Plant Soil (2010) 328:433–446
DOI 10.1007/s11104-009-0123-x

REGULAR ARTICLE

# Carbon storage in relation to soil size-fractions under tropical tree-based land-use systems

**Subhrajit K. Saha · P. K. Ramachandran Nair · Vimala D. Nair · B. Mohan Kumar**

Received: 26 January 2009 / Accepted: 23 July 2009 / Published online: 11 August 2009


**Abstract** The extent of carbon (C) sequestration in soils under agroforestry systems in relation to soil types (fraction sizes) and vegetation structure remains largely unexplored. This study examined soil C storage, an indicator of C sequestration potential, in homegardens (HGs), natural forest, and single-species stands of coconut (*Cocos nucifera*), rice (*Oryza sativa*)-paddy, and rubber (*Hevea brasiliensis*), in Thrissur district, Kerala, India. Soil samples collected from four depth zones up to 1 m were fractionated to three size classes (250 – 2000 μm, 53 – 250 μm, <53 μm) and their total C content determined. Total C stock (Mg ha$^{-1}$) was highest in forests (176.6), followed by managed tree-based systems, and lowest in rice-paddy field (55.6). The results show storage of higher amounts of C in the <53 μm fraction, the most stable form of C in soil, up to one- meter depth, in land-use systems with high stand density of trees such as forests and small-sized HG. Although the results do not allow comparison of changes in soil C stock in different land-use systems, they show higher C storage in soils under tree-based land-use systems compared with the treeless (rice-paddy) system, especially in lower soil depths, suggesting the higher soil C sequestration potential of tree-based systems, and thereby their role in reducing atmospheric concentration of carbon dioxide.

**Keywords** Agroforestry · Carbon sequestration · Global warming · Homegarden · Soil aggregates

**Abbreviations**

| | |
|---|---|
| AFS | Agroforestry systems |
| CSP | Carbon sequestration potential |
| GHG | Greenhouse gas |
| HG | Homegarden |
| HGL | Large homegarden |
| HGS | Small homegarden |
| SOC | Soil organic carbon |

Responsible Editor: Klaus Butterbach-Bahl.

S. K. Saha · P. K. Ramachandran Nair (✉)
School of Forest Resources and Conservation, Institute of Food and Agricultural Sciences, University of Florida, P.O. Box 110410, Gainesville, FL 32611, USA
e-mail: pknair@ufl.edu

V. D. Nair
Soil and Water Science Department, Institute of Food and Agricultural Sciences, University of Florida, P.O. Box 110510, Gainesville, FL 32611, USA

B. Mohan Kumar
Department of Silviculture and Agroforestry, Kerala Agricultural University, Kerala, India

## Introduction

Storing carbon (C) in vegetation and soils is one of the strategies accepted by the United Nations for mitigating high atmospheric concentrations of carbon dioxide ($CO_2$) that causes global warming. For example, the United Nations Framework Convention on Climate Change (UNFCCC) allows the use of C sequestration through afforestation and reforestation (A & R) as GHG offset activities (UNFCCC 2009). Consequently, agroforestry became recognized as a C sequestration activity under the A & R approach (Albrecht and Kandji 2003; Nair and Nair 2003; Makundi and Sathaye 2004; Sharrow and Ismail 2004; Nair et al. 2009). Improved agroforestry-related land-use changes are estimated to cause a net increase of 0.41 Pg (billion tons) of C year$^{-1}$ in global C stocks in 2010 (IPCC 2007). Wright et al. (2001) even suggested that agroforestry would be the only system that could realistically be implemented to mitigate the atmospheric $CO_2$ through terrestrial C sequestration.

Several important aspects, such as the extent of C sequestration in soils under agroforestry systems (AFS) in relation to soil types and vegetation structure, remain largely unexplored. Soil is an important part of the biosphere in sequestering C and has a higher potential to store C compared to vegetation and atmosphere (Bellamy et al. 2005). The extent of soil C retention in soils depends, among other things, on the nature of soil aggregation (Carter 1996; Haile et al. 2008, 2009; Takimoto et al. 2008a). It can be short-term storage in macroaggregates (>250 μm diameter) and long-term storage in microaggregates (<250 μm diameter) including the widely accepted stability of C stored in the smallest size class, the silt and clay size fraction (<53 μm) (Six et al. 2002).

The few reports that are available on soil C storage under AFS indicate that soil C stocks under AFS vary widely depending on ecological conditions and land-use systems. Shaded perennial and other multistrata systems of agroforestry in humid tropical regions are reported to contain much higher stock of soil C than under AFS with lesser tree density especially under semiarid conditions. The soil organic carbon (SOC) stock in cacao+gliricidia (*Gliricidia sepium*) AFS in Indonesia amounted to 155 Mg C ha$^{-1}$ (0 – 100 cm soil depth) (Smiley and Kroschel 2008) and SOC reserves in cacao+Erythrina (*Erythrina poeppigiana*) in Costa Rica was 240 Mg ha$^{-1}$ (0 – 45 cm depth) (Fassbender et al. 1991). A cacao alleycrop system in Costa Rica was reported to contain 162 Mg C ha$^{-1}$ in the 0 – 40 cm soil depth (Oelbermann et al. 2006), and a West African cacao AFS had 18.2 Mg C ha$^{-1}$ in the 0 – 15 cm soil depth (Isaac et al. 2005). On the other hand, SOC storage in AFS under dry (semiarid to arid) conditions is considerably lower than under humid regions. Takimoto et al. (2008b) reported that SOC to a meter depth varied from 24 Mg C ha$^{-1}$ in a live fence AFS to 33 Mg C ha$^{-1}$ in fodder bank and parkland systems in Mali in the West African Sahel. Silvopastoral systems with slash pine (*Pinus elliottii*)+ bahiagrass (*Paspalum notatum*) accumulated<25 Mg C ha$^{-1}$ to a depth of 1.20 m in Florida, USA (Haile et al. 2008).

These limited studies on soil C storage under AFS have not examined the extent of C- storage variation under different land-use systems involving various plant forms (trees and crops alone and in association) under same or similar ecological conditions. Homegardens, described as intimate, multistory combinations of various trees and crops around the homesteads (Fernandes and Nair 1986; Kumar and Nair 2006), provide an excellent setting for exploring such variations. Homegardens are rich in plant diversity and have been ranked top among all manmade agroecosystems for their high biological diversity after natural forest (Swift and Anderson 1993). These multispecies plant associations are speculated to have high carbon sequestration potential (CSP) due to their forest-like structure and composition (Nair et al. 2009), particularly in accumulating C in the soil. Kerala state in the southwestern part of India is well known for its traditional HG, and the ecological and socioeconomic sustainability values of HG in the state are well recognized (Nair and Sreedharan 1986; Jose and Shanmugaratnam 1993; Kumar et al. 1994; Peyre et al. 2006). In addition to HG, other tropical land-use systems that provide a wide spectrum of plant species diversity and arrangement, such as forest, sole stands of rubber (*Hevea brasiliensis*) trees and coconut (*Cocos nucifera*) palms, and rice (*Oryza sativa*)-paddy fields are also common in Kerala, and often these different land-use systems exist together in close proximity. This unique land-use assemblage offers an excellent setting for investigating the extent of soil C storage under different land-use systems within the same set of ecological conditions. The objective of this study was to investigate the soil C storage in different fraction-size classes of soils in homegardens, coconut and rubber plantations, rice-paddy fields, and forests up to one meter depth in Kerala, India.

## Materials and methods

### Study location

This study was conducted in the central part of the state of Kerala, India. The study location was in the Madakkathara subdivision (*Panchayat*) in the district of Thrissur: 10°0' – 10°47′N latitude and 75°55′–76°54′E longitude. Three villages (Pandiparambu, Chirakkakode, and Vellanikkara) were selected for the study based on the availability of various land-use types: rice-paddy fields, rubber plantations, intercropped as well as sole stands of coconut, and homegardens. The mean annual climatic parameters of the study region are: 2783 mm rainfall, 27.7 °C temperature, and 74.8% humidity; the soils are Inceptisols (Govt. of Kerala 2005).

### Land-use systems

Homegardens that consist of multispecies combinations of various trees and crops in intimate association around the homes are a popular agroforestry land-use system in Kerala (Kumar et al. 1994; Peyre et al. 2006; Kumar and Nair 2006; Mohan et al. 2007). In Kerala state, about 80% of the operational agricultural holdings practice homegardening (Govt. of Kerala 2008); the state has an estimated 4.32 million HGs covering 1.4 M ha, or 36% of the total area of the state (Kumar and Nair 2006). The vast majority of them are less than 0.5 ha in area (Kumar and Nair 2006). The species density and composition vary with size: the smaller the size of the garden, the higher the species and tree density (Mohan et al. 2007). Considering that the extent of soil C storage is dependent on species diversity, in this study, the HGs were categorized into "Small Homegarden" (HGS) (less than 0.4 ha=1.0 acre) and "Large Homegarden" (HGL) (more than 0.4 ha).

The HGs selected for the study were "typical" Kerala HGs as described in previous studies (Kumar et al. 1994; Peyre et al. 2006; Kumar and Nair 2006; Mohan et al. 2007). The forest in the study region belonged to the Government Forestry Department (as is all forestland in the state); it is moist deciduous and is reported to contain more than 100 tree species (B. M. Kumar: personal observation). The rubber plantations selected for the study were under that land use (rubber cultivation) for more than 50 years. They had mature trees under tapping, planted 4.5 m×4.5 m spacing, with tree density varying from 450 to 500 trees per hectare. Coconuts are abundant and ubiquitous in the region. They are usually cultivated in mixed stands in association with various understory species or mix-cropped with other tree crops. For this study, a sole stand of coconuts was selected from the Kerala Agricultural University (KAU) farm, which is located within the study region. The plantation was 30 years old, and the palms were planted at 8 m×8 m spacing, and maintained according to KAU recommended package of cultivation practices. The rice-paddy sites selected for the study had been under cultivation for more than 100 years, and land-holding size varied in area from 0.12 to 0.4 ha. Rice is usually planted at a spacing of 15 – 20 cm×10 – 15 cm, and fertilized with 40 – 110: 20 – 45: 20 – 55 kg ha$^{-1}$ of N: $P_2O_5$: $K_2O$. Some cultivation details of the major perennial species in HG are given in Table 1; details of cultivation practices of all crops in the study are available in the KAU "Package of Practices" (KAU 2009). Owners of all selected HGs, rubber, and rice systems were surveyed to gather detailed information about site history, demographic features, and management practices. For the coconut plantations and forest, the relevant information was gathered from KAU and Forestry Department records, respectively.

### Soil sampling

Soil samples were collected from four randomly selected plots of HGS, HGL, rubber plantation, and rice-paddy field, from each of the three villages, totaling 12 plots for each land-use type. Soil samples were also collected from four randomly selected plots from the forest adjacent to the villages, as well as from the coconut plantation at the KAU campus. In each plot, soils were collected from four depths (0 – 20, 20 – 50, 50 – 80, and 80 – 100 cm) from three randomly selected sampling points. The three sub-samples at each location and depth class were composited to get one composite sample for each depth class per plot. There were a total of 192 samples (4 land-use types×3 villages×4 replications/plots × 4 depths) from the three villages and 16 samples each from (1 location×4 replications/plots×4 depths) forest and coconut plantation, totaling 224 samples. Soil sampling for bulk density (BD) measurement was done using a 178 cm³ steel cylinder.

**Table 1** Cultivation practices of common perennial crops in homegardens of Kerala, India‡

| Crop | Planting Pit Size (cm) | Average Spacing (m) | Fertilizer‡ ($N:P_2O_5:K_2O$ g plant$^{-1}$year$^{-1}$) |
|---|---|---|---|
| Arecanut (*Areca catechu*) | 60×60 × 60 | 2.7×2.7 | 100:40:140 |
| Banana, plantain (*Musa* spp.) | 50×50 × 50 | 2.1×2.1 | 60–200:160–200:320–400 |
| Cacao (*Theobroma cacao*) | 50×50 × 50 | 2.7×2.7 | 100–200:40–80:140–280 |
| Cashew (*Anacardium occidentale*) | 50×50 × 50 | 8×8 | 750:325:750 |
| Cinnamon (*Cinnamomum zeylanicum*) | 60×60 × 60 | 2×2 | 200:180:200 |
| Clove (*Syzygium aromaticum*) | 60×60 × 60 | 6×6 | 300:250:750 |
| Coconut (*Cocos nucifera*) § | 100×100 × 100 | 8×8 | 340–500:170–320:680–1200 |
| Guava (*Psidium guajava*) | 100×100 × 100 | 6×6 | 200:80:260 |
| Jackfruit (*Artocarpus heterophyllus*) | 60×60 × 60 | 12×12 | Seldom fertilized. |
| Mango (*Mangifera indica*) | 100×100 × 100 | 9×9 | 500:360:750 |
| Nutmeg (*Myristica fragrans*) | 90×90 × 90 | 8×8 | 500:250:1000 |
| Orange (*Citrus reticulata*) | 70×60×70 | 7×7 | 800:275:1000 |
| Papaya (*Carica papaya*) | 50×50 × 50 | 2×2 | 40:40:80 |
| Tamarind (*Tamarindus indica*) | 100×100 × 100 | 10×10 | 500:360:750 |
| Rubber (*Hevea brasiliensis*)§ | 75×75 × 75 | 4.5×4.5 | 900:900:900 |

Source: KAU Package of Practices (www.kau.edu/pop); Table 12.3 in Nair (1993)

‡ The listed practices are as recommended by extension services for the crops when grown in sole stands. In HGs, these crops are always grown in close association with other species. Tree crops are either planted or they get regenerated from seeds discarded after household consumption of fruits. Planting, when done, is usually during the monsoon season of June to August. Harvesting of most tree crops occurs year-round except for seasonal fruits. Tree crops other than cash crops such as cacao and coconut are seldom fertilized in HGs; organic materials such as green leaf, compost, and farmyard manure are applied to all crops at the rate of 5–20 kg per plant annually

§ Rubber is not commonly cultivated in HGs; but its description is included as it forms a land-use system in our study. Coconut, a dominant component of HG, is also grown in sole stands; a sole stand of coconut was one of the land-use systems of the study

Pits of 1 m×1 m × 1 m size were dug and the steel cylinder was inserted horizontally on the wall of the pits at the center of each depth class. Soil inside the cylinder was collected, dried, and weighed, and composite of three samples obtained for each depth. All samples were air-dried and sieved (2 mm sieve) at the KAU soils laboratory, bagged, and sent to the University of Florida, Gainesville, FL, USA, for further analyses.

## Soil preparation and analysis

The soil samples were manually fractionated into three aggregate size classes (250–2000 μm, 53–250 μm, <53 μm) at the Soil and Water Science Department laboratory, University of Florida, according to a procedure from Elliott (1986) and Six et al. (2002), adapted as followed by Haile et al. (2008; 2009) and Takimoto et al. (2008a; 2008b). The overall average recovery mass percentage of soil fractions after the wet sieving procedure was 97.5% of the initial soil mass as reported by Haile et al. (2008); Takimoto et al. (2008b) reported a recovery range from 97 to 99% of the initial soil mass. The soil samples were physically fractionated by wet-sieving using disruptive forces of slaking and wet-sieving through a series of two sieve sizes (250 and 53 μm) to obtain three fraction size classes: macro (250 – 2000 μm), micro (53 – 250 μm), and silt- and clay-sized fraction (<53 μm). The procedure, modified by Haile et al. (2008), consisted of submerging a subsample of 100 g of the composite soil sample in a 500 mL beaker of de-ionized water for about 5 min prior to placing it on top of 250 μm sieve to release the air that is trapped inside soil pores. The sieving was done manually. The fraction remaining on the top of a 250 μm sieve was collected in a hard plastic pan and allowed to oven-dry at 65°C and weighed. Water plus soil <250 μm was poured through a 53 μm sieve and the same sieving procedure was repeated. The overall procedure yielded a water-stable, macro-sized fraction 250–2000 μm; a micro-sized fraction 53–250 μm, and silt+clay sized <53 μm fraction. The overall average recovery mass percentage of soil fractions after wet sieving ranged from 95 to 99% of the initial soil mass. For further analysis, whole and fractionated soil was oven-dried at 60°C for 72 h, and crushed to fine powder using a QM-3A High Speed Vibrating Ball Mill (Cianflone Scientific Instruments, Pittsburgh, PA.). Total nitrogen and SOC content were determined for both whole and fractionated soil samples by dry combustion and gas chromatography on an automated FLASH EA 1112 N C elemental analyzer (LECO Corporation, St. Joseph, Mich.). Soil pH was determined in a 1:10 soil: water suspension; particle-size density was also determined (Day 1965). Details of soil characteristics are presented in Table 2.

The C storage was calculated as:

$$C\,storage = C\,concentration \times BD \times Depth \times Fraction\ weight \quad (1)$$

where,

| | |
|---|---|
| C storage | = C expressed in Mg ha$^{-1}$ in each fraction class for a given depth |
| C concentration | = C in fraction size, g per kg of soil of that fraction size |
| BD | = Bulk density, Mg m$^{-3}$ |
| Depth | = Depth of soil profile, cm, and |
| Fraction weight | = % weight of the fraction in the whole soil |

The total C stored to a meter depth is the sum of the C stored at each of the depths within the soil profile.

### Statistical analysis

A split-plot design with land-use as a factor was employed. The tropical land-use systems were considered subplots (i.e. total 6 subplots) and three study villages were considered as whole plots (i.e. total 3 whole plots). Multiple linear tests were performed using the general linear model (GLM) and analysis of variance (ANOVA). Waller Duncan K-ratio test was used to compare the mean differences between land-management practices on SOC in whole soil, macro-sized, micro-sized and silt- and clay- sized fractions for all sites. All statistical tests were performed with SAS 9.0 (SAS Institute Inc. 2004) and differences were considered significant when $p<0.05$.

## Results

### Soil organic carbon storage in whole soil

In the absence of a time-sequence study involving long time intervals, the C stock data were considered as an indicator of the CSP of the systems. The amount of SOC in whole soil (0 – 100 cm depth; all depth classes combined) varied with the land-use systems (Fig. 1). The SOC was highest in the forest (176.6 Mg ha$^{-1}$) and lowest in rice-paddy (55.6 Mg ha$^{-1}$). The small HG and the rubber plantation had higher SOC values compared to coconut plantation. The HGS (small HG) had 30% and 114% more SOC than in coconut plantations and rice-paddy, respectively, whereas for HGL (large HG), the corresponding numbers were 18% and 94%. Between the two homegarden size classes, HGS showed 10% greater SOC content than HGL (statistically not significant). The overall results for SOC content within 1 m depth were in the following order: Forest>HGS=Rubber≥HGL≥coconut>rice-paddy (Fig. 1).

In general, the depth class comparison of SOC showed similarities with the overall ranking results of the land-use systems (Fig. 2). The forest had a higher value of SOC (49.99 Mg ha$^{-1}$) than HGL, HGS, coconut, and rice-paddy at the upper-most soil layer (0–20 cm). At the upper-medium soil layer (20–50 cm), SOC of forest and rice-paddy remained highest (58.19 Mg ha$^{-1}$) and lowest (15.3 Mg ha$^{-1}$), respectively. At the lower-medium soil layer (50–80 cm), again, the SOC value for forest was the highest (47.23 Mg ha$^{-1}$) compared to other land-use systems. At this depth, rice-paddy followed by coconut had lower amounts of SOC than the rest of the systems. Finally, at the lower-most soil layer studied (80–100 cm), the pattern remained the same as for the lower- medium layer, and the SOC decreased in the following order: Forest>HGS, rubber, HGL>coconut >rice-paddy (Fig. 2 and Fig. 3).

**Table 2** Soil characteristics (bulk density, pH, and particle-size distribution) at different depths in six land-use systems in Thrissur, Kerala, India

| Land-use Types | Depth (cm) | Bulk Density ($Mg\ m^{-3}$) | pH | Particle size distribution ($g\ 100\ g^{-1}$ soil) | | |
|---|---|---|---|---|---|---|
| | | | | Sand‡ | Silt | Clay |
| Forest | 0 – 20 | 0.93 | 6.1 | 46.41 | 21.46 | 32.13 |
| | 20 – 50 | 1.04 | 5.9 | 40.00 | 20.76 | 39.24 |
| | 50 – 80 | 1.18 | 5.8 | 40.95 | 20.23 | 38.82 |
| | 80 – 100 | 1.35 | 5.7 | 41.57 | 20.94 | 37.49 |
| Coconut Plantation | 0 – 20 | 1.26 | 5.8 | 64.96 | 12.68 | 22.36 |
| | 20 – 50 | 1.21 | 5.7 | 73.51 | 11.23 | 15.26 |
| | 50 – 80 | 1.12 | 5.7 | 80.67 | 8.191 | 11.14 |
| | 80 – 100 | 1.04 | 5.6 | 78.85 | 9.123 | 12.03 |
| Large Homegarden | 0 – 20 | 1.60 (0.117)§ | 6.2 | 60.93(8.523) | 15.44(6.697) | 23.63(2.364) |
| | 20 – 50 | 1.43 (0.043) | 6.0 | 54.01(5.337) | 12.25(1.176) | 33.74(4.889) |
| | 50 – 80 | 1.49 (0.164) | 5.8 | 50.18(3.818) | 15.50(6.468) | 34.32(3.013) |
| | 80 – 100 | 1.49 (0.032) | 5.9 | 47.94(4.075) | 10.91(1.213) | 41.15(3.588) |
| Small Homegarden | 0 – 20 | 1.58 (0.085) | 6.2 | 62.04(6.492) | 12.36(1.875) | 25.60(4.751) |
| | 20 – 50 | 1.44 (0.117) | 6.0 | 54.92(2.125) | 11.53(1.181) | 33.54(2.138) |
| | 50 – 80 | 1.44 (0.130) | 6.1 | 52.00(1.483) | 12.45(2.316) | 35.55(1.356) |
| | 80 – 100 | 1.49 (0.146) | 5.9 | 50.23(6.604) | 11.74(2.545) | 38.03(7.755) |
| Rubber Plantation | 0 – 20 | 1.37 (0.043) | 5.9 | 62.51(4.790) | 13.07(2.803) | 24.42(3.655) |
| | 20 – 50 | 1.23 (0.017) | 6.1 | 55.90(3.432) | 12.74(3.853) | 31.36(6.995) |
| | 50 – 80 | 1.19 (0.017) | 5.9 | 51.10(3.092) | 11.52(3.748) | 37.39(6.841) |
| | 80 – 100 | 1.10 (0.029) | 5.8 | 49.58(4.747) | 11.98(5.031) | 38.44(3.474) |
| Rice-Paddy Field | 0 – 20 | 1.65 (0.117) | 5.8 | 72.49(8.142) | 13.59(3.377) | 13.95(4.843) |
| | 20 – 50 | 1.46 (0.085) | 5.9 | 79.34(3.721) | 10.98(2.124) | 9.69(3.610) |
| | 50 – 80 | 1.07 (0.056) | 6.1 | 82.44(4.785) | 7.220(1.782) | 10.34(1.135) |
| | 80 – 100 | 1.04 (0.028) | 6.0 | 80.29(3.208) | 7.782(1.864) | 11.93(1.943) |

‡According to the standard classification, sand is particle between 0.05 – 2 mm in equivalent diameter, silt is particle between 0.002 – 0.05 mm in equivalent diameter, and clay is particle <0.002 mm in equivalent diameter (Brady and Weil 2008)

§Values in parentheses are standard deviations

There was only one site each for the forest and coconut plantations. Values reported are those obtained from composited samples within the site. For all other land-use systems, means and standard deviations are for soil samples from three different villages

## Distribution of soil fraction-size classes

The distribution of soil fraction-size classes was different in different land-use systems (Tables 3, 4, 5). The macro-sized (aggregate) fraction (2000 – 250 μm) accounted for about 40% under forest and 55% under rice-paddy, whereas the silt-and clay fraction (<53 μm) was 21% under forests and 13% under rice-paddy; the other land-use systems came in between (Table 6). Similar differences among the systems were observed for all depth classes (data not presented). The relation between whole soil carbon ($g\ kg^{-1}$) and silt+clay ($g\ kg^{-1}$) (Table 2) by depth for all land-uses combined were as follows:

$$0-20\,\mathrm{cm}: 0.073[\mathrm{silt}+\mathrm{clay}] - 14.8\ \left(R^2 = 0.82\right);$$
$$20-50\,\mathrm{cm}: 0.03[\mathrm{silt}+\mathrm{clay}] + 0.56\ \left(R^2 = 0.67\right);$$
$$50-80\,\mathrm{cm}: 0.016[\mathrm{silt}+\mathrm{clay}] + 0.56\ \left(R^2 = 0.65\right);\ \text{and}$$
$$80-100\,\mathrm{cm}: 0.01[\mathrm{silt}+\mathrm{clay}] + 1.28\ \left(R^2 = 0.72\right).$$

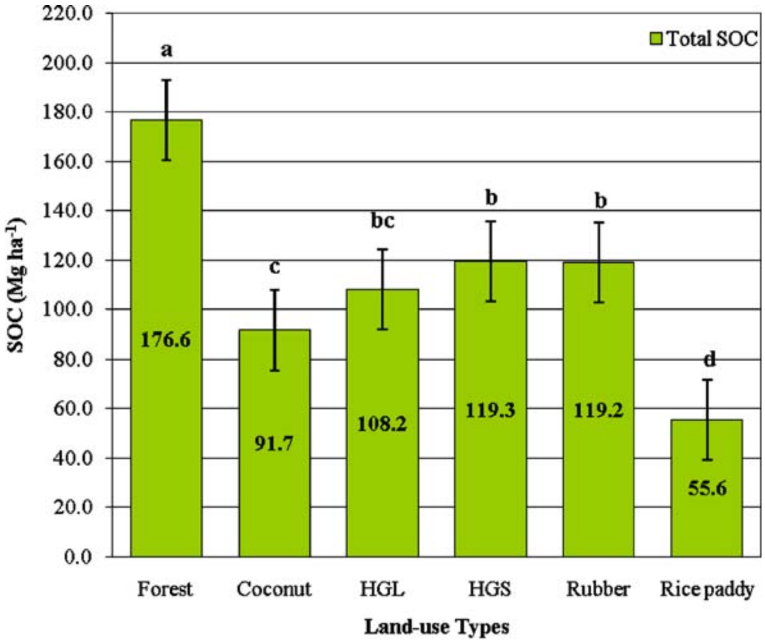


**Fig. 1** Total soil organic carbon (SOC) content in the whole soil up to 1 m depth in six different land-use systems in Thrissur district, Kerala, India. Lower case letters indicate differences (at the 0.05 probability level) in SOC among land-use systems within 1 m soil depth. HGL=Large Homegarden (>0.4 ha); HGS=Small Homegarden (<0.4 ha)

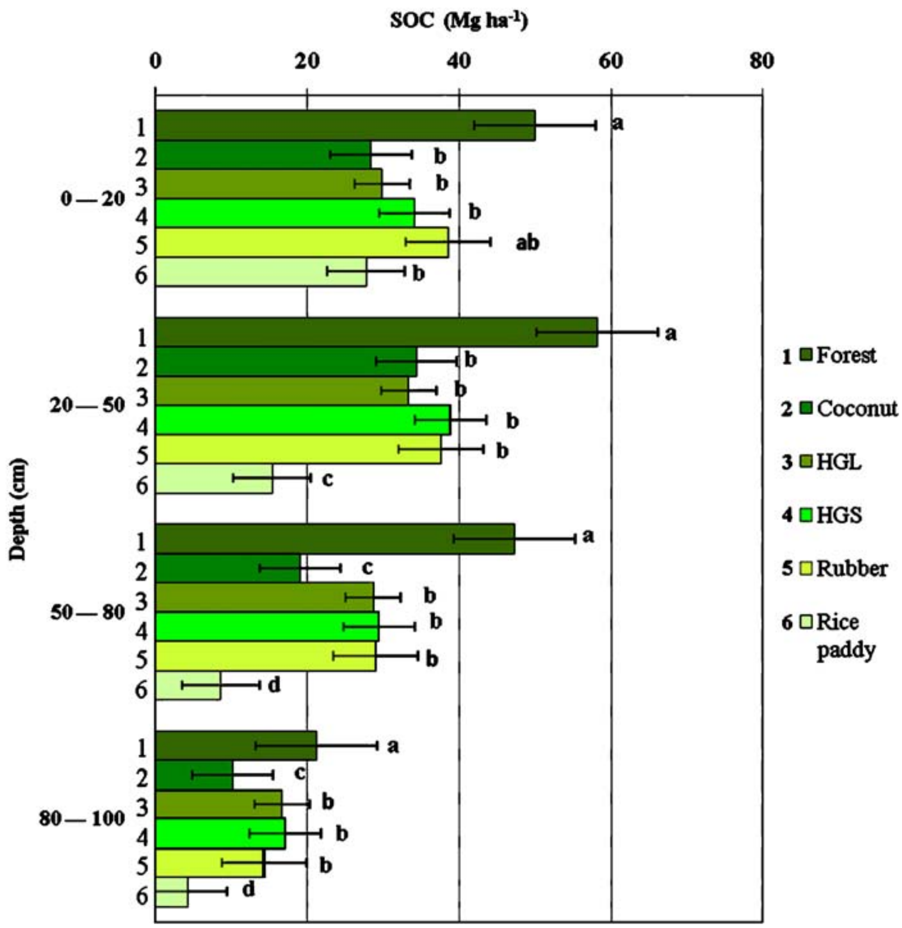


**Fig. 2** Mean soil organic carbon (SOC) content in the whole soil of six different land-use systems across soil depth classes in Thrissur district, Kerala, India. Lower case letters indicate differences (at the 0.05 probability level) in SOC among land-use systems compared within each depth class. Numbers 1 to 6 on the left (y-axis) of various depth classes refer to the different land-use systems. HGL=Large Homegarden (>0.4 ha); HGS=Small Homegarden (<0.4 ha)

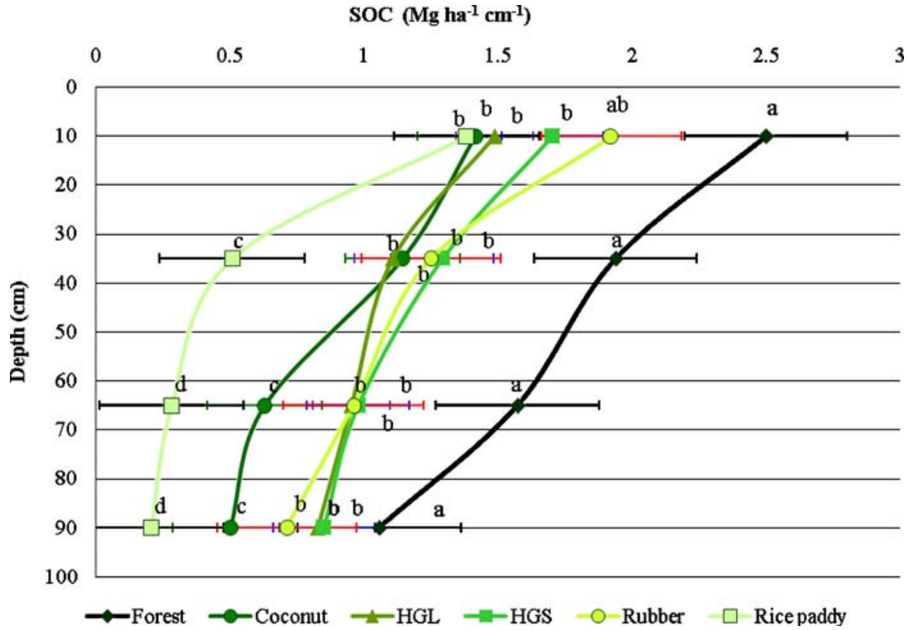


**Fig. 3** Depth-wise mean soil organic carbon (SOC) stock in the whole soil up to 1 m depth in six different land-use systems in Thrissur district, Kerala, India. Lower case letters indicate differences (at the 0.05 probability level) in SOC among land-use systems compared within 1 m soil depth. HGL=Large Homegarden (>0.4 ha); HGS=Small Homegarden (<0.4 ha)

## Soil organic carbon in macro-sized fraction (250 μm–2000 μm)

The cumulative value of total SOC for all four depth classes, hereafter referred to as "total SOC," of the macro-sized fraction within 1 m soil profile were 55.4, 43.73, 37.78, 32.65, 26.42, and 17.74 Mg ha$^{-1}$ in forest, rubber, HGS, HGL, coconut, and rice-paddy, respectively (Table 3). The mean values for SOC content of all sites indicate that at all depth classes forest had higher SOC content than HGL, coconut, and rice-paddy (Table 3). The SOC content of rice-paddy was lower compared to forest and rubber at all depths. The rubber plots had higher SOC than those of coconut throughout the 1 m soil profile. However, SOC content in rubber did not differ from that in HG (except with HGL at the upper medium layer). The two homegarden size classes did not differ from each other in SOC content at any depth. At the lower-most depth studied, the homegardens (both small and large) contained more C in the macro-sized soil fraction than in the coconut and rice-paddy systems.

## Soil organic carbon in micro-sized fraction (53 μm–250 μm)

The total SOC of the micro-sized fraction within 1 m soil profile were 58.72, 40.13, 37.09, 36.95, 28.58, and 13.56 Mg ha$^{-1}$ in forest, rubber, HGS, HGL, coconut, and rice-paddy, respectively (Table 4). Below 20 cm, the SOC content of forest and rice-paddy were highest and lowest, respectively. The SOC contents of rubber,

**Table 3** Total soil organic carbon (SOC) in macro-sized fraction (250 μm–2000 μm) at different soil depths of six land-use systems (mean of all three sites) in Thrissur, Kerala, India

| Mg ha$^{-1}$ | | | | | | |
|---|---|---|---|---|---|---|
| Depth (cm) | Forest | Coconut | HGL | HGS | Rubber | Rice-paddy |
| 0 – 20 | 14.63 $^{a}$ † (7.445) ‡ | 7.35 $^{c}$ (3.551) | 8.86 $^{bc}$ (4.836) | 10.21 $^{abc}$ (5.995) | 13.18 $^{ab}$ (3.887) | 5.82 $^{c}$ (2.959) |
| 20 – 50 | 18.25 $^{a}$ (4.546) | 10.04$^{cd}$ (3.863) | 9.54$^{cd}$ (3.487) | 12.55 $^{bc}$ (4.725) | 15.22 $^{ab}$ (3.648) | 6.72 $^{d}$ (4.127) |
| 50 – 80 | 14.46 $^{a}$ (3.991) | 5.67$^{cd}$ (1.934) | 8.37 $^{bc}$ (3.562) | 9.10 $^{b}$ (3.342) | 9.65 $^{b}$ (1.833) | 3.76 $^{d}$ (1.941) |
| 80 – 100 | 8.06 $^{a}$ (1.070) | 3.36 $^{c}$ (0.578) | 5.88 $^{b}$ (2.698) | 5.92 $^{b}$ (1.667) | 5.68 $^{b}$ (1.446) | 1.44 $^{d}$ (0.858) |

†Means for SOC in land-use systems at a given depth followed by different letters designate statistical significance at the 0.05 probability level

‡Values in parentheses are standard deviations

**Table 4** Total soil organic carbon (SOC) in micro-sized fraction (53 μm−250 μm) at different soil depths of six land-use systems (mean of all three sites) in Thrissur, Kerala, India

Mg $ha^{-1}$

| Depth (cm) | Forest | Coconut | HGL | HGS | Rubber | Rice-paddy |
|---|---|---|---|---|---|---|
| 0 – 20 | 16.11 $^{a}$ † (2.094)‡ | 8.42 $^{c}$ (3.819) | 10.10 $^{bc}$ (3.049) | 10.01 $^{bc}$ (3.842) | 12.73 $^{ab}$ (4.121) | 9.30 $^{c}$ (4.533) |
| 20 – 50 | 20.70 $^{a}$ (4.102) | 12.9 $^{b}$ (4.062) | 11.51 $^{b}$ (2.950) | 13.80 $^{b}$ (3.530) | 12.86 $^{b}$ (3.511) | 2.78 $^{c}$ (2.188) |
| 50 – 80 | 16.60 $^{a}$ (3.055) | 6.90 $^{c}$ (4.331) | 9.66 $^{b}$ (1.882) | 10.40 $^{b}$ (2.506) | 10.90 $^{b}$ (3.662) | 1.90 $^{d}$ (0.925) |
| 80 – 100 | 8.33 $^{a}$ (0.995) | 3.24 $^{c}$ (2.405) | 5.70 $^{b}$ (1.273) | 5.83 $^{b}$ (2.021) | 4.81$^{b}$ (1.087) | 1.17 $^{d}$ (0.476) |

†Means for SOC in land-use systems at a given depth followed by different letters designate statistical significance at the 0.05 probability level

‡Values in parentheses are standard deviations

HGL, and HGS were higher than that of coconut at all but the upper-most layer. The SOC content of rubber, HGL, and HGS did not differ among themselves.

### Soil organic carbon in silt and clay-sized fraction (<53 μm)

The total SOC of the silt-and-clay-sized fraction within 1 m soil profile was also highest under forest, followed by HGS, HGL, rubber, coconut, and rice-paddy systems (Table 5). The differences were significant only in depth classes below 20 cm, where the forest (highest) and rice-paddy (lowest) were significantly different, but not the other systems.

## Discussion

### Soil organic carbon in whole soil

The total amount of SOC within 1 m soil profile varied significantly among the selected land-use types (Fig. 1). The forest had the highest and rice-paddy the lowest SOC content. It is only natural that tree-dominated systems such as forests characterized by high amounts of litterfall and root activity contain higher SOC compared to a sole-crop agricultural system such as the rice-paddy. Incorporation of trees into treeless systems is reported to increase the belowground C stock in a number of situations; for example, in central highlands of Mexico (Reyes-Reyes et al. 2002); Costa Rica (Andrade et al. 2008); South Africa (Yelenik et al. 2004); and Florida (Haile et al. 2008).

As expected, the total SOC content decreased with soil depth under all land-use types (Fig. 3). Furthermore, SOC contents by depth in all land use systems were related to the silt+clay content of the soil, as observed in a previous study (Takimoto et al. 2008a). The amount of SOC in the top half of the 1 m soil profile (0–50 cm) was greater than in the lower half (50–100 cm) by 37%, 28%, and 36% in forest, HGL, and HGS, respectively; the corresponding values were 54% and 43% for coconut and rubber systems; for rice-paddy system, it was 71%. These differences

**Table 5** Total soil organic carbon (SOC) in silt+clay-sized fraction (<53 μm) at different soil depths of six land-use systems (mean of all three sites) in Thrissur, Kerala, India

Mg $ha^{-1}$

| Depth (cm) | Forest | Coconut | HGL | HGS | Rubber | Rice-paddy |
|---|---|---|---|---|---|---|
| 0 – 20 | 13.62 (1.604)‡ | 9.04 (2.515) | 9.10 (2.431) | 10.2 (3.259) | 9.80 (4.346) | 9.07 (5.929) |
| 20 – 50 | 16.95 $^{a}$† (3.085) | 10.65 $^{b}$ (2.640) | 10.45 $^{b}$ (3.435) | 10.64 $^{b}$ (2.735) | 10.70 $^{b}$ (5.018) | 5.060 $^{c}$ (3.226) |
| 50 – 80 | 16.70 $^{a}$ (2.376) | 6.62 $^{b}$ (3.015) | 9.70 $^{b}$ (1.877) | 8.74 $^{b}$ (2.914) | 7.10 $^{b}$ (4.572) | 3.04 $^{c}$ (0.819) |
| 80 – 100 | 8.10 $^{a}$ (1.778) | 3.53 $^{b}$ (1.480) | 4.90 $^{b}$ (1.403) | 4.90 $^{b}$ (1.656) | 3.51 $^{b}$ (1.811) | 1.90 $^{c}$ (0.742) |

‡Values in parentheses are standard deviations

†Means for SOC in land-use systems at a given depth followed by different letters designate statistical significance at the 0.05 probability level

**Table 6** Depth-wise distribution of different soil-fraction-size classes and their soil organic carbon (SOC) under six land-use systems in Thrissur, Kerala, India

| Soil | | Percent weight of size-fraction classes and total SOC at various soil depths in different land-use systems | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Depth (cm) | Size Fraction (μm) | | Forest | Coconut | HGL | HGS | Rubber | Rice-paddy |
| 0 – 20 | 2000 – 250 | Fraction | 40.96 | 44.68 | 52.34 | 54.22 | 51.42 | 56.20 |
| | | SOC | 32.98 | 29.63 | 31.58 | 33.56 | 36.91 | 24.06 |
| | 250 – 53 | Fraction | 38.97 | 38.84 | 32.14 | 29.51 | 34.52 | 31.71 |
| | | SOC | 36.32 | 33.94 | 35.99 | 32.91 | 35.65 | 38.45 |
| | <53 | Fraction | 20.07 | 16.48 | 15.52 | 16.27 | 14.06 | 12.10 |
| | | SOC | 30.70 | 36.44 | 32.43 | 33.53 | 27.44 | 37.49 |
| 20 –50 | 2000 – 250 | Fraction | 39.70 | 46.83 | 48.38 | 50.33 | 54.64 | 53.37 |
| | | SOC | 32.65 | 29.89 | 30.29 | 33.93 | 39.25 | 43.19 |
| | 250 – 53 | Fraction | 41.43 | 36.67 | 34.47 | 32.93 | 30.96 | 33.18 |
| | | SOC | 37.03 | 38.40 | 36.54 | 37.31 | 33.16 | 24.29 |
| | <53 | Fraction | 18.88 | 16.49 | 17.15 | 16.73 | 14.40 | 13.45 |
| | | SOC | 30.32 | 31.71 | 33.17 | 28.76 | 27.59 | 32.52 |
| 50 –80 | 2000 – 250 | Fraction | 38.71 | 44.16 | 48.80 | 47.21 | 49.44 | 53.07 |
| | | SOC | 30.28 | 29.55 | 30.18 | 32.22 | 34.90 | 43.22 |
| | 250 – 53 | Fraction | 36.06 | 40.08 | 34.44 | 34.54 | 31.15 | 33.93 |
| | | SOC | 34.76 | 35.96 | 34.84 | 36.83 | 39.42 | 21.84 |
| | <53 | Fraction | 25.23 | 15.76 | 16.77 | 18.26 | 19.42 | 13.00 |
| | | SOC | 34.97 | 34.50 | 34.98 | 30.95 | 25.68 | 34.94 |
| 80 – 100 | 2000 – 250 | Fraction | 40.57 | 49.33 | 49.78 | 48.35 | 48.88 | 53.84 |
| | | SOC | 32.91 | 33.17 | 35.68 | 35.56 | 40.57 | 31.93 |
| | 250 – 53 | Fraction | 37.79 | 36.00 | 32.73 | 33.88 | 31.06 | 32.65 |
| | | SOC | 34.01 | 31.98 | 34.59 | 35.02 | 34.36 | 25.94 |
| | <53 | Fraction | 21.65 | 14.67 | 17.49 | 17.76 | 20.06 | 13.51 |
| | | SOC | 33.07 | 34.85 | 29.73 | 29.43 | 25.07 | 42.13 |
| Total within 1 m(0 – 100) | 2000 – 250 | Fraction | 39.98 | 46.25 | 49.82 | 50.03 | 51.09 | 54.12 |
| | | SOC | 32.11 | 30.12 | 31.46 | 33.64 | 37.65 | 33.50 |
| | 250 – 53 | Fraction | 38.56 | 37.90 | 33.44 | 32.72 | 31.92 | 32.87 |
| | | SOC | 35.79 | 35.86 | 35.63 | 35.65 | 35.56 | 30.49 |
| | <53 | Fraction | 21.45 | 15.85 | 16.73 | 17.25 | 16.98 | 13.02 |
| | | SOC | 32.10 | 34.02 | 32.91 | 30.70 | 26.79 | 36.01 |

are likely a manifestation of the root distribution and activities in the different systems. Forests and home-gardens have high species diversity and contain a large number of tree species of different age groups (Saha et al. 2009). Root proliferation and activity is expected to be higher in such systems compared to monoculture stands of coconut and rubber. Dea et al. (2001) reported that although the main taproot of a 3-year old rubber tree went 100 cm deep, the lateral roots were restricted within 70 cm with a high root density above 30 cm. Similarly, the vast majority of coconut roots are concentrated in the upper 50 cm of soil in regularly cultivated stands of coconuts (Nair 1979). The majority of the rice-paddy roots are also found in the surface soil above the 50 cm depth (Kusnarta et al. 2004).

The difference in SOC content between forests and the homegardens — that are also tree-dominated — is a reflection of the differences in tree population and anthropogenic (management) factors. Overall plant density, especially tree density, was higher under forests than under HGs (Saha et al. 2009). The pattern of root growth and development is also important for SOC accumulation. In Kerala HGs, coconuts and arecanuts (*Areca catechu*) are the major tree species. These are palms (monocots) with shallow fibrous root systems. In contrast, in the forest, the majority of the trees are hardwoods (dicots) (Chandrashekara and Ramakrishnan 1994) with taproots that extend to deeper soil depths. Amount of litterfall is also higher in forests compared to HGs (Isaac and Nair 2006). Furthermore, unlike the forests, the HGs experience disturbances such as tillage, manual weeding, and removal of trees, all of which affect the process of SOC accumulation. Trees in HGs are generally not retained beyond their economic life span, but trees in natural forest senesce and provide a good source of SOC after they die and decompose. This difference in SOC contents between forest and HGs may not hold under all conditions. For example, Kirby and Potvin (2007) observed no difference in SOC content between forests and agroforests (home and outfield gardens, consisting of perennial tree crops that include fruit-, timber- and medicinal species) up to 40 cm soil depth in Inceptisols and Vertisols of Eastern Province, Panama. Obviously, the SOC content in any system is dependent upon a large number of location- and system-specific factors such as climate, soil type, vegetation, and management practices.

The mean difference in SOC of HGS and HGL across the three sites was 10% within top 1 m soil (Fig. 1). This difference is probably due to the differences in species and plant (especially tree) density between the two systems. Smaller home-gardens have higher species diversity (Kumar et al. 1994; Saha et al. 2009) and higher species density (Mohan et al. 2007). Plant diversity survey of the HGs under this study indicated that HGS had higher species density (1.61 species 100 $m^{-2}$) than HGL (0.71 species 100 $m^{-2}$) (Saha et al. 2009). Furthermore, plant density (especially tree density) was higher in the HGS (7.5 trees 100 $m^{-2}$) compared to HGL (5.8 trees 100 $m^{-2}$) (Saha et al. 2009). High species assemblages are likely to harbor species with greater response to the resources compared to systems with limited species richness (Tilman et al. 1997; Tilman et al. 2001) and may promote a resource-use-efficient system that favors greater net primary production (Vandermeer 1989), which in turn promote C sequestration. The total amount of SOC (76 Mg $ha^{-1}$) within the top 1 m of soil of the rubber stand was 33% lower than that of forest. However, the SOC values under rubber and HGs were somewhat similar. The SOC in top soil of HGs are affected by disturbances such as tillage, manual weeding, and partial removal of plant residues. In contrast, the rubber plantation has little soil management disturbances, which may also facilitate higher root activity in the top soil. Overall, these differences between the homegardens and the rubber stand evened out with soil depth such that total SOC from all soil depths yielded similar SOC values in the two systems.

## Soil organic carbon in fraction-size classes

The percentage distribution of various soil fraction-size classes under different land-use systems showed the relative abundance of silt-and-clay fraction (<53 μm) in the soil under forest (about 21% in the entire 0 – 100 cm depth), compared with 13% under rice-paddy (Table 6). Similarly, the macro-sized fraction (250 – 2000 μm) was highest (about 40%) in forest soil and the lowest (13%) in rice-paddy soil. In all land-use systems, the SOC was distributed more or less equally in the different fraction-size classes (one third in each class) (Table 6). In the macro-sized fraction, the SOC percentage varied from 30% (coconut) to 37% (rubber); in the micro-sized fraction, it ranged from 30% (rice-paddy) to 36% (rest of the land-use systems); and in the silt-and-clay fraction, the range was from 27% (rubber) to 36% (rice-paddy). The calculated values of total SOC obtained by summing up the SOC in each soil fraction at a given depth to a 1 m soil profile were 96%±2% of the directly calculated values of SOC (by summing up total C at a given depth) presented in Fig. 1.

The macro-sized fraction class (250–2000 μm) roughly represents the macroaggregates that contain the more active pool of C, which is influenced by the land-use and soil management (Six et al. 2002). This pool contains the recent C depositions in soil (Carter 1996); therefore, it is sensitive to changes in organic matter dynamics with time. The micro-sized class (53–250 μm) (micro-aggregates) is the building block of soil structure and more stable in storing C (Tiessen and Stewart 1983). Organic C inside this class has lower decomposition rate and can store C for a longer time than in larger-size fractions (Six et al. 2000). In other words, the micro-sized class would be in between the macro-sized class and the silt-and-clay-sized class in terms of SOC stability. The SOC content in silt-and-clay-sized class (>53 μm) is considered to be more stable than in larger soil fractions (Six et al. 2002). Interaction between clay minerals and humic substances provide the stability of C in the silt-and-clay sized class (Brady and Weil 2008). Clay particles create small pores (<1 μm), where organic matter can be stored and can remain unreachable to decomposing organism. In addition, organic matter may also get combined with layer silicate clays (e.g. vermiculite) in their interlayers and form compounds highly resistant to decomposition.

The SOC contents in different size classes may vary with the land-use changes within relatively "short" time spans (<100 years). The differences in SOC contents of macro-sized fraction (Table 3) among soils under coconuts, homegardens point to this. The forest and rice-paddy systems have been in place for a long period of time (>100 years) and those C stock values can be considered as characteristic of each system. On the other hand, coconuts and rubber represent "recent" land-use changes (in this study, coconuts were 30 years and rubber 50 years old; the homegardens were of varying ages from 30 to 100 years). Thus, the differences in SOC stock in various fraction-size classes could also be a reflection of the "tree effect" in time. For the micro-sized class (53 – 250 μm) (Table 4), the SOC differences among coconut, rubber, and HGs were comparatively lower than those in the macro-sized class (Table 3), but were higher than those of the silt-and-clay-sized class (Table 5). This suggests that the effects of land-use changes on the SOC of micro-sized class are less than that on macro-sized class, but more than that on silt-and-clay-sized class. Similar results were reported by Lehman et al. (2001) in a Xanthic Ferralsol of the central Amazon, where they observed that compared to the smaller size classes, the fraction class of 0.25 – 0.5 mm (250 – 500 μm) was more sensitive to the land-use change. Comparatively older land-use systems like forest and rice-paddy showed more differences in the SOC stock than in "newer" systems such as rubber and homegardens in micro-sized fraction class too just as in the case of the macro-sized class.

The SOC content in silt+clay-sized class (>53 μm) showed a clear trend of increasing amount with increasing tree density, with the lowest value in the rice-paddy and highest value in the forest soils (Table 5). It could be because of the relatively higher content of the silt+clay fraction in forest soils compared to the other systems, particularly rice-paddy (Table 6). There were no differences in SOC contents in the silt-and-clay fractions under coconuts, homegardens, and rubber at any depth class below 20 cm (Table 5). Among land-use systems, the amount of SOC in silt-and-clay fraction size class — which is known to represent stable C — up to 1 m soil depth was related to tree density. Systems with higher tree-density (e.g. forest) stored higher amounts compared to old treeless systems such as rice-paddy (Table 5). While investigating changes in SOC storage following deforestation, Veldkamp (1994) made adjustments to current SOC values from pasture systems established in deforested areas, based on the soils' current BD values. That study entailed a sequential comparison of systems, as opposed to the simultaneous comparison in our study.

Carbon sequestration is a rate process; time-sequence studies are needed to quantify its extent. Such time-sequence studies are difficult and time consuming, and are often supplanted with other approaches such as the one used in this study. However, in the absence of any "baseline" data to relate the results to, our study does not allow a comparison of different systems in terms of changes in soil C stocks with changes in land-use. Thus, it is difficult to say if the soils under treeless land-use systems would have attained the same level of C storage as those under tree-based systems had the land remained under forest cover. Although such an analysis would be scientifically interesting, it would not reflect the practical reality of irreversible land conversion that has already taken place. Although this one-time study may not exactly represent C sequestration, the C stock values can be taken as good indicators of C sequestration potential of the systems. The ecological process by which trees contribute to such higher amounts of C in stable form is believed to be mediated via litterfall and decomposition, and root activity especially decomposition of sloughed-off roots (Schlesinger et al. 1990; Lemma et al. 2007). The relative proportions of finer soil fractions (silt-and-clay) in the soil were also higher under tree-based systems compared to treeless system. Taken in conjunction with the results of similar studies reported from other ecological regions and different agroforestry systems (Haile et al. 2008; Takimoto et al. 2008a; 2008b), the supposed role of trees in increasing C storage in deeper soil depths in finer soil particles seems credible.

In a broader context, these results have implications on the role of tree-based systems in greenhouse mitigation through soil carbon storage. It shows that homegardens and such other integrated multistrata systems that are a common land-use system in many parts of the tropics (Kumar and Nair 2006) with a significant economic and agricultural role can also provide an important environmental service through mitigation of $CO_2$ emission to atmosphere.

## Conclusion

Land-use systems with higher tree density and less soil disturbance contributed to greater soil C storage, an indicator of higher C sequestration in soils. Highest SOC stock was found in the forest and the lowest in the rice-paddy system. Soil organic carbon contents of homegardens and rubber plantations did not vary significantly. Carbon content in soil profiles decreased with soil depth; but lower depths up to 1 m contained substantial amount of C, indicating the importance of considering the soils below the surface horizon in soil C studies. Comparatively more SOC was found in the lower half of 1 m depth in forest and homegardens than the other land-use systems, indicating the possible contribution of tree roots. Soil organic carbon contents in macro-sized class (250–2000 μm) showed more difference among land-use systems followed by those of micro-sized (53–250 μm) and silt-and-clay-sized (>53 μm) classes suggesting that changes in land-use types in course of time are reflected first in macro-sized class, followed by micro-sized, and then the silt-and-clay sized fractions. Due to the structural stability of silt and clay-sized class, more time is required to observe any effect of land-use changes on this size class. In a broader context, these results have implications on the role of tree-based systems, especially traditional integrated systems such as homegardens, in greenhouse mitigation through soil carbon storage. This unappreciated and underexploited benefit merits further research and policy attention.

## References


Albrecht A, Kandji ST (2003) Carbon sequestration in tropical agroforestry systems. Agric Ecosyst Environ 99:15–27

Andrade HJ, Brook R, Ibrahim M (2008) Growth, production and carbon sequestration of silvopastoral systems with native timber species in the dry lowlands of Costa Rica. Plant Soil 308:11–22

Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England. Nature 437:245–248

Brady NC, Weil RR (2008) The nature and properties of soil (14th edition). Prentice Hall, New York

Carter MR (1996) Analysis of soil organic matter in agroecosystems. In: Carter MR, Stewart BA (eds) Structure and organic matter storage in agricultural soil. CRC press, Boca Raton, pp 3–11

Chandrashekara UM, Ramakrishnan PS (1994) Vegetation and gap dynamics of a tropical wet evergreen forest in the Western Ghats of Kerala, India. J Trop Ecol 10:337–354

Day PR (1965) Particle fractionation and particle-size analysis. In: Black CA (ed) Methods of soil analysis, Part 1. ASA, Madison, pp 545–567

Dea G, Assiri AA, Gabla OR, Boa D (2001) Influence of soil preparation method on root and vegetative growth of rubber tree (Hevea brasiliensis) in the southwest Côte d'Ivoire. Soil Till Res 59:3–11

Elliott ET (1986) Aggregate structure and carbon nitrogen and phosphorus in native and cultivated soils. Soil Sci Soc Am J 50:627–633

Fassbender HW, Beer J, Heuveldop J, Imbach A, Enriquez G, Bonnemann A (1991) Ten year balances of organic matter and nutrients in agroforestry systems at CATIE, Costa Rica. For Ecol Manage 45:173–183

Fernandes ECM, Nair PKR (1986) An evaluation of the structure and function of tropical homegardens. Agrofor Syst 21:279–310

Government of Kerala (2005) Soil and land resources of Madakkathara panchayat. Soil Survey Organization, Report no. 468. Kerala, India

Government of Kerala (2008) Available via www.kerala.gov. Accessed 16 Jan 2009

Haile SG, Nair PKR, Nair VD (2008) Carbon storage of different soil-size fractions in Florida silvopastoral systems. J Environ Qual 37:1789–1797

Haile SG, Nair VD, Nair PKR (2009) Contribution of trees to carbon storage in soils of silvopastoral systems in Florida, USA. Global Change Biology doi: 10.1111/j.1365-2486.2009.01981.x. (in press)

Intergovernmental Panel on Climate Change (IPCC) (2007) Climate change 2000: The scientific basis. Oxford Univ Press, Oxford

Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashie-Sam J (2005) Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor Syst 65:23–31

Isaac SR, Nair MA (2006) Litter dynamics of six multipurpose trees in a homegarden in southern Kerala India. Agrofor Syst 67:203–213

Jose D, Shanmugaratnam N (1993) Traditional homegardens of Kerala: A sustainable human ecosystem. Agrofor Syst 24:203–213

KAU (2009) Package of practices. Available at http://www.kau.edu/pop/index.htm. Last accessed: May 2009

Kirby KR, Potvin C (2007) Variation in carbon storage among tree species: Implications for the management of a small scale carbon sink project. For Ecol Manage 246:208–221

Kumar BM, George SJ, Chinnamani S (1994) Diversity structure and standing stock of wood in the homegardens of Kerala in peninsular India. Agrofor Syst 25:243–262

Kumar BM, Nair PKR (2006) Tropical homegardens: A time-tested example of sustainable agroforestry. Springer, Netherlands, p 377

Kusnarta IGM, Tisdall J, Sukartono M, Ma'shum M, Gill JS, VanCooten D (2004) Rice root distribution under various systems of soil management on rainfed Vertisols in Southern Lombok, Eastern Indonesia. New directions for a diverse planet: Proceedings of the 4th International Crop Science Congress, Brisbane, Australia, 26 Sep – 1 Oct 2004

Lehmann J, da Silva Cravo M, Zech W (2001) Organic matter stabilisation in a Xanthic Ferralsol of the central Amazon as affected by single trees: chemical characterisation of density, aggregate and particle size fractions. Geoderm 99:147–168

Lemma B, Kleja DB, Olsson M, Nilsson I (2007) Factors controlling soil organic carbon sequestration under exotic tree plantations: A case study using the CO2Fix model in southwestern Ethiopia. For Ecol Manage 252:124–131

Makundi WR, Sathaye JA (2004) GHG mitigation potential and cost in tropical forestry — relative role for agroforestry. Environ Dev Sust 6:235–260

Mohan S, Nair PKR, Long AJ (2007) An assessment of the ecological diversity of homegardens: A case study of Kerala State, India. J Sust Agric 29:135–153

Nair PKR (1979) Multiple cropping with coconuts in India. Verlag Paul Parey, Berlin 147 p

Nair PKR (1993) An introduction to agroforestry. Kluwer, Dordrecht, The Netherlands 499 p

Nair PKR, Kumar BM, Nair VD (2009) Agroforestry as a strategy for carbon sequestration. J Soil Sci Plant Nutr. 172:10–23

Nair MA, Sreedharan C (1986) Agroforestry farming systems in the homesteads of Kerala southern India. Agrofor Syst 4:339–363

Nair PKR, Nair VD (2003) Carbon storage in North American Agroforestry Systems. In: Kimble J et al (eds) The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press, Boca Raton, pp 333–346

Oelbermann M, Voroney RP, Kass DCL, Schlönvoigt AM (2006) Soil carbon and nitrogen dynamics using stable isotopes in 19- and 10-year-old tropical agroforestry systems. Geoderma 130:356–367

Peyre A, Guidal A, Wiersum KF, Bongers F (2006) Dynamics of homegarden structure and function in Kerala, India. Agrofor Syst 66:101–115

Reyes-Reyes G, Baron-Ocampo L, Cuali-Alvarez I, Frias-Hernandez JT, Olalde-Portugal V, Fregoso LV, Dendooven L (2002) Carbon and nitrogen dynamics in soil from the central highlands of Mexico as affected by mesquite (Prosopis spp.) and huizache (Acacia tortuoso): A laboratory investigation. Appl Soil Ecol 19:27–34

SAS Institute (2004) SAS user's guide: Statistics SAS/C Online Doc™ Release 7.50 Cary, NC, USA

Saha S, Nair PKR, Nair VD, Kumar BM (2009) Soil carbon stock in relation to plant diversity of homegardens in Kerala, India. Agrofor Syst 76:53–65

Schlesinger WH, Reynolds JE, Cunningham GL, Huenneke LF, Jarrell WM, Virginia RA, Whitford WG (1990) Biological feedbacks in global desertification. Science 247:1043–1048

Sharrow SH, Ismail S (2004) Carbon and nitrogen storage in agroforests tree plantations and pastures in western Oregon, USA. Agrofor Syst 60:123–130

Six J, Elliott ET, Paustian K (2000) Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biol Biochem 32:2099–2103

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. Plant Soil 241:155–176

Smiley GL, Kroschel J (2008) Temporal change in carbon stocks of cocoa—Gliricidia agroforests in Central Sulawesi, Indonesia. Agrofor Syst 73:219–231

Swift MJ, Anderson JM (1993) Biodiversity and ecosystem function in agricultural systems. In: Schulze ED, Mooney HA (eds) Biodiversity and ecosystem function. Springer-Verlag, Berlin, Germany, pp 15–42

Takimoto A, Nair PKR, Nair VD (2008a) Carbon stock and sequestration potential of traditional and improved agroforestry systems in the West African Sahel. Agric Ecosyst Environ 125:159–166

Takimoto A, Nair VD, Nair PKR (2008b) Contribution of trees to soil carbon sequestration under agroforestry systems in the West African Sahel. Agrofor Syst 76:11–25

Tiessen H, Stewart JW (1983) Particle-size fractions and their use in studies of soil organic matter: II., Cultivation effects on organic matter composition in size fractions. Soil Sci Soc Am J 47:509–514

Tilman D, Lehman CL, Thomson KT (1997) Plant diversity and ecosystem productivity: Theoretical considerations. Proc Nat Acad Sci (USA) 94:1857–1861

Tilman D, Reich PB, Knops J, Wedin D, Mielke T, Lehman C (2001) Diversity and productivity in the long-term grassland experiment. Science 294:843–845

UNFCCC (2009) Glossary of climate change (http://unfccc.int/essential_background/glossary/items/3666.php#C). Last accessed: May 2009

Vandermeer J (1989) The ecology of intercropping. Cambridge University Press, Cambridge 249 p

Veldkamp E (1994) Organic carbon turnover in three tropical soils under pasture after deforestation. Soil Sci Soc Am J 58:175–180

Wright DG, Mullen RW, Thomason WE, Raun WR (2001) Estimated land area increase of agricultural ecosystems to sequester excess atmospheric carbon dioxide. Commun Soil Sci Plant Anal 32:1803–1812

Yelenik SG, Stock WD, Richardson DM (2004) Ecosystem level impacts of invasive Acacia saligna in the South African Fynbos. Rest Ecol 12:44–51