 (6.48)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value= 47.16 p value< 0.01		F value= 105.87 p value< 0.01		F value= 12.34 p value< 0.01		F value= 40.63 p value< 0.01		F value= 77.30 p value< 0.01	

(Values in parenthesis are standard error of mean)

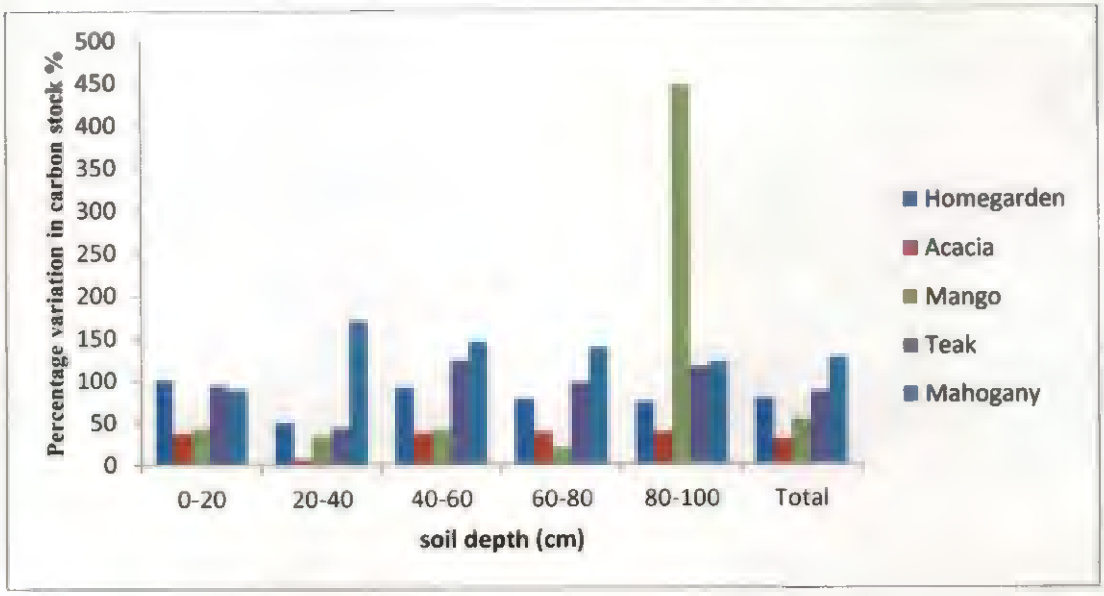

Figure 2. Percentage variation in soil carbon stock in the selected woody ecosystem from its contiguous open plots in Central Kerala.

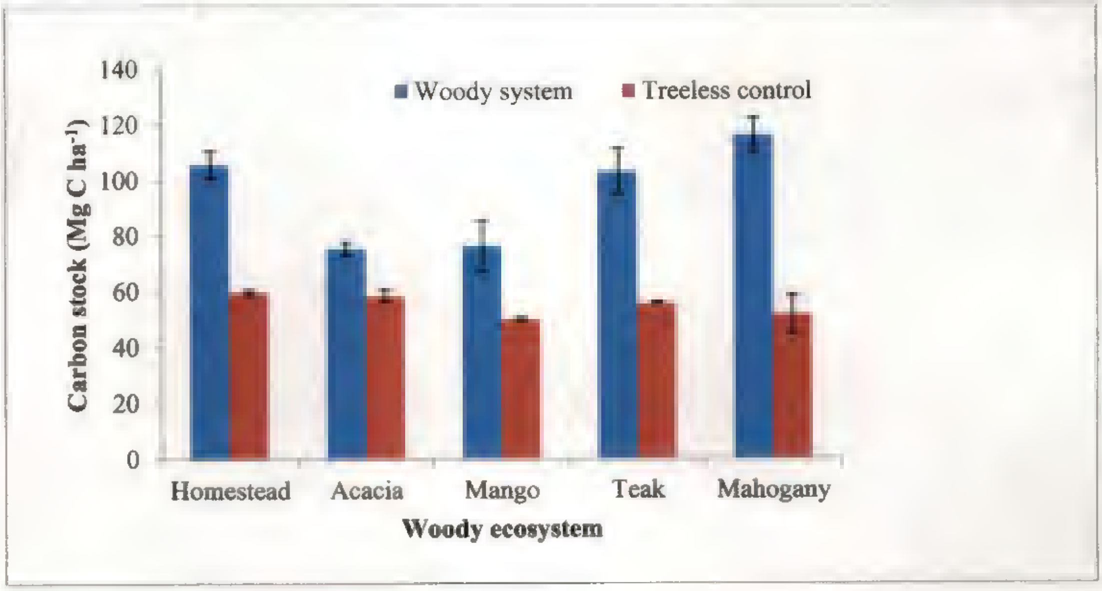

Figure 3. Total carbon stock in soil over 1m depth across selected woody ecosystems in Central Kerala

Table 14. Nitrogen stock across in soils of selected woody ecosystems in Central Kerala

Depth (cm)	Nitrogen stock (Mg N ha^{-1})				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	7.66 (0.36)	6.45 (0.33)	7.82 (0.23)	9.83 (0.54)	13.63 (0.73)
20-40	6.17 (0.61)	6.05 (0.39)	6.35 (1.17)	8.54 (0.80)	12.06 (1.00)
40-60	6.17 (0.27)	5.23 (0.35)	5.50 (0.18)	7.17 (0.62)	9.11 (0.89)
60-80	5.49 (0.23)	4.80 (0.41)	4.08 (0.29)	6.67 (0.52)	10.31 (0.41)
80-100	4.68 (0.39)	4.24 (0.12)	2.97 (0.18)	6.08 (0.61)	8.50 (0.95)
Total	30.17 (1.86)	26.77 (1.6)	26.72 (2.05)	38.29 (3.09)	53.61 (3.98)

Plantation (F value)= 78.15 p value < 0.01
Depth (F value)= 32.53 p value < 0.01
Interaction (F value)= n.s p value = 0.261

(Values in parenthesis are standard error of means)
(n.s means non significant)

Table 15. Nitrogen stock in soils of selected woody ecosystems and their contiguous open plots in Central Kerala

Depth (cm)	Nitrogen stock (Mg N ha^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	7.66^{a} (0.36)	4.71^{b} (0.21)	6.45^{a} (0.33)	4.15^{b} (0.18)	7.82^{a} (0.23)	4.36^{b} (0.17)	9.83^{a} (0.54)	4.93^{b} (0.20)	13.63^{a} (0.73)	5.88^{b} (0.19)
20-40	6.17^{a} (0.61)	3.90^{b} (0.00)	6.05^{a} (0.39)	3.89^{b} (0.19)	6.35^{a} (1.17)	4.58^{b} (0.33)	8.54^{a} (0.80)	4.15^{b} (0.34)	12.06^{a} (1.00)	4.48^{b} (0.18)
40-60	6.17^{a} (0.27)	3.75^{b} (0.23)	5.23^{a} (0.35)	3.50^{b}	5.50^{a} (0.18)	4.66^{a} (0.21)	7.17^{a} (0.62)	3.53^{b} (0.19)	9.11^{a} (0.89)	4.22^{b} (0.18)
60-80	5.49^{a} (0.23)	2.93^{b} (0.21)	4.80^{a} (0.41)	3.18^{b}	4.08^{a} (0.29)	4.45^{a} (0.23)	6.67^{a} (0.52)	3.21^{b} (0.20)	10.31^{a} (0.41)	4.45^{b} (0.22)
80-100	4.68^{a} (0.39)	2.65^{b} (0.00)	4.24^{a} (0.12)	3.13^{b}	2.97^{a} (0.18)	2.79^{a} (0.22)	6.08^{a} (0.61)	3.36^{b} (0.20)	8.50^{a} (0.95)	3.46^{b} (0.22)
Total	30.17 (1.86)	16.16 (0.65)	26.77 (1.6)	17.85 (0.37)	26.72 (2.05)	20.84 (1.16)	38.29 (3.09)	19.18 (1.13)	53.61 (3.98)	22.49 (0.99)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value= 27.20 p value< 0.01		F value= 21.07 p value< 0.01		F value= 10.25 p value< 0.01		F value= 23.88 p value< 0.01		F value= 36.46 p value< 0.01	

(Values in parenthesis are standard error of mean)

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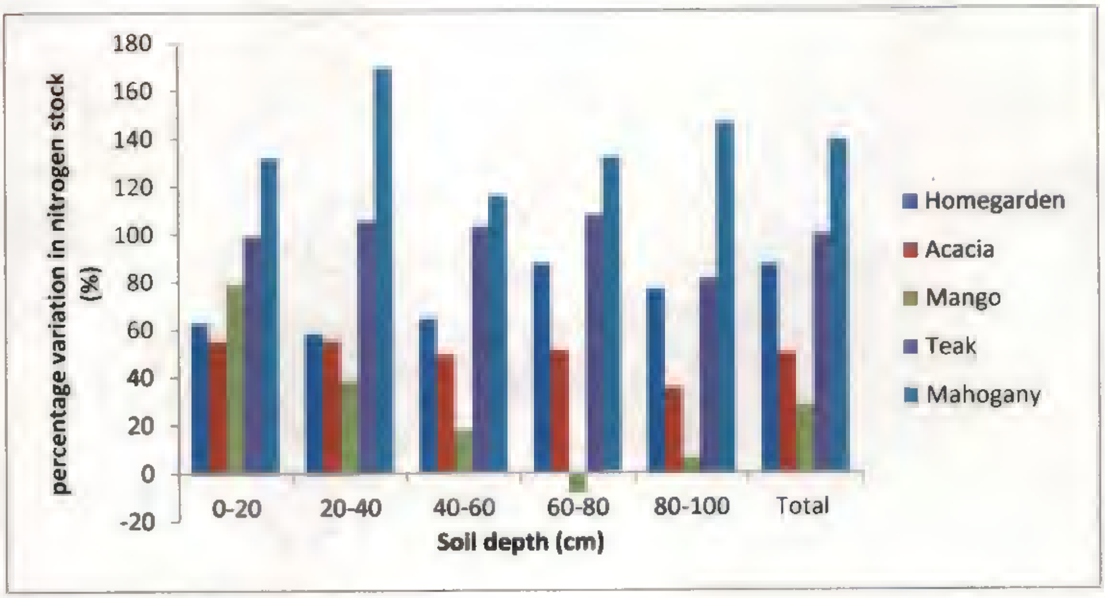

Figure 4. Percentage variation in soil nitrogen stock in woody ecosystem from corresponding contiguous open plot in Central Kerala

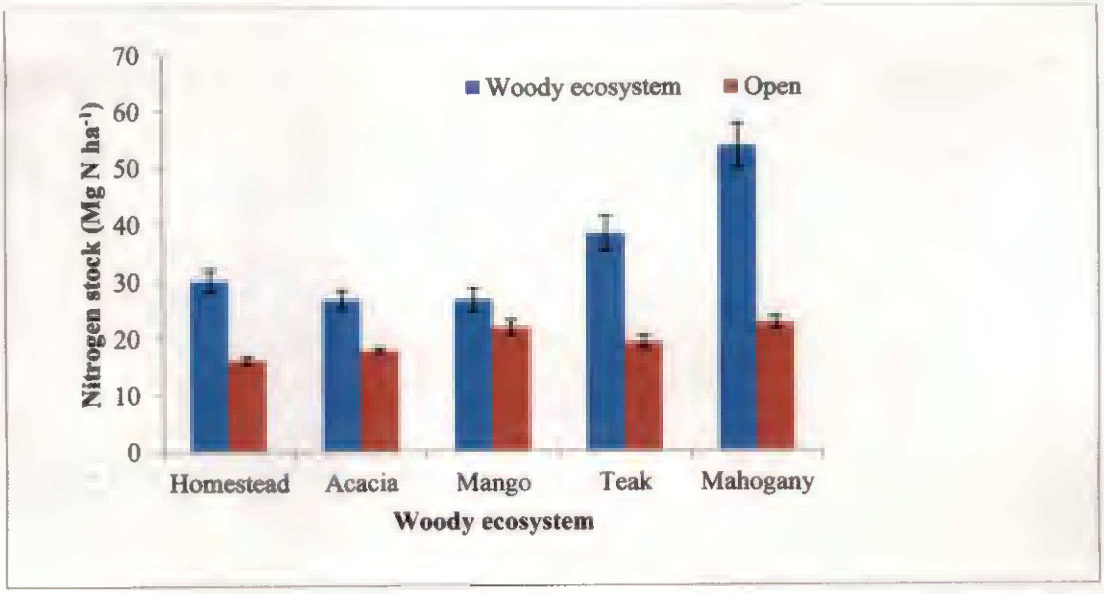

Figure 5. Total nitrogen stock in soil over 1m depth across selected woody ecosystems in Central Kerala

4.3.3.3. *Phosphorous stock*

Total phosphorous stock over 1m depth in soils of selected woody ecosystems is presented in Table 16 and Figure 7. Phosphorous stock over 1m was higher in homegarden (154.56 kg P ha^{-1}) followed by teak (65.33 kg P ha^{-1}) (Table 15). Mango orchard had the least phosphorous stock of 15.24 kg P ha^{-1}. At surface, homegarden had a phosphorous content of 75.96 kg P ha^{-1} which decreased to 4.95 kg P ha^{-1} at 80-100 cm soil layer. When compared with treeless control plots homegarden had fairly high buildup than other woody ecosystem especially in the surface horizons. The increase from treeless plot was in the order of homegarden (449%), teak (198%), acacia (163%), mango (80%), and mahogany (65%) (Figure 6). The entire selected woody ecosystems had fairly high phosphorous content in the top layer. Corresponding values were homegarden (410%), teak (245%), acacia (225%), mango (110%), and mahogany (80%). Even in the deep layers also the woody systems maintained higher buildup. Mahogany irrespective of lower increment at surface had fairly high buildup in the deepest soil layer. With increasing depth, phosphorous stock reduced severely. Most of the systems had about 90 percent decline in phosphorous content at deeper depths (homegarden, 93%; mango; 93%, teak, 94%; mahogany, 90%). Acacia had comparatively lower reduction (71%). Homegarden had higher concentration than other ecosystems at each depth layer. Mango had lowest phosphorous content at surface as well as at 1m depth (7.19 kg P ha^{-1}and 0.50 kg P ha^{-1}). Large proportion of total stock was concentrated in the top 40 cm depth in each ecosystem. Homegarden had about 82.9 percent of total phosphorous stock in 40 cm depth. Similar trend was observed for teak (81.5%), mango (71.3%), and mahogany (70.6%). Acacia had comparatively shallower distribution across depth with 58.6 percent of total stock distributed in the top 40 cm depth.

Table. 17 depict the variation across selected systems and treeless control plots. Acacia had significantly higher value in each depth while a non-significant high value was recorded at 80-100 cm depth for homegarden, mango, teak and mahogany woody systems. Variation in total phosphorous stock over 1m was highest for homegarden with an increase of 126.43 kg P ha^{-1}from treeless control and lowest in mango woody ecosystem (6.77 kg P ha^{-1}).

4.3.3.4. *Potassium stock*

The trends in potassium stock across depth and plantation is depicted in Table 18. There was significant variation across depth and plantation. Highest potassium stock was recorded in the mahogany plantation (1030.06 kg K ha^{-1}) followed by teak (857.55kg K ha^{-1}), homegarden (813.58 kg K ha^{-1}), acacia (805.88 kg K ha^{-1}). Mango orchard had the least stock (721.05 kg K ha^{-1}). In the surface layer, teak had higher potassium stock (256.91 kg K ha^{-1}) followed by mahogany plantation (247.92 kg K ha^{-1}) (Figure 9). There was no significant variation between homegarden, acacia and mango though. A general declining trend was observed across depth. At deeper layer, mahogany had higher stock (177.50 kg K ha^{-1}). Although teak had higher concentration at surface there was a sharp reduction with depth. Only 11 percent of total stock was retained in the deeper layers. Corresponding value for other systems were mahogany 17 percent, mango 16 percent, acacia 14 percent, homegarden 13 percent.

Comparison of potassium stock in woody ecosystems and treeless control over each depth group is illustrated in Table 19 and Figure 8. Each system was significantly different from its contiguous treeless plots in each depth groups. Figure 24 portrays the comparison of total potassium stock over 1m depth in woody ecosystems and open plots. It shows that mahogany plantation had higher variation from open plot (136%) and least variation was observed for homegarden (30%) (Table 22). Likewise, in the surface soil within 20cm depth, mahogany plantation had highest increment over treeless (172%). Teak (113%), mango (73%) and acacia (79%) also had considerably high increment from treeless control. Homegarden had comparatively low increase over treeless soil (43%). Along with depth, the increment reduced considerably. At 1m depth mahogany had about 97 percent increase over treeless control plot followed by mango (30%), teak (24%), acacia (18%) and homegarden (17%).

Table 16. Phosphorous stock in soils of selected woody ecosystems in Central Kerala

Depth (cm)	Phosphorous stock (kg P ha^{-1})				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	75.96^{Aa} (1.85)	12.83^{Ad} (0.79)	7.19^{Ae} (0.42)	33.19^{Ab} (2.67)	19.25^{Ac} (2.11)
20-40	52.08^{Ba} (6.48)	10.30^{Ac} (0.67)	3.68^{ABd} (0.16)	16.13^{Bb} (1.16)	10.94^{Bc} (0.21)
40-60	13.97^{Ca} (0.23)	9.00^{Ab} (0.76)	3.03^{ABc} (0.31)	8.65^{Cb} (0.81)	7.77^{Bb} (0.19)
60-80	7.59^{Da} (1.30)	3.50^{Aabc} (0.53)	0.84^{Bc} (0.09)	5.54^{CDab} (0.67)	2.81^{Cbc} (0.12)
80-100	4.95^{Da} (0.67)	3.70^{Ba} (0.47)	0.50^{Ba} (0.09)	2.02^{Da} (0.27)	1.99^{Ca} (0.05)
Total	154.56 (10.53)	39.43 (3.22)	15.24 (1.07)	65.53 (5.58)	42.76 (2.68)

Plantation (F value) = 226 p value < 0.01
Depth (F value) = 253.30 p value < 0.01
Interaction (F value) =56.12 p value < 0.01

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 17. Phosphorous stock in soils of selected woody ecosystems and their contiguous open plots in Central Kerala

Depth (cm)	Phosphorous stock (kg P ha^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	75.96^{a} (1.85)	14.89^{b} (0.38)	12.83^{a} (0.79)	3.94^{b} (0.05)	7.19^{a} (0.42)	3.42^{b} (0.10)	33.19^{a} (2.67)	9.65^{b} (0.42)	19.25^{a} (2.11)	10.68^{b} (0.24)
20-40	52.08^{a} (6.48)	3.86^{b} (0.09)	10.30^{a} (0.67)	3.83^{b} (0.11)	3.68^{a} (0.16)	2.83^{b} (0.06)	16.13^{a} (1.16)	7.58^{b} (0.16)	10.94^{a} (0.21)	8.57^{b} (0.18)
40-60	13.97^{a} (0.23)	5.12^{b} (0.28)	9.00^{a} (0.76)	3.99^{b} (0.08)	3.03^{a} (0.31)	1.34^{b} (0.09)	8.65^{a} (0.81)	2.93^{b} (0.11)	7.77^{a} (0.19)	4.55^{b} (0.18)
60-80	7.59^{a} (1.30)	2.65^{a} (0.10)	3.50^{a} (0.53)	2.73^{b} (0.00)	0.84^{a} (0.09)	0.67^{a} (0.06)	5.54^{a} (0.67)	1.36^{b} (0.06)	2.81^{a} (0.12)	1.72^{a} (0.09)
80-100	4.95^{a} (0.67)	1.61^{a} (0.16)	3.70^{a} (0.47)	0.50^{b} (0.00)	0.50^{a} (0.09)	0.21^{a} (0.00)	2.02^{a} (0.27)	0.50^{a} (0.06)	1.99^{a} (0.05)	0.41^{a} (0.10)
Total	154.56 (10.53)	28.13 (1.01)	39.43 (3.22)	14.99 (0.24)	15.24 (1.07)	8.47 (0.31)	65.53 (5.58)	22.02 (0.81)	42.76 (2.68)	25.93 (0.79)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value = 132.56 p value < 0.01		F value = 70.26 p value < 0.01		F value = 133.30 p value < 0.01		F value = 97.65 p value < 0.01		F value = 71.94 p value < 0.01	

(Values in parenthesis are standard error of mean)

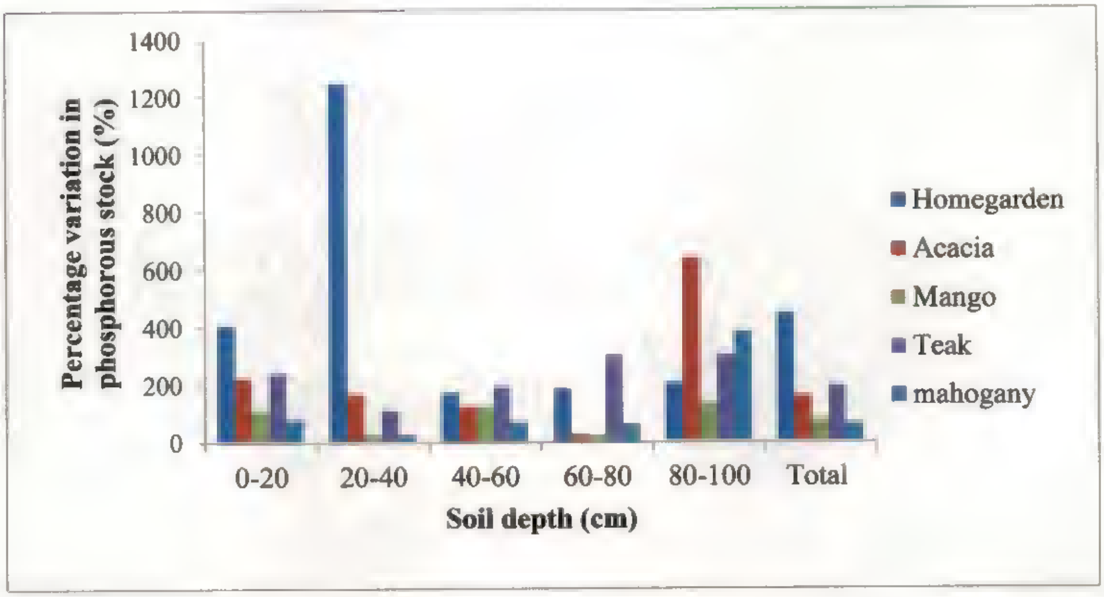

Figure 6. Percentage variation in phosphorous stock in woody ecosystems from its contiguous open plots in Central Kerala.

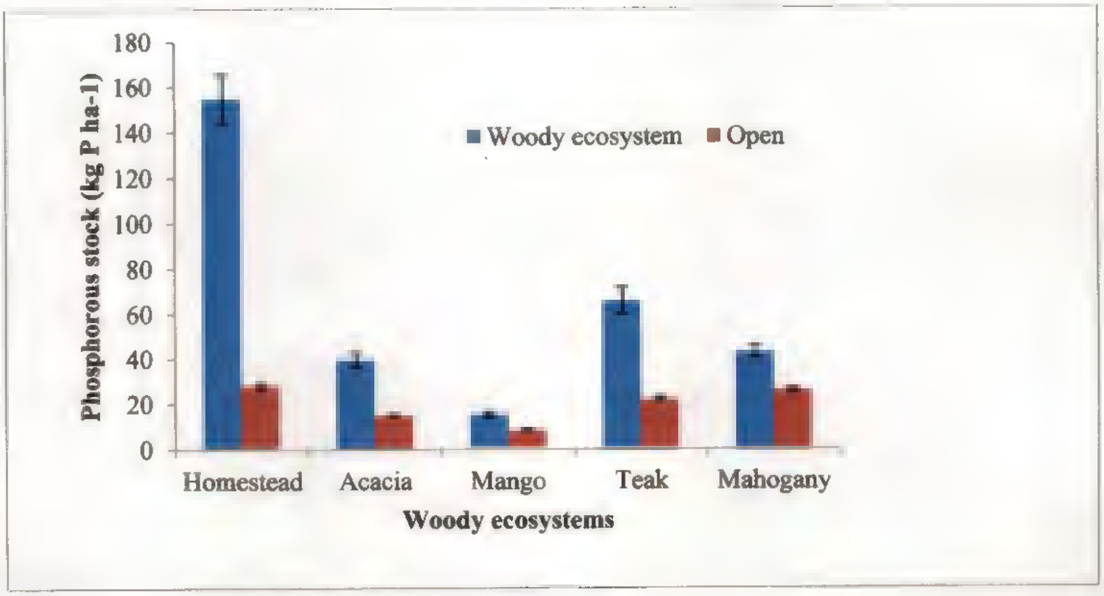

Figure 7. Phosphorous stock in soil over 1m depth across selected woody ecosystems in Central Kerala

Table 18. Potassium stock in soils of selected woody ecosystems in Central Kerala

Depth (cm)	Potassium stock (kg K ha^{-1})				
	Homegarden	Acacia	Mango	Teak	Mahogany
0-20	205.03^{A}_{b} (7.83)	195.09^{A}_{b} (2.89)	189.30^{A}_{b} (11.05)	256.91^{A}_{a} (7.11)	247.92^{A}_{a} (3.56)
20-40	175.82^{B}_{b} (10.26)	195.36^{A}_{ab} (3.16)	142.37^{B}_{c} (4.97)	200.23^{B}_{ab} (15.86)	222.88^{B}_{a} (12.56)
40-60	179.34^{B}_{a} (6.04)	173.34^{B}_{a} (7.13)	147.21^{B}_{b} (16.57)	163.68^{C}_{b} (15.56)	192.45^{C}_{a} (7.22)
60-80	142.44^{C}_{b} (9.84)	127.53^{C}_{b} (12.38)	124.49^{B}_{b} (6.57)	140.86^{C}_{b} (9.02)	189.31^{C}_{a} (7.40)
80-100	104.98^{D}_{d} (8.86)	114.56^{C}_{b} (6.91)	117.68^{B}_{b} (11.31)	95.87^{D}_{b} (15.65)	177.50^{C}_{a} (4.57)
Total	813.58	805.88	721.05	857.55	1030.06

Plantation (F value)=27.40 p value <0.01
Depth (F value)= 72.85 p value<0.01
Interaction (F value)=3.27 p value<0.01

(Values in parenthesis are standard error of means)
(Values with same superscripts do not differ significantly across row)
(Values with same subscripts do not differ significantly across column)

Table 19. Potassium stock in soils of selected woody ecosystems and their contiguous open plots in Central Kerala

Depth (cm)	Potassium stock (kg K ha^{-1})									
	Homegarden	Open	Acacia	Open	Mango	Open	Teak	Open	Mahogany	Open
0-20	205.03^{a} (7.83)	143.39^{b} (2.34)	195.09^{a} (2.89)	108.69^{b} (2.07)	189.30^{a} (11.05)	109.57^{b} (0.37)	256.91^{a} (7.11)	120.69^{b} (1.54)	247.92^{a} (3.56)	91.28^{b} (0.34)
20-40	175.82^{a} (10.26)	140.77^{b} (4.22)	195.36^{a} (3.16)	100.04^{b} (1.38)	142.37^{a} (4.97)	112.64^{b} (1.39)	200.23^{a} (15.86)	88.98^{b} (0.79)	222.88^{a} (12.56)	82.82^{b} (0.51)
40-60	179.34^{a} (6.04)	132.76^{b} (1.70)	173.34^{a} (7.13)	89.46^{b} (0.61)	147.21^{a} (16.57)	99.02^{b} (0.65)	163.68^{a} (15.56)	72.53^{b} (1.06)	192.45^{a} (7.22)	79.28^{b} (0.70)
60-80	142.44^{a} (9.84)	118.74^{b} (0.81)	127.53^{a} (12.38)	89.82^{b} (0.84)	124.49^{a} (6.57)	101.19^{b} (0.30)	140.86^{a} (9.02)	83.77^{b} (0.53)	189.31^{a} (7.40)	92.74^{b} (0.56)
80-100	104.98^{a} (8.86)	89.36^{b} (0.92)	114.56^{a} (6.91)	96.92^{b} (1.58)	117.68^{a} (11.31)	89.90^{b} (1.65)	95.87^{a} (15.65)	77.10^{a} (1.10)	177.50^{a} (4.57)	90.07^{b} (0.38)
Total	813.58 (42.83)	625.02 (9.99)	805.88 (32.47)	484.93 (6.48)	721.05 (50.47)	512.32 (4.36)	857.55 (63.2	443.07 (5.02)	1030.06 (35.31	436.19 (2.49)
	Values with similar super scripts do not differ significantly across corresponding depth groups in each system									
	F value= 32.65 p value< 0.01		F value= 64.98 p value< 0.01		F value= 14.58 p value< 0.01		F value= 42.53 p value< 0.01		F value= 143.96 p value< 0.01	

(Values in parenthesis are standard error of mean)

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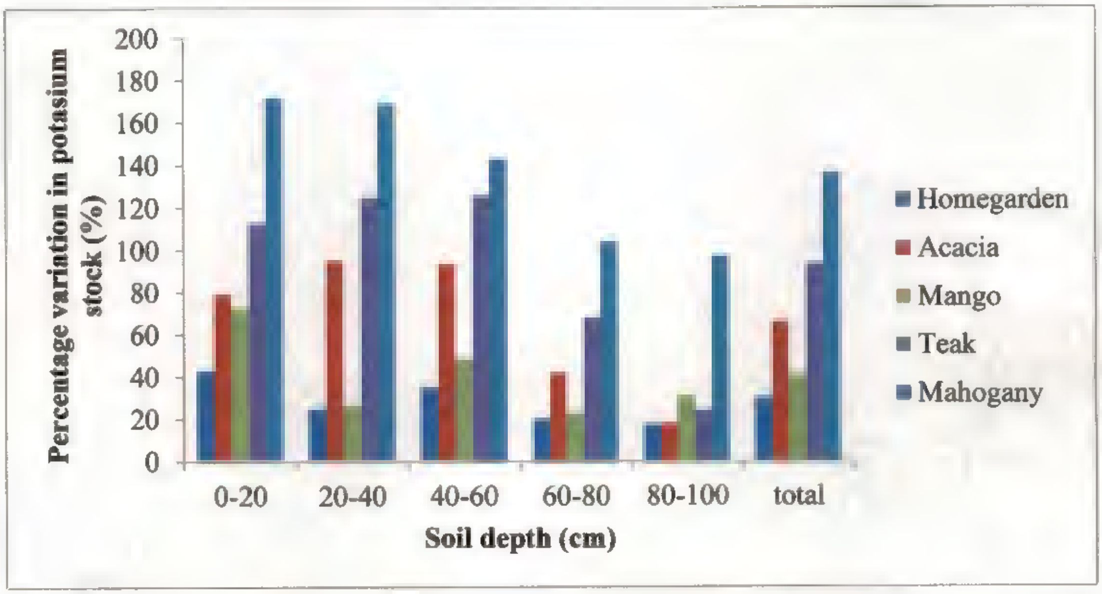

Figure 8. Percentage variation in potassium stock in selected woody ecosystems from its contiguous open plots in Central Kerala

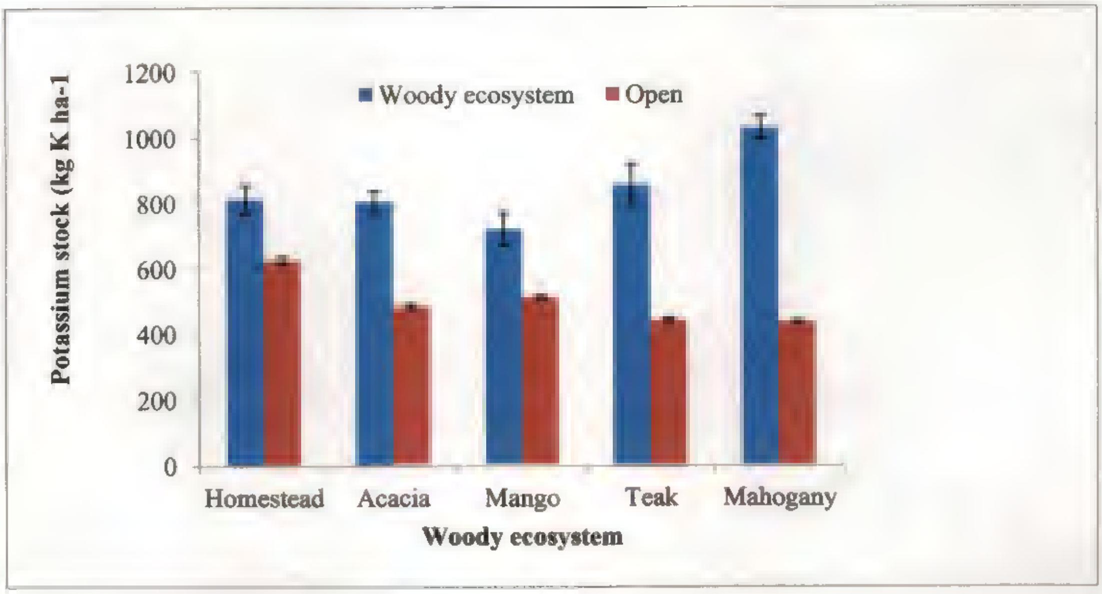

Figure 9. Potassium stock in soil over 1m depth across selected woody ecosystems in Central Kerala

DISCUSSION

The study was done to analyze the variations in soil carbon and nutrient pools across selected woody ecosystems. The variations in soil physical and chemical parameters which were significant across woody ecosystems and depth are discussed here.

5.1. SOIL PHYSICAL PROPERTIES

5.1.1. Bulk density

Bulk density of soil had an increasing trend with depth although not consistent (Table 2). Studies have shown that bulk density increases with depth in relation to organic matter content, porosity and compaction (Chaudari *et al.*, 2013). Porosity and organic matter content had negative correlation with bulk density (Askin and Ozdemir 2003; Sakin 2012; Chaudari *et al.*, 2013). There was no significant difference in bulk density of soils in the selected woody ecosystems with contiguous treeless plots.

5.2. SOIL CHEMICAL PROPERTIES

5.2.2. Soil organic carbon and carbon stock

Investigations on soil organic carbon concentration and carbon stock clearly showed that there was considerable variation among the selected woody ecosystems. Also all the woody ecosystems showed profound variation in C stocks and allocation patterns across soil depths.

The total carbon stock in the soil representing various selected woody ecosystems varied from 75.19 to 116.01 Mg C ha^{-1}. Higher carbon stock was observed in the mahogany plantation and least for mango woody ecosystem. The total carbon stock was in the decreasing order mahogany > homegarden > teak > mango > acacia. The soil organic carbon content of a site is determined by both inherent properties and the extrinsic factors to which the soil is exposed. Among these the type of land use followed has a strong bearing on the soil productivity. Tree based land use systems have prominent role in modifying the soil properties by virtue of their deeper root systems and efficient carbon and nutrient cycling. Since biomass production and carbon sequestration are directly linked with the site quality, woody species, and related silvicultural management practices, different woody ecosystems at different locations may have differences in the carbon stored in the soil (Swamy *et al.*, 2003).

The present study indicated that mahogany plantation had highest carbon stock at one meter soil depth. The woody ecosystems when compared with their contiguous treeless open plots showed that soil carbon sequestration rendered by mahogany was the highest. For instance, mahogany plots had as much as 125% increase in soil C stock as compared to tree less open which acacia had the least value (29%). Percentage increase in soil C stocks compared to contiguous treeless plots was in the order of mahogany > teak > homegarden > mango > acacia. The higher increment of soil carbon stock for mahogany and teak woody systems especially in the top horizons (up to 40cm depth), might be due to longer gestation periods (mahogany > 85 years and teak > 45 years) and associated accumulation of carbon and nutrients to the soil through elemental cycling (Mafongoya *et al.,* 1998). A unique property of woody ecosystems is that they produce more recyclable biomass over long term (Buresh *et al.*, 2004). The primary way of carbon accumulation in the soil is through the return of plant-fixed carbon to the soil mainly through leaves and roots (Lal and Kimble, 2000), which is absent or nearly scarce in a treeless region. The contribution from deep root system in species such as mahogany and teak might help in enhanced contribution to the soil carbon and nutrient pools. The study results converges to the generalization that woody ecosystems have great potential to enrich the soil carbon stocks even at deeper soil depths. Yet another observation is that the present reported C sequestration values for various woody ecosystems were lower as compared to moist deciduous forests (168 Mg ha^{-1}). However, our values were considerably higher than treeless paddy fields (59 Mg ha^{-1}) (Saha *et al.*, 2010).

Present study showed that homegarden also had fairly high carbon stock over 1m depth (105.41 Mg C ha^{-1}). In a similar trial, Saha *et al.* (2010) found that large homegardens in central Kerala had 108.2 Mg C ha^{-1} up to 1m depth which is comparable with the present study. The multi-tier vegetation structure and differential resource absorption potential mimicking natural forests, is explained as the major reasons for high soil carbon sequestration potential of homegardens (Kumar, 2006; Nair *et al.,* 2009). Up to 40cm depth, mahogany had higher stock but in the subsequent layers, homegarden accounted for higher carbon sequestration. A similar pattern was observed in a study on tropical homegardens (Saha, 2009). Since homegardens account for diverse tree species belonging to different age groups, rooting intensity at lower depths may also be higher than monoculture plantations, (Saha, 2009). Consistent with this, homegarden had higher soil carbon stock than its corresponding treeless plots when compared with the monoculture plantations of acacia and mango. Lower carbon sequestration of the mango and acacia, might be the result of lower litter quality (Issac and Nair, 2006) which is yet another important factor deciding carbon contribution to the soil.

Variation in soil organic carbon content across depth suggested a general declining trend with increasing soil depth (Figure 10). The study showed that variation across depth was eventually contributed by the existing woody ecosystem (Table 4; Table 12). Invariably carbon concentration as well as carbon stocks was higher at surface than deeper depths in all woody ecosystems, which is common for all mineral soils (Brady and Weil, 2007). Fine roots of woody perennials are the major source of carbon stock in deeper depths though the root carbon input declines substantially with depth (Buresh *et al.,* 2004). This could be the reason for steep reduction in SOC with depth especially in acacia, teak, and mahogany. Mahogany and teak accounted nearly 60% of total SOC in the top 40cm depth. However, it is interesting to observe that all the woody ecosystems showed higher carbon content in the deeper soil as compared to their corresponding soil depths in the treeless open plots.

Homegarden represented the highest improvement in soil carbon stock in the surface soils (0-20 cm) as compared to open soil, followed by teak and mahogany. Deeper depths of woody ecosystems had remarkably higher SOC and carbon stock while in treeless control plots there was sharp reduction with depth. Teak, mango and mahogany ecosystems had about 100 percent increase in SOC over treeless control plot at the 80cm depth. Mahogany plantation had above 100% increment at all soil depths except top 20 cm layer. Similarly, soils of other woody ecosystems also had relatively higher enrichment at deeper depths. For example mango had about 444% increase against treeless control. Likewise mahogany (120.13%) teak (115%) and homegarden (73.83%) showed much variation even at 80-100cm depth. This distinct change is due to the fact that tree based systems had higher potential to sequester carbon than other systems (Post and Mann, 1990) as the deep-rooted systems store considerable amount carbon deep in the soil (Fisher *et al.*, 1994; Jobbagy and Jackson, 2000). Acacia (37.57%) had comparatively low carbon stock at deeper depth than treeless control. Investigations on soil carbon accretion lead to the general conclusion that woody ecosystems contribute substantially to enrich the soil carbon stocks which however may vary with tree species.

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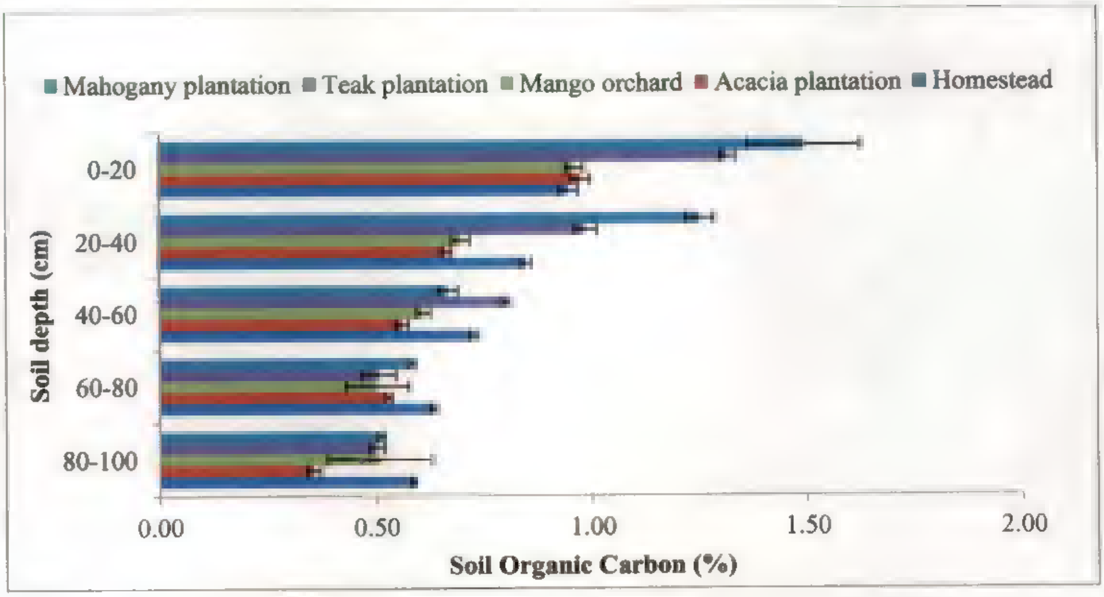

Figure 10. Soil organic carbon in different depth of the selected woody ecosystems in Central Kerala

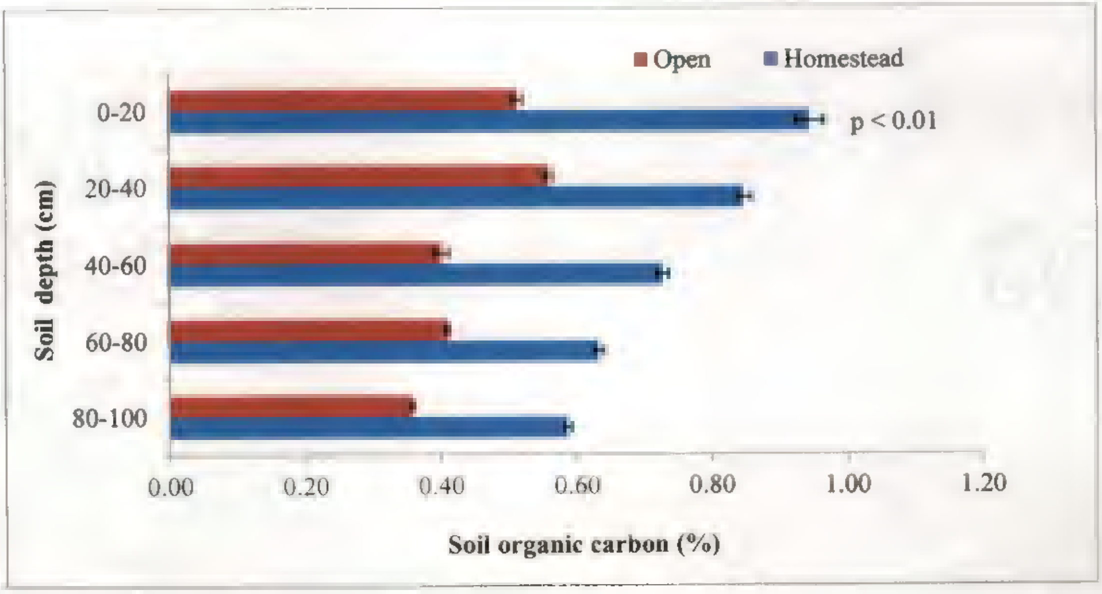

Figure 11. Variation in soil organic carbon at different soil depths of homegarden and contiguous open plot in Central Kerala

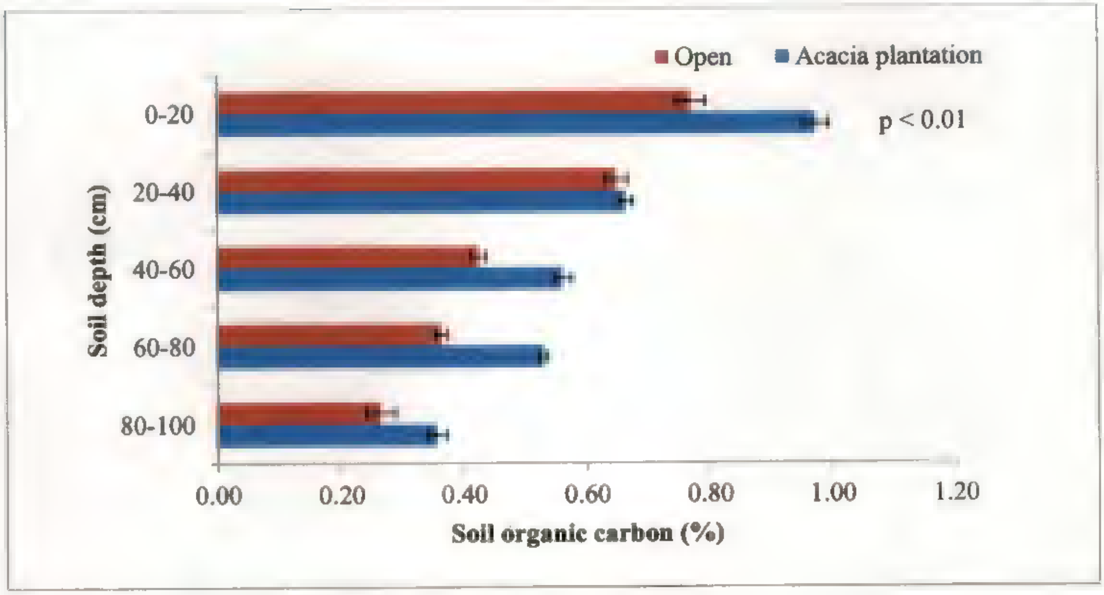

Figure 12. Variation in soil organic carbon at different soil depths of acacia plantation and contiguous open plot in Central Kerala

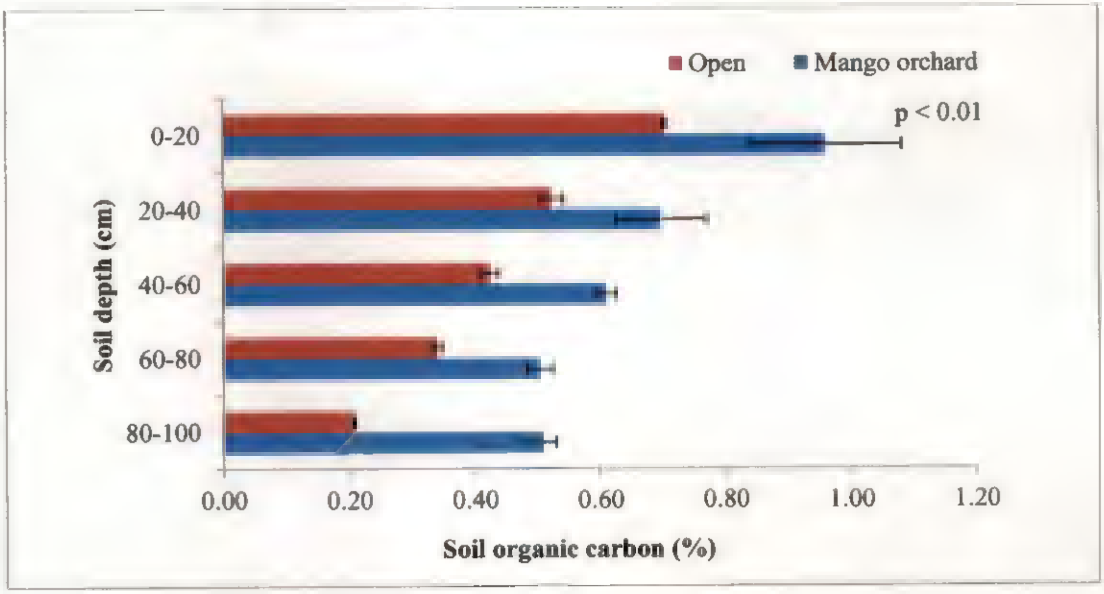

Figure 13. Variation in soil organic carbon at different soil depths of mango woody ecosystem and contiguous open plot in Central Kerala

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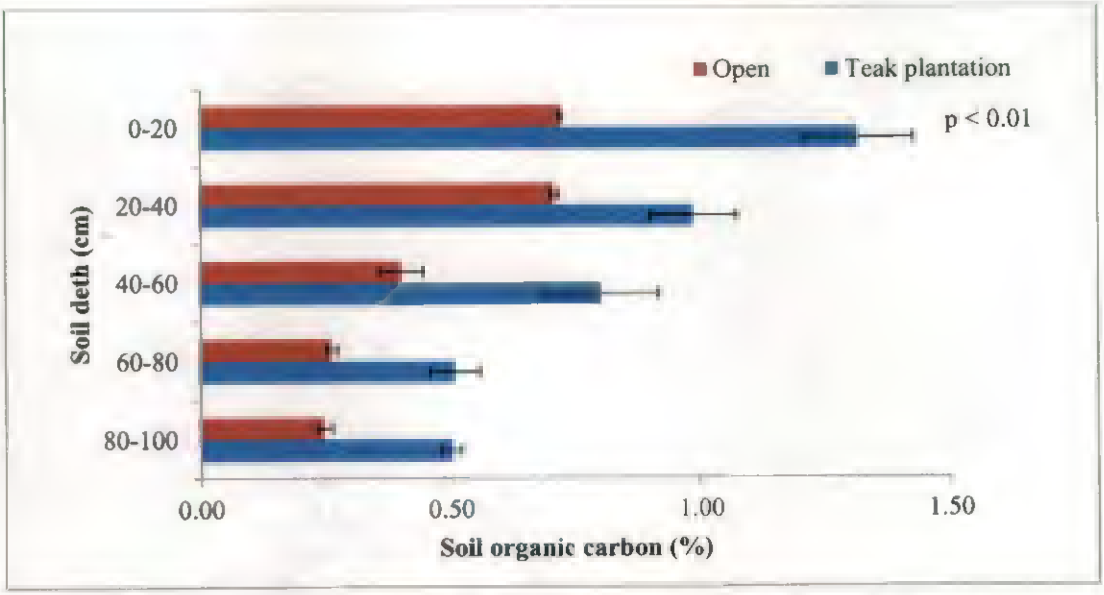

Figure 14. Variation in soil organic carbon at different soil depths of teak plantation and contiguous open plot in Central Kerala

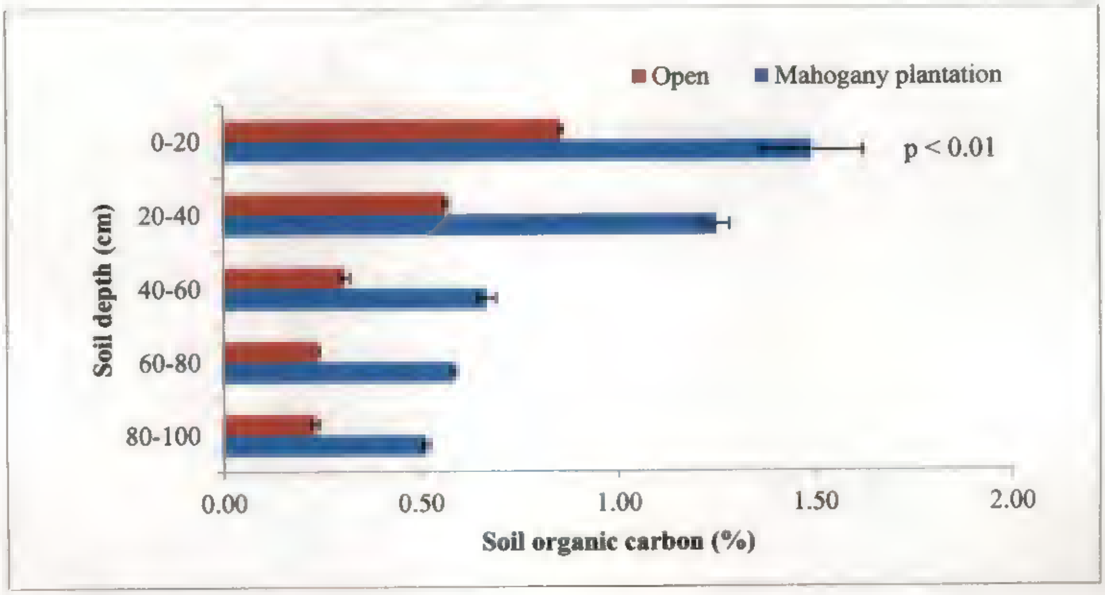

Figure 15. Variation in soil organic carbon at different soil depths of mahogany plantation and contiguous open plot in Central Kerala

5.2.3. Soil nutrient concentration and stock

The order of nitrogen, phosphorous and potassium stock over selected woody ecosystems were:

Nitrogen stock: Mahogany > Teak > Homegarden > Acacia > Mango;
Phosphorous stock: Homegarden > Teak > Mahogany > Acacia > Mango;
Potassium stock: Mahogany > Teak > Homegarden > Acacia > Mango.

Also there was considerably higher increment in nutrient concentration and stocks in the selected woody ecosystem when compared with their respective treeless control. The nutrient concentration in soil is determined by the soil's intrinsic properties and several other external factors like organic matter addition. Furthermore, nature of the existing vegetation had profound influence on the soils' nutrient pool through their litter characteristics (quantity and quality) as well as the belowground root productivity. The root architecture and spatial distribution tree roots also have prominent role in determining the soil nutrient stocks (Lynch, 1995).

Considerable species variation in soil nutrient stocks has been observed in the present study. For instance, acacia and mango consistently had lower total nutrient stock (N, P and K) than homegarden, teak and mahogany. Poor litter quality and associated slow decay process of acacia and mango could be the major reasons for this trend. For example, the safety net mechanism in monoculture plantations is not as much efficient as multistrata-multispecies woody ecosystem such as homegardens (Kumar 2006). Safety net role is important in nutrient cycling through different depths (Schroth *et al.*, 2001, Seneviratne *et al.*, 2006). Also, the monospecific tree stands fails to ensure enough biomass turnover and protection against soil erosion until they are well established (Kumar 2006). In addition, short rotation plantations because of their intensive management and rapid growth rates accounts to rapid nutrient removal from the ecosystem (Kumar *et al.*, 1998). Also when compared with its corresponding treeless plots it is evident that the percentage increase in total nitrogen stock is low for acacia (50%) and mango (28%).

Total nitrogen concentration as well as stocks in soils of treeless control plots was significantly lower compared to that of woody ecosystem (Table 7 and 16). Since nitrogen is mobile and highly soluble in water, the chances to leach out with rain water and erosion is very high (Espinoza *et al.*, n.d). Hence without root system and ground cover, soil nitrogen is highly susceptible to leaching, which might be the reason for low concentration in treeless control plots. Similarly mango had very low phosphorous and potassium enrichment than its corresponding treeless soils (Table 19 and 22).

Total nitrogen, available phosphorous and exchangeable potassium shows a general declining trend when analyzed over soil depth in the selected woody ecosystems (Table 6, Figure 16; Table 8, Figure 22; Table 10, Figure 28). A higher amount of nutrient concentration in upper layer is contributed by high organic matter enrichment through litterfall, herbaceous biomass and intense biological activity in top porous and nutritious soil (Manjunatha *et al.*, 2016). Mineralization or biological breakdown of soil organic matter decreases with depth leading to reduction in nutrient concentration with depth (Buresh *et al.*, 2004). Woody ecosystems had considerably higher concentration of nutrient stocks in each depth. For example, in the top most soil, selected woody ecosystems had 50-112% increase in nitrogen over treeless control. Similarly, for available phosphorous and exchangeable potassium, there was significant enrichment than the corresponding treeless soil across depth. This shows that improvements in soil takes place when it is integrated with trees especially in the surface soil (Kumar, 2006). Although mango had higher nitrogen addition than treeless control plot in the surface soil (79%; 0-20 cm), the increase was marginal at deeper depths (6%; 80-100 cm). Similarly, for acacia also nutrient addition rates were comparatively less at deeper depths than surface, while homegarden, mahogany and teak retained fairly high addition even at deeper depth

(76%, 145% and 81%). Likewise, phosphorous and potassium, increments are higher in the surface soil than deeper depths. This shows that nutrient enrichment as compared with the treeless control plot decreases with depth and variable with tree species. The higher belowground biomass buildup of mahogany and teak consequent to longer lifespan and multistrata-multispecies property of homegarden provide enough litter layer and root activity to maintain comparatively higher nutrient stock even at deeper depths (Mafongaya *et al.*, 1998; Saha 2009).

Woody ecosystems had significant effect on the available phosphorous with soil depth (Table 8). Homegarden ecosystem dominated in the phosphorous concentration especially up to top 60 cm soil depth. Studies have shown that the leaf litter of certain common trees in homegarden (for example *Ailanthus* and *Anacardium*) has higher phosphorous concentration and faster decomposition rate of litter than others (Issac and Nair, 2005).This might be the reason for fairly high phosphorous concentration in the surface layer. This also shows that litter turnover has considerable effect in the surface layers (Ola-Adams and Egunjobi, 1992). Litter quality is an important factor thus governing the decomposition rates. Litter with high phenol and lignin content decompose slowly (Chesson, 1997). Mango litter is high in lignin and phenol that inhibit decomposition, while low in cellulose that favors decomposition (Issac and Nair, 2005). The lower concentration of nutrients over different depths in mango might be due to the lower decomposition rate of litter. It is also obvious that phosphorous is often present in unavailable forms (Buresh *et al.*, 2004), which might be the reason for lower concentration of available phosphorous at deeper depths of selected ecosystems.

Irrespective of being monoculture, teak and mahogany had higher nutrient stocks in soil especially nitrogen and potassium. Both are long rotation crops and in the present study, the teak plantation was about 45 years old and mahogany was above 85 years old. When compared with other fast growing monocultures, teak and mahogany thus had long term addition of nutrients. The larger biomass of the trees favors higher addition of litter and root turnover thereby enriching the soil for long period of time until harvest.

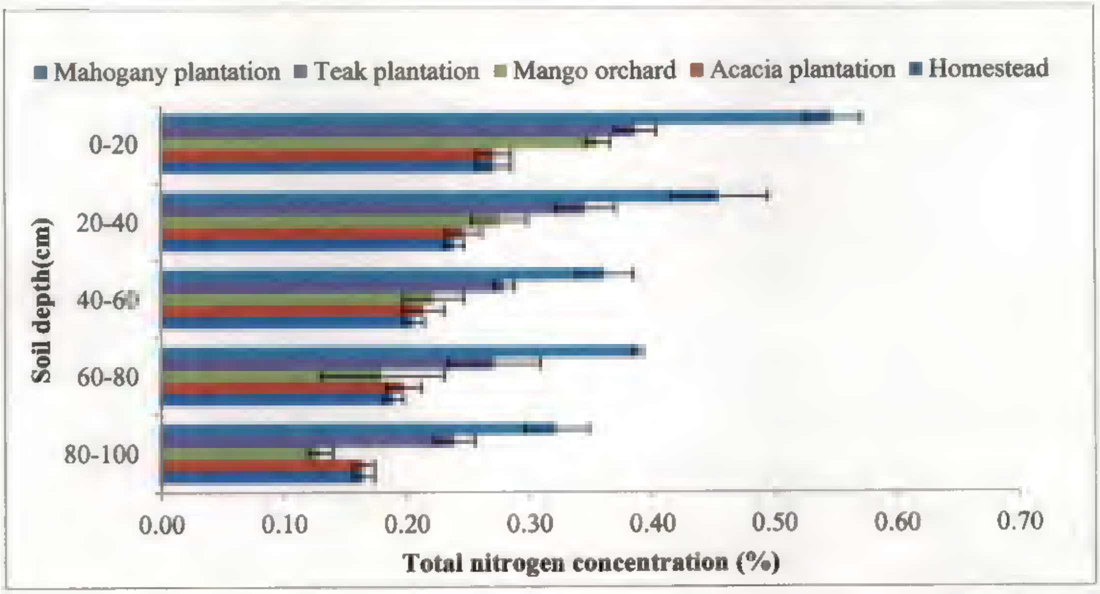

Figure 16: Total nitrogen concentration in different soil depth of the selected woody ecosystems in Central Kerala

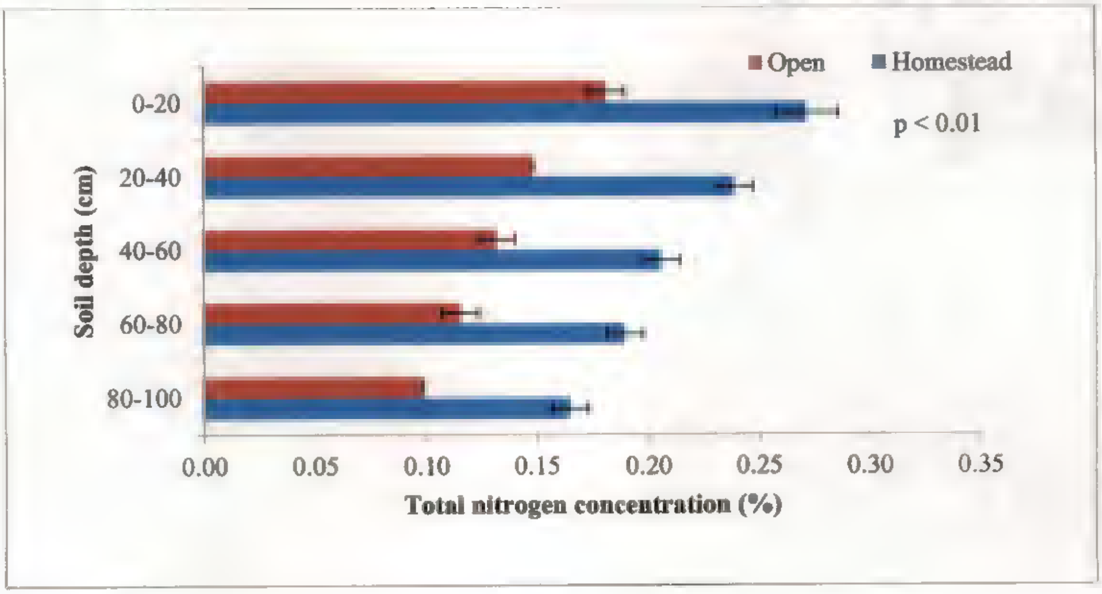

Figure 17. Variation in total nitrogen concentration at different soil depths of homegarden and contiguous open plot in Central Kerala

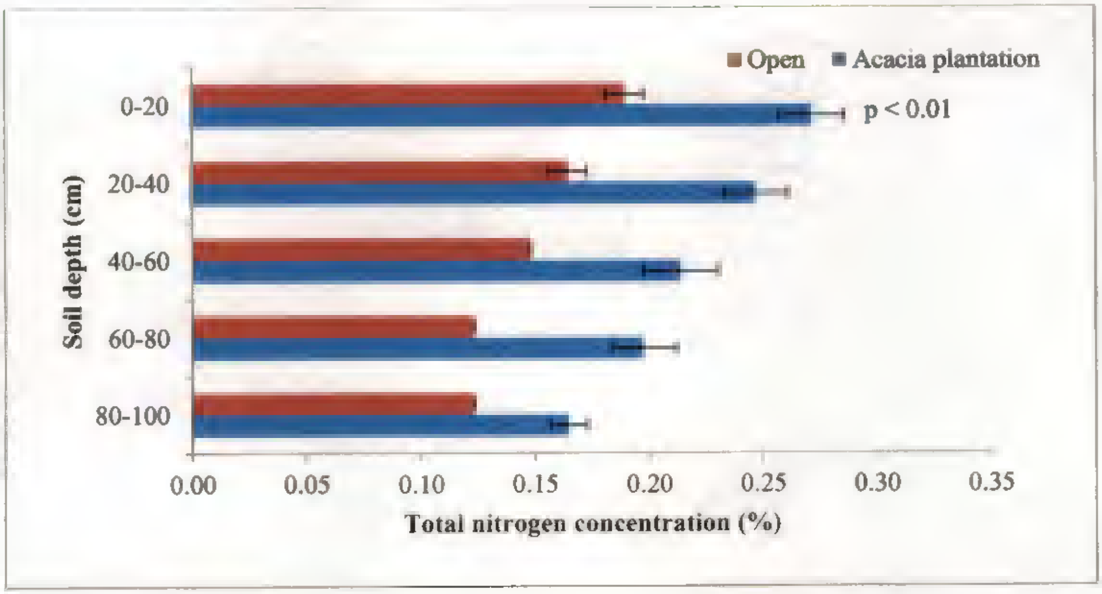

Figure 18. Variation in total nitrogen concentration at different soil depths of acacia plantation and contiguous open plot in Central Kerala

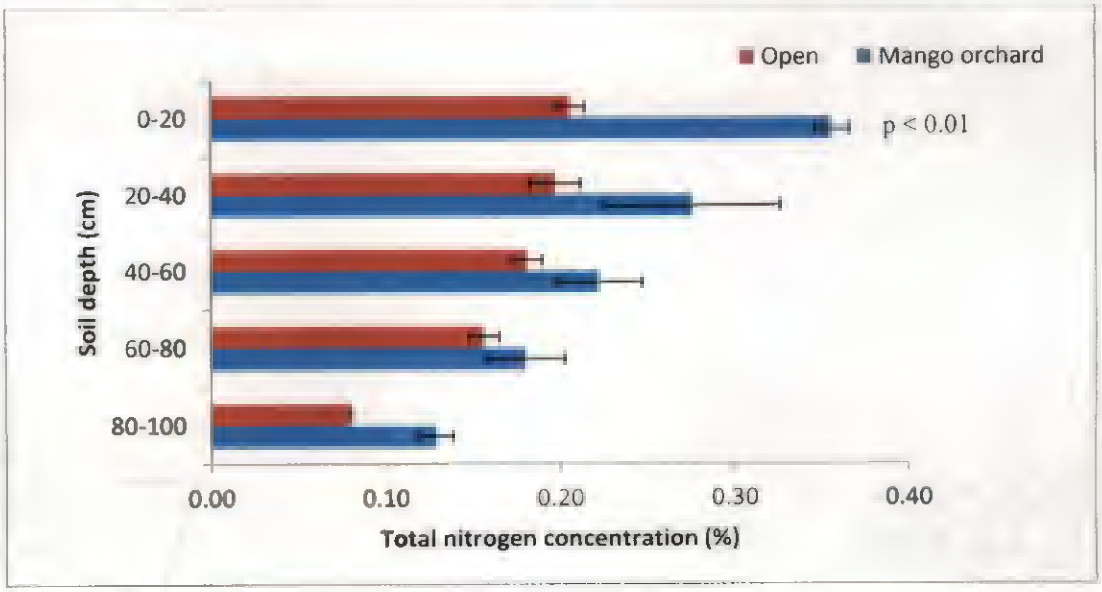

Figure 19. Variation in total nitrogen concentration, across at soil depths, between mango woody ecosystem and contiguous open plot in Central Kerala

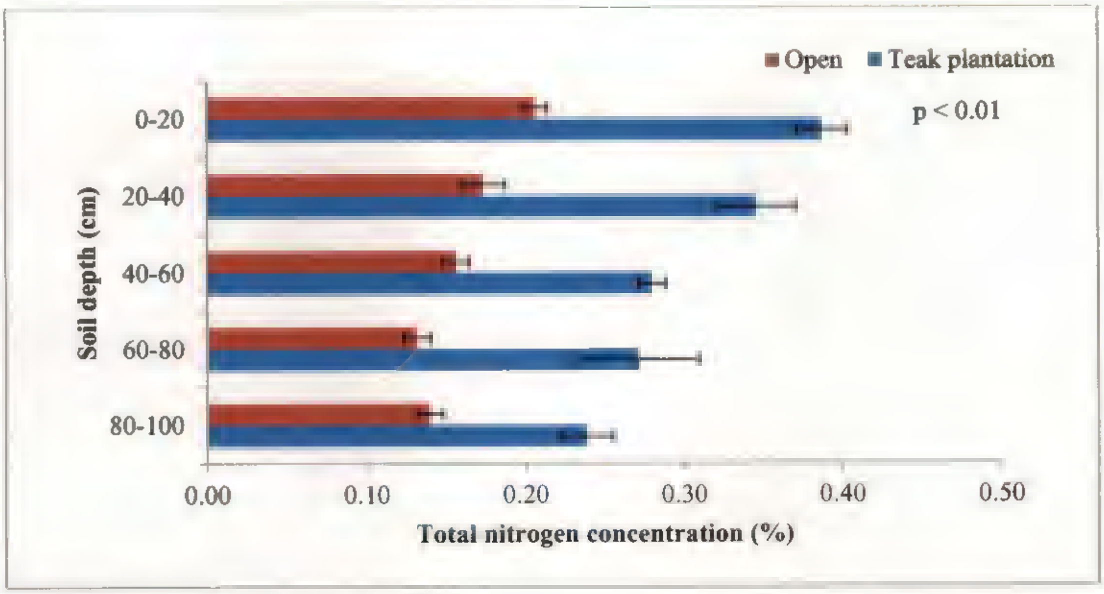

Figure 20. Variation in total nitrogen concentration at different soil depths of teak plantation and contiguous open plot in Central Kerala

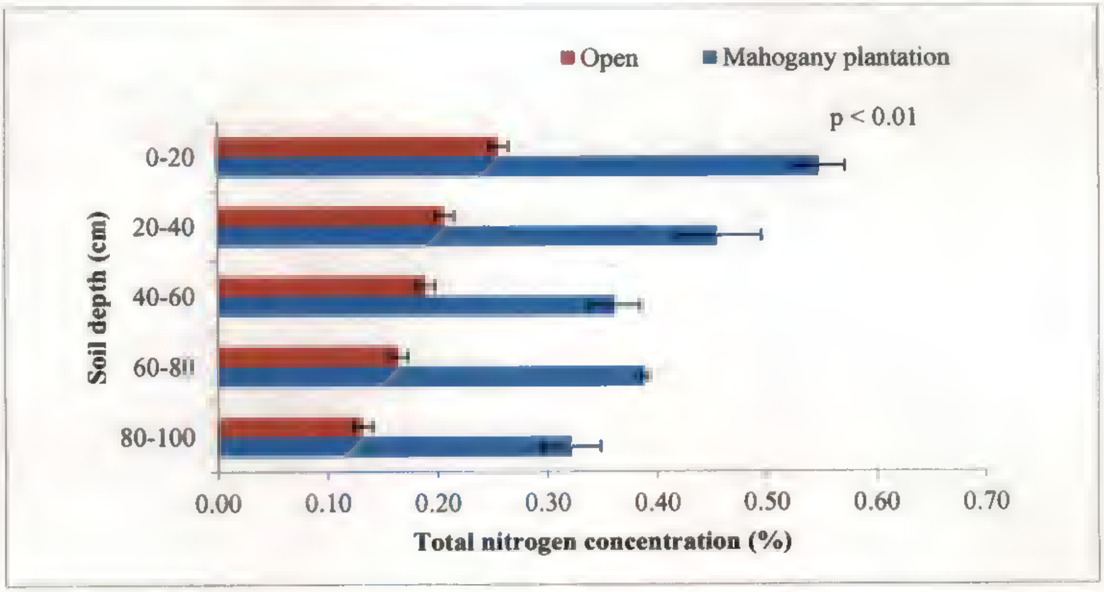

Figure 21. Variation in total nitrogen concentration at different soil depths of mahogany plantation and contiguous open plot in Central Kerala

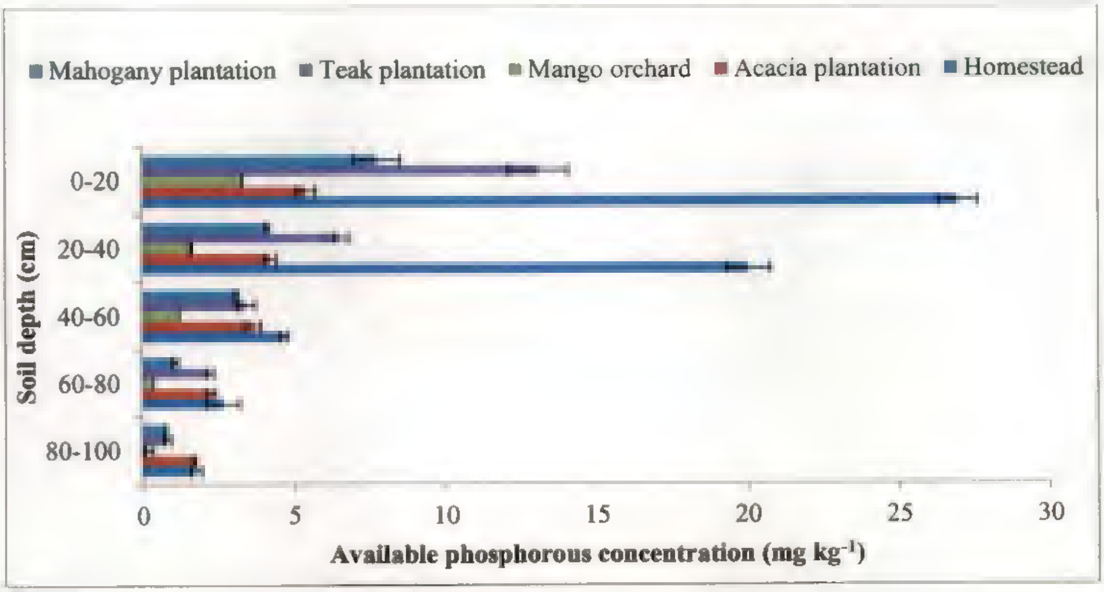

Figure 22. Available phosphorous concentration at different soil depth of the selected woody ecosystems in Central Kerala

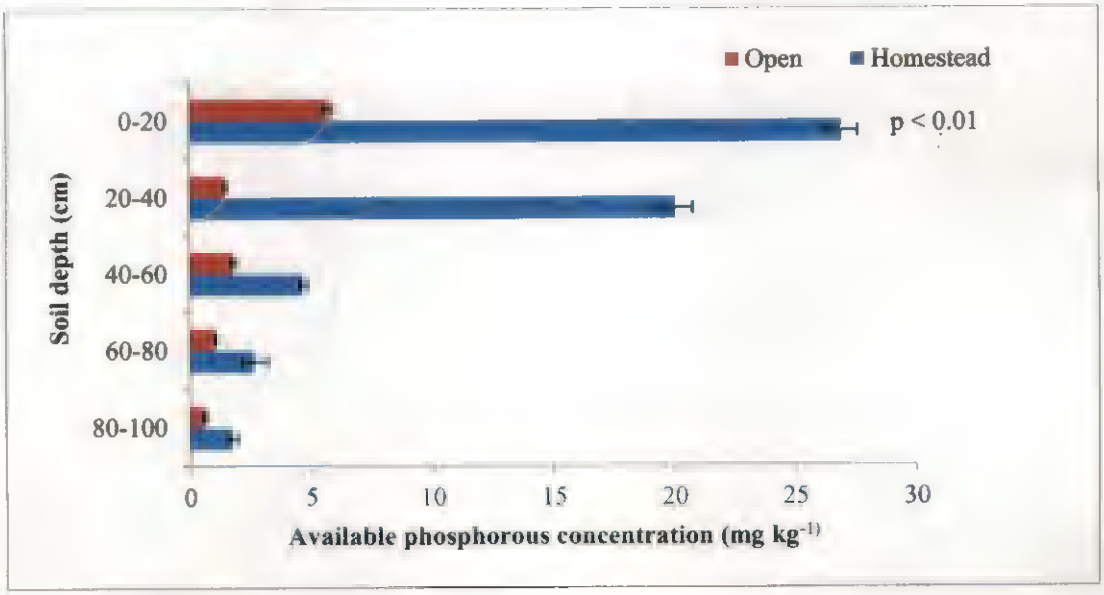

Figure 23. Variation in available phosphorous concentration at different soil depths of homegarden and contiguous open plot in Central Kerala.

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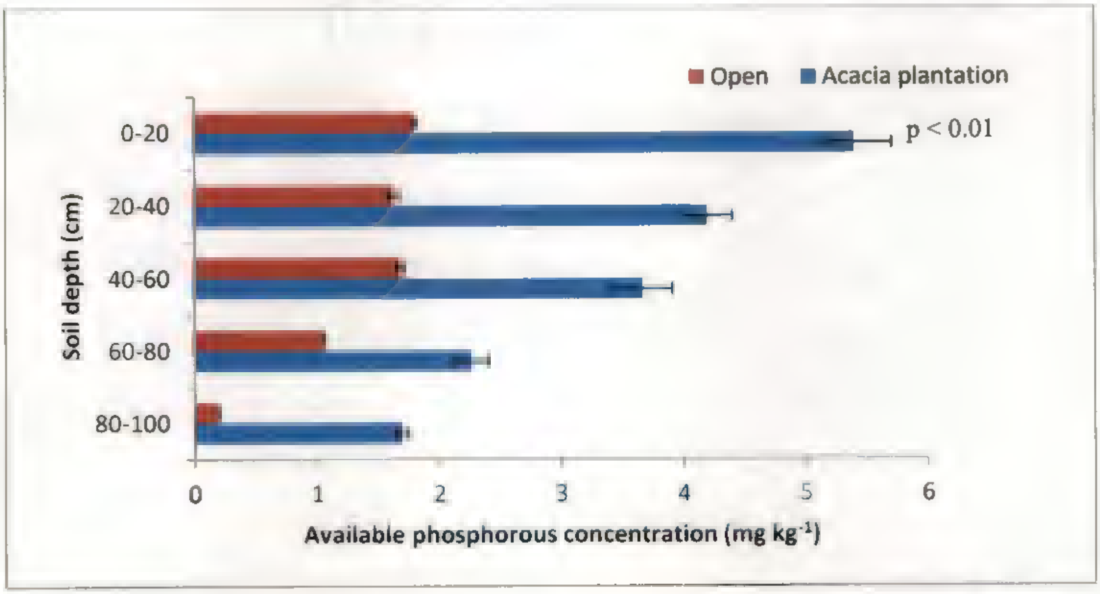

Figure 24. Variation in available phosphorous concentration at different soil depths of acacia plantation and contiguous open plot in Central Kerala.

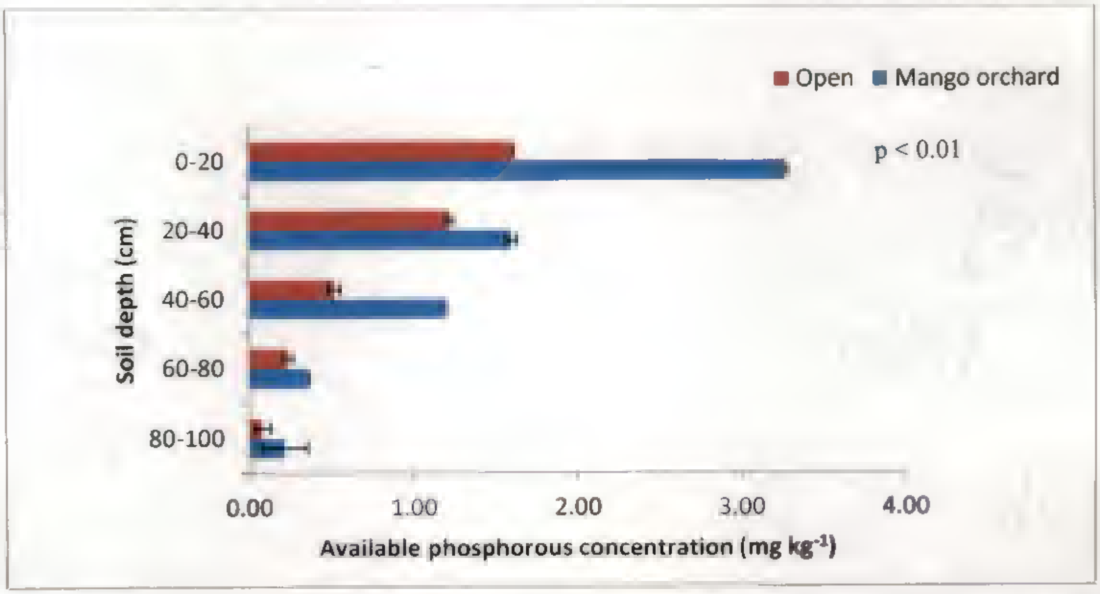

Figure 25. Variation in available phosphorous concentration between different soil depths of mango woody ecosystem and contiguous open plot in Central Kerala.

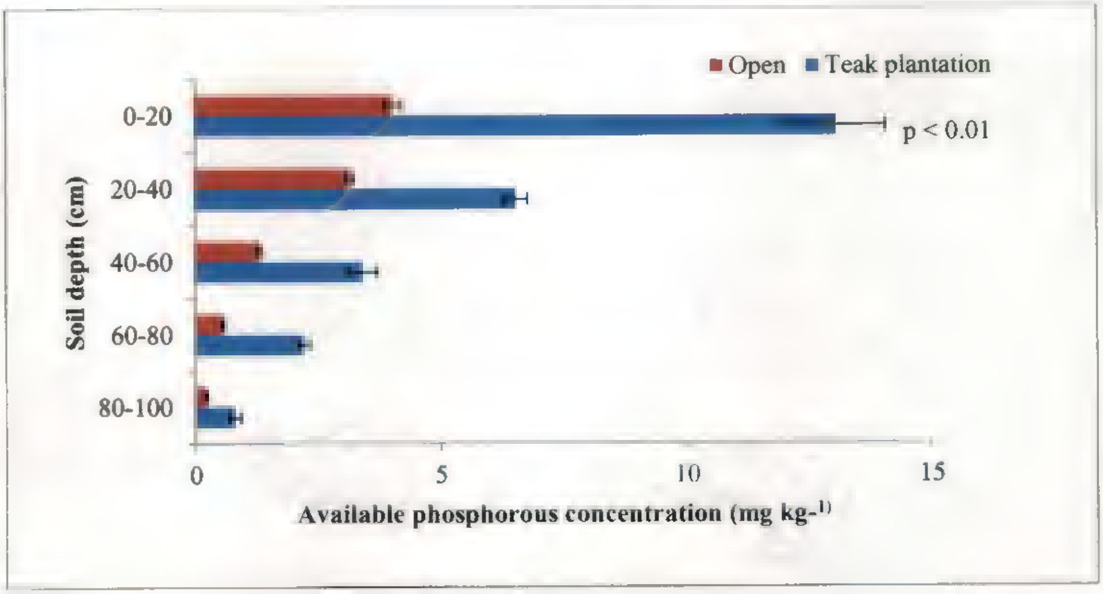

Figure 26. Variation in available phosphorous concentration between different soil depths of teak plantation and contiguous open plot in Central Kerala.

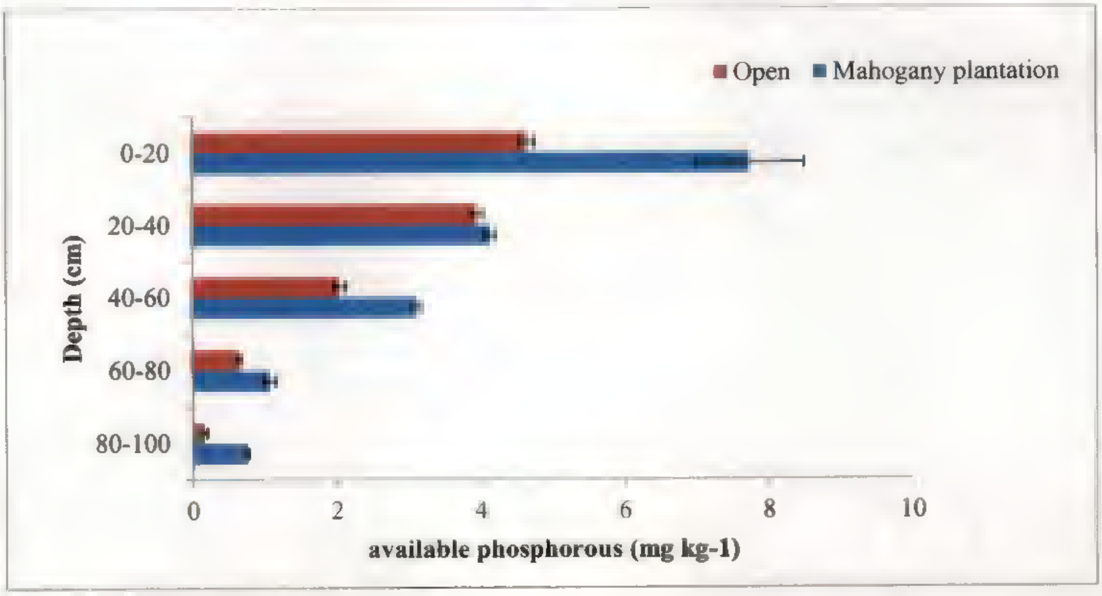

Figure 27. Variation in available phosphorous concentration between different soil depths of mahogany plantation and contiguous open plot in Central Kerala.

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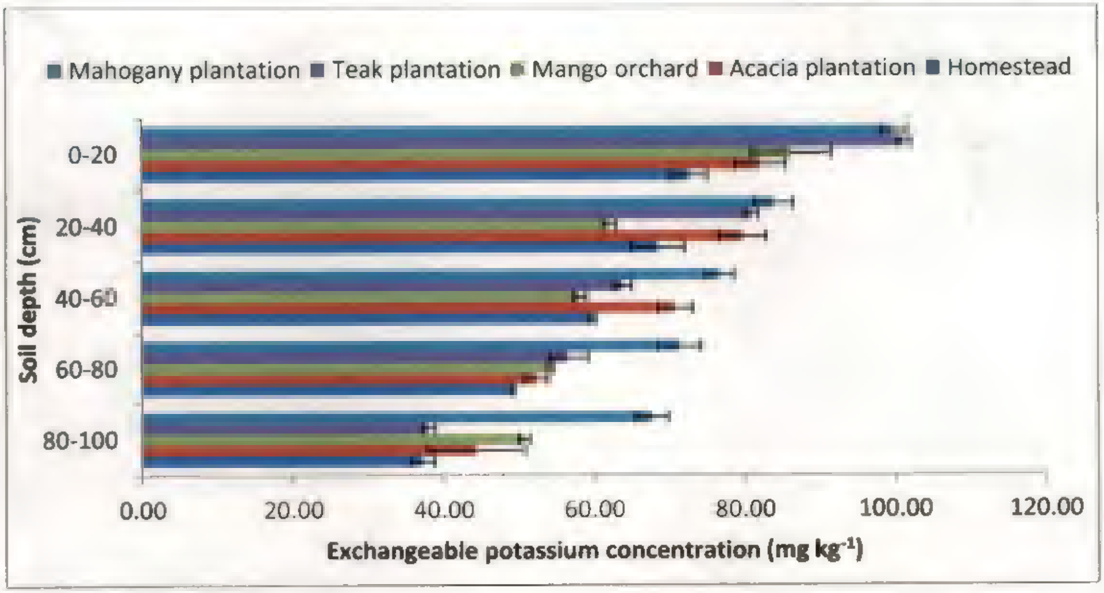

Figure 28. Exchangeable potassium concentration in different soil depth of the selected woody ecosystems in Central Kerala

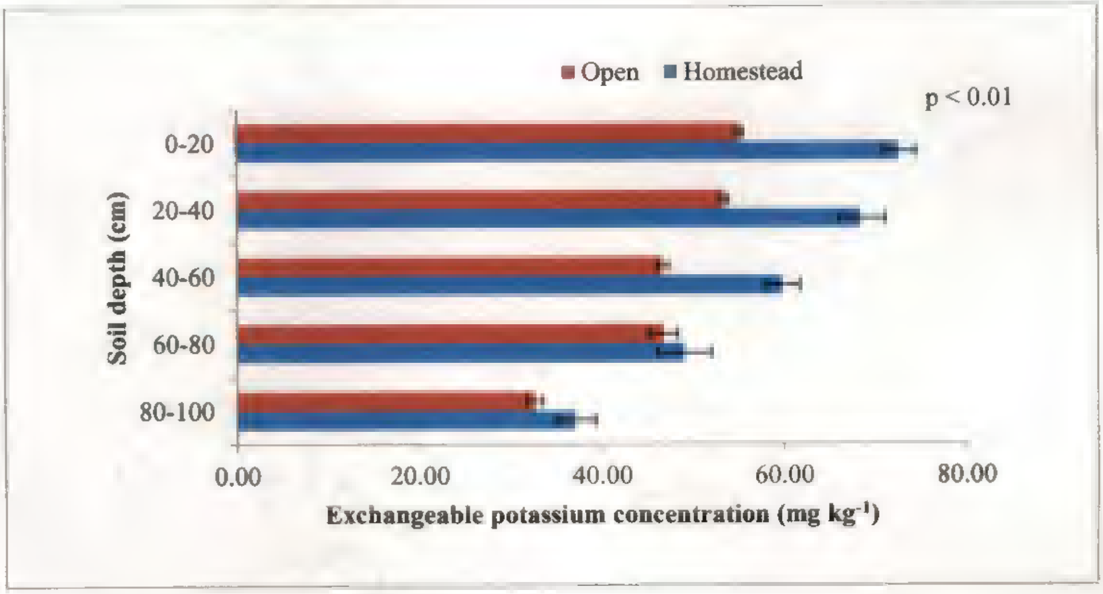

Figure 29. Variation in exchangeable potassium concentration at different soil depths of homegarden and contiguous open plot in Central Kerala

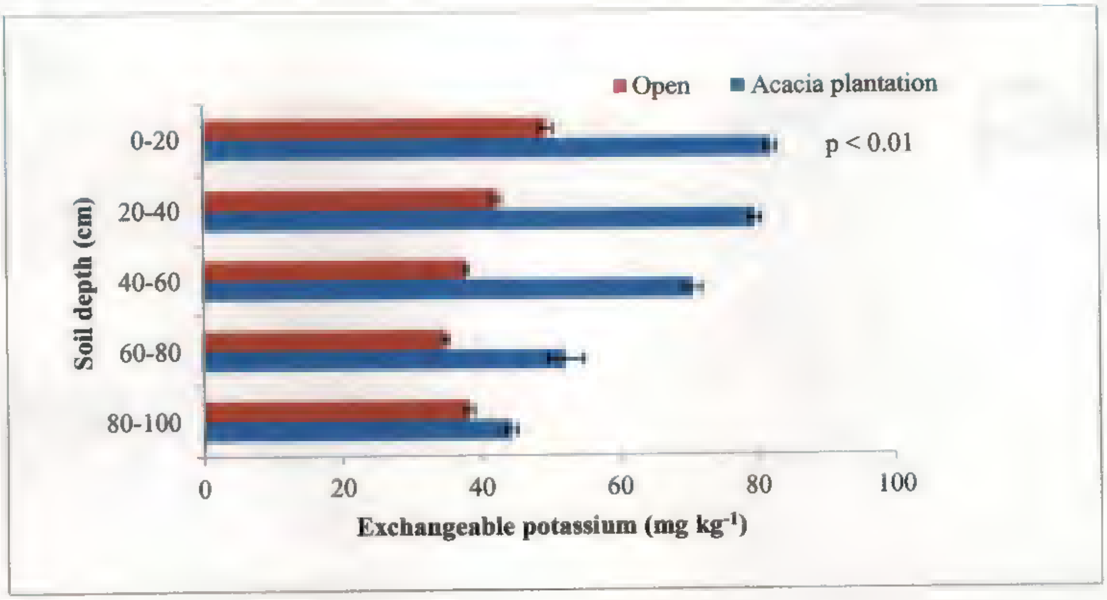

Figure 30. Variation in exchangeable potassium concentration at different soil depths of acacia plantation and contiguous open plot in Central Kerala

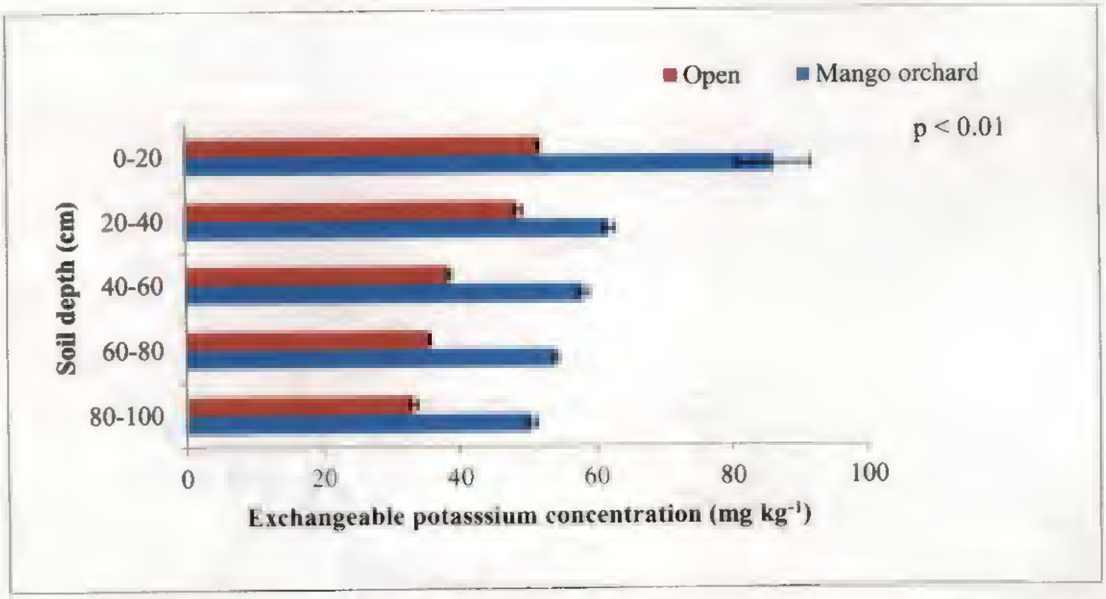

Figure 31. Variation in exchangeable potassium concentration at different soil depths of mango woody orchard and contiguous open plot in Central Kerala

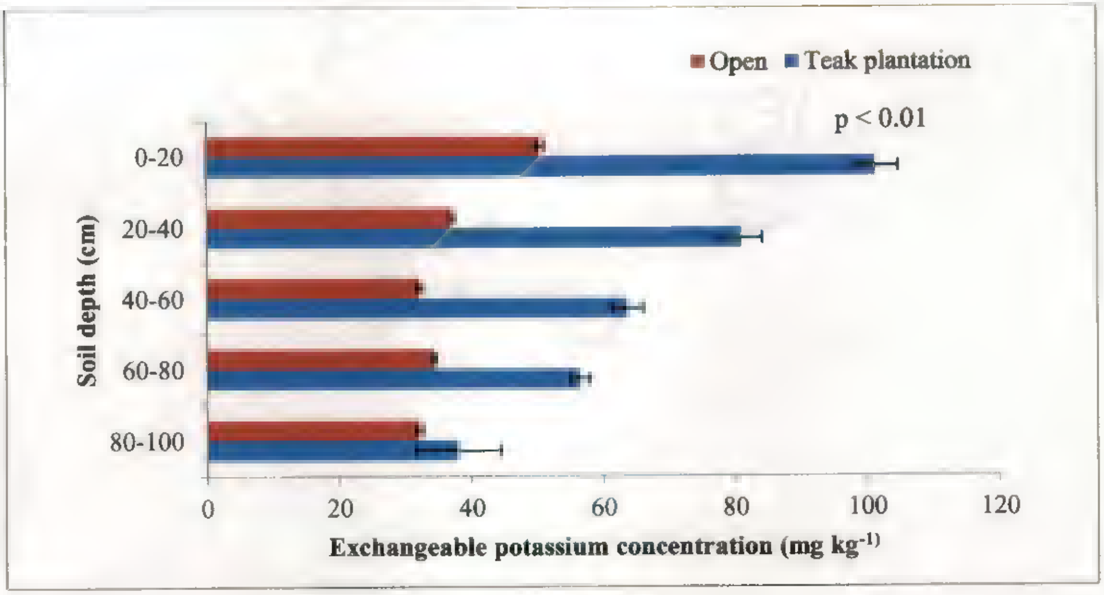

Figure 32. Variation in exchangeable potassium concentration at different soil depths of homegarden and contiguous open plot in Central Kerala

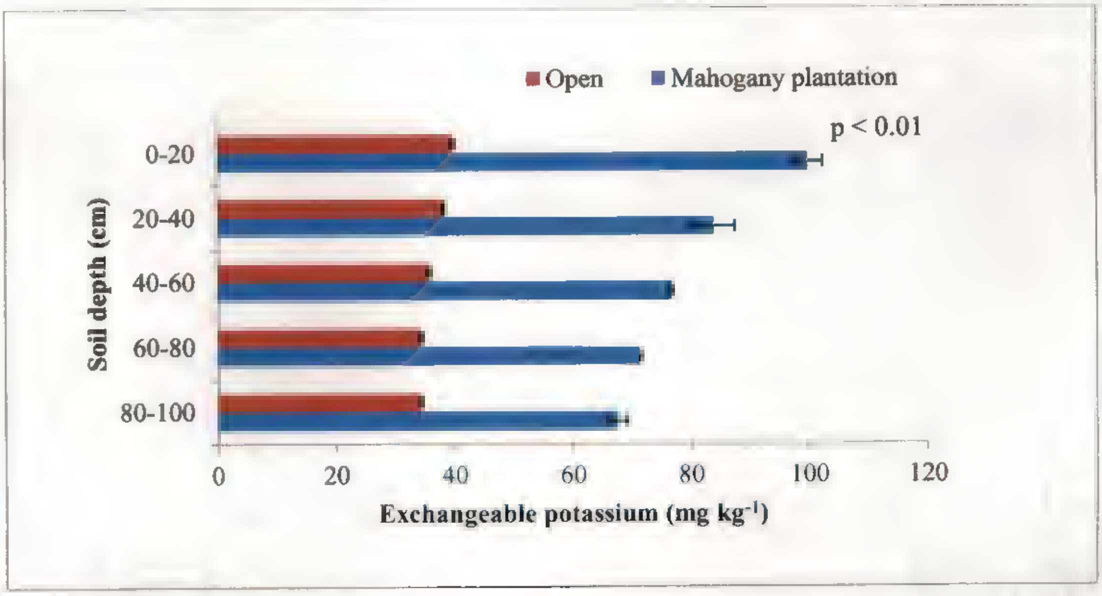

Figure 33. Variation in exchangeable potassium concentration at different soil depths of mahogany plantation and contiguous open plot in Central Kerala

5.3. MANAGEMENT IMPLICATIONS OF THE STUDY

The extensive field investigations on the variability in the soil carbon and nutrient stocks revealed interesting observations. In general, all the woody ecosystems showed substantial improvement in soil carbon and nutrient buildup as compared to their respective treeless open soils. Long rotation species such as mahogany and teak had significant advantage in enhancing the soil carbon stocks as compared to other woody ecosystems. Also multitier multispecies characteristics of homegardens showed profound leverage in improving the soil carbon and nutrient status even at deeper depths. This study converges to the conclusion that intensively managed short rotation species such as acacia may function as soil nutrient drainers by allocating more of the nutrients in their biomass. Hence such short rotation plantations could lead to massive drains of carbon and nutrient in soil through repeated harvest related exports from the site. Hence it would be desirable to retain leaves, twigs branches and roots in the soil which resorting to total clear felling. The improvement in soil fertility in long rotation tree species such as mahogany and teak suggest the possible integration of compatible crop components with these systems. However the above ground species limitations need to be considered while integrating other crop components.

SUMMARY

Woody ecosystems play a major role in the mitigation of climate change through this property of sequestration of atmospheric carbon dioxide in the soils. In this context present study entitled "Comparative analysis of carbon and nutrient stocks in soils of selected woody ecosystems of central Kerala, India" was carried out at the Academy of Climate Change Education and Research, Kerala Agricultural University, Vellanikkara, Thrissur during 2015-2016.

Soil samples were collected from the mature woody ecosystems located over central Kerala. Three replications were selected randomly from each woody ecosystem. Correspondingly samples were collected from treeless control for each woody ecosystem. Samples were analyzed for bulk density, pH, soil organic carbon, available phosphorous and exchangeable potassium. Carbon and nutrient stocks were calculated from this. The study generalized following conclusions.

The carbon and nutrient stocks were significantly influenced by the treatments. Soil organic carbon was significantly different in each plantation and also there was significant reduction in depth. Carbon stocks were higher for mahogany plantation (116.01 Mg C ha^{-1}) followed by homestead (105.41 Mg C ha^{-1}) and teak (103 Mg C ha^{-1}). Lower carbon stock was found for mango (76.08 Mg C ha^{-1}) and acacia (75.19 Mg C ha^{-1}). Carbon stock for each plantation was significantly higher than contiguous open plot. When compared with treeless control plots the percentage increase was higher for mahogany (125.26%) followed by teak (85.62%), homegarden (77.34%), mango (52.83%) and acacia (29.17%). More than half of the carbon stocks were concentrated in the top 40cm layer. Slow growing species like mahogany and teak had more potential to sequester carbon than short rotation species like acacia.

Considering the nutrient stocks, all woody ecosystems had significantly higher soil nutrient stocks from their respective contiguous treeless soils. The highest nitrogen and potassium stocks were recorded in the soils of mahogany plantation

(53.61 Mg N ha^{-1}; 138.37% and 1030.6 Kg K ha^{-1}) which were significantly different from contiguous open plot. Nitrogen stocks were lower for acacia (26.77 Mg N ha^{-1}, 49.97%) and mango (26.77 Mg N ha^{-1}, 28.21%) but were significantly higher from treeless condition. Nitrogen stock in soils of teak (38.29 Mg N ha^{-1}, 99.64%) and homestead (30.17 Mg N ha^{-1}, 86.70%) were higher than acacia and mango but lower than mahogany. Like carbon stock nitrogen and potassium stocks were higher for slow growing species than fast growing acacia species.

All the selected woody ecosystems had significantly higher phosphorous stock in soil from its contiguous plots. Soils of homestead woody ecosystem had higher available phosphorous stock (154.56 Kg P ha^{-1}, 449.45%). the increase from contiguous plots followed the order teak (197.59%) > acacia (163.04%) > mango (79.93%) > mahogany (64.9%)

The results of the present study revealed soil organic and nutrient stock varied significantly with woody ecosystems. Slow growing species as well as multi-strata ecosystem enrich soil with carbon and nutrient better than slow growing species. Also is significantly higher than treeless condition. Enhancing tree cover is thus an efficient method to mitigate global warming. Short rotation species because of the intensive management could lead to massive drain of carbon and nutrient pools. Hence choice of the species and their management conditions are important considerations while designing plantation forestry programs particularly when their carbon sequestration and greenhouse gas mitigation potential are considered.

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COMPARATIVE ANALYSIS OF CARBON AND NUTRIENT POOLS IN SOILS OF SELECTED WOODY ECOSYSTEMS OF CENTRAL KERALA, INDIA

By

VEENA PRASAD

ABSTRACT OF THE THESIS

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Faculty of Agriculture

Kerala Agricultural University

ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH
VELLANIKKARA, THRISSUR - 680 656
KERALA, INDIA
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ABSTRACT

Present study entitled “Comparative analysis of carbon and nutrient stocks in soils of selected woody ecosystems of central Kerala, India” was carried out at the Academy of Climate Change Education and Research, Kerala Agricultural University, Vellanikkara, Thrissur during 2015-2016.

The study showed that the carbon and nutrient stocks were significantly influenced by the treatments. Soil organic carbon is significantly different in each plantation and was significantly higher than corresponding contiguous treeless soils ($p < 0.005$). Also there was significant reduction in depth. Carbon stock was higher for mahogany plantation (116.01 Mg C ha^{-1}) followed by homestead (105.41 Mg C ha^{-1}) and teak (103Mg C ha^{-1}). Lower carbon stock was found for mango (76.08Mg C ha^{-1}) and acacia (75.19 Mg C ha^{-1}). Carbon stock for each plantation was significantly higher than contiguous open plot. Similarly highest nitrogen and potassium stock was recorded for mahogany plantation (53.61 Mg N ha^{-1} and 1030.6 Kg K ha^{-1}) which were significantly different from contiguous open plot. Nitrogen stocks were lower for acacia (26.77 Mg N ha^{-1}) and mango (26.77 Mg N ha^{-1}) but are significantly higher from treeless condition. Nitrogen stock in homestead (30.17 Mg N ha^{-1}) and teak (38.29 Mg N ha^{-1}) was higher than acacia and mango but lower than mahogany. Available phosphorous was lower in all woody ecosystems other than homestead (154.56 Kg P ha^{-1}) with significant reduction across depth.

The results of the present study revealed that soil organic and nutrient stock varied significantly with woody ecosystems and slow growing species as well as multi-strata ecosystem enrich soil with carbon and nutrient better than fast growing species like acacia. Also is significantly higher than treeless condition. Enhancing tree cover is thus an efficient method to mitigate global warming. Hence choice of the species and their management conditions are important considerations while designing

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plantation forestry programs particularly when their carbon sequestration and greenhouse gas mitigation potential are considered.

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