

Soil carbon stock in relation to plant diversity of homegardens in Kerala, India

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Abstract Conservation of biodiversity and mitigation of global warming are two major environmental challenges today. In this context, the relationship between biodiversity (especially plant diversity) and soil carbon (C) sequestration (as a means of mitigating global warming) has become a subject of considerable scientific interest. This relationship was tested for homegardens (HG), a popular and sustainable agroforestry system in the tropics, in Thrissur district, Kerala, India. The major objectives were to examine how tree density and plant-stand characteristics of homegardens affect soil C sequestration. Soil samples were collected at four depths (0–20, 20–50, 50–80, 80–100 cm) from HG of varying sizes and age classes, and their total C content determined. Tree density and plant-stand characteristics such as species richness (Margalef Index) and diversity (Shannon Index) of the HG were also determined. Results indicated that the

soil C stock was directly related to plant diversity of HG. Homegardens with higher, compared to those with lower, number of plant species, as well as higher species richness and tree density had higher soil carbon, especially in the top 50 cm of soil. Overall, within 1 m profile, soil C content ranged from 101.5 to 127.4 Mg ha⁻¹. Smaller-sized HG (<0.4 ha) that had higher tree density and plant-species density had more soil C per unit area (119.3 Mg ha⁻¹) of land than larger-sized ones (>0.4 ha) (108.2 Mg ha⁻¹). Soil C content, especially below 50 cm, was higher in older gardens. The enhanced soil-C storage in species-rich homegardens could have relevance and applications in broader ecological contexts.

Keywords Agroforestry · Carbon sequestration · Global warming · Species density · Species richness · Tree density

Abbreviations

GHG Greenhouse gas
HG Homegarden
HGL Large homegarden
HGS Small homegarden
SOC Soil organic carbon

Introduction

Biodiversity decline and global warming are two major environmental issues of the world today. The

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seriousness of the former is evident from the estimates of the Convention on Biological Diversity (CBD) that human activity is causing species extinction at a rate of 100–1,000 times the natural rate of extinction (CBD 2006). Increase in atmospheric concentrations of greenhouse gases (GHG), of which the most common is carbon dioxide (CO₂), is the primary cause of global warming and the Intergovernmental Panel on Climate change (IPCC) estimates (IPCC 2007) that the current GHG concentrations are 30% more than the pre-industrial level. The CBD and the United Nations Framework Convention on Climate Change (UNFCCC), the two major international covenants that have been developed to address the issues of biodiversity loss and global warming, respectively, have developed various action plans and strategies to combat these problems. But each has focused on its own mandate area with little effort being given to looking at the issues together. For example, efforts to explore the potential of sequestering carbon (C) (capture and storage of carbon in a temporal sequence) (as a GHG-mitigating strategy) and at the same time conserving biodiversity under a single project are relatively few (World Bank 2002). Although the relationship between biodiversity (especially plant diversity) and C sequestration has been a subject of scientific interest (Schwartz et al. 2000; Tilman et al. 2001; Srivastava and Vellend 2005), investigations on this topic are limited. Tilman et al. (1997) and Kirby and Potvin (2007) have suggested that plant assemblages with high species-diversity may promote more efficient use of resources compared with those of lesser species diversity and thus lead to greater net primary production (Vandermeer 1989), and consequently higher C sequestration. High plant diversity in a system may alleviate disturbances (Huston and Marland 2003) such as temporal instabilities caused by climate change; on the other hand, it is widely agreed that more C is better sequestered in systems with lesser disturbance (Six et al. 2002).

Land-use systems with high plant-species-diversity offer a good ground for investigating the plant diversity-C sequestration relationship. Homegardens (HG) are one such system consisting of intimate, multistory combinations of various trees and crops, sometimes in association with domestic animals, around the homesteads (Fernandes and Nair 1986; Kumar and Nair 2004). They constitute a very common land-use system in the tropics and are

regarded as ‘the epitome of sustainability’ (Torquebiau 1992). Homegardens are distributed throughout the tropics in Africa, Asia, Central and South America, the Caribbean, and the Pacific Islands (High and Shackleton 2000; Nair and Kumar 2006). The high plant-species diversity of tropical HG has been illustrated in a number of reports (Swift and Anderson 1993; Kumar et al. 1994; Mohan et al. 2007). Some studies that have estimated the diversity indices from ecological points of view have indicated that plant-diversity indices of HG are comparable to those of adjacent forest (Kumar et al. 1994; Gajaseneni and Gajaseneni 1999; Wezel and Bender 2003).

Homegardens are considered to have high C sequestration potential (CSP) due to their forest-like structure and composition (Kumar 2006) and also due to specific management practices that tend to enhance nutrient cycling and increase soil organic matter, such as those used in many regions of Mesoamerica today. Many of these practices have been in use for hundreds of years especially among descendants of Maya populations (Montagnini 2006). Trees play an important role in soil C sequestration (Montagnini and Nair 2004; Takimoto et al. 2008): with an increase in the number of trees (high tree density) in a system, the overall biomass production per unit area of land will be higher, which in turn may promote more C storage in soils. In fact, recent research has reported higher soil C stock (amount of carbon stored in soil) under deeper soil profiles in agroforestry systems compared to treeless agricultural or pasture systems under similar ecological settings (Haile et al. 2008; Nair et al. 2009). Thus, it is logical to assume that HG soils will store more C than soils of treeless agricultural systems. It is also likely that the amount of C stored in the soil will depend on HG characteristics such as size of the holding and “age” of the system (the length of time during which the land has been under the practice). Plant-species diversity in HG is inversely proportional to the land-holding size (Kumar et al. 1994; Mohan et al. 2007); therefore, smaller-sized HG are likely to sequester more soil C per unit area of land compared to larger-sized ones. Furthermore, the mean residence time (MRT) of soil organic C (SOC) at lower soil depths is influenced by the permanence of the system (indicated by its age) and the extent of soil disturbance (Fontaine et al. 2007); therefore, older systems can be expected to store more quantities of soil C than younger ones. No

research reports are available on these topics. In this background, the present study was conducted with the overall objective of examining the relationship between plant species diversity and soil C sequestration in homegardens in Kerala, India.

Materials and methods

Study area

The study was conducted in the state of Kerala, India (Fig. 1), a region that is rich in HG of various size classes and varying species diversity (Nair 1993; Kumar and Nair 2004). The Madakkathara subdivision (*Panchayat*), at 10°32' and 10°36' north latitudes and 76°14' and 76°18' east longitudes, in the district of Thrissur, in central Kerala, where the Kerala Agricultural University (KAU) is located, was selected for the study. Within the Madakkathara *Panchayat*, three villages (Pandiparambu, Chirakkakode, and Vellanikkara) were chosen for the study based on the availability of homegardens. The study area and villages are representative of the region as determined by local officials of KAU and the Kerala Forest Department. In addition, the selected study region had homegardens of varied size and age class that were required for the study.

Climate and soil

Madakkathara *Panchayat* has a humid tropical climate with two monsoon seasons. About 65% of the rainfall is received from the so-called “southwest monsoon” during June–August and 30% from the “northeast monsoon” during October–November. Mean annual rainfall is 2,783 mm. The average annual temperature is 27.7°C with a mean maximum temperature of 32°C and a mean minimum of 23.3°C. The mean humidity and evaporation are 74.8% and 105.4 mm, respectively. According to local norms, lowlands are those lying <20 m above mean sea level (MSL), midlands: 20–100 m, mid-uplands: 100–300 m, and uplands: >300 m above MSL (Government of Kerala 2005). The study villages are located in the lowland area; the land has a gentle slope varying from 1–5%. The parent material of the soils in Madakkathara *Panchayat* is granite gneissic rocks formed by the weathering of charnokites and laterites,

which were transported and deposited as soils of sedimentary origin that are low in bases. The major soil order of the area is Inceptisols and the soil suborder, great group, subgroup, family are Tropepts, Dystropepts, and Fluventic Dystropepts, and fine mixed isohyperthermic, respectively (Government of Kerala 2005). The soil series are ‘*Maraickal*’ and ‘*Koottala*’ (local name).

Homegardens of Kerala

Homegardens constitute the most important agroforestry system in Kerala. There are about 5.4 million small operational holdings covering a total area of 1.8 Mha in Kerala, and about 80% of them are homegardens (Government of Kerala 2008), therefore the state is estimated to have 4.32 million HG covering 1.4 Mha of land (Kumar 2006). Homegardens are diverse in nature in terms of species composition, size, and age (Mohan et al. 2007). A total of 24 HG were selected for the study; they were categorized into two classes: “Small Homegarden” (HGS), less than 0.4 ha (1.0 acre) in area; and “Large Homegarden” (HGL), more than 0.4 ha (1.0 acre) in area. Eight gardens, four each of HGL and HGS, were selected from each of the three study villages. Each HG was unique in terms of its size, ¹plant diversity, ²age, and management practices. Indeed, it is difficult, if not impossible, to find two HG that are identical in all these characteristics, although the plant diversity and management practices may be somewhat similar among the HG within a location. Owners of all 24 HG were interviewed to collect background information about their gardens. Size and the age of the HG can vary regardless of the location; special attention was given to these factors during the interview survey. Information was collected on plant diversity parameters such as number and species of trees, shrubs, and herbs—including ornamentals and medicinal plants, but excluding weeds in the garden.

¹ Based on taxonomic identification of species (with the help of KAU professionals) and experience of local farmers, the plants were categorized as trees, shrubs, and herbs.

² The age of HG that refers to the length of the period when the land has been managed as a homegarden was assessed based on discussion with its owners. While annuals are replanted every season, perennial plants including trees, are removed and replanted only when they become senile or unproductive.

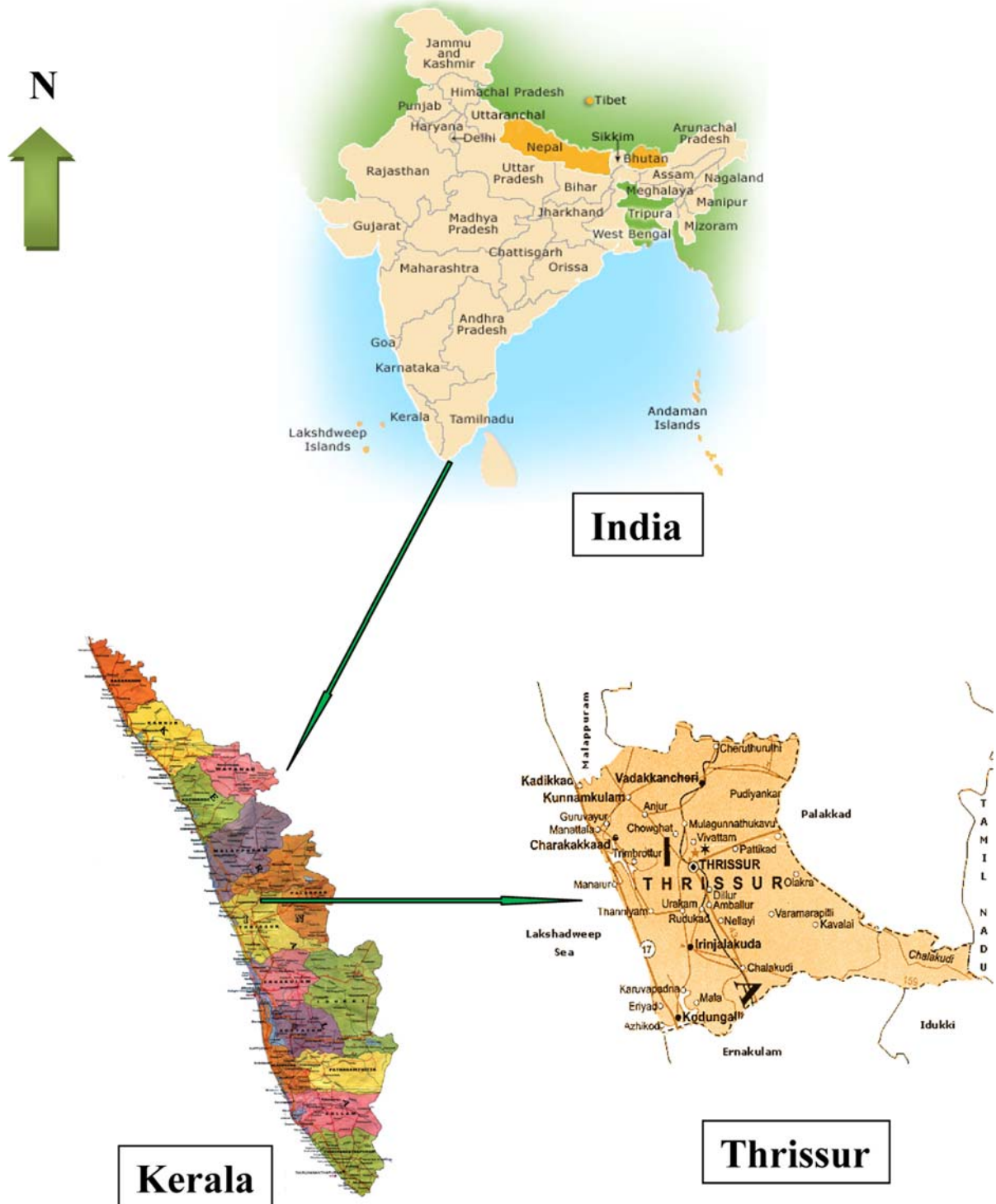


Fig. 1 Geographical location of the study site (in Thrissur, Kerala, India). Source: <http://maps.locateindia.com>, <http://hikerela.googlepages.com>. Last accessed July 2008

Taxonomic identification of plant species was obtained from the Kerala Agricultural University. Details of plant composition of Kerala homegardens are available in Saha (2008) and other sources (Kumar et al. 1994; Mohan et al. 2007).

Soil sampling and analysis

Soil samples were collected in November–December 2006 from eight HG from each of the three study villages. In each HG (plot), three sampling sites were selected randomly and from each site, soils were collected from four depths 0–20, 20–50, 50–80, and 80–100 cm. A composite sample for each depth interval was prepared by mixing soils from three sampling sites, resulting in one sample per depth level from each study plot. Thus, there were a total of 96 samples (1 land-use type \times 3 villages \times 8 replications/plots \times 4 depths) from the three villages. Soil sampling for bulk density measurement was done using a 178 cm³ steel cylinder. For bulk density measurement soil pits of 1 m \times 1 m \times 1 m size were dug and the cylinder was horizontally inserted on the wall of the pit at the center of each depth class to collect the samples. All samples were air-dried, sieved (passed through 2 mm sieve), bagged, and sent to University of Florida, Gainesville, Florida for analyses.

The soil samples were 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 soil organic C (SOC) concentrations were determined on an automated FLASH EA 1112 N C elemental analyzer (LECO Corporation, St. Joseph, MI). Soil pH and particle size analysis (Day 1965) were also determined. ³The C storage (Mg ha⁻¹ in 1 m vertical depth) was calculated by multiplying the C concentration (g per kg of soil in fraction size) with bulk density of depth interval (kg m⁻³) and the thickness of the depth.

Ecological indices

Plant species richness of the HG was estimated according to the Margalef Index (Margalef 1958)

and plant species diversity by the Shannon Index (Krebs 1985). Sorenson's Index of similarity (Sorenson 1948) was used to estimate the magnitude of similarity in plant species between homegardens. Species density (number of species per unit area) was measured by dividing the total number of plant species of an HG by the total area of that HG).

Species richness (Margalef Index): This index calculates the number of species in an area divided by the log of the total number of individuals sampled, added over species. The higher the Margalef Index, the higher the species richness of the population (Margalef 1958).

$$\text{Margalef Index} = \frac{(N - 1)}{\ln(n)}$$

Where, N is the number of species, and n is the total number of individuals in the sample.

Species diversity (Shannon Index) is the product of its richness and evenness. Richness refers to the presence or absence of species and evenness is the balance between the numbers of individual members of species (Krebs 1985). There are several ecological indices to measure species diversity, of which Shannon Index is most commonly used.

$$H = \sum_{i=1}^n p_i \ln p_i$$

where, H = Shannon Index, n = number of species, and p_i = proportion of total sample belonging to i th species.

The proportion of species relative to the total number of species is calculated and multiplied by the natural logarithm of this proportion. The resulting product is summed across species and multiplied by negative one (-1).

Similarity (Sorensen's Index): The vegetative similarity was estimated using Sorensen's Index of similarity and presented in percentage (Sorenson 1948).

$$S = \frac{\text{number of common species}}{(s_x + s_y)/2} \times 100$$

where S is the Sorensen's Index, S_x the number of species in homegarden X, S_y the number of species in homegarden Y.

³ In the absence of a time-sequence study involving long time intervals, the C stock data were considered as a reliable indicator of the C sequestration potential (CSP) of the HG.

Relative difference in soil organic matter (SOC) contents

The ‘relative difference’ between the SOC contents of two groups (within the same parameter class, e.g., low and high species density) was expressed as a percentage of the lower value.

$$\Delta \text{Relative Difference (\%)} = \left(\frac{\text{Difference between the higher and lower values}}{\text{Lower value}} \right) \times 100$$

Statistical methods

The data were analyzed using the general linear model (GLM) and analysis of variance (ANOVA). Waller Duncan K-ratio test was used to compare the mean differences between effects of plant-stand characteristics and HG operational characteristics

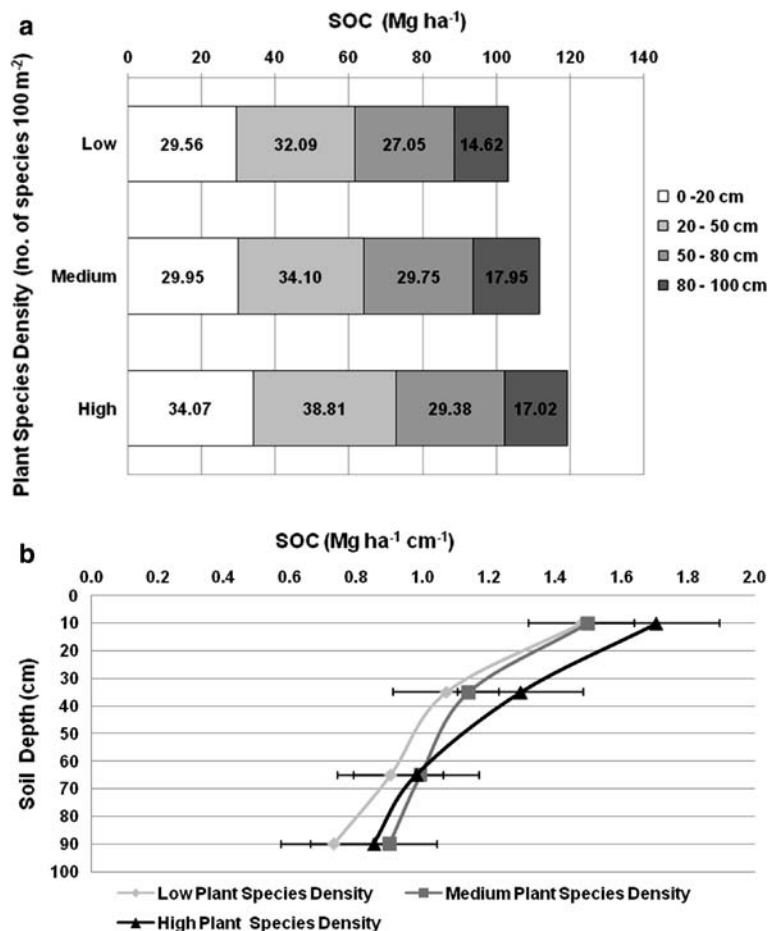
such as age and size on SOC for all sites. All statistical tests were performed with SAS 9.0 (SAS Institute Inc. 2004) and differences were considered significant when $P < 0.05$.

Results

The SOC varied with overall plant species density: HG with high species density had the highest SOC (119.3 Mg ha^{-1}) within 1 m soil profile (Fig. 2a), and HG with medium and low species densities had 7 and 14% less SOC, respectively, than the HG with high species density. The plant (or tree) species density refers to density of specific a species of plant (or tree), whereas plant (or tree) density refers to number of plants (or trees) regardless of species.

No statistical difference in SOC content was observed in relation to the overall plant density. The SOC varied also with tree density: HG with high

Fig. 2 Soil organic carbon (SOC) content across soil depths in homegardens with different plant species densities in Thrissur District, Kerala, India. **a** SOC, in Mg ha^{-1} **b** SOC calculated in $\text{Mg ha}^{-1} \text{ cm}^{-1}$ for a given depth class; depth indicated is the mid-point of the sampled depth class. Plant species density classes (species 100 m^{-2}): Low (<0.66), Medium (0.66–1.1), High (>1.1)



tree density had the highest SOC (126 Mg ha^{-1}) within 1 m soil profile and those with medium and low tree density had 10 and 20% lower SOC, respectively (Fig. 3a). But, no statistical difference in SOC was observed due to the tree species density. When compared across the 1 m column (per ha per cm) significant SOC difference was not observed in either of plant species density and tree density category (Figs. 2b, 3b).

The relative difference between low and high tree density categories was lower in bottom half than that of top half of 1 m soil (although not statistically different) (Table 1). Homegardens with high species richness (Margalef Index) had the highest SOC storage (127.4 Mg ha^{-1}) within 1 m soil profile; those with medium and low species richness had 16 and 17% lower SOC, respectively (Fig. 4a). The SOC storage per unit depth ($\text{Mg ha}^{-1} \text{ cm}^{-1}$) was higher in HG with high species richness than those with low species richness in the upper 50 cm depth (Fig. 4b).

No clear difference was observed for Shannon Index parameters.

A total of 106 plant species were found and taxonomically identified (excluding weeds). Average number of total species among all HGL and HGS were 37 and 33.5, respectively. The HGS had higher plant density, plant species density, tree density, and tree species density compared with HGL (though not always statistically different) (Table 2). Plant density ranged from 4.6 to 23.3 plants 100 m^{-2} , with means of 11.1 and 14.4 in HGL and HGS, respectively. Plant species density varied from 0.38 to 2.4 species 100 m^{-2} , with the HGS having higher mean value (1.6) than HGL (0.7) (P value 0.04*). Tree density ranged from 1.55 to 13.5 trees 100 m^{-2} , with means of 5.8 and 7.5 in HGL and HGS, respectively. Tree species density varied from 0.25 to 1.25 species 100 m^{-2} , the mean value for HGS (0.95) was higher than that for HGL (0.4) (P value 0.03*). Mean Margalef Index was 5.94 in HGS and 5.74 in HGL,

Fig. 3 Soil organic carbon (SOC) content across soil depths in homegardens with different tree densities in Thrissur District, Kerala, India. **a** SOC, in Mg ha^{-1} **b** SOC calculated in $\text{Mg ha}^{-1} \text{ cm}^{-1}$ for a given depth class; depth indicated is the mid-point of the sampled depth class. Tree density classes (trees 100 m^{-2}): Low (<5.5), Medium (5.5–7.5) and High (>7.5)

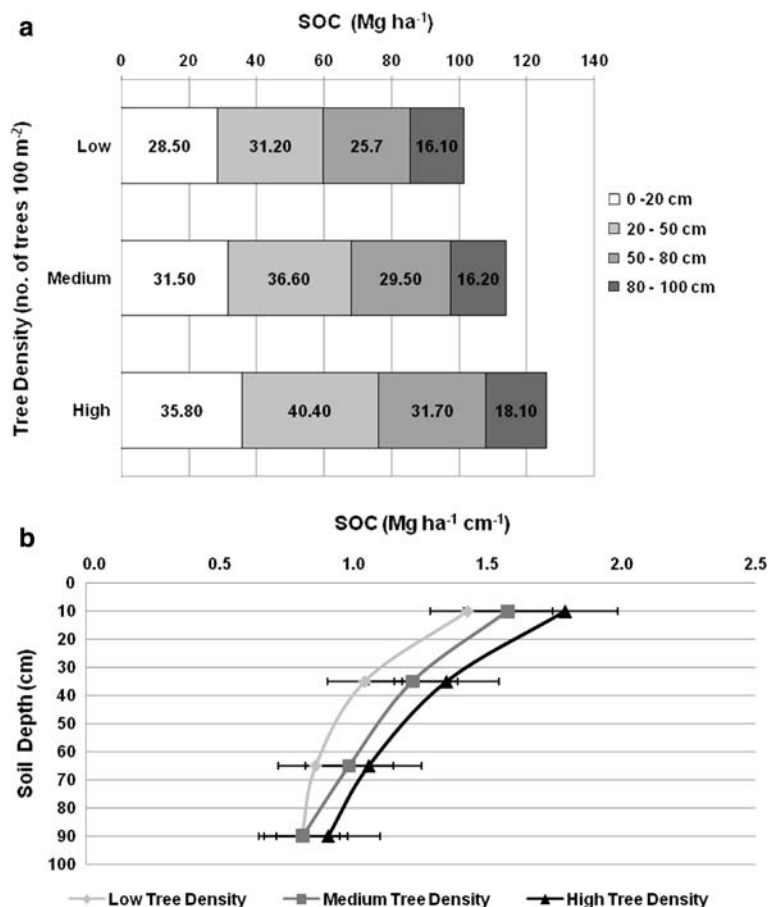


Table 1 Relative difference of soil organic carbon between high and low tree density at different soil depth classes in homegardens of Madakkathara *Panchayat*, Thrissur, Kerala, India

Depth (cm)	Low tree density value (LTDV)	High tree density value (HTDV)	Δ Relative difference = (HTDV – LTDV)/LTDV	Relative difference (%)
0–20	1.43	1.79	0.2561	25.61
20–50	1.04	1.35	0.2948	29.48
50–80	0.86	1.06	0.2334	23.34
80–100	0.81	0.91	0.1242	12.42

indicating higher species richness in smaller HG. Shannon Index was also slightly higher (though not statistically) (2.38) in HGS than in HGL (2.27). Sorenson's Index of similarity showed that the similarity of plant species among three study villages ranged from 86 to 88% and mean similarity between the HGS and HGL was 91.4%.

The size of HG in this study varied from 0.1 to 1.1 ha, with mean values of 0.22 ha for HGS and 0.55 ha for HGL. The HGS had higher SOC content (119.3 Mg ha^{-1}) than the HGL (108.2 Mg ha^{-1}) throughout the 1 m soil profile and the difference between the two size classes was more conspicuous in the upper 50 cm soil depth (Fig. 5a, b). Based on the information obtained from the landowners, the age of HG varied from 35 to 100 years with 74 and 67 years as the mean values for HGS and HGL, respectively.

Discussion

The SOC stock increased with the increase in plant species density (Fig. 2) and species richness (Margalef Index) (Fig. 4). Both these parameters are associated with the number of plant species and their values increase with an increase in the number of species in a system. A Margalef Index of 7.07, which is comparable to the values of this study (Table 2), had been reported for wet evergreen forests of southern Western Ghat mountains of Kerala located about 100 km away from the present study site (Varghese and Balasubramanyam 1998). Such rather high values of species richness support Swift and Anderson's (1993) ranking of homegardens, based on biological diversity, as the highest among all human-made agroecosystems, next only to natural forest. Kirby and Potvin (2007) suggested that, in general, as more species are included in a system, more complete utilization of resources takes place and the system becomes more

productive. High species assemblage of HG is likely to harbor species with strong resources-utilization characteristics compared with less species-intensive systems (Tilman et al. 1997) and may promote a greater net primary production (Vandermeer 1989), which in turn could contribute to higher C sequestration.

In general, the SOC stock decreased with soil depth across all treatments. This is common in almost all cultivated mineral soils and is a reflection of the accumulation of higher quantities of litter and other organic materials on the surface and their rapid decomposition. The SOC stocks in HG in relation to both species density and species richness were also higher in the upper, than in the lower, soil layer (Fig. 2b, 4b). This can be explained by the plant composition of HG. Homegarden are comprised of trees, shrubs, and herbs and these plant classes have different belowground growth patterns. The majority of root growth and activity of shrubs and herbs are expected to be restricted within the upper 50 cm of the soil (Waisel et al. 1991). In contrast, tree roots are distributed to deeper soil layers (1 m depth and lower) (Van Noordwijk et al. 2004). Increase in number of species means increase of species from all three plant classes and this promotes higher SOC accumulation in the upper soil. On the other hand, the relative differences in SOC stock between HG with high and low tree density were equally conspicuous at the lower depth as in the upper depth (Fig. 3b), suggesting the existence of increased root activity in the lower soil layers in tree-based compared to treeless systems.

Although SOC content of HG showed a positive relationship with overall plant species density, no clear relationship was observed between SOC and tree species density at any depth. A clear-cut statistical significance has not been established between tree species density (i.e., the density of particular species of trees) and SOC accumulation. Chen (2006) reported a positive relationship between

Fig. 4 Soil organic carbon (SOC) content across soil depths in homegardens with different species richness in Thrissur District, Kerala, India. **a** SOC, in Mg ha^{-1} **b** SOC calculated in $\text{Mg ha}^{-1} \text{cm}^{-1}$ for a given depth class; depth indicated is the mid-point of the sampled depth. Plant Species Richness classes based on Margalef Index (MI) values: Low (<5.2), Medium (5.2–6) and High (>6). The letters a and b indicate statistically significant difference ($P < 0.05$) between SOC of different species richness classes at any given depth

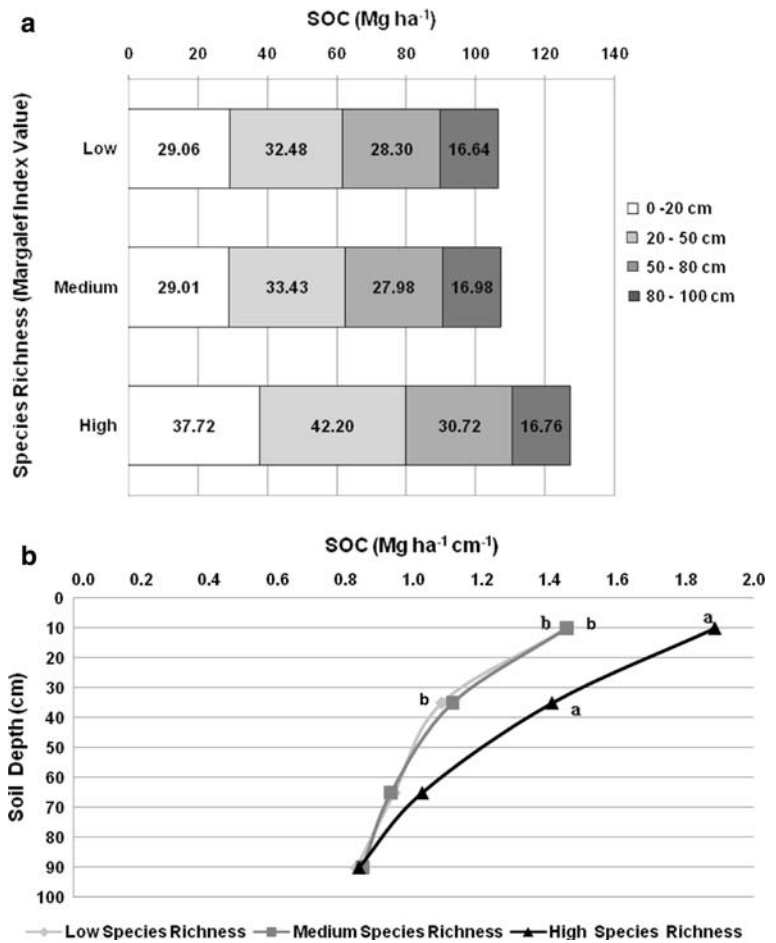


Table 2 Plant-stand characteristics of large and small homegardens selected for the study in Madakkathara Panchayat, Thrissur, Kerala, India

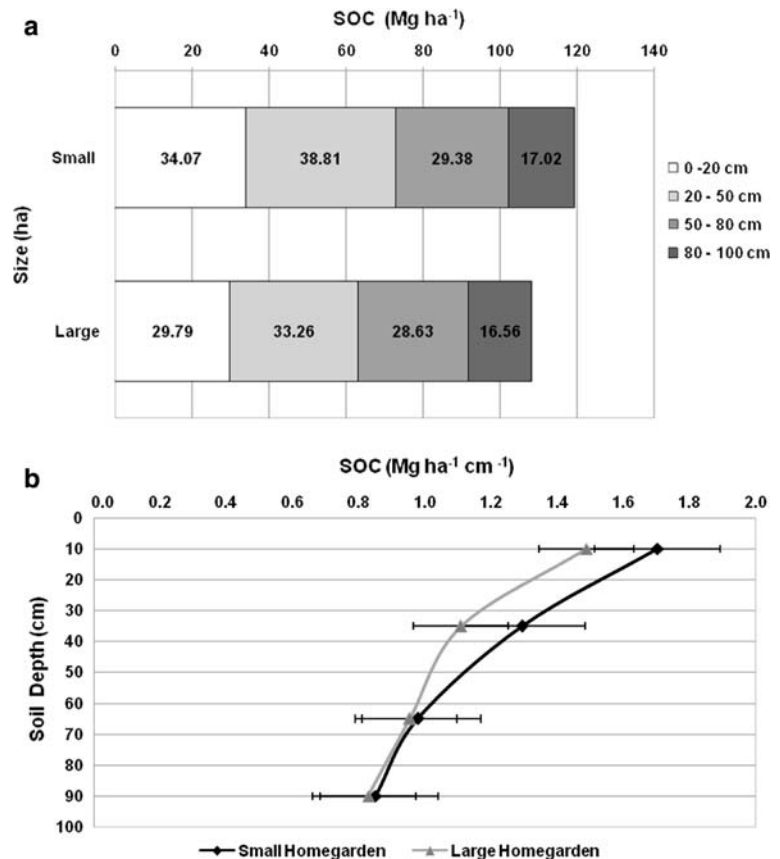
Plant-stand characteristics	Large homegarden (>0.4 ha)	Small homegarden (<0.4 ha)
Total no. of species	105	96
Mean no. of species/homegarden	37	33.5
Mean plant density (no. of plants 100 m^{-2})	11.14	14.42
Mean species density (no. of species 100 m^{-2})	0.71b [‡]	1.61a
Mean tree density (no. of trees 100 m^{-2})	5.84	7.51
Mean tree species density (no. of tree species 100 m^{-2})	0.41b	0.95a
Mean Margalef index	5.74	5.94
Mean Shannon index	2.27	2.38

[‡] a or b following the mean value indicates a statistically significant difference (at $P < 0.05$), between means of different plant-stand characteristics

tree species and SOC content above 30 cm depth in old growth forests of China, but Kirby and Potvin (2007) did not find any such relationship at 0–10 cm and 30–40 cm soil depths in managed forests and

agroforests in Eastern Panama. Nevertheless, SOC content increased with increasing tree density. Throughout the 1 m soil profile the SOC of the HG with high tree density remained higher compared to

Fig. 5 Soil organic carbon (SOC) content across soil depths in homegardens of two size classes in Thrissur District, Kerala, India. **a** SOC, in Mg ha^{-1} **b** SOC calculated in $\text{Mg ha}^{-1} \text{cm}^{-1}$ Size classes (ha): Small (<0.4) and Large (>0.4)



HG with medium and low tree density (Fig. 3b). Thus, it can be surmised that there is a clear indication of the influence of trees on SOC accumulation throughout the soil profile; however, no conclusion can be drawn from this study on the influence of specific tree species on soil C storage; this could be a subject of future investigations.

The effect of operational characteristics of HG such as garden size on SOC stock can be explained in terms of the effect of these parameters on the plant-stand characteristics such as plant species density and tree density, and in turn, their effect on SOC stock. For example, smaller HG has higher (though not always statistically different) species density, richness (Margalef Index), and diversity (Shannon Index) compared to larger HG (Table 2). Consequently, the higher SOC content in HGS compared to HGL can be taken as a direct reflection of the higher species density, richness, and diversity associated with HGS. In this study the mean Margalef Index was slightly higher (5.94) in HGS than in HGL (5.74), pointing to greater species richness in HGS than in HGL.

Previous research in Kerala also had indicated that smaller homegardens had higher species diversity and higher species density. Kumar et al. (1994) reported that Margalef Index ranged from 3.4 to 7.4 in Kerala HG, which is similar to the results (3.4–7.8) of a study conducted on Kerala HG by Mohan et al. (2007). The Shannon Index was also slightly higher (but statistically not significant) for HGS (2.38) than for HGL (2.27). Studies from Thailand (Gajaseni and Gajaseni 1999) showed that Shannon Index values of HG ranged from 1.9 to 2.7, which are comparable to the range of values (1.45–3.14) of the present study.

Soil organic carbon content within 1 m soil depth under moist deciduous forests and rice-paddy fields in the same location as this study were 176.6 and 55.6 Mg ha^{-1} , respectively. Thus, forests had about 50% more and rice-paddy fields had about 50% less SOC than the homegardens in the 1 m soil profile (Saha 2008). Obviously, forests (characterized by little or no soil disturbance, high plant species diversity, and high rates of litterfall) and rice-paddy fields (with high soil disturbance and practically no

plant species diversity and litterfall) represent two ends of the spectrum, and the homegardens came in between, in terms of SOC content. The inverse relationship between soil disturbances on SOC content was also evident from the fact that SOC content was higher in older HG than in younger HG (Saha 2008; data not presented here). This can be explained in terms of the mean residence time (MRT) of SOC. Based on the interview with landowners, the age of HG of this study varied from 35 to 100 years, with an average of 70 years. The flora of homegardens includes trees, herbs, and shrubs and all of them contribute to the soil C sequestration. Shrubs and herbs are comparatively short-lived but trees can survive as high as 100 years or more. Longer life of trees in HG ensures prolonged SOC accumulation. With increase in age, above- and below-ground volume of trees also increase (to a certain age) and this contributes to continued and prolonged addition of leaf and fine root biomass to the soil. However, the growth rates of trees do not stay the same forever; depending on species it decreases with age and the rate levels off after a certain period of time. But, even at that stage, although the rate of growth is zero or close to it, trees continue to add leaf and root litter throughout their life. When mature trees are removed from homegardens, their roots are left in the soils, which upon subsequent decomposition could contribute substantially to SOC accumulation. Therefore, the older a HG, the higher are the chances for SOC accumulation. Reduced microbial activity caused by lack of supply of aeration and minimal physical disturbance would probably have contributed to the increase in the MRT of SOC at lower depths (Fontaine et al. 2007). Thus, it is likely that SOC accumulation at lower depths will be more prominent in older than in younger HG.

Although the soil carbon sequestration potential of homegardens is higher than that of agricultural systems such as rice-paddy and comparable to that of single-species tree-crop systems of rubber and coconut (Saha 2008), the overall impact of homegardens on GHG gas mitigation will obviously depend on their distribution and area coverage. In Kerala, homegardens cover 1.4 Mha (Kumar 2006), which is about 36% of the total area of the state (3.88 Mha) (Government of Kerala 2008). Thus, homegardens play a significant role in GHG mitigation and environmental amelioration in Kerala. The situation

could also be similar in other parts of the tropics where homegardening is widely practiced such as several countries of South- and Southeast Asia, Central America and the Caribbean, and East and West Africa (Nair and Kumar 2006). This signifies a hitherto unrecognized benefit of this age-old land-use system.

Conclusion

Overall, the study showed that the C stock in soil increased with the increase in number of plant species in the tropical homegarden system. There were differences between smaller and larger homegardens in terms of their plant-stand characteristics such as tree and tree-species density, and overall plant and species density. Perhaps because of the differences in plant-stand characteristics, SOC content also varied with the size of HG: smaller-sized gardens had more SOC per unit volume of soil than the larger ones. Furthermore, HG with higher number of species retained more C in the soil compared to those with lower number. The species influence on SOC was prominent at the top 50 cm of soil and decreased with depth below 50 cm. The C stock estimates are considered as approximations to CSP. Therefore, it is logical to infer that increase in plant species increases the CSP of HG. Viewed in context of their high plant-species diversity (a surrogate of biodiversity), this enhanced C sequestration (GHG mitigation) potential of homegardens could be useful for the emerging scientific interest on understanding the relationship between species diversity and C sequestration. More elaborate studies are needed with larger number of homegardens at study locations with varying soil and agro-climatic conditions to explore this relationship. Furthermore, different patterns of plant-species compositions should be compared for their C sequestration characteristics to develop C sequestration-friendly species-composition models for different situations.

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