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Alterations in soil aggregate stability of a tropical Ultisol as mediated by changes in land use

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Abstract: Aggregate stability is considered to be an appropriate indicator of the relative resistance of soils to detachment by the forces of wind or water. Structural weakness and high rates of erosion in red yellow podzolic (RYP) soils of Matara district are, in general, discussed as prominent problems in intermediate scale agricultural estates. The present study was conducted to ascertain the impacts incurred on the stability of soil aggregates by the alteration of natural forests to agricultural lands, using tea, rubber, and tea/rubber intercropping soils. Surface soils were taken to assess the wet and dry aggregate stabilities, bulk density (D_B), clay content, and soil organic carbon (SOC) content. The D_B of rubber (1.62 g cm^{-3}) and tea/rubber intercropping (1.61 g cm^{-3}) soils differed significantly ($P < 0.05$) from forest (1.33 g cm^{-3}) and tea (1.48 g cm^{-3}) soils. Rubber and tea/rubber intercropping soils had significantly high clay contents as well. Forest soil had the highest SOC content, whereas tea, tea/rubber, and rubber soils respectively showed 45, 50, and 70% decline. The aggregate size distribution did not differ noticeably in forest, tea, and tea/rubber intercropping soils. However, rubber soils with the least SOC content had a lower percentage of macro-aggregates (> 0.5 mm) and significantly low wet and dry mean weight diameters. Above results revealed that the changes in land use negatively influenced the SOC pool and the stability of aggregates. Significant and consistent relationship between the carbon stocks and the wet and dry stabilities of aggregates has not been noted. It was clear that the content of SOC would not be considered as the solitary factor that affects wet and dry stabilities of aggregates in the tested Rhodudults.

Key words: aggregate stability; land uses; soil organic carbon; Sri Lanka.

Introduction

Aggregation, or the arrangement of primary soil particles into groupings, resulting in good agronomic soil structure is a favorable property. It reduces erosion and improves the pore size distribution thereby resulting in better soil-water-air relationships. The stability of aggregates determines the resistance of soils to disruptive forces, specifically caused by the impacts of water and wind.

Stability of soil aggregates is generally believed to be strongly correlated with soil organic carbon (SOC) content. Organic matter increases the cohesion of aggregates through the binding of mineral particles by organic polymers or the physical enmeshment of particles by fine roots or fungi (Chenu et al. 2000). Appropriate levels of SOC ensure the fertility of soils while minimizing the impacts of agriculture on the environment through carbon sequestration, reducing erosion, and preserving soil biodiversity. In general, soils with lower organic carbon contents are more sensitive to mechanical damage. The loss of SOC and fertility levels lead soils to serious degradation making them strong when dry and weak when wet (Munkholm et al. 2002). The conservation of sufficient levels of SOC is crucial for the physicochemical and biological functioning of soils in both temperate and tropical ecosystems.

The total carbon storage and turnover in soils are explicated to be a series of pools with different turnover rates that are ranging from seasonal to millennial time scales. Compared with the generally emphasized importance of climatic factors, the influence of the nature of plant material from which it is derived on SOC dynamics is assumed to be minimal. Still, the vegetation is identified to play a significant role in influencing various physicochemical properties of soil (Lichner et al. 2007, 2012, 2013).

Furthermore, the stabilization of aggregates with SOC is mutually beneficial for the protection of SOC because soil aggregates are known to physically protect

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Table 1. General specifications of the land uses. AMSL: above mean sea level.

General Specifications	Land use			
	Forest	Tea	Tea/rubber	Rubber
Area (ha)	455	2	13	14
Slope (%)	5 ± 2	4 ± 2	7 ± 3	7 ± 3
Elevation AMSL (m)	65	18	63	40
Percent ground surface cover (excluding canopy cover)				
Undergrowth (%)	50–60	10–30	20–30	0–5
Litter (%)	30–40	70–90	10–20	0–10
Logs/Stumps (%)	5–20	0–5	0–5	0–5
Rock (%)	0	0	0–10	5–20
Bare soil (%)	0	0	20–50	70–90
Geology	Precambrian crystalline rocks	Precambrian crystalline rocks	Precambrian crystalline rocks	Precambrian crystalline rocks
pH	4.9	5.4	5.9	5.8
ECe (dS m^{-1})	0.030	0.026	0.023	0.020
CEC ($cmol_c$ kg^{-1})	13.5	12.4	11.5	10.0

C and N. Aggregates physically protect SOC by (1) forming a physical barrier for micro-organisms, microbial enzymes, and their substrates, (2) controlling food web interactions, and (3) influencing microbial turnover (Six et al. 2002). The processes involved in aggregate formation and stabilization indicate a close relationship between soil biota and SOC dynamics, where the type of vegetation cover would play an important role.

Forest soils are typical examples for soils with natural conditions. Transformation of the natural forest vegetation into agricultural fields may alter the physical, chemical, and biological properties, including aggregate stability of soils (An et al. 2009). Conversion of natural forest lands in numerous ways to fulfill the demands of agricultural purposes prevents the replacing of nutrients harvested in agricultural products that are made available through mineralization of SOC, causing depletion of the SOC pool subsequently inducing other degradation processes such as deterioration in soil structure and aggregation.

Soils in the study area are locally known to be red yellow podzolic (RYP) soils (USDA great group: Rhodudults). Highly wettable soils are characterized by low contents of SOC and low stability of aggregates against slaking (Leelamanie et al. 2013). Originally less fertile soils are further degraded by the conversion of natural forests into agricultural lands, corresponding to the rapidly growing demands for economical crops. The RYP soils are reported to have physically strong structures (Panabokke 1996). On the contrary, erosion that associated with rapid disruption of aggregates is one of the major problems of these soils. The objective of this study was to identify the impacts incurred by the alterations in land use on the stability of aggregates using tea (*Camellia sinensis*), rubber (*Havea braziliensis*), and tea/rubber intercropping soils, in comparison to the soils from a natural forest.

Material and methods

The experiment was conducted in the low country (< 300 m in elevation) wet zone (Matara district) of Sri Lanka, which is identified as WL2 zone (annual rainfall >2400 mm) in the agro-ecological map (National Atlas of Sri Lanka 2007). The area is known for some of the world's best cinnamon, tea with high tannin, and rubber production. Samples were taken from a natural forest (Wilpita, 6°05′ N 80°31′ E), tea (6°03′ N 80°34′ E), rubber, (6°02′ N 80°33′ E), and tea/rubber (6°05′ N 80°34′ E) intercropping lands. The forest is existing for more than 200 years. The rubber land is established in 1984, tea land in 1988, and tea/rubber intercropping land in 1986. Landscapes of the areas are rolling to undulating with geology of Precambrian origin. Soils contain low levels of base cations (base saturation < 35%) with low pH, EC, and CEC (Table 1).

Percentage ground surface cover was estimated with the plot method using scaled photographs. A rich ground surface cover that dominated by shrubs, herbs and grasses was observed on the forest floor. The thick canopy and the prominent litter layer of green manure prevent the tea lands from exposing. Large proportion of tea/rubber intercropping land is bare and exposed irrespective of the presence of creeping legumes (major) and grasses (minor). Contrasting to forest and tea lands, some rock outcrops can be seen. Rubber land is mostly exposed bare soil with more prominent existence of rock outcrops, where the undergrowth is limited to almost negligible growing of grasses and herbs (Table 1).

Fields were divided into three blocks against the slope, where the blocks did not cover the whole fields due to the large sizes of the areas. The length was set to 30–40 m depending on the site characteristics. Samples were collected in four replicates. Standing plants and crop residues on the ground were carefully removed before taking the soil samples from a depth of 15 cm using a soil core. Soils obtained from the tea, rubber, and tea/rubber intercropping lands were compared with the forest soil, which was considered to be the control.

Wet and dry stabilities of aggregates, bulk density, D_B (0–15 cm), clay content, and the SOC contents of the soils were determined separately for the four land uses. The SOC content was measured colorimetrically by Walkley-Black dichromate digestion method. Clay content was determined using the hydrometer method. The aggregate size class separation was done based on the general procedure explained

Table 2. Basic physical properties of soils from different land uses. SOC: soil organic carbon (means with different lowercase letters are significantly different at $P \leq 0.05$).

Land Use	Bulk density (g/cm^3)	Clay content (%)	SOC content (%)	SOC stock (t/ha)
Forest	1.33 **a**	5.45 **a**	1.79 **a**	40.34
Tea	1.48 **b**	4.97 **a**	0.98 **b**	21.73
Tea/Rubber	1.61 **c**	9.73 **b**	0.89 **b**	21.57
Rubber	1.62 **c**	9.98 **b**	0.53 **c**	12.78

in Cambardella & Elliott (1993), using wet and dry sieving techniques.

Before use, the soils were air-dried and passed through 3 mm sieve. Fifty grams of soil subsamples (< 3 mm) were taken for the wet sieving method. The subsamples were set on a moist filter paper and left for 10 min for the pre-moistening, and then used for the wet sieving in a rotary sieve shaker with set of five sieves having 2.0, 1.0, 0.5, 0.25 and 0.1 mm apertures. The water level was adjusted so that the aggregates on the upper sieve were just submerged at the highest point of the upstroke. The amplitude of the sieving action was 30 mm and the period of sieving was 2 min. An apparatus with 10 sieves was used for the dry sieving. Mean weight diameter (MWD) was calculated using the following equation:

$$\text{MWD} = \sum_{i=1}^{n} x_i w_i$$

where x_i is the mean diameter of any particular size range of aggregates separated by sieving, and w_i is the weight of aggregates in that size range as a fraction of the total dry weight of soil used (Kemper & Rosenau 1986). The MWD was calculated for both wet (MWD_{WET}) and dry (MWD_{DRY}) sieving methods. High MWD values indicate more cohesive soil conditions, where MWD_{WET} and MWD_{DRY} respectively representing the resistance of soils to water and wind erosion. Data were statistically analyzed using STATISTICA software (Statsoft Inc., 2010), with analysis of variance (ANOVA) at 5% level of significance ($P < 0.05$). The mean separation was tested using Least Significant Difference (LSD) method.

Results and discussion

Basic properties

Selected basic physical properties of soils from four land uses are presented in Table 2. The D_B of forest, tea, rubber, and tea/rubber intercropping soils were 1.33, 1.48, 1.62, and 1.61 g cm^{-3}, respectively. Rubber and tea/rubber intercropping soils did not differ significantly ($P > 0.05$) from each other, however, significantly differed ($P < 0.05$) from forest and tea soils. Various land use categories had a significant effect on SOC content (Table 2). The SOC contents of tea, tea/rubber, and rubber soils were significantly lower ($P < 0.05$) than that of the forest soil which was the highest (1.79%). Rubber soils showed the least SOC content. Compared with the forest soil, the SOC content of tea, tea/rubber, and rubber soils respectively showed 45, 50, and 70% decline. Clay content of rubber and tea/rubber intercropping soils were significantly (about 80%) higher than that of forest and tea soils.

From a global perspective, grasslands are considered to store about 34% of the global terrestrial carbon stock, while forests store about 39% and agro-ecosystems store only about 17% (Sreekanth et al. 2013). Therefore, the conversion of natural forest to other land uses can be expected to cause a decline in the SOC pool as observed in the present study (Table 2). In general, understory vegetation highly contributes to the SOC levels (Jimenez et al. 2007). The level of understory vegetation was significantly high in the natural forest, ascertaining a regular provision of a high amount of SOC into the soil. Obviously negligible groundcover and the consequent low addition of organic matter to the soil might be the reason for the rubber field to show a low SOC level. Although the tea and tea/rubber plantation also lacks proper understory vegetation, continuous addition of green manure (*Gliricidia maculata* L.) in the tea land and the presence of creeping legumes in the tea/rubber land might have supported to maintain comparatively high SOC level. Human-controlled factors during the conversion of natural forests to agricultural lands, specifically the activities such as ground clearance and plowing, result in exposing the soil surface and breaking of aggregates subsequently increasing the magnitude of erosion and the depletion of SOC stocks.

The D_B of soil is expected to be negatively correlated with soil organic matter content. Although the organic matter contents of all the land are considerably low, which is a result of the hot humid tropical conditions (Leelamanie 2014), results revealed a negative correlation between SOC content and D_B. Forest soil with the highest SOC content showed the least D_B, whereas rubber soils showed the vice versa. This is in line with former findings on negative correlations of D_B to the organic carbon of soil (Perie & Ouimet 2008).

Although high bulk densities would theoretically suggest lower clay content, we observed high clay contents in rubber and tea/rubber intercropping lands. This confirms that the high clay content is not a characteristic of the entire 0–15 cm soil layer. The forest floor is in general concealed with different components including leaf litter and remnants (Table 1), and therefore, protected from erosion. Tea land is also not exposed due to the thick canopy and the mulches of green manure. However, tea/rubber intercropping and rubber lands are mostly exposed to the direct impact of rainfall as well as to the surface runoff, resulting erosion of the top soil. Consequent exposure of the sub-surface (Bt) horizon, which is characterized by high clay contents

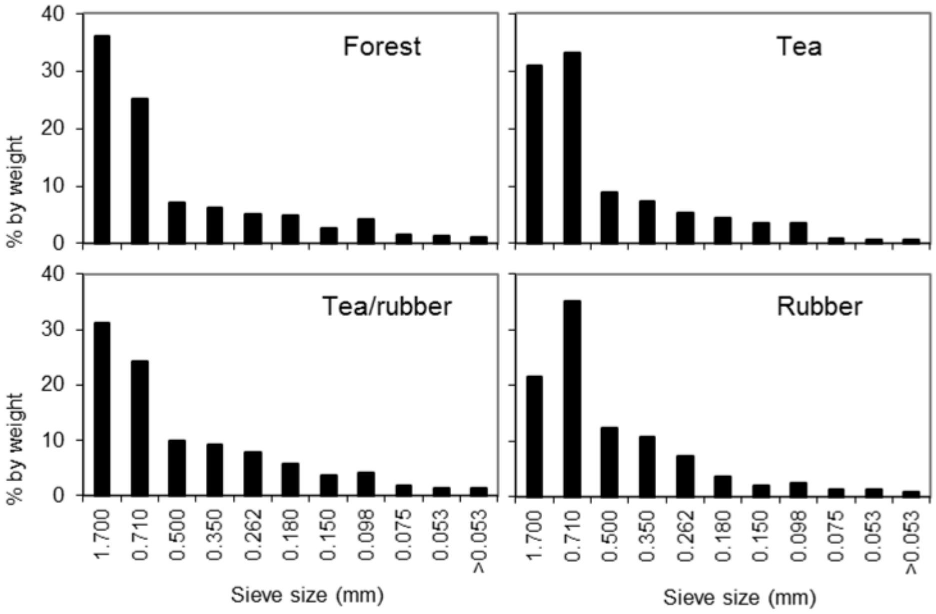

Fig. 1. Dry Aggregate Distribution of soils from different Land Uses.

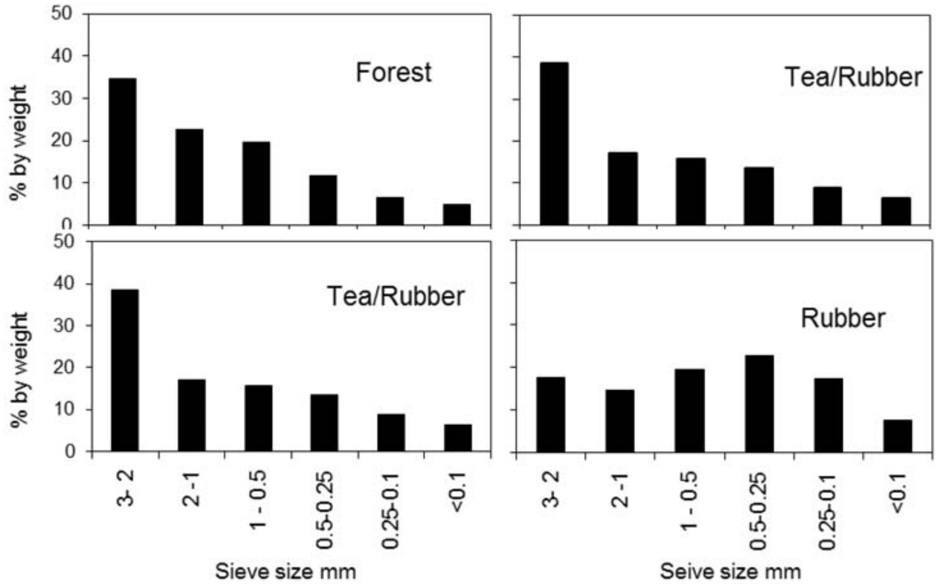

Fig. 2. Wet Aggregate Distribution of soils from different Land Uses.

(Panabokke 1996), might be the reason for high clay contents in the top most soils of rubber and tea/rubber intercropping lands.

Aggregate stability

Samples were tested for the resistance of aggregates to disruption using dry and wet sieving. According to the diameter of aggregates, the samples were categorized as micro (< 0.5 mm) and macro (> 0.5 mm) aggregates. The stability of aggregates is represented with the size distributions and MWD.

Distribution of dry aggregates in soils is presented in Fig. 1 and $\mathrm{MWD_{DRY}}$ values in Table 3. Dry aggregate distribution patterns did not show a clear difference between land uses. All soils showed a higher amount of large-size and lesser amount of small-size aggregates. The $\mathrm{MWD_{DRY}}$ of rubber soils was significantly lower ($P < 0.05$) than that of the forest and the tea soils, however, not significantly different from that of tea/rubber intercropping soils. The dry stability of aggregates did not show comparable results with SOC levels of soils. Although the SOC content of the forest soil differed significantly ($P < 0.05$) from that of tea and tea/rubber soils, $\mathrm{MWD_{DRY}}$ of all these three soils did not differ significantly ($P > 0.05$). Similarly, the rubber and tea/rubber intercropping soils, which differed significantly in SOC content, did not differ significantly in $\mathrm{MWD_{DRY}}$.

The wet aggregate size distribution of soils is presented in Fig. 2 and the $\mathrm{MWD_{WET}}$ values in Table 3.

Table 3. Mean weight diameter (MWD) of soils from different land uses in wet and dry aggregate analysis (means with different lowercase letters are significantly different at $P \leq 0.05$).

Land Use	MWD_{WET}	MWD_{DRY}
Forest	1.410 **a**	1.254 **a**
Tea	1.445 **a**	1.250 **a**
Tea/Rubber	1.406 **a**	1.163 **ab**
Rubber	0.930 **b**	0.982 **b**

The wet aggregate distribution of rubber soil was different compared with that of the other three soils with higher amount of small-size aggregates, and lesser amount of large-size aggregates, while all other soils showed higher amount of large-size aggregates.

The wet size distribution pattern of soils under four land uses clearly revealed that the land use exerted a considerable effect on aggregate size distribution. The high proportion of macro-aggregates (> 0.5 mm) in forest soils indicated minimal land disturbance, whereas extremely exposed rubber soils showed a high proportion (about 50%) of micro-aggregates (< 0.5 mm). The amount of micro-aggregates in other three soils was only about 20–25%. It was quite noticeable that the rubber soil had about 86% higher micro-aggregates compared with the forest soils. The amount of aggregates < 0.25 mm was about 26% in rubber soils and below 15% in other three soils. Results of the wet aggregate analysis revealed that the rubber soil would be highly vulnerable to water erosion compared with other soils.

A periodical supply of organic residues and the physical enmeshment of particles by plant roots, which is similar to forest condition, are important to maintain soil aggregation at a higher level (Mapa & Wanasundara 1991). That means a lower addition of organic matter would result in lower aggregation. The high percentage of micro-aggregates in rubber soils can be considered as a result of the less availability of SOC.

In contrast, tea and tea/rubber intercropping soils with significantly low SOC contents compared with the forest soils showed comparable wet aggregate distribution patterns with forest soils. According to Abiven et al. (2009), no direct or universal relationship was identified between the aggregative factors induced by organic input decomposition and temporal aggregate stability. Although the SOC content of tea soil is significantly lower than that of the forest, the MWD_{WET} in tea soil was slightly higher (not significant, $P > 0.05$) than that of the forest soil. It suggests that the periodical addition of *Gliricidia* did not considerably improve the SOC level of tea soil, which might possibly be due to the high decomposition rates in the tropical climate. However, it might still have a positive effect in the stabilization of aggregates (Mapa & Gunasena 1995). Creeping legumes in tea/rubber intercropping land can be considered to play a significant role in maintaining better SOC level and higher water stability of aggregates (MWD_{WET}) compared with bare rubber land soil.

Results revealed that low SOC content led to a low proportion of macro-aggregates and a high proportion of micro-aggregates in rubber soils (Fig. 2) suggesting a positive correlation between the SOC content and stability of aggregates. However, the SOC contents in all the tested soils (Table 2) are not necessarily correlated with the dry or wet stabilities of aggregates as indicated by MWD (Table 3). Despite the fact that organic matter is an important binding agent in aggregate formation, changes in water stable aggregates produced under different land uses might not always related with total soil organic matter variations. There are lines of evidence for soils from different land uses with differences in aggregate stability to show no significant differences in SOC content (Devine et al. 2014), indicating that high stability of aggregates is not always linked with high SOC content. Differences in the composition and the hydrophobicity of organic material are as well considered to play a role in this behavior (Chenu et al. 2000; Leelamanie et al. 2013). The hydrophobic nature of organic matter may change responding to high soil temperatures (Leelamanie & Karube 2014) altering the organic matter effects on the stability of aggregates, and this might possibly be applied to the soils in the study area with tropical climate.

In summary, soils under tea, rubber, and tea/rubber intercropping lands were compared with forest soils to determine the stability of aggregates as affected by the alterations in the type of vegetation. Forest soils showed the highest content of SOC content, whereas rubber soils showed the lowest. Rubber and tea/rubber intercropping soils showed high clay contents compared with tea and forest soils. It was clear that the alteration in land use from natural forests to agricultural estates negatively influenced the SOC pool as well as the stability of aggregates.

There was a tendency to suggest a positive correlation between the SOC content and the stability of aggregates as rubber soil with low content of SOC showed a low percentage of macro-aggregates and significantly low wet and dry mean weight diameters. Still, a significant and consistent relationship between the carbon stocks and the soil wet and dry stabilities of aggregates has not been noted. Accordingly, it can be concluded that the content of SOC would not be considered as the single solitary factor to promote wet and dry stabilities of aggregates. Besides, other factors such as the composition and the hydrophobicity of organic matter, which are known to be interrelated with the content of organic matter, might have affected the stability of aggregates of the tested Rhodudults.

Considering the observed high clay contents of the tea/rubber and rubber lands, which are not corresponding with their high bulk densities, we suggest that the lands are subjected to water erosion subsequently exposing the Bt horizon characterized by high clay content. Noticeable absence of understory vegetation with the obvious evidence of surface erosion is a situation which, in case of continuation, would lead to further land degradations. Maintaining understory vegetation in this land is given less attention by the owners because such maintenance necessitates high requirement of labor, which is considered not cost effective. Further experiments to estimate the actual annual soil loss would be required to acquire the concern of the owners as well as the relevant authorities on the degradations of these lands.

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