

FOREST CARBON SEQUESTRATION AND ITS CONTROL: A COMPARISON BETWEEN A DRY ZONE TROPICAL FOREST AND AN ARBORETUM

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ABSTRACT

Tropical forest carbon sequestration (CS) has been identified as an important carbon (C) sink necessary for mitigating global warming. Most studies on C budgeting have considered soil organic carbon (SOC) as a whole without taking into account its constituent fractions. The present study assesses uniquely dynamics of SOC fractions, litterfall, above-belowground C stock, climatic parameters and their control on CS in a dry zone forest (DZF) and a dry zone arboretum (DZA) within the same Sri Lankan eco-climatic zone. Thermal oxidation of total SOC in both the DZF and DZA revealed that fulvic fraction (FF) comprised of 50% of SOC, whereas the humic and free soil litter fraction (FLF) were 30% and 20% of total SOC, respectively. The total ecosystem C stock was significantly higher in the DZF (180.42 t/ha.) than the DZA (151.69 t/ha.). There was no such variation found in litterfall C stocks [DZF (4.76 t/ha.), DZA (4.35 t/ha.)] or total soil C stocks [DZF (93.62 t/ha.), DZA (93.95 t/ha.)] for these forest stands. The present study suggests that DZF and DZA show similar dynamics and similar soil C stocks (except biomass C stocks) and hence similar CS ability. The variation in biomass C stock and hence total C stock could be due to the age difference [DZF (>100 years), DZA (<50 years)] of two land use patterns. In conclusion, the soil C stocks and their dynamics are almost equal in observed two forest stands in the same eco-climatic regions, however biomass C stocks are different. Hence, rehabilitation of degraded forests through silvicultural method is useful to increase ecosystem carbon sequestration.

Key words: Carbon sequestration, soil organic carbon, tropical forests, dry zone, litter

Introduction

The atmospheric CO₂ concentration has risen from about 260 ppm prior to the industrial revolution to about 380 ppm at present, and is projected to double by the year 2100 (Prentice et al., 2001). Global mean surface temperatures are expected to continue to rise by about 2°C late in the 21st century, when CO₂ concentrations would be approximately twice the current amount (Kattenberg et al., 1996), which would result in severe environmental problems such as global climate change. Improving our understanding of the global C cycle including, its fluxes and reservoirs, is intimately tied to successful implementation of C storage technologies.

Forests can be considered as a major terrestrial C reserve which covers about 4.1 billion global hectares (Dixon and Wisniewski, 1995) and sequesters high C quantity in above and belowground biomass (Black et al., 2008). Studies on CS confirm that tropical forestry is the most cost effective greenhouse gas mitigation strategy (Ramachandran et al., 2007). The total terrestrial C stock in forest biomes is 37% in low latitude forests, 14% in mid-latitudes and 49% in high latitudes (Dixon et al., 1994). The aboveground plant C density increases with decreasing latitude from tundra to tropical rainforests (Lal, 2005). This plant C density ranges from 120 to 194 Mg C/ha in tropical forests, 60 to 130 Mg C/ha in temperate forests and 40 to 60 Mg C/ha in boreal forests (Prentice, 2001).

As much as two-thirds of the terrestrial C is contained in soils of forest ecosystems. The soil C stock may comprise as much as 50% of the terrestrial C in the tropical forests (Dixon et al., 1994). It has been shown that forests of the temperate and boreal countries were a net sink of atmospheric C of about 0.7 Pg/yr, but the tropics were a net source of about 1.6 Pg/yr, mainly due to

deforestation (Sohngen et al., 2008). However, Brown et al. (1996) studies suggest that there is potential to manage forests to conserve and sequester C to mitigate emissions of CO₂ by 11-15% of the fossil fuel emissions over the same time period. Tropical forests are characterized by high species richness, standing biomass and productivity, and their diversity has attracted much attention (Sagar and Singh, 2006). Aboveground biomass of tropical forests can be recognized as the most important component for CS compared to that of temperate or boreal forests (Baishya et al., 2009). It accumulates 37% of the total or 90% of world's terrestrial vegetation C (Houghton, 1996), and has further potential for CS.

However, there are knowledge gaps in tropical forest CS studies (IPCC, 2000) due to difficulties in collection of ground data, diversity of tree species, wood densities, tree architectures and life forms, complex forest and tree structure and high species densities (Clark et al., 2001).

Being a small island nation, Sri Lanka falls into the United Nations Framework Convention on Climate Change (UNFCCC) and Intergovernmental Panel on Climate Change (IPCC) category of vulnerable small island nations under serious threat from various climate change impacts (IPCC, 2001). The total emission of CO₂ in Sri Lanka is estimated at 8,122,000t in 1998, which is negligible compared to global emissions. Emission of CO₂ from solid fuels (92,000t), liquid fuels (7,482,000t), and cement manufacturing (548,000t) are the major emission sources. The maximum amount of CO₂ (60% of total) emitted was from transportation, 20% from manufacturing industries and 14% from electrical and heat production. As a whole, 92% of CO₂ emission is from liquid fuel combustion (Millennium Development Goals, 2005). The biggest land mass of the island is covered by the dry zone vegetation (ca. 80%) (Kuruppuarachchi & Senevirathne, 2013a), and therefore it is very important to examine the role of micro carbon cycle of perennial vegetation for forest CS.

This study was carried out to evaluate the influence of climatic, plant and soil parameters on the CS in two selected tropical dry zone vegetation comprising natural forest (DZF) and a silviculturally managed arboretum (DZA) in Sri Lanka. This paper highlights the physicochemical parametric influences towards CS by estimating the amount of carbon sequestered.

Materials and methods

Study area

Representative sampling sites were selected from the dry zone forest (DZF) at the Sigiriya sanctuary and the managed arboretum (DZA) of Sri Lanka (5° 54' N - 9° 52' N; 79° 39' E - 81° 53' E). Sigiriya sanctuary surrounds the ancient rock fortress of Sigiriya, an archeologically important World Heritage Site at 150 m altitude. In the 1990s, it was declared a sanctuary with 5,099 hectares and belongs to Ceylonese monsoon forest (Green, 1990). The DZA was established in 1963 by Popham, where the degraded shifting cultivation land was converted into productive forest using simple silvicultural practices known as the Popham method (Popham, 1993). In 1989, the arboretum was extended to 14.4 ha by acquiring adjoining land, which is now designated as woodland. The vegetation types covered by the arboretum were dry mixed evergreen forest, woodland, scrubland and rocky outcrop. The dry mixed evergreen forest area in the arboretum was selected as a sampling site.

Climate

Sri Lanka is divided into three climatic zones based on the annual rainfall and its distribution: Dry Zone (1,250-1,525mm) in parts of the south-east and north-west; Intermediate Zone (1,525-2,280 mm); and Wet Zone (2,280-5,100 mm) mostly in the south-western parts (Premaratne and Premalal, 2005). Monthly average climatic data for ten years at the study area in the dry zone revealed 27.7 °C as average air temperature, 1380 mm as annual rain fall, 79% as monthly relative humidity and 7.6 as sunshine hours. In addition, the rainfall pattern of the study period slightly deviated from the normal pattern, that is, inter-monsoonal rainfall during March and April (75 mm) was lower in the study period. North-eastern monsoonal rainfall during October to December (375 mm) was higher than the normal rainfall. Generally, the dry zone experiences a five-month dry spell from May to the end of September.

Design of experimental plots

Eight (08) sampling plots, 2 m x 2 m, were demarcated randomly in the dry zone forest and the arboretum. Within the main plot, a subplot of 1 m x 1 m was established. A trench was dug around this sub plot to a depth of 30 cm and a width of 15 cm. A thick polythene sheet was fixed vertically to cut off the fine root growth into the sub plot, and the trench was filled with soil. A Nylon mesh sized 2 mm (2 m x 2 m) was fixed 20 cm above the plot as a litter-trap. Then, the plot was fenced by thick polythene sheets to: (a) protect the plot from wild animals; (b) prevent the accumulation of litter from the forest floor outside the plot, and (c) to arrest the flow of runoff water.

Soil and litter sampling

Litter accumulation in the litter trap (2 m x 2 m) was collected at monthly intervals over a year and sorted into fine (leaves, flowers etc.) and coarse (woody parts) litter. In addition, a litter sample was collected using 30 cm x 30 cm quadrat outside the main plot. Initial fresh weight was recorded and then the samples were oven-dried (at 65 °C for 72 hrs.), weighed and stored for further chemical analyses. In addition, a litter sample was collected from 30 cm x 30 cm sharp-edged steel square outside the plot, oven-dried, weighed and stored. Two soil samples were collected using an auger (cross section area = 19.6 cm²), one from the center of the 1 m x 1 m square (with no root growth or litterfall) and from outside the 1 m x 1 m square within the main plot (root growth occurs, but no litterfall) to a depth of 25 cm. Another soil core sample was taken to a depth of 25 cm outside the permanent plot (where root growth as well as litterfall occur, i.e. forest floor). These samples were collected at monthly intervals over a year.

Preparation of samples

Soil samples were air-dried and sieved (< 2 mm). Root fractions (fine roots < 2 mm, and coarse roots > 2 mm) were hand-picked, oven-dried, weighed and stored for later analyses. Very fine root fraction was separated by floating method (Anderson and Ingram, 1998). The fine root fraction was oven dried at 60°C for constant weight, and the root biomass was recorded as a percentage of total soil weight. Litter samples were first cleaned with a brush and separated into fine (leaves, flowers and buds) and coarse (twigs, plant materials such as seeds and seed coats) litter. Initial fresh weight was recorded. Then, the litter was oven dried at 65°C to a constant weight and dry weights recorded. Dry samples were ground and stored for further chemical analyses.

Soil analyses

Soil moisture was determined by oven drying the samples at 105°C to constant weight. Soil pH was measured using a glass calomel electrode fixed to a pH meter (Schofield and Taylor, 1955) with soil to water ratio of 1:2. The wet oxidation method without external heating was used to determine C content colorimetrically at 600 nm by using a UV-Visible spectrophotometer (for example Anderson and Ingram, 1998; Walkley and Black, 1947). Soil total N was determined by using the Micro-Kjeldahl procedure. The digestion was performed by heating the sample with concentrated H₂SO₄ at 420 °C for three hrs. Ammonium-N content in the digest was determined by using Autoanalyzer (Tecator 1030 Kjeltec Autoanalyzer). Fractionation of soil C was done by the weight loss on ignition (LOI) method (Ratnayake et al., 2007). In this procedure, soil was subjected to sequential thermal oxidation from 100°C to 550°C using a muffle furnace (Gallenkamp-box furnace F SL-340-0160). Weight loss steps at temperatures between 150-200°C, 200-400°C and 400-550°C corresponded to oxidation of free soil litter fraction (labile), fulvic fraction (intermediate) and humic fraction (stable), respectively (for example Evans et al. 2001; Ratnayake et al., 2007).

Litter analyses

Dry and wet weights of litterfall (coarse and fine litter separately) as well as forest floor litter layer were recorded at each sampling time and litter density in grams per square meter was calculated. Annual litterfall was then calculated for the study sites. Litter moisture was measured through oven drying the litter at 65 °C till a constant weight was reached, and weight difference between dry and wet litter was noted and thereafter litter moisture was calculated. Litter organic C content was evaluated by the same wet oxidation/colorimetric determination technique applied for soil C. Litter (0.5 g) of composite (fine and coarse litter separately) samples in selected sampling times was analysed.

Forest floor litter decomposition

Litter decomposition was evaluated using mass balance procedure (Golley et al., 1978). This method was chosen due to the drawbacks of the litter bag method such as faunal exclusion and leaching of water soluble materials (Besson et al., 2005). Litter decomposition rate was calculated using following relation.

$$W_{ld} = (W_o + W_{lf}) - W_t, \quad (1)$$

Where W_o is forest floor litter weight at time, $t = 0$, W_t is forest floor litter weight at time, $t = t$, W_{lf} is weight of litterfall from time, $t = 0$ to time, $t = t$, and W_{ld} is weight of decomposed litter from time, $t = 0$ to time, $t = t$.

Aboveground and belowground biomass and C stock

Aboveground biomass was calculated from Diameter at Breast Height (DBH) using standard biomass equations. Using area specific correlation factors, belowground biomass and both above and belowground C stocks were calculated as detailed below. Internationally accepted two biomass regression equations (Anderson and Ingram, 1998; Brown et al., 1989) were applied to calculate aboveground biomass stock. Sigiriya sanctuary as well as Popham arboretum with an annual rainfall of 1380 mm could be regarded as dry forests (Kurupparachchi *et al.*, 2013a). Thus, an equation developed for dry forests with annual rainfall < 1500 mm; $B = \exp(-1.996 + 2.32 \times \ln D)$; $R^2 = 0.89$ (Brown et al., 1989) was used, where B and D are biomass and DBH, respectively. According to IPCC guidelines for national greenhouse gas inventories (IPCC, 2006), aboveground C stock of tropical forests is calculated as Biomass x 0.49 (Hughes et al., 2000). Aboveground to belowground biomass ratio, and hence its C ratio, for tropical rain forests (annual rainfall > 2000 mm) and moist deciduous forests (annual rainfall between 1000–2000 mm) was found to be 0.2 (Mokany et al., 2006). Therefore, belowground biomass or C content is calculated as, aboveground biomass or C x 0.2.

Results

Biomass and carbon stocks

Aboveground and belowground biomass and C stocks for the DZF and DZA are given in Table 1. DZF has higher aboveground biomass and C stock than that of the DZA. In the DZF, the belowground biomass (35.93 t/ha) and C stock (16.89 t/ha) were also high, compared to the DZA (22.05t/ha and 10.36 t/ha, respectively). Mean fine root biomasses of the DZF and the DZA were 5.72 ± 0.57 t/ha (C content, 2.69 ± 0.05 t/ha) and 7.88 ± 0.81 t/ha (C content, 3.70 ± 0.38 t/ha), respectively.

Ecosystem carbon stocks

The results of this study showed that above and belowground biomass stock, litterfall and floor litter amounts were higher in the DZF, but not significantly different. Fine root biomass and its C stock in the DZA was significantly different ($p \leq 0.01$), from fine root biomass and its C stock in the DZF (Table 1). Total ecosystem C stock of the DZF (ca. 180 t/ha) was significantly higher ($p \leq 0.05$) than the DZA (ca. 152 t/ha). In the DZF, ca. 52% of the total C stock was in the soil, and ca. 44% was in the plant biomass,

and corresponding values of the DZA were ca. 62% and ca. 31%, respectively. Although these proportions were different, soil C stocks were almost equal in the DZF and DZA (Table 1).

Table 1. Aboveground, belowground, total ecosystem carbon stocks and soil organic matter fraction of the DZF and arboretum. Carbon stocks as a percentage of total ecosystem C stock are within parentheses

C component	Parameter	Dry zone forest	Dry zone arboretum
Biomass & C stock	Aboveground biomass (t/ha)	128.34 ± 26.73 a	78.77 ± 11.26 a
	*C stock (t C/ha)	60.32 ± 12.56 (34.2%) a	37.02 ± 5.29 (24.40%) a
	Belowground biomass (t/ha)	35.93 ± 7.48 a	22.05 ± 3.15 a
	*C stock (t C/ha)	16.89 ± 3.51 (9.6%) a	10.36 ± 1.48 (6.82%) a
	Total Biomass C Stock (t/ha)	77.21 (43.8%) a	47.38 (31.23%) a
Fine root biomass & C stock	Fine root biomass (t/ha)	5.72 ± 0.57 a [†]	7.88 ± 0.81 b [†]
	*C stock (t/ha)	2.69 (1.53%) a [†]	3.70 (2.43%) b [†]
C of floor litter	Fine litter (t/ha)	4.58 ± 0.38 a	2.87 ± 0.42 a
	Coarse litter (t/ha)	1.88 ± 0.15 a	3.43 ± 0.34 a
	Total floor litter (t/ha)	6.46 ± 0.45 a	6.30 ± 0.69 a
	**Floor litter C stock* (t/ha)	2.36 ± 0.04 (1.31%) a	2.34 ± 0.05 (1.52%) a
C of litter fall	Fine litter fall (t/ha/yr)	8.16 ± 0.14 a	7.29 ± 0.15 a
	Coarse litter fall (t/ha/yr)	3.66 ± 0.17 a	3.51 ± 0.16 a
	Total litter fall (t/ha/yr)	11.82 ± 0.20 a	10.80 ± 0.20 a
	** Litter fall C stock* (t/ha/yr)	4.76 (2.63%) a	4.35 (2.86%) a
Soil organic matter	Free soil litter fraction (t/ha)	25.37 ± 0.52 (15.73%) a	27.81 ± 6.9 (17.21%) a
	Fulvic fraction (t/ha)	87.29 ± 0.30 (54.11%) a	87.12 ± 4.63 (53.90%) a
	Humic fraction (t/ha)	48.65 ± 0.36 (30.16%) a	46.68 ± 6.73 (28.89%) a
	Total soil organic matter (t/ha)	161.31 a	161.62 a
Soil C	***Total soil C stock (t/ha)	93.62 (51.89%) a	93.95 (61.93%) a
	Total ecosystem C stock (t/ha)	180.42 a ^{††}	151.69 b ^{††}

*Carbon stock = $0.47 \times \text{Biomass}$ (McGroddy *et al.*, 2004; IPCC, 2006)

**Floor litter C stock = Fine litter C + Coarse litter C; Dry zone vegetations: fine litter C = 36% of the litter mass, coarse litter C = 38% of the litter mass (Walky and Black, 1947).

** Litterfall C stock = Fine litter C + Coarse litter C; Dry zone vegetations: fine litter C = 39% of the litter mass, coarse litter C = 43% of the litter mass (Walky and Black 1947).

***Total soil C stock = Total soil organic matter/1.72 (Bukman and Brandy, 1960)

Standard error for the mean value of C component was calculated. Means in the same row followed by different letters ('a' and 'b') denotes significantly different ($\dagger P \leq 0.01$, $\dagger\dagger P \leq 0.01$). Following formulas were used to calculate particular C components

Soil parameters

Our results showed that the soil pH, moisture and SOC contents were comparable in both forests. In contrast, bulk density and NO_3^- -N were significantly higher in the DZF. There was a relatively low acidic soil pH from May to the end of September (dry spell) in the DZF (Fig. 1a). Soil moisture ranged from 5% to 16% during the study period. There were two distinguishable peaks of soil moisture for the inter-monsoonal (April) and monsoonal (October to December) rainy periods (Fig. 1b). There was a dry spell of about five months with low soil moisture from May to September. Fluctuations of soil N were comparable in both DZF and DZA (Fig. 1c). Soil N increased gradually from February to May and then declined until October. The SOC ranged from 1.1% to 1.7% during the study period. There were two peaks of SOC, one in the inter-monsoonal period (March to April) and the second at the end of the dry spell in both DZF and DZA (Fig. 1d). SOC was comparatively higher in the DZF, especially from July to the end of September dry spell. The two C peaks coincided with soil moisture (Fig. 1b).

Soil C fractions were predominated by the fulvic fraction, which was followed by the humic fraction and then the free soil litter. In the DZF, the fulvic fraction represented ca. 50% of total C, the humic fraction 30% and the remaining portion by the free soil litter. However, in the DZA, the free litter fraction increased while humic fraction decreased (Table 1). Total C fractions of both DZF and DZA were comparable, but a higher fluctuation was observed in the DZA. Free soil litter declined from January to August, in both the DZF and DZA (Fig. 1e). Organic matter fractions sequestered in the DZF (93.62 t C/ha) and the DZA (93.95 t C/ha) are not

significantly different (Table 1). Percentages Soil C fractions of this study shows almost similar results with other tropical forests in Sri Lanka (Kuruppuarachchi *et al.*, 2013).

C/N Ratio

The C/N ratios of both DZF and DZA showed similar trends, where C/N ratios declined from January to July and then it increased during August to December (Fig. 1f). These results coincided with soil C sink developments (Fig. 1d), which decreased over five months during the dry spell and then it increased during August to December.

Litterfall

Higher litterfalls were evident during the dry spell (i.e. May to June) and monsoonal rainy seasons (October to November) in both DZF and DZA (Fig. 2). Floor litter mass of both sites was similar, and heavy accumulation of floor litter was observed during the dry spell between May and September (Fig. 2). Floor litter quantity was always higher than the litterfall. The highest accumulation of floor litter occurred towards the end of the dry spell (i.e. September).

Total floor litter mass was not significantly different between the DZF and the DZA. Total litterfall and litterfall C content of DZF are slightly higher than that of arboretum (Table 1). In the floor of the DZF, the fine litter mass was higher than the coarse litter mass, but in the DZA, the opposite was observed (Table 1, Fig. 1). The fine litter fraction of the total litterfall was higher in both DZF (69%) and DZA (68%). Hence, Annual biomass increment would be different according to Kuruppuarachchi *et al.* (2013b)

Figure 1. Physical and chemical analysis of soil parametric, sampled at the dry zone forest and the dry zone arboretum (a) soil pH (b) soil moisture (c) soil nitrogen (d) soil organic carbon (e) soil C fractions (f) C/N ratios.

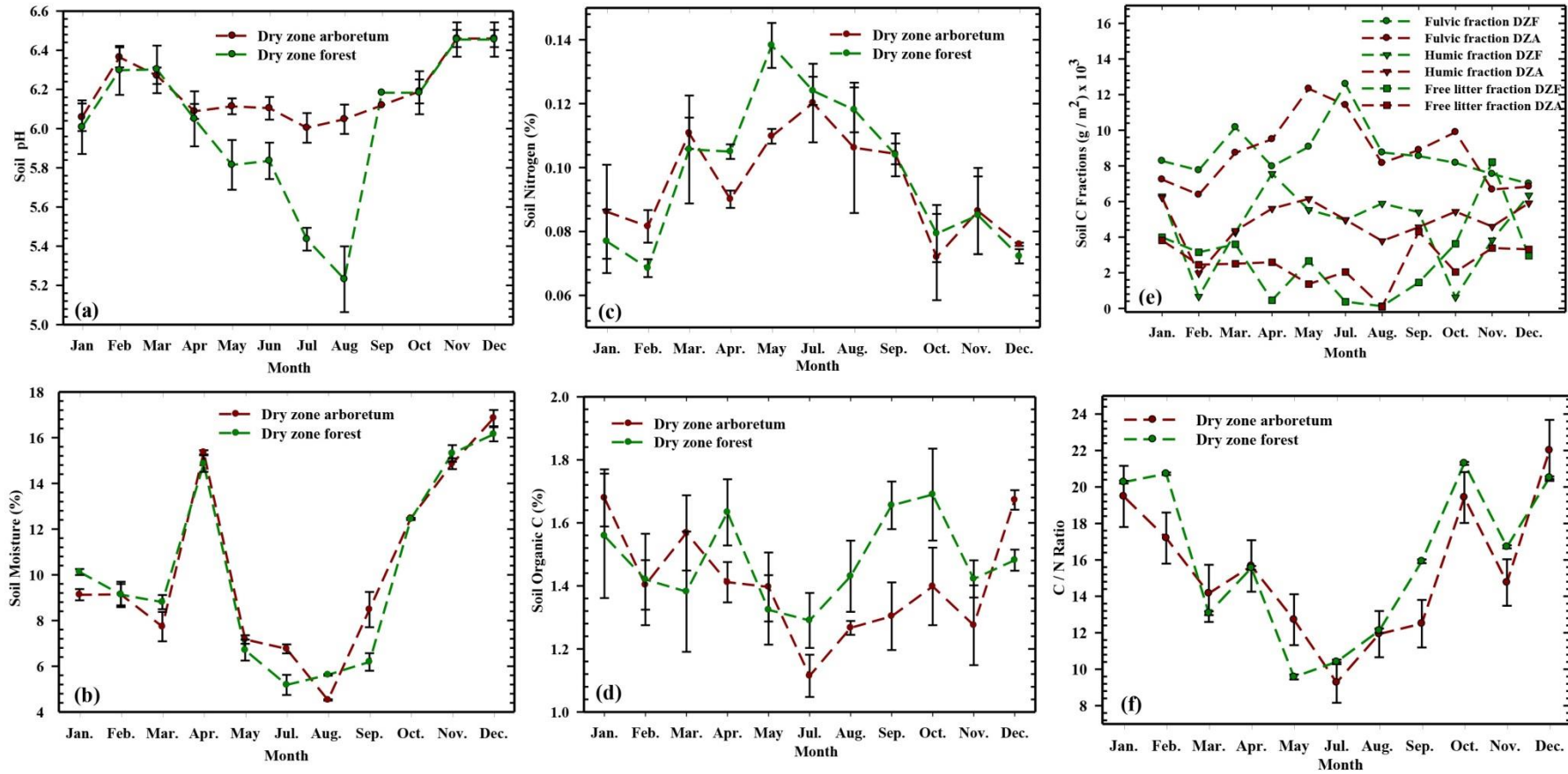
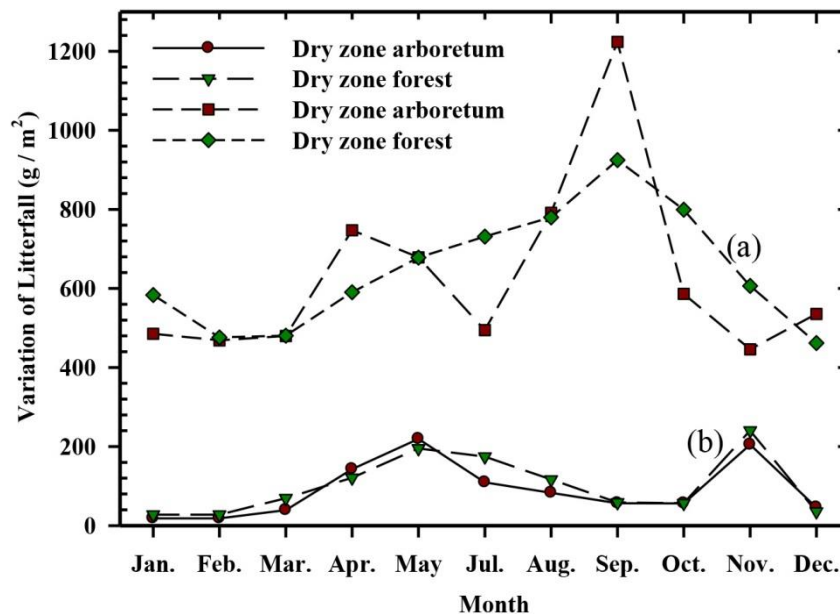


Figure 2. Variation of floor litter (a) and total litterfall (b) of the dry zone forest and arboretum for the annual cycle.



Discussion

Biomass and carbon stocks

Aboveground biomass C stocks of observed dry zone vegetation were within the range of global tropical forests (i.e. 4.9-275 t C/ha) (IPCC, 2006). The high biomasses are important for water absorption and soil moisture retention in a dry climate. The average standing fine root biomass (0-50 cm depth) in global tropical moist forests is 451 ± 45 g/m² (Hertel and Leuschner, 2005), which increases with altitude. However, root biomass can differ largely between stands depending on tree species, soil conditions and profile depth. The fine roots represent the most dynamic part of the root system and mainly occur in the upper soil horizons. Our results are slightly higher compared with global data. In the DZA, there is a higher amount of fine roots than in the DZF. This may be due to increased fine root growth in the DZA under significantly low soil bulk density (Table 1).

During the dry spell of both DZF and DZA, there was an increased production of fine roots. In August, the driest month, there was the maximum root biomass. The increased fine root growth in the dry season allows the trees to absorb more water in water stressed situations. This event may be due to an undisclosed survival mechanism of such ecosystems for drought conditions which requires further research (Kurupparachchi et al., 2013c). Still, the response of root production to drought is less clear. However, two assumptions have been proposed (Fisher et al., 2007): 1) critical minimum leaf water potential, and 2) variable soil-to-root water transport. These assumptions form a paradigm for the mechanism underlying tree responses to drought stress. Fisher et al. (2007) found that the restriction on transpiration in the dry season was caused by limitation of soil-to-root water transport, driven by low soil water potential and high soil-to-root hydraulic resistance.

Gibbs et al. (2007) reviewed tropical forest biomass C stocks from the literature and found that the dry forest C stocks range from 105 to 169 t/ha. However, this is not consistent with the results of the present study. The floor litter layer acts as a persisting C store in the forest ecosystem with continuous turnover. Thus, the floor litter can be considered as a sequestered C pool in modelling approaches. Floor litter quantity has been reported to range from 3.5-4.2 t/ha for a tropical wet evergreen forest in India (Swamy et al., 2010), floor litter C being 1.6-2.0 t/ha, which is slightly lower than that of the DZF and DZA in the present study (DZF: 2.36 t C/ha; DZA: 2.34 t C/ha).

Ecosystem carbon stocks

In tropical forests, total ecosystem C stocks range from 83-384 t/ha (Kirby and Potvin, 2007, Sierra et al. 2007). It is reported that their total plant biomass accounts for 14-62% of the total ecosystem C stock (Glenday, 2006; Sierra et al., 2007). Corresponding values of the total soil C stock range from 51-84% (Palm et al., 2000). All those values in the present study are well within acceptable ranges.

Secondary forests have potential for sequestering larger C pools than primary forests (Paquette et al., 2009). The total belowground C stocks of secondary dry tropical forests range from 14-56% (Vargas et al., 2008). The total soil C stocks of the DZF and DZA of the present study were ca. 52% and ca. 62% respectively; provided from total ecosystem C which could be placed as an upper range. However, soil C pools of both sites were comparable. In general, long-term deposition of C in belowground soil pools is very important for terrestrial CS. Although the aboveground C stock of the DZA was lower, it acted as a very important sink for belowground CS.

Soil parameters

Decreased soil pH during the dry spell of the DZF, compared to the DZA may have been due to decomposition of the organic matter fractions in the soil with relatively high soil moisture (Fig. 1b) and production and accumulation of organic acids. During the late monsoonal rainy period (November to December), relatively high pH was recorded, when the organic acids washed away. Wieder et al. (2009) reported that precipitation directly determines the litter decomposition rates and hence soil pH. Bimodal pattern of litterfall is due to rainfall occurring during the periods, as reflected by soil moisture (Fig. 1b), which has also been observed in tropical forests in India (Pragasam and Parthasarathy, 2005).

Litter decomposition rates reported in the present study are comparable to those reported in another tropical study by Nsabimana (2009), which used a mass balance approach and CO₂ emission rates to evaluate C stock and fluxes. Negative values of litter decomposition during March to April may be due to less microbial activity and forest litter accumulation. Fine and coarse litter decomposition may have been primarily dependent on the availability of moisture from rainfall and soil. Low decomposition during the dry spell was probably caused by low moisture and hence low microbial activities, which has been the case in tropical forests in general (for example Zewdie et al., 2008). After the inter-monsoonal period, however soil moisture content and decomposition rates increased.

C/N ratio

It is apparent that observed dry zone soils act as a net C sink from March to April and then from July to October. From April to May and October to November, the soil acts as a net C source, thus the C sink is temporary. The C sink development could be attributed to leaching of dissolved organic C from the floor litter layer to the soil as well as incorporation of decomposed and fragmented litter particles into the soil with the inception of rains (Nhantumbo *et al.*, 2009). This is evident from the variation of free soil litter fraction during the same periods.

Litterfall and decomposition

During dry seasons, research shows that C rich litterfall contributes to a more C rich SOC pool (Anaya *et al.*, 2007). Likewise, this study indicates that microbial activities may be very low during the dry period, which seems to facilitate the C sink development. The observed drop in the C/N ratio during the dry period concurred with the C accumulation in soil due to defoliation of deciduous trees. Microbial decomposition of accumulated SOC during north-eastern monsoonal rainy season lowers soil C and hence C/N ratio changes (Montaño *et al.*, 2007).

Decomposition and transformation of the free soil litter to the fulvic fraction (Gulde *et al.*, 2008) is attributable to their simultaneous reciprocal dynamics (Fig. 1f). When there was an accumulation of the free soil litter fraction, the fulvic fraction declines. Generally, fresh C supply as dissolved organic C from the floor litter layer to the soil helps to decompose rapidly the humic fractions by the rapidly growing microbial biomass after the rains (Müller *et al.*, 2009), which was also evident from the present study. Different studies report that soil C storage in tropical forests ranges from 90-200 t C/ha (Lewis *et al.*, 2009; Kurupparachchi and Seneviratne, 2013). Therefore, it is apparent that the soil CS capacity of the DZF and the DZA studied here is in the lower range of the tropics.

Our study showed that the seasonal fluctuation patterns of soil parameters such as moisture, pH, N, organic C, C fractions (Fig. 1e) and C/N ratio (Fig. 1f) as well as plant parameters such as litterfall (Fig. 2), fine root biomass, and litter decomposition were comparable in both DZF and DZA. The highest SOC losses were caused by conversion of primary forest into perennial crops (30%), and cropland (25%). In contrast, forest conversion into grassland reduced SOC by 12%. Secondary forests stored less SOC than primary forests (9%) underlining the importance of primary forests for C stores. SOC losses are partly reversible if agricultural land is afforested (+29%) or under cropland fallow (+32%) and with cropland conversion into grassland (+26%) (Don *et al.*, 2011). Hence, it is very important to plant suitable forest tree species in the abandoned shifting cultivation lands as DZA to increase SOC.

Temporal dynamics of soil parameters in the two forest stands are more or less similar since they locate in same eco-climatic region and the similarity of floristic composition. Hence, rehabilitation of degraded forest through simple silvicultural method is much effective for increasing ecosystems carbon sequestration. In addition, a forest management system adapted for DZA is environmental friendly, as is shown by the degree of CS.

Overall, we conclude that both managed forests and natural forests in the tropics are equally important for CS. Therefore, we strongly recommend silvicultural management programs for degraded forests as seen in DZA to increase biomass C stocks. This is partly due to the fact that soil C sequestration may be governed by the prevailing climatic and other non-anthropogenic induced parameters. It is highly advocated from the study that the future forest management plans should be altered to accommodate multi strata designs for more productive and environment-friendly forestry practices in the tropics to increase biomass C pools.

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