Variations in type of vegetal cover and heterogeneity of soil organic carbon in affecting sink capacity of tropical soils

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Understanding the role of the soil–vegetation system in the carbon cycle is important. Movement of carbon inside the soil across different physical and chemical pools is crucial to maintain the soil as a sink or turn it into a source. Understanding these processes at the tropics becomes more imperative because of the heterogeneity of the carbon pool, and also of the diverse vegetal cover. The present study aims at assessing the influence of different vegetal covers, changes in land-use pattern and heterogeneity of physical fractions of the soil organic carbon (SOC) pool on soil carbon. A tropical sanctuary area with some anthropogenic activities was taken as the study area. A total of 306 soil samples were collected for analysis. SOC was measured at different depths for soils with different vegetal covers. Physical fractionation (soil aggregate separation) was done to measure carbon in four different pools. ANOVA was performed to test the levels of significance across different vegetal covers, different depths of soil, and different physically protected carbon pools. All the differences were found to be significant (at 0.05 level). SOC was much higher in soils with natural tree cover. Difference in vegetal cover not only influenced SOC content of the top layer, but also of the deeper layers. Changes in land-use pattern severely reduced sink capacity of soils. Physical SOC fractionation gave a better understanding of SOC movement in the soil. We conclude that the type of vegetal cover has a significant impact on SOC up to a depth of 1.5 m. SOC content in soils with natural vegetal cover (trees) is sufficiently large, indicating their sink capacity. From physical fractionation of the carbon pool we hypothesize that the SOC gets decomposed from one fraction to another in an unidirectional manner towards the recalcitrant (<53 μm) pool. Seasonal herbaceous cover in tropical systems can be taken as a potential sink as more proportion of carbon moves downwards compared to the inputs.

Keywords: Physical fractionation, recalcitrant pool, sink capacity, soil organic carbon, tropical soils.

SOIL–VEGETATION systems play an important role in the global carbon cycle. Soil is the largest pool of terrestrial organic carbon[1–6]. Soil organic carbon (SOC) is dynamic on decadal timescales and is sensitive to climate and human disturbance[7]. Soil contains about 1.5–3 times more organic carbon than vegetation[8] and about twice as much carbon than is present in the atmosphere[5]. About half of the 6.5 billion tonnes of carbon emitted globally by burning of fossil fuels is taken up by vegetation[9] and stored as organic matter (OM). Soil OM is a heterogeneous mixture consisting of plants, animals and microbial materials in all stages of decay, combined with a variety of decomposition products of different ages and levels of complexity[10–12]. Depending on the changes happening to soil OM, soils can act as a sink or a source for carbon in the atmosphere. Equilibrium between the rate of decomposition and rate of supply of OM is disturbed when forests are cleared and the land use is changed[5,10]. Soil OM can also increase or decrease depending on numerous factors, including climate, vegetation type, nutrient availability, disturbance, land use and management practices[11,13,14]. A recent report[14] mentions that less CO_2 may be taken up by the Southern Ocean, and more by the tropical land areas than previously thought. This re-emphasizes the importance of terrestrial systems in carbon cycle processes.

Temporal dynamics following stand-replacing disturbances in forests does indeed account for a large fraction of the overall variability in carbon sequestration[15]. Land-use alteration can convert a soil system from a sink to a source of carbon (C). Such changes are more prevalent in tropical systems of fast-growing countries like India, thereby modifying the sink capacity of the soils. Globally, agriculture activity[7] reduces the original soil C content by ~30%. Deforestation is one of the single biggest threats to the terrestrial carbon sink and climate change along with soil management practices influences sink capacity of the soils[16]. Many uncertainties persist in the estimation of net flux of CO_2 from the soils of tropical forests largely due to inconsistency in land-use and land-cover pattern[17–19]. The rate of cycling of C at different depths and in different pools across different vegetal covers is still not clear for the fast-growing tropical systems. In the tropical systems, the dynamic nature of deep soil C is important in the decadal-scale soil C process[20]. There is not, as yet, enough information to predict how the size and residence time of different fractions of SOC vary.

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Understanding the trends in the vertical distribution of multiple pools of soil C is necessary[7]. This gains more importance for a country like India.

Physical soil properties such as soil structure, particle size and composition have an impact on soil C. Soil particle size has an influence on the rate of decomposition of SOC[1,21]. OM found on the exterior of soil aggregates is physically far more accessible to degradation than C compounds physically protected in the interior of these aggregates[22–24]. Soil aggregation is an important process of carbon sequestration[25] and perhaps an useful strategy to mitigate the increase in concentration of atmosphere CO_2. Information available on the physical fractionation of the soil carbon pool is sketchy. Distribution of SOC into soil aggregates (>500–2000 μm) and recalcitrant pools (<53 μm) has not been thoroughly studied. Understanding variations in SOC content across different depths of soils with different vegetal covers is important. It is equally important to consider the proportion of SOC moving towards micro-aggregates or recalcitrant pools as it shifts carbon to pools of longer residence time. Evaluating the influence of changes in land-use pattern on carbon sequestration in tropical systems is necessary as tropical systems have a greater role in regulating the carbon cycle. Keeping these in view the present study was carried out to study SOC distribution and physical fractionation in the soils of fast-changing tropical systems.

Materials and methods

Study area

Six study sites were selected in and around the vicinity of the Shoolpaneshwar Wildlife Sanctuary lying between lat. 21°29′N–21°52′N and long. 73°29′E–73°54′E, situated in Narmada District, Gujarat, India. The Sanctuary occupies an area of 675 sq. km. Soils are reddish-brown in colour and loamy, with different depths. Alluvium deposits of clay-loam type are also seen with light brown to grey-black colour (Gujarat State Forest Department, unpublished data). Annual average rainfall is 90 cm. Rainfall is restricted to the months of June–September. Dominant vegetation of the study area is *Tectona grandis* L. (teak) and *Dendrocalamus strictus* Nees. (bamboo). Other species growing in large numbers are *Dalbergia latifolia* (Roxb.), *D. paniculata* (Roxb.), *Anogeissus latifolia* (Wall.), *Terminalia bellirica* (Gaerth.) Roxb, *Anthocephalus indicus* (A. Rich.), *Wrightia tinctoria* (R.Br.), *Bridellia retusa* (L.) and *Morus alba* (L.). Few ethnic tribes are allowed to stay inside the Sanctuary. For sustenance, these people clear the forest cover for agriculture and housing. This activity has been more prevalent during the past 10 years. Some areas are covered by seasonal ground vegetation (herbs and grasses) during monsoon and remain barren in summer. For a comparative account, an agriculture area outside the Sanctuary was considered. Here cultivation has been in progress for the past 50 years. All the six study sites were marked for soil sampling, to study the influence of variations in vegetal cover on SOC. These are: (1) predominantly occupied by teak, (2) predominantly occupied by bamboo, (3) occupied by mixed vegetation of trees, (4) covered by seasonal herbaceous vegetation, (5) agricultural area inside the Sanctuary (~10 years of cultivation) and (6) agricultural area outside the sanctuary (~50 years of cultivation) (Table 1). Cereals and potato are the normally grown crops in sites 5 and 6 respectively. Density of vegetation in the first three sites is 855 per ha teak trees, 355 per ha bamboo clumps, and 655 per ha mixed trees. Agricultural activity is restricted to the monsoon (June–September) period, but at times is extended up to February. Herbaceous cover is seen from June to December. For the rest of the year, these three sites (4–6) remain uncovered/barren.

Soil sampling

Soil samples were collected using the trench method. Composite soil samples were made. At each of the selected site three sampling points of 750 m × 750 m were chosen. The distance between two neighbouring points was ~10 km. The three selected sampling points showed homogeneity for the kind of site they were chosen. Based on our preliminary survey (unpublished results), 17 soil

Table 1. Sampling pattern of the study

Location	Site	Sampling points	Distance from each sampling point (km)	Soil samples from each point	Total soil samples
Inside the Sanctuary	Site 1 (teak)	3	~10	17	51
	Site 2 (bamboo)	3	~10	17	51
	Site 3 (mixed)	3	~10	17	51
	Site 4 (herbaceous)	3	~10	17	51
	Site 5 (agricultural land ~10 years)	3	~10	17	51
Outside the Sanctuary	Site 6 (agricultural land ~50 years)	3	~10	17	51
	Total	18			306

Table 2. Soil organic carbon (SOC) of soils from different vegetal covers

Soil depth (cm)	Teak Site 1 (t per ha)	Bamboo Site 2 (t per ha)	Mixed tree species Site 3 (t per ha)	Herbaceous Site 4 (t per ha)	Agricultural land ~10 years Site 5 (t per ha)	Agricultural land ~50 years Site 6 (t per ha)
0–2	8.9	9.2	11.0	2.7	3.9	2.8
2–4	8.3	8.8	9.7	2.4	3.4	2.8
4–6	7.4	8.6	9.3	1.5	3.4	2.7
6–8	6.8	7.7	7.4	1.4	3.4	2.6
8–10	6.5	7.7	6.8	1.4	3.4	2.1
10–12	6.2	7.6	6.1	1.4	3.3	2.2
12–14	5.7	6.8	5.8	1.0	3.1	1.9
15–20	14.3	17.2	13.5	2.6	7.1	3.7
20–25	13.6	16.3	11.9	2.6	6.8	3.1
25–30	11.9	13.7	12.4	1.7	6.4	2.9
30–45	33.0	27.4	24.7	4.5	18.0	8.4
45–60	28.6	17.2	17.9	4.5	16.4	6.9
60–75	23.1	13.5	14.5	3.9	15.3	6.1
75–90	15.3	9.7	14.0	3.9	11.9	8.4
90–100	9.0	8.4	11.0	3.1	11.7	6.1
100–125	22.3	14.2	13.3	5.1	18.1	10.0
125–150	18.1	11.8	11.1	5.1	18.1	7.4
Total	239	205.8	200.4	48.8	153.7	80.1

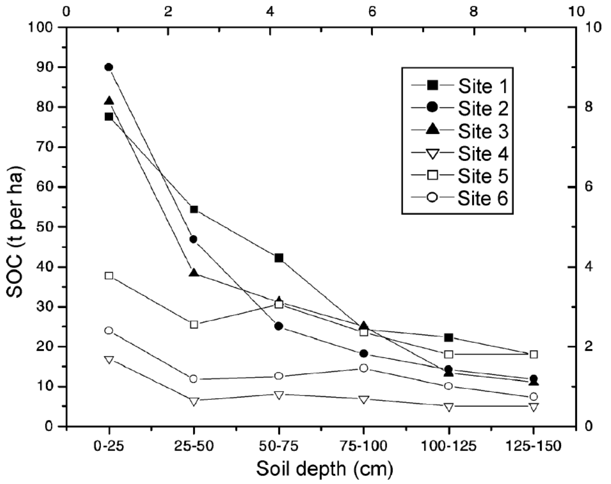

Figure 1. Soil organic carbon (SOC) of soils (summation values for larger depth intervals) from different vegetal covers.

samples were collected sequentially up to a depth of 1.5 m in the following manner: Seven samples between 0 and 14 cm depth with a 2 cm interval, three samples up to 30 cm with 5 cm interval, four samples up to 90 cm with 15 cm interval, one sample up to 100 cm with 10 cm interval and two samples with 25 cm interval up to 150 cm. At each sampling point five soil samples were collected independently for different depths mentioned. Samples for each depth at a sampling point were mixed homogeneously and considered as a composite sample. In this manner three composite samples were collected for each of the sites (Table 1). Soil samples were brought to the laboratory in sealed bags, air-dried and stored in a cool, dry room. Sampling was done during April. A total of 306 soil samples were collected for analysis (6 × 17 × 3).

Soil analysis

SOC was estimated in all the composite samples collected from six sites by wet oxidation method[26]. Prior to wet oxidation, soil samples were passed through 2 mm sieve to remove any bulk remains of plants. In order to estimate the SOC at different particle sizes, physical fractionation[27] of soil aggregates was done. Soil aggregates were physically fractionated to four different pools by passing through four sieves of sizes 2000, 500, 250 and 53 μm. SOC was estimated in all these four aggregates of all the composite samples. SOC was calculated for all the composite samples. Soil particle size distribution[28] and bulk density[29] were estimated to calculate the SOC density. Results are mentioned as averages of three composite readings. Two-way ANOVA was done to find out significance of SOC variation across different depths of the soil, different vegetal covers, and different physical fractions.

Results and discussion

Results are mentioned in Tables 2 and 3 and Figures 1 and 2. ANOVA indicated that SOC values are significantly different (at 0.05 level) for different vegetal covers, across different depths, and for different physical fractions. Study sites 1–3 had high SOC content followed by sites 4–6 (Table 2). Our data are in accordance with earlier studies[8,30–32] which reported that soils under natural vege-

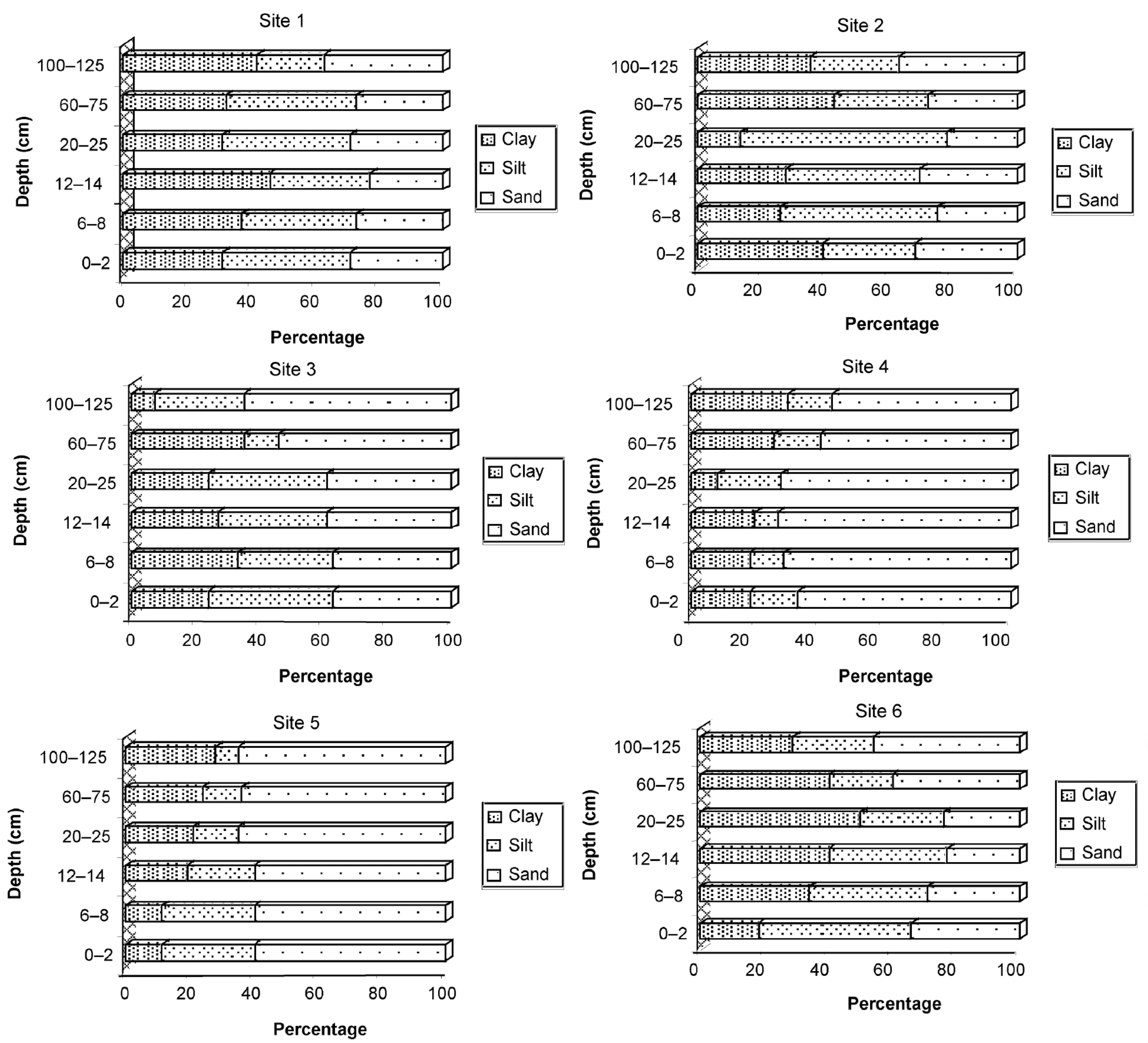

Figure 2. Particle size variation in different soils at different depths.

tation had high SOC content compared to other land-use systems. In all the sites, SOC decreased as the depth of the soil increased. SOC in the top layer (0–2 cm) differed corresponding to the type of vegetal cover. Site 1 stored more SOC (239 t per ha) compared to other sites with different vegetal covers (Table 2). Agriculture soils showed lower SOC, indicating anthropogenic impact on soil carbon processes. SOC in top soils of site 5 also was less, indicating the impact of human alterations (land-use change) on the SOC. A similar conclusion has been drawn[30], mentioning that continuous cultivation lowers SOC content. In this study we found significant influence of different land-cover types on distribution, storage and nature of SOC at different depths of the soils. Similarly, an earlier finding[33] indicated that the distribution of SOC with depth and total SOC density (kg per sq. m) are affected by vegetation, soil texture, landscape position, soil truncation, and the effect of run-on and run-off or wind erosion/deposition. Results of our study are in confirmity.

Pooled SOC with a depth interval of 25 cm showed how SOC movement across the soil system gets differed due to vegetal cover (Figure 1). A steep fall in the SOC content was observed up to ~50 cm and at subsequent depths, the decrease was much lesser. This is an indication of higher biological activity associated with top layers, reflecting greater degradability of SOC at these depths. Values were significantly different across vegetal covers. In a similar manner, an earlier study[34] reported significant differences in SOC decomposition across different vegetal covers due to substrate availability. In this study varia-

Table 3. SOC content (t per ha) in different particle size fractions

Soil depth (cm)	Location	>500–2000 μm	>250–500 μm	>53–250 μm	<53 μm
0–2	Site 1	8.7	9.7	8.9	7.3
	Site 2	6.6	9.7	7.8	7.3
	Site 3	10.7	8.8	9.5	8.1
	Site 4	2.7	2.4	1.6	4.0
	Site 5	3.0	3.7	3.4	3.9
	Site 6	2.8	4.4	2.0	2.7
6–8	Site 1	4.3	5.1	5.0	7.1
	Site 2	6.7	7.6	6.4	6.4
	Site 3	6.2	5.4	6.0	6.0
	Site 4	1.5	1.1	1.1	3.1
	Site 5	1.9	3.0	2.8	2.3
	Site 6	2.7	3.4	1.8	2.7
12–14	Site 1	4.3	5.1	5.0	5.6
	Site 2	5.4	5.7	5.7	5.9
	Site 3	4.5	4.6	5.0	5.0
	Site 4	0.9	0.8	0.8	1.8
	Site 5	2.2	2.5	2.5	3.1
	Site 6	2.3	2.6	1.5	1.5
20–25	Site 1	9.4	12.8	13.1	14.3
	Site 2	11.2	12.9	13.0	13.7
	Site 3	8.9	8.8	9.8	11.0
	Site 4	2.0	1.8	1.7	3.8
	Site 5	4.9	7.1	6.9	6.2
	Site 6	3.8	4.2	2.1	3.2
30–45	Site 1	20.7	30.6	37.5	45.6
	Site 2	28.4	33.5	33.2	28.1
	Site 3	25.9	25.1	26.4	26.4
	Site 4	5.2	7.2	5.0	11.4
	Site 5	21.4	25.4	30.0	32.4
	Site 6	10.2	19.5	8.8	8.8
60–75	Site 1	11.4	16.2	17.0	22.7
	Site 2	11.0	10.5	1.9	11.6
	Site 3	9.5	13.8	12.1	13.9
	Site 4	3.5	3.1	3.5	5.8
	Site 5	9.9	13.7	14.8	16.6
	Site 6	6.5	6.9	4.9	8.4
100–125	Site 1	14.8	15.5	27.4	31.9
	Site 2	13.0	17.2	11.3	16.0
	Site 3	4.4	8.5	15.9	21.4
	Site 4	5.1	5.1	3.8	8.3
	Site 5	11.6	13.1	22.5	28.4
	Site 6	5.2	11.0	5.2	12.9

tions in vegetal cover brought in different SOC substrates influencing their decomposition. SOC decomposition was less in soils of sites 4–6, where the input was much lesser compared to sites 1–3. Sites 5 and 6 are currently agricultural fields. SOC at lower depths of site 5 was in tune with soils of sites 1–3, in contrast to the contents of site 6. This is because the land at site 5 was earlier covered by natural vegetation and the contribution to soil carbon is indicative of recorded values. This rapid change in SOC as land-use pattern changes in the tropics indicates the potential risk of soils turning into a source of carbon. Elsewhere, Magnani *et al.*[15] reported variability in forest carbon sequestration due to stand-replacing disturbances. A large amount of CO_2 gets released from the surface soil when the vegetation communities are deforested and converted into grazing and cultivation[35]. OM depletion and reduction in the number and stability of soil aggregates is seen when native ecosystems are converted to agriculture land[36]. Our results are in agreement with these reports. SOC content is maximum in the top 25 cm. This is in confirmation with earlier reports[1,8]. Bamboo showed the highest content, which could be attributed to its shallow root systems with prolific growth. The carbon sequestration potential in soils is strongly affected by root production[37]. Our results and inferences are also similar. Another significant observation is regarding soils from sites 4–6, where the magnitude of SOC decomposition was lesser than from soils of sites 1–3, as indicated by the ratios of SOC at 125–150 and 0–25 cm respectively. Our reasoning is that soil microbial activity is proportional to inputs of SOC at the top layers. Lesser microbial activity in these soils (sites 4–6) because of fewer inputs in the top layers could be responsible for the higher ratios. Soils with larger inputs (sites 1–3) may have had higher microbial activity, which was responsible for a larger fall in the ratios of SOC between 125–150 and 0–25 cm. The proportion of SOC moving down in these soils is much lesser. It is reported that carbon losses by accelerated microbial respiration are offset by increases in carbon input to the soil[38]. Our findings are in coherence with this view.

Soils with seasonal herbaceous cover in the tropics can be considered as one of the potential sinks (though small) for carbon. SOC movement in soils with seasonal herbaceous cover (site 4) showed an interesting pattern. Here, SOC decomposition is much slower and proportion of SOC at 125–150 cm is much higher compared to the inputs at 0–25 cm. This can make these soils an important sink of carbon in the tropical systems in spite of the shorter lifespan, as the proportion of carbon going down is significantly larger compared to the inputs. Total SOC in these soils is less than at other sites. For soils from sites 1 to 3, site 1 showed larger proportion of SOC at 100–150 cm, indicating that decomposition of teak litter is much slower compared to that of bamboo (site 2) and mixed cover (site 3). This could be due to the chemical nature of the material. Work is in progress to study the impact of chemical characteristics of litter in the SOC decomposition.

Results of physical fractionation of SOC (into four pools of different particle size) at six different sites with different depths gave a better understanding of SOC movement in the soil (Table 3). We disagree with the assumption of considering SOC as a homogenous pool[34] and agree with another considering it as a heterogeneous pool[39]. From our results we hypothesize that within a layer, SOC gets decomposed from one fraction to another in a unidirectional manner towards the <53 μm (recalcitrant) pool. This is contrary to the complex carbon model[38] (four-pool), with carbon transfers between the stabilized pool and the other three pools. SOC in this pool is stable for longer duration and does not move backward to the other three pools. Our results are also indicative of this. SOC content in different size fractions increased as the aggregate size decreased in all sites (1–6), with some exceptions (Table 3). SOC concentration in different physical fraction pools decreased with increase in depth (up to 14 cm) in all sites (1–6) (Table 3). Across layers of different depths the size of the recalcitrant pool increased, as it is more stable. This is in accordance with earlier findings[25]. Surprisingly, from 20–25 to 100–125 cm, the SOC content in all aggregates increased. We attribute this to the proportion of silt and clay content of the soils (Figure 2). This is in agreement with earlier reports, where SOC concentration was shown to increase with decreasing particle size[40,41]. We conclude that from each physical fraction the SOC moves across different depths, getting decomposed and converted towards the recalcitrant pool. Decomposition of SOC was dependent on the type of fraction and microbial activity at that depth. Percentage of recalcitrant pools increases with increasing depth in all types of vegetal cover due to addition of SOC to this pool by the decomposition of the other three pools at each layer. Increase in SOC beyond 50 cm depth could be due to particle size/composition variation.

Conclusion

The type of vegetal cover has a significant impact on SOC up to a depth of 1.5 m. SOC content in soils with natural vegetal cover (trees) is sufficiently large, indicating their sink capacity. Herbaceous cover in tropical systems can be taken as a potential sink as more proportion of carbon moves downwards compared to inputs. Land-use change significantly lowers the sink capacity of soils. The heterogeneity of SOC at different land-cover types is clearly evident from the results obtained. Results of physical fractionation of SOC show that the movement of SOC is unidirectional towards the recalcitrant pools. The movement is dependent on type and quality of leaf litter.

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