

Organic Carbon Fractions, Aggregate Stability, and Available Nutrients in Soil and Their Interrelationships in Tropical Cropping Systems: A Case Study

R. R. Ratnayake^{a,*}, T. Roshanthan^b, N. Gnanavelrajah^b, and S. B. Karunaratne^c

^aNational Institute of Fundamental Studies, Hantana Road, Kandy, Sri Lanka

^bFaculty of Agriculture, University of Jaffna, Jaffna, Sri Lanka

^cHawkesbury Institute for the Environment, Western Sydney University, Richmond NSW, Australia

*e-mail: renuka.ra@nifs.ac.lk

Received January 9, 2019; revised March 3, 2019; accepted May 22, 2019

Abstract—Tropical agricultural soils have been claimed as a source of carbon. As agricultural systems in the tropics are highly diverse, it is useful to study soil organic C (SOC) of different agricultural systems. We quantified the SOC fractions, available nutrients, and aggregate stability in eight different tropical agricultural systems, including annual crops under different management scenarios, such as organic, inorganic, and combined fertilizer applications. Annual crops treated with organic fertilizer only (A–OF), inorganic fertilizer only (A–IF), both organic and inorganic fertilizers (A–O/IF), perennial crops (PC), home gardens (HG), and abandoned home gardens (AHG) in Eutrustox soils and annual crops with organic fertilizer only (A–OFS) and uncultivated land on Quartzipsamments soil (USR) were studied. The links between SOC fractions, available nutrients, and aggregate stability in these soils were analyzed. Regression models were fitted for SOC fractions and available nutrients. Our results indicated that the different land use types exhibited significant variations in organic carbon fractions, aggregate stability, and available nutrients in soils. The available macro and micronutrients, except for nitrogen, showed a significant positive correlation with either total organic C (TOC) or carbon fractions indicating the synergy between them. The differences in soil C stocks clearly reflected the differences in litter fall and soil disturbance, as indicated by the highest C stocks in AHG. The dry weight of collected litter showed that AHG accumulated the highest litter content (97.38 g/m²) compared to the lowest (37.63 g/m²) in A–I/F. Organic matter addition to soil also increased the C stocks, even in annual crops. Aggregate stability showed a positive correlation with C fractions. The regression models developed in this study can be used to predict available nutrients by measuring TOC or C fractions in similar land use types in the tropics. This study confirmed that tropical agricultural systems that include annual crops have potential for storing and maintaining C in soils, if appropriately managed. The beneficial influence of SOC on available nutrients and aggregate stability could be a driving force to increase carbon stock in tropical agricultural systems.

Keywords: soil C fractions, annual crops, perennial crops, home gardens, organic fertilizer

DOI: 10.1134/S1064229319120123

INTRODUCTION

Soil organic carbon (SOC) plays an important role in maintaining ecosystem services that are vital for sustainable agriculture [45]. Though decline of carbon stock of agricultural lands [20, 10] have been reported depending on the agricultural and forestry management practices and climatic scenarios, stored SOC can act as a greenhouse gas source or sink [47]. Enhancing carbon storage in soil is of great interest, as the soil itself contain approximately 2500 Pg (10¹⁵ g) of C at the global level [48]. Therefore, understanding the behavior of SOC is critical for managing it in a way that minimizes the increase in greenhouse gasses. It is estimated that improving agricultural management

practices could sequester between 400 and 800 Mt C per year worldwide [49].

Soil organic C consists of different SOC fractions that play different ecological roles and have various biological influences [43]. Soil organic C fractions vary in turnover rates and resistance to decomposition [21, 30, 43]. Therefore, when studying C sequestration, it is important to explore not only these fractions, but also total SOC. Different systems are used to classify these SOC fractionations. Soil itself is a matrix of these fractions that is combined by the formation of both macro and micro aggregates [22]. These aggregates will provide protection and allow the SOC to remain in soils for a long period. Additionally, SOC fractions are important for initializing process based SOC models, such as the Roth C carbon model, by

replacing the conceptual pools of SOC, as demonstrated by Karunaratne et al. [56].

Land use management practices and land use/land cover changes influence the total SOC and the proportions of the various fractions [34, 51, 53, 63]. Generally, in commercial agriculture, continuous cultivation is practiced with conventional tillage and inorganic fertilizer is used without the addition of organic manure. Such cultivation practices lead to land degradation, which is mainly due to the depletion of soil organic matter (SOM).

Many studies have focused on assessing the changes in labile pools of SOC associated with different soil management practices in the temperate regions of the world [29], but only a few studies have focused on the tropical regions, particularly in agricultural soils. A study by Benbi et al. [8] on poplar-based agroforestry involving wheat-legume rotation, as well as rice-wheat and maize-wheat agro ecosystems, in semiarid India reported that organic C fractions in soils were less stable and thus could be lost during land use change. Further, Benbi et al. [9] reported that C fractions except water soluble C, were strongly correlated with each other in cultivated and undisturbed soils in northern India. SOC in tropical soils appears to be more easily degraded compared to that of temperate soils [42]. Hence, increasing the SOC contents of soils in the tropics and subtropics is not an easy task [48]. On the other hand, the need for higher SOC levels to maintain suitable agricultural production systems in the tropics is equally important, if not more important than doing so in temperate regions.

Soil organic matter (SOM) consists of dead plant and animal material and includes SOC [21]. Some of the nutrients in the soil are held in the organic matter, comprising almost all the N, a large amount of P and some S [5]. When organic matter decomposes, these nutrients are released into the soil in a form that plants can absorb [3]. Building soil organic matter or SOC has a significant relevance Kyoto protocol [46] to mitigate global warming. The carbon sequestration potential of soils plays an important role in mitigating the effect of climate change, because soils serve as sinks for atmospheric carbon [20]. Agricultural soils if properly managed could act as sink of carbon [45, 63]. Altering crop rotation can influence soil C stocks by changing quantity and quality of organic matter input. More research is needed, especially in the tropical areas where quantitative information is lacking [4]. Building SOC in agricultural soils depends on decisions made by farmers in terms of managing SOM which in turn depend on benefits gained. As studies in tropical agricultural systems are limited in this aspect present research aimed to study selected beneficial influences of SOC in tropical agricultural soils.

The main aims of this study were to quantify the SOC and its fractions and available nutrients (extractable) in soils under different agricultural land use types

managed with organic, inorganic and combined fertilizer applications and to study the connections between SOC fractions and available nutrients. Additionally, we explored the interrelationships between SOC fractions and aggregate stability. We hypothesized that the SOC fractions would form a primary component of the SOM, thereby influencing the soil available nutrients and aggregate stability of the considered land use types. Here, we present a case study from tropical agricultural production systems in Northern Sri Lanka.

MATERIALS AND METHODS

Study Area

This study was carried out in the Jaffna District, which is located in the northern tip of the dry zone of Sri Lanka (5°54' N to 9°52' N latitude and 79°39' E to 81°53' E longitude). The main soil types of the study area are Eutrustox and Quartzipsamments [61] which are known locally as Calcic Red Yellow Latosol and Sandy Regosols [15]. The mean annual rainfall in the study area reported in between 696 to 1125 mm and the mean annual temperature is reported as 26 to 33°C [39].

Landscape-Scale Different Treatment Structure Adopted in the Study

The nine different types of land uses were selected. They are namely: (1) annual crop—organic fertilizer only (A–OF), (2) annual crop—inorganic fertilizer only (A–IF), (3) annual crop—organic/inorganic both (A–O/IF), (4) home gardens (HG), (5) abandoned home gardens (AHG), (6) agricultural fields of perennial crops (PC), within the same soil type calcic red-yellow Latosol, (7) annual crop with organic fertilizer only (A–OFS), and (8) uncultivated land (USR) in a sandy Regosol. These land uses maintained the same land use for more than 10 years except the annual crop-organic fertilizer only (A–OF). This land use maintained the same condition only for 7 years. The abandoned home gardens are those which had not been either maintained or disturbed for almost twenty-five years due to civil war in this part of Sri Lanka. Crop history, yield and cultural practices are given in Table 1.

Soil Sampling

For each land use type three (3) plots having a size of 20 × 20 m dimensions were demarcated in the farmer's fields. Each subplot was about 0.5 km apart from each plot. Within each plot, samples were collected (after removing the surface litter layer) at two depth intervals namely 0–0.15, 0.15–0.30 m. Then three sub plot data were pooled for respective depth intervals and created composite samples per sub-plot which resulted in 16 composite samples per sub plot (8 each for considered depth intervals). Finally, 48 samples for each land use type were resulted.

Table 1. Crop history and management practices of the land uses

| Land Use | Present Crop | Duration under present crop | Annual Fertilizer application | | Land preparation and residue management |
|----------|---|-----------------------------|--|--------------------|---|
| | | | inorganic, kg/ha | organic, tons/ha | |
| (A–OF) | Annual crop (chilli and onion) rotation | More than 10 years | None | 20–25 twice a year | Till/residue removal |
| (A–IF) | Annual crop (chilli and onion) rotation | More than 10 years | N 250 P ₂ O ₅ 200 K ₂ O 200 | None | Till/residue removal |
| (A–O/IF) | Annual crop (chilli and onion) rotation | More than 10 years | N 250 P ₂ O ₅ 200 K ₂ O 200 | 20–25 twice a year | Till/residue removal |
| (PC) | Perennial crop (Banana) | More than 10 years | None | None | Till/residue incorporation |
| (HG) | Home garden mixed crops | More than 10 years | None | None | Till/residue removal |
| (AHG) | Home garden Mixed crops | More than 25 years | None | None | No-till/residue not removed |
| (A–OFS) | Annual crop (Paddy) | 7 years | None | 20–25 once a year | Till/residue removed |
| (USR) | Natural shrub vegetation | More than 25 years | None | None | No Till/residue not removed |

Soil sample preparation and laboratory analysis. All visible organic debris, stones, plant roots were removed from the soil. Large soil aggregates were crushed and sieved using a 2 mm mesh sieve. MBC, soil moisture content and soil pH were analyzed using fresh soil. MBC was determined by using the chloroform fumigation and extraction method [11]. After fumigation, MBC was extracted using 0.5 M K₂SO₄ and quantified using the TOC analyzer (multi N/C 2100, Analytikjena, Germany). The remaining soil samples were air dried and ground (0.15 mm) using a grinder (M20 IKA, WERAKE) for further analysis [28].

The following analyses were carried out using dry soil. TOC content was determined using ‘wet’ oxidation by acidified dichromate of organic carbon [31]. The labile fractions of SOC were determined by POC estimation [54]. The water-soluble organic carbon (WSC) was estimated as described by Ghani et al. [2]. KMnO₄-oxidizable carbon (POC) was extracted using 0.2 M KMnO₄ in 1 M CaCl₂. Water soluble organic carbon (WSC) was extracted after shaking at 200 rpm for 30 min and filtering (Whatman42, ash less). The extract was analyzed for C by titration with ferrous ammonium sulfate after dichromate oxidation in acidic medium. Macronutrients (K, Ca, Mg) were extracted by a modified Morgan extractant (NH₄OH/CH₃COOH) [26] while micronutrients (Cu, Mn, Fe, Zn) were extracted using diethylene triaminepentaacetic acid [41]. The extracts were analyzed using atomic absorption spectrophotometer (GBC 933 AA, Australia). Soil phosphorus was extracted using 0.5 M Na₂CO₃ and the color develop-

ment was carried out using the molybdenum blue method [16]. The concentration was measured using UV-2450 (Shimadzu) spectrophotometer. Forms of soil available N, namely Soil NH₄⁺, was extracted using 1 N KCl [57] and determined colorimetrically. Soil NO₃⁻ was extracted using 0.5 M K₂SO₄ and determined colorimetrically.

As soil physical properties both aggregate stability and particle size analysis were performed. Aggregate stability index was measured as mean weight diameter by the dry sieving method [62]. Particle size analysis was determined using the pipette method [19] and derived data were used to determine the soil textural classes.

Litter Sampling

Litter was collected from 1 × 1 m area of each plot. The samples were oven dried at 60°C for 48 h and the dry weight was measured.

Bulk Density

Bulk density of soil was determined by method described by [18]. The samples for bulk density were drawn by removing the top 1–2 cm of the surface soil layer. Soil cores collected from each site were dried in an oven at 105°C for 2 days. Bulk density was calculated as the ratio of dry mass of soil core and internal volume of the metallic core.

Table 2. Soil available nutrients at 0–15 cm depth in different land uses

| Land use | NH ₄ ⁺ | NO ₃ ⁻ | Available N | K | P | Ca | Mg | Cu | Mn | Fe | Zn |
|--|------------------------------|------------------------------|---------------------|----------------------|---------------------|----------------------|---------------------|--------------------|----------------------|----------------------|---------------------|
| Depth 0–15 cm (µg g ⁻¹ soil) | | | | | | | | | | | |
| (A–OF) | 7.72 ^a | 22.0 ^a | 29.72 ^a | 62.95 ^e | 23.67 ^a | 3929.1 ^a | 285.8 ^a | 3.78 ^a | 30.38 ^{ab} | 35.37 ^a | 11.15 ^a |
| (A–IF) | 6.32 ^b | 11.0 ^b | 17.32 ^d | 146.34 ^{cd} | 18.67 ^a | 1291.8 ^e | 111.4 ^{cd} | 2.44 ^b | 16.93 ^{abc} | 15.38 ^c | 1.98 ^{cd} |
| (A–O/IF) | 6.00 ^b | 20.0 ^a | 26.0 ^{ab} | 87.30 ^{de} | 20 ^a | 2137.3 ^{cd} | 139.5 ^c | 2.59 ^b | 12.99 ^c | 30.71 ^a | 4.07 ^{bc} |
| (PC) | 6.34 ^b | 10.0 ^b | 16.34 ^{de} | 153.40 ^c | 20.67 ^a | 2357.3 ^{bc} | 235.1 ^b | 2.23 ^{bc} | 15.93 ^{bc} | 20.13 ^{bc} | 5.19 ^b |
| (HG) | 3.49 ^{cd} | 3.67 ^c | 7.16 ^f | 240.50 ^b | 6.67 ^b | 2011.7 ^d | 140.7 ^c | 1.78 ^{bc} | 19.95 ^{abc} | 18.45 ^c | 3.19 ^{bc} |
| (AHG) | 6.12 ^b | 6.00 ^{bc} | 12.12 ^e | 374.15 ^a | 10.67 ^b | 1999.8 ^d | 312.6 ^a | 4.06 ^a | 31.61 ^a | 28.25 ^{ab} | 5.20 ^b |
| (A–OFS) | 2.82 ^d | 18.0 ^a | 20.82 ^{cd} | 21.05 ^{cd} | 18 ^a | 556.4 ^f | 115.8 ^c | 1.23 ^{cd} | 21.05 ^{abc} | 20.07 ^{bc} | 4.35 ^{bc} |
| (USR) | 4.12 ^c | 18.67 ^a | 22.79 ^{bc} | 10.79 ^c | 4.67 ^c | 465.0 ^f | 78.3 ^d | 0.49 ^d | 10.79 ^c | 15.88 ^c | 0.72 ^d |
| Depth 15–30 cm (µg g ⁻¹ soil) | | | | | | | | | | | |
| (A–OF) | 2.02 ^{cd} | 14.00 ^{ab} | 16.02 ^{ab} | 43.67 ^f | 22.67 ^a | 3808.2 ^a | 134.2 ^b | 3.30 ^a | 23.43 ^a | 31.77 ^a | 6.12 ^a |
| (A–IF) | 3.02 ^a | 8.00 ^{cd} | 11.02 ^{cd} | 137.98 ^{cd} | 18 ^b | 1268.0 ^d | 64.4 ^{de} | 1.68 ^b | 10.27 ^{bc} | 13.13 ^d | 1.83 ^{de} |
| (A–O/IF) | 2.25 ^{bcd} | 12.67 ^b | 14.92 ^{bc} | 70.38 ^{ef} | 16.67 ^b | 1935.2 ^c | 66.7 ^{de} | 1.80 ^b | 7.48 ^c | 22.86 ^b | 3.64 ^{bcd} |
| (PC) | 2.45 ^{bc} | 4.67 ^{de} | 7.12 ^{de} | 136.86 ^{cd} | 19.33 ^{ab} | 2195.7 ^b | 96.8 ^c | 1.58 ^b | 15.37 ^b | 17.27 ^{bcd} | 4.92 ^{ab} |
| (HG) | 1.76 ^{ed} | 1.67 ^e | 3.43 ^e | 220.49 ^b | 3.67 ^d | 1554.5 ^d | 89.2 ^{cd} | 1.74 ^b | 10.41 ^{bc} | 15.18 ^{cd} | 2.37 ^{cd} |
| (AHG) | 2.25 ^{bcd} | 5.00 ^{de} | 7.25 ^{de} | 339.82 ^a | 5.67 ^d | 1993.8 ^{bc} | 275.7 ^a | 4.00 ^a | 22.18 ^a | 20.71 ^{bc} | 4.02 ^{bc} |
| (A–OFS) | 2.70 ^{ab} | 17.33 ^a | 20.03 ^a | 11.19 ^{de} | 17.67 ^b | 250.4 ^e | 80.5 ^{cd} | 1.04 ^{bc} | 11.19 ^{bc} | 17.14 ^{bcd} | 1.57 ^{de} |
| (USR) | 2.63 ^{ab} | 10.67 ^{bc} | 13.30 ^{bc} | 7.12 ^{ef} | 3.34 ^d | 448.0 ^e | 54.9 ^e | 0.46 ^c | 7.12 ^c | 13.29 ^d | 0.25 ^e |

Estimation of C Stocks

Carbon stocks were calculated using the following equation [9].

$$\text{C stock (t ha}^{-1}\text{)} = \text{C content (\%)} \\ \times \text{bulk density (Mg m}^{-3}\text{)} \times \text{depth (m)} \times 100.$$

Statistical Analysis

The data were analyzed using analysis of variance (ANOVA), on the basis of a completely randomised design with 8 treatments and 3 replicates of each treatment. All comparisons were completed using SAS [60]. The relationships between different SOM fractions and soil nutrients were established through correlation and simple regression analyses.

RESULTS

Status of Soil Nutrient Availability with Different Land Use Types and Sampling Depth Intervals

Significant differences were observed in the availability of macronutrients (N, P, K, Ca, Mg) among the different land use types and between the surface and subsoils (Table 2). Available N ranged from 7.16–29.72 µg g⁻¹ at depths of 0–0.15 m. There was significantly higher available N in A–OF at depths of 0–15 cm. P availability ranged from 4.67–23.67 µg g⁻¹ and was

highest in A–OF at depths of 0–0.15 m. USR exhibited the lowest available surface soil P. Ca availability ranged from 465–3929 µg g⁻¹ and was highest in A–OF. Mg availability ranged from 78.33–312.63 µg g⁻¹. AHG exhibited the highest available Mg, although this was not significantly different from that of A–OF. The availability of K ranged from 10.79–374.15 µg g⁻¹ with AHG containing the highest amounts and USR containing the lowest.

All macronutrients were significantly lower in the subsoil (0.15–0.30 m depth) than in the topsoil (Table 3). Among the subsoil samples, the highest available N (20.03 µg g⁻¹) was observed in A–OFS. Nevertheless, it was not significantly different from that of A–OF (Table 2b). On the other hand, the lowest available N was found in HG. Available K in the subsoil ranged from 7.12 µg g⁻¹ in USR to 339.82 in AHG. P availability was highest in A–OF (22.67 µg g⁻¹) and lowest (3.34 µg g⁻¹) in USR. Available Ca and Mg ranged from 250.47–3808 µg g⁻¹ and 54.97–275.74 µg g⁻¹, respectively, in subsoils.

Levels of available micronutrients (Zn, Fe, Cu, Mn) varied significantly with depth and among land use types (Tables 2 and 3). Available Zn ranged from 0.25–11.15 µg g⁻¹, being highest in A–OF. Available Mn ranged from 7.12–31.61 µg g⁻¹ with AHG and A–OF exhibiting the highest concentrations. Available Fe ranged from 15.38–35.37 µg g⁻¹. A–OF had the highest available Fe. Available Cu varied significantly

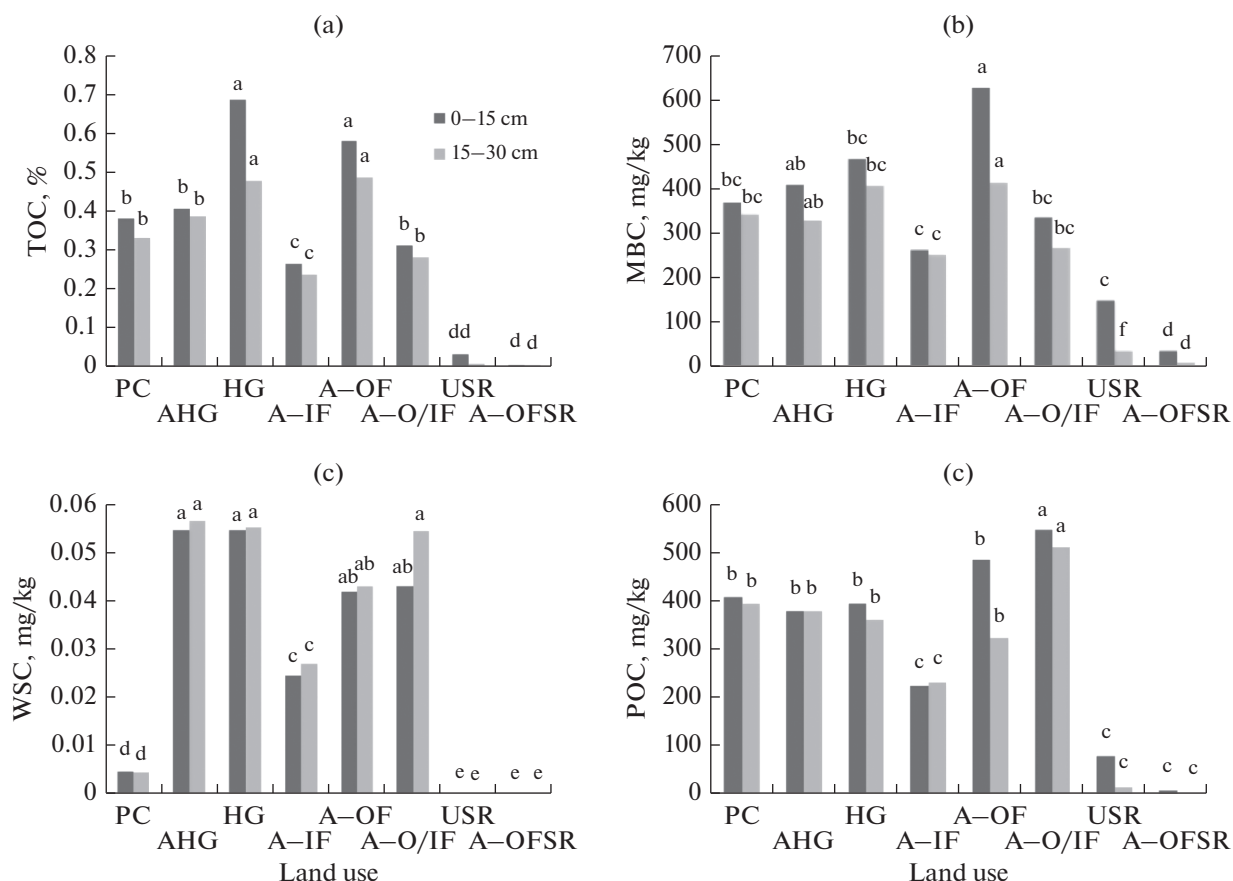


Fig. 1. C fractions levels at selected land uses: total organic C (TOC) variation in different land uses (a), microbial biomass carbon (MBC) variation in different land uses (b), water soluble C (WSC) variation in different land uses (c), KMnO_4 oxidizable carbon (POC) variation in different land uses. Bars with the same letter are not significantly different at $P < 0.05$.

among the land use types but did not vary much with the depth. Available Cu ranged from $0.49\text{--}4.06\ \mu\text{g g}^{-1}$ and was highest in AHG and A-O/IF and lowest in USR.

Distribution of Soil Organic Carbon Fractions Across Land Use Types and Sampling Depth Intervals

AHG showed the highest TOC, although it was not significantly different from that of A-O/IF in both soil layers (Fig. 1a). On the other hand, the lowest TOC was recorded in A-OFS in both layers. However, it was not significantly different from that in USR. The highest MBC was observed in A-O/IF at both depths, although it was not significantly different from that of HG (Fig. 1b). The lowest MBC, at both depths, was found in A-OFS, and the difference was significant. Water-soluble C (WSC) content was relatively high in home gardens (HG, AHG) and A-O/IF, while it had lowest mean values in A-OFS and USR (Fig. 1c). Permanganate oxidizable C (POC) was the highest in A-O/IF at both depth interval and the difference was statistically significant when compared with other land uses types (Fig. 1d). In contrast, the lowest POC was found in A-OFS at both depth intervals, while it was not significantly different from those in USR and A-I/F.

Relationship between Soil Organic Carbon Fractions and Available Nutrients

Except for available N, all of the nutrient elements tested (P, Mg, Ca, K, Zn, Mn, Cu and Fe) showed a significant positive relationship with at least one of the

Table 3. Depth-wise nutrient availability in the study area, $\mu\text{g g soil}^{-1}$

| Available nutrients | 0–15 cm | 15–30 cm | LSD |
|---------------------|---------|----------|-------|
| NH_4^+ | 5.14 | 2.28 | 0.25 |
| NO_3^- | 13.11 | 9.41 | 1.5 |
| K | 171.76 | 145.60 | 17.98 |
| P | 17.11 | 13.22 | 1.65 |
| Ca | 1922 | 1768 | 74.73 |
| Mg | 183 | 120 | 11 |
| Mn | 18.87 | 12.92 | 3.84 |
| Fe | 22.31 | 18.45 | 2.66 |
| Zn | 4.34 | 3.03 | 0.73 |
| Cu | 2.14 | 1.78 | 0.44 |

Difference is significant at 0.05 level.

Table 4. Pearson correlation matrix between Soil C, available nutrients Aggregate stability and clay content

| Parameter | N | P | K | Ca | Mg | Mn | Fe | Zn | Cu | Ag.st | Clay |
|-----------|--------|-----------|-----------|-----------|-----------|----------|----------|-----------|-----------|-----------|----------|
| MBC | 0.174 | 0.619(**) | 0.628(*) | 0.877(**) | 0.606(*) | 0.614(*) | 0.593(*) | 0.771(**) | 0.715(**) | 0.888(**) | 0.356 |
| TOC | 0.083 | 0.504(*) | 0.605(*) | 0.808(**) | 0.521(*) | 0.545(*) | 0.489 | 0.658(**) | 0.656(**) | 0.916(**) | 0.432 |
| POC | -0.047 | 0.409 | 0.424 | 0.787(**) | 0.408 | 0.385 | 0.402 | 0.642(**) | 0.612(*) | 0.860(**) | 0.229 |
| WSC | 0.046 | 0.304 | 0.643(**) | 0.549(*) | 0.408 | 0.413 | 0.538(*) | 0.418 | 0.682(**) | 0.838(**) | 0.429 |
| Ag.st | 0.118 | 0.414 | 0.638(*) | 0.771(**) | 0.559(*) | 0.620(*) | 0.604(*) | 0.664(**) | 0.785(**) | 1 | 0.518(*) |
| clay | -0.053 | 0.129 | 0.744(**) | 0.588(*) | 0.675(**) | 0.352 | 0.254 | 0.334 | 0.754(**) | 0.518(*) | 1 |

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

carbon fractions (Table 4). Available P, K, Ca and Mg exhibited significant positive relationships with MBC and TOC. Available Ca also exhibited a significant positive correlation with POC fractions (Table 4, Fig. 2a). The fitted regression models are presented in Table 5. Though MBC exhibited a linear relationship ($r^2 = 0.76$) with Ca availability, the exponential model exhibited the highest correlation ($r^2 = 0.83$) (Table 5, Fig. 2b). Similarly, with TOC, the exponential model showed a significant positive trend with available Ca that was superior to the linear model (Fig. 2c, Table 5). In addition, K exhibited a highly significant correlation with WSC (Table 4).

Micronutrients exhibited similar trends. For example, Cu exhibited very strong positive relationships with all of the labile fractions and TOC (Table 4). All elemental micronutrients analyzed (Mn, Fe, Cu and Zn) showed significant positive relationships with MBC. Mn, Zn and Cu showed significant positive relationships with TOC. Fe did not show a clear relationship with TOC. However, it showed a strong relationship with WSC (Table 3). Zn was positively correlated with POC. The linear models had higher r^2 values of 0.505, 0.43 and 0.599 for TOC vs. Zn, TOC vs. Cu and MBC vs. Zn, respectively. The exponential models had high r^2 values (0.502, 0.493, 0.518, 0.461 and 0.398) for MBC vs. Mn, WSC vs. Cu, TOC vs. Fe, WSC vs. Fe and MBC vs. Fe, respectively. On the other hand, the power model exhibited the highest r^2 (0.678) for TOC vs. Mn (Table 5).

Dry weight of litter collected showed that AHG accumulated the highest content (97.38 g/m²) compared to the lowest (37.63 g/m²) in A-I/F. A-OF and A-O/IF accumulated litter content of 62.37 and 45.63 g/m² respectively. The average organic C content of the residues returned to soil was estimated as 41.5% of the dry weight.

Soil C Stocks Across Land Use Types

Among the cropping systems included in the study, AHG maintained the highest carbon stocks (31.32 T/ha)

followed by A-OF (25.44 T/ha) (Fig. 3). A-OFS maintained the lowest C stocks (0.26 T/ha).

Aggregate Stability Across Land Use Types and Sampling Depth Intervals and Its Relationship with Soil Carbon Fractions and Nutrient Availability

Aggregate stability varied significantly among land use types and with sampling depth (Fig. 4). The abandoned home garden (AHG) exhibited the highest aggregate stability index (4.11) in the 0–0.15 m layer. However, it was not significantly different from that of HG or A-OF. USR had the lowest stability index value (0.2). Other land use types exhibited stability index values between 2.4 and 3.96 in the 0–0.15 m layer. Aggregate stability was significantly positively correlated with carbon fractions such as MBC, TOC, POC and WSC ($r^2 = 0.888, 0.916, 0.860$ and 0.838 , respectively). The highest correlation was observed with TOC (0.916).

Among the macronutrients, Ca, K and Mg were significantly correlated with aggregate stability. Micronutrient (Zn, Cu, Mn and Fe) availability also showed a significant positive correlation with aggregate stability. K, Mg and Ca availability exhibited highly significant correlations with clay content, while Cu availability also showed a significant correlation with clay content.

Effect of Soil Texture on Aggregate Stability and Nutrient Availability

Soil texture varied with land use type from sandy loam to loamy sand and sand (Table 6). Soils from A-OF, A-IF, A-O/IF, PC and HG had sandy loam texture in both surface and subsurface layers while soils of AHG were loamy sand in both layers. The surface and subsurface of both A-OFS and USR exhibited loamy sand and sand soil textures, respectively.

Although the clay content of soils was positively correlated with TOC, POC, MBC and WSC, the relationships were not statistically significant. However, clay content was significantly correlated with aggre-

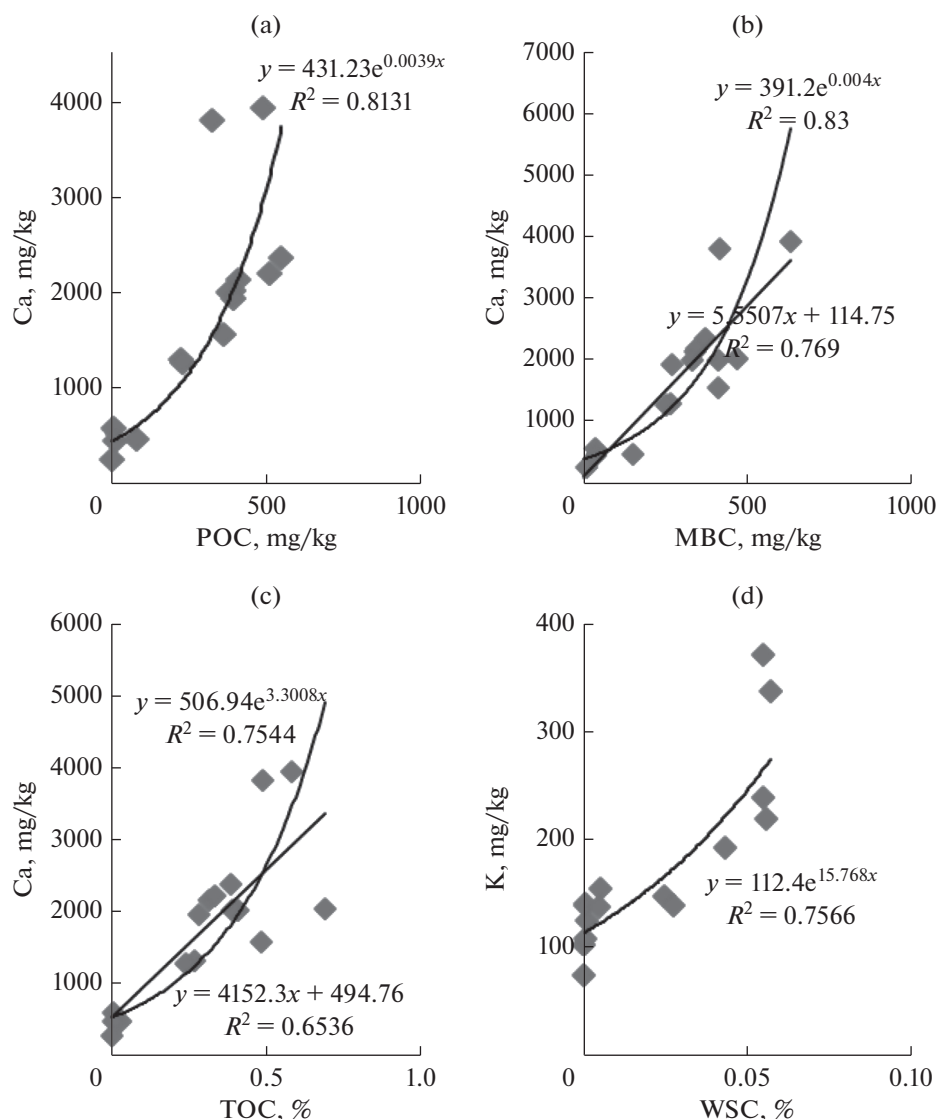


Fig. 2. Correlation between C fractions and nutrient availability: KMnO_4 oxidizable carbon (POC) vs. Ca (a), microbial biomass carbon (MBC) vs. Ca (b), total organic C (TOC) vs. Ca (c), water soluble C (WSC) vs. K (d).

gate stability (Table 4). Clay content was positively correlated with all nutrients tested except N. This relationship was strongly significant for K, Mg and Cu ($p = 0.01$), and significant for Ca ($p = 0.05$). The other nutrients did not show a significant correlation with clay content.

DISCUSSION

Nutrient Dynamics Across Different Land Use Types

Direct nutrient release by organic matter and its nutrient retaining ability has increased the available N content under A–OF and A–O/IF. Increased N content may also be due to the effect of changes in soil microbial dynamics [27]. Annual crops with organic fertilizer inputs in sandy soil (A–OFS) showed the

highest total available N at depths of 0.15–0.30 m, possibly due to the leaching of nitrate to deeper layers. Home gardens (HG) had more soluble carbon as a result of the presence of multiple crops and allowed for better microbial growth as indicated by microbial biomass C. Increased microbial growth could sometimes completely exhaust the N resources in the soil resulting in nitrate depletion [38] as seen by the low N availability in HG.

Continuous application of phosphate fertilizers in soil leads to a build-up of soil P, commensurate with the amount of fertilizer applied annually [7]. Although A–OF had the highest value of P, all land use types in which organic or inorganic P fertilizers had been applied (A–O/IF, A–IF, A–O/IF, A–OFS) also recorded similar values of P. On the other hand, the

Table 5. Regression relation of carbon fractions and nutrients

| Tested relation | Model | r^2 | Tested relation | Model | r^2 |
|-----------------|--------------------------------------|-------|-----------------|--------------------------------------|-------|
| MBC vs. P | Linear $y = 0.084x + 9.786$ | 0.545 | TOC vs. P | Power $y = 42.36x^{0.263}$ | 0.362 |
| MBC vs. Ca | Exponential $y = 386.0e^{0.004x}$ | 0.83 | TOC vs. Ca | Exponential $y = 506.9e^{3.300x}$ | 0.754 |
| | Linear $y = 5.629x + 91.50$ | 0.769 | POC vs. Ca | $y = 431.2e^{0.003x}$ | 0.813 |
| MBC vs. K | Linear $y = 0.404x + 71.26$ | 0.511 | WSC vs. K | $y = 112.4e^{15.76x}$ | 0.756 |
| POC vs. K | Power $y = 9.124x^{0.448}$ | 0.360 | | | |
| MBC vs. Mg | Linear $y = 0.361x + 35.24$ | 0.516 | WSC vs. Mg | Exponential $y = 77.74e^{15.46x}$ | 0.474 |
| MBC vs. Mn | Exponential $y = 8.557e^{0.002x}$ | 0.502 | TOC vs. Mn | Power $y = 10.00e^{1.810x}$ | 0.687 |
| MBC vs. Zn | Linear $y = 0.011x + 0.937$ | 0.599 | TOC vs. Zn | Linear $y = 8.103x + 0.911$ | 0.505 |
| MBC vs. Cu | Exponential $y = 0.704e^{0.003x}$ | 0.639 | TOC vs. Cu | Linear $y = 3.611x + 1.034$ | 0.43 |
| | | | WSC vs. Cu | Exponential $y = 1.021e^{19.38}$ | 0.493 |
| TOC vs. Fe | Exponential $y = 16.01e^{1.324x}$ | 0.518 | MBC vs. Fe | Exponential $y = 16.37e^{0.001x}$ | 0.398 |
| | | | WSC vs. Fe | Exponential $y = 17.90e^{9.756x}$ | 0.461 |
| WSC vs. Ca | $y = 726.1e^{22.22x}$ | 0.44 | | | |

Table 6. Soil texture and pH of different land-uses

| Land uses | Soil texture | | pH | |
|-----------|--------------|------------|---------|----------|
| | 0–15 cm | 15–30 cm | 0–15 cm | 15–30 cm |
| (A–OF) | Sandy loam | Sandy loam | 8.05 | 8.28 |
| (A–IF) | Sandy loam | Sandy loam | 7.60 | 7.80 |
| (A–O/IF) | Sandy loam | Sandy loam | 6.12 | 8.07 |
| (PC) | Sandy loam | Sandy loam | 8.27 | 8.14 |
| (HG) | Sandy loam | Sandy loam | 7.9 | 7.75 |
| (AHG) | Loamy sand | Loamy sand | 7.3 | 7.50 |
| (A–OFS) | Loamy sand | Sand | 5.7 | 5.7 |
| (USR) | Loamy sand | Sand | 7.0 | 7.1 |

land use types in which no fertilizers were added and/or were only subject to natural nutrient cycling such as AHG, HG and USR had relatively low P content compared to other land use types.

High Ca availability was observed in all land use types included in the study. This is because the parent material of the soils in this region is calcareous in

nature [55]. The high availability of Ca^{2+} in A–OF may also be due to the stimulatory effect by high nitrate content in A–OF [51]. Quartzipsamments have inherently low calcium content as shown by the low levels of Ca in USR and A–OFS [55].

High levels of organic matter mineralization and the chelating effect of organic matter on Mg [13] may have

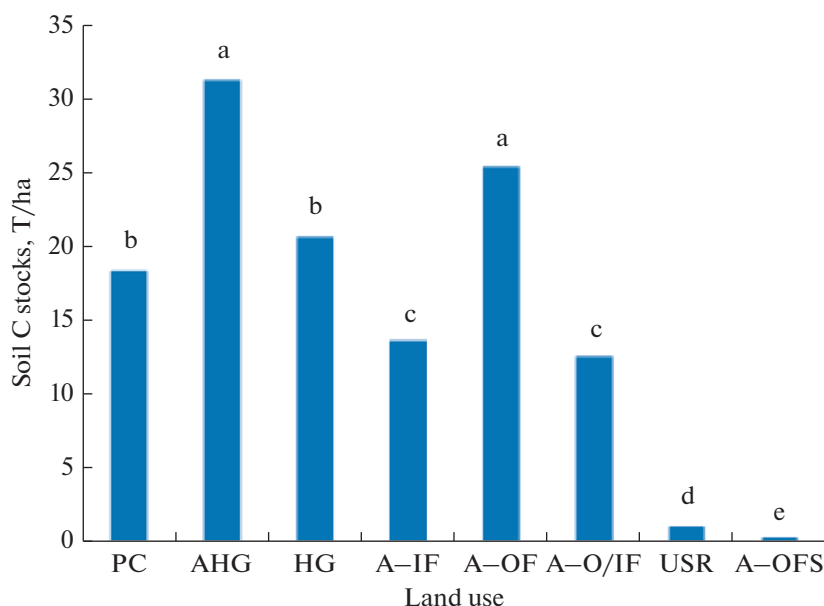


Fig. 3. Soil C stocks maintained by different land uses (T/Ha). Bars with the same letter are not significantly different at $P < 0.05$.

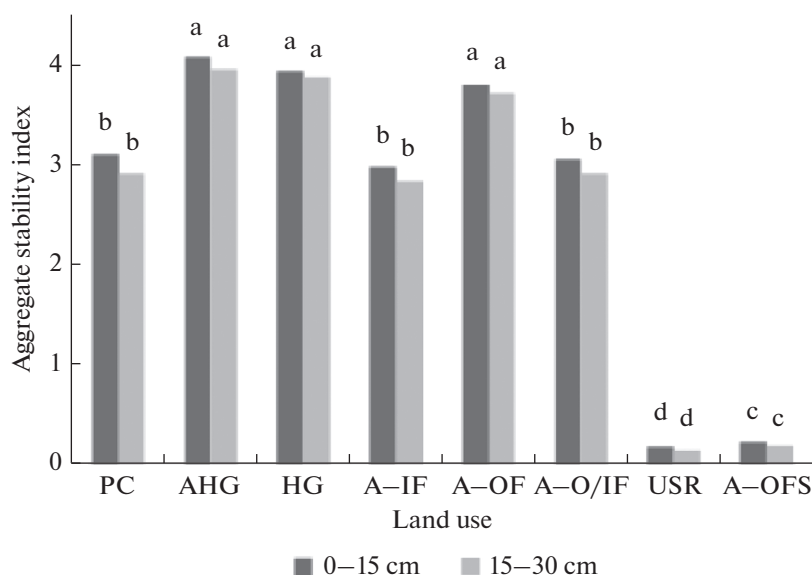


Fig. 4. Soil aggregate stability index of different Land uses. Bars with the same letter are not significantly different at $P < 0.05$.

resulted in the higher availability of Mg in A-OF and AHG. The high concentration of Zn in A-OF could also be due to the same effect. Low availability of Mg and Zn in USR, may be due to the leaching loss and low cation exchange capacity of sandy soils [55, 64]. Relatively high Fe concentration in A-OF and A-O/IF could be due to higher chelation promoted by regular organic manure applications in these land use types [25].

Variation of Soil Organic Carbon Fractions

Our results indicated that the continuous supply of organic fertilizer in A-OF for several years resulted in

the highest SOC and other labile C fractions among the land use types tested. Furthermore, greater decomposition of SOM under mineral fertilizer has lowered SOC and other labile C fractions measured in the A-IF.

Differences in Soil C Stocks

The differences in soil C stocks clearly reflected the differences in litter fall and soil tillage, as indicated by the occurrence of the highest C stocks in AHG [51]. AHG were left abandoned for 25 years and therefore nutrient and C status of soil has improved [53] without

human intervention. Organic matter addition to soil has also increased the C stocks even in annual crops [53]. Similar results were reported based on the experimental data over the last 37 years, relationship between total carbon input and the change of organic carbon stock, stock and rate of change in brown soil presented the following rank: high-levels of organic manures group > low-levels of organic manures group > chemical fertilization group [35].

Organic carbon stocks in sandy soils are highly dynamic and sensitive to management practices that influence decomposition rates, as shown by low C stocks in 2 sandy soil locations [23].

Effect of Soil Texture on Aggregate Stability and Nutrient Availability

No-till management is one of the most efficient practices for sequestering C in croplands. Soil organic C content in AHG has likely been improved by slow decomposition activity and the absence of disturbance. Relatively higher MBC in A–OF indicates that the microbiological activity in agricultural soils is higher under organic fertilizer application relative to the other intense soil management practices. Water-soluble C (WSC) is relatively high in both home garden types (HG/AHG), possibly as a result of the fresh residues returned to the soil, whereas residue returns in annual crop sites were minimal [51].

One study has reported that the use of plowing in seed-bed preparation of annual cropland causes a rapid decline in SOC; approximately 8–15 Mg C ha⁻¹ within 10 years [44]. However, an increase was shown in our study in annual croplands that apply organic fertilizer. These values exceeded the values reported for tropical agroforestry systems by [24], showing that even annual crops were able to fix more C in soils with appropriate management practices. Hence, this study showed that SOC of annual crop lands can be increased through organic fertilizer application compared to all other perennial land uses types. In organic fertilizer application in annual crops improves soil carbon storage only when combined with organic fertilizers.

Relationships between Soil Texture, Aggregate Stability, Carbon Fractions and Available Nutrients

The high value of aggregate stability in AHG suggests that the formation of soil aggregates has been improved in undisturbed conditions and thereby has minimized the potential for rapid oxidation of SOC [36]. Compost additions to soil improve soil structure and lower bulk density by increasing macro aggregation and rhizosphere aggregate stability as shown by the organic additions in the experiments [14].

The amount and quality of plant residues returned to soil influences the improvement of soil structure [6], by adding SOC as shown by the strongly significant cor-

relation between aggregate stability and SOC fractions in our study.

Cropping systems that produce large amounts of biomass and provide quick ground cover conserve soil and maintain better SOC levels over time, as evident from abandoned home gardens [24]. It is well known that adding N fertilizer usually enhances crop production resulting in an increase in C sequestration in soils [1, 24]. However, we noted a decrease in C sequestration with inorganic fertilizer applications, probably due to the presence of a fallow period [24]. Addition of compost or organic manure enhances carbon stock in soils [35] which is also evidenced by higher SOC in organic (A–OF) or organic + inorganic (A–O/IF) land uses.

Organic matter in soil generally increases microbial activity and lowers C/N ratios. Immobilization of N fertilizer is also possible with the addition of labile carbon sources [59], such as organic manure, resulting in a lack of correlation with N and organic C fractions, as observed in our study. The strong correlations between nutrient cations and aggregate stability in our study indicated that nutrient cations have a profound effect on aggregate stability. Chan and Heenan [32] reported that aggregate stability increased with the formation of strong bonding involving Ca²⁺ bridges, as shown by a significant positive correlation. Increased aggregate stability could also be a result of bonds formed with Fe [37].

Correlation between nutrient cations such as Ca and Cu and soluble C fractions could be a result of the chelating effect of organic matter [17]. The complexation of metals with soluble organic matter in the soil influences the solubility and mobility of these metals [33]. As we hypothesized, available P, Mg, Ca, K, Zn, Mn, Cu and Fe showed a positive correlation with carbon fractions because organic matter acts as a source of nutrients as well as improving greater nutrient retention [52]. In addition metal organic complexes could have contributed to enhanced metal ion concentration with increasing SOC in soils [40]. P availability has an indirect effect on aggregate stability by influencing colonization of arbuscular mycorrhizal fungi and thereby increases root biomass and soil aggregation [12]. Available P, K, Ca and Mg exhibited significant positive relationships with MBC and TOC. Similar results of increased available P and K in garden soils with accumulation of SOC was recorded by other workers [65]. Heavy leaching loss of nitrate in the agricultural fields due to intense irrigation and higher ammonia volatilization loss due to high pH (Table 6) has been reported earlier in the study area [50, 58]. These are the possible reasons for poor correlation between available N and SOC fractions.

CONCLUSIONS

Soil organic C and its fractions varied widely among land use types and with sampling depth within each land use type. Availability of macronutrients,

except nitrogen and micronutrients, showed significant positive correlations with either TOC and/or carbon fractions such as POC, MBC and WSC. We found a positive relationship between aggregate stability and carbon fractions. Regression models developed in this study could be used to predict available nutrients by measuring TOC or C fractions in similar land use types. We conclude that enhancing SOC could improve the availability of K, P, Ca, Mg, Fe, Mn, Cu and Zn in soils. In addition, soil structure could also be improved as indicated by the increase in aggregate stability. This study confirmed that tropical agricultural systems including annual crops with organic fertilizers have potential for storing and maintaining SOC and its fractions. The positive correlation observed between available nutrients, aggregate stability and SOC fractions could help to convince farmers to increase carbon stocks in tropical agricultural systems.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Anura Pathirana and Ms. Kumuduni Karunaratne, National Institute of Fundamental Studies, Kandy for assistance in sampling and chemical analysis.

REFERENCES

1. A. Campbell, F. Selles, G. P. Lafond, V. O. Biederbeck, and R. P. Zentner, "Tillage-fertilizer changes: effect on some soil quality attributes under long-term crop rotation in a thin Black Chernozem," *Can. J. Soil Sci.* **81**, 157–165 (2001).
2. A. D. Ghani, M. Dexter, and K. W. Perrott, "Hot water extractable carbon in soils, a sensitive measurement determining impacts of fertilization, grazing and cultivation," *Soil Biol. Biochem.* **35**, 1231–1243 (2003).
3. B. Alexandra and J. Benites, *The Importance of Soil Organic Matter: Key to Drought-resistant Soil and Sustained Food Production*, FAO Soils Bulletin no. 80 (Food and Agriculture Organization, Rome, 2005).
4. B. Govaerts, N. Verhulst, A. Castellanos-Navarrete, K. D. Sayre, J. Dixon, and L. Dendooven, "Conservation agriculture and soil carbon sequestration: between myth and farmer reality," *Crit. Rev. Plant Sci.* **28**, 97–122 (2009).
5. A. Bot and J. Benites, *The Importance of Soil Organic Matter: Key to Drought-resistant Soil and Sustained Food Production* (Food and Agriculture Organization, Rome, 2005).
6. D. A. Martens, "Plant residue biochemistry regulates soil carbon cycling and carbon sequestration," *Soil Biol. Biochem.* **32**, 361–369 (2000).
7. D. K. Benbi and J. S. Brar, "A 25-year record of carbon sequestration and soil properties in intensive agriculture," *Agron. Sustainable Dev.* **29**, 257–265 (2009).
8. D. K. Benbi, K. Bra, A. S. Toor, P. Singh, and H. Singh, "Soil carbon pools under poplar-based agroforestry, rice-wheat, and maize-wheat cropping systems in semi-arid India," *Nutr. Cycl. Agroecosyst.* **92**, 107–118 (2012).
9. D. K. Benbi, K. Brar, A. S. Toor, and P. Singh, "Total and labile pools of soil organic carbon in cultivated and undisturbed soils in northern India," *Geoderma* **237**, 149–158 (2015).
10. D. Murty, M. U. Kirschbaum, R. E. Mcmurtrie, and H. Mcgilvray, "Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature," *Global Change Biol.* **8**, 105–123 (2002).
11. E. D. Vance, P. C. Brookes, and D. S. Jenkinson, "An extraction method for measuring soil microbial biomass carbon," *Soil Biol. Biochem.* **19**, 703–707 (1987).
12. E. Facelli and J. M. Facelli, "Soil phosphorus heterogeneity and mycorrhizal symbiosis regulate plant intra-specific competition and size distribution," *Oecologia* **33**, 54–61 (2002).
13. E. P. Robert, "Organic matter, humus, humate, humic acid, fulvic acid and humin: Their importance in soil fertility and plant health," in *Proceedings of the IEEE Geoscience and Remote Sensing Symposium (IGARSS) 2014* (Quebec City, 2014), pp. 1–5.
14. F. Caravaca, T. Hernandez, C. Garcia, and A. Roldan, "Improvement of rhizosphere aggregate stability of afforested semiarid plant species subjected to mycorrhizal inoculation and compost addition," *Geoderma* **108**, 133–144 (2002).
15. F. R. Moormann and C. R. Panabokke, "A new approach to the identification and classification of the most important soil groups of Ceylon," in *Soils of Ceylon* (Department of Agriculture, Peradeniya, 1961), pp. 33–37.
16. F. S. Watanabe and S. R. Olsen, "Test of an ascorbic acid method for determining phosphorus in water and NaHCO₃ extracts from soil," *Soil Sci. Soc. Am. Proc.* **29**, 677–678 (1965).
17. *Plant Nutrition for Food Security: A Guide for Integrated Nutrient Management*, FAO Fertilizer and Plant Nutrition Bulletin No. 16 (UN Food and Agriculture Organization, Rome, 2006).
18. G. R. Blake and K. H. Hartge, "Bulk density," in *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*, SSSA Book Series 5.1, Ed. by A. Klute (American society of Agronomy, Madison, 1982), pp. 374–390.
19. G. W. Gee and J. W. Bauder, "Particle size analysis," in *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods*, SSSA Book Series 5.1, Ed. by A. Klute (American Society of Agronomy, Madison, 1986), pp. 383–411.
20. H. Shaheen, Y. Saeed, M. K. Abbasi, and A. Khaliq, "Soil carbon stocks along an altitudinal gradient in different land-use categories in Lesser Himalayan foothills of Kashmir," *Eurasian Soil Sci.* **50**, 432–437 (2017).
21. J. A. Baldock and P. N. Nelson, "Soil organic matter," in *Handbook of Soil Science*, Ed. by E. M. Sumner (CRC Press, Boca Raton, FL, 2000), pp. B25–B84.
22. J. A. E. T. Six, E. T. Elliott, and K. Paustian, "Soil macro aggregate turnover and micro aggregate formation: a mechanism for C sequestration under no-tillage agriculture," *Soil Biol. Biochem.* **32**, 2099–2103 (2000).

23. J. C. Carlyle, "Organic carbon in forested sandy soils: properties, processes, and the impact of forest management," *N. Z. J. Sci.* **23**, 390–402 (1993).
24. J. J. Hutchinson, C. A. Campbell, and R. L. Desjardins, "Some perspectives on carbon sequestration in agriculture," *Agric. For. Meteorol.* **142**, 288–302 (2007).
25. J. L. Havlin, J. D. Beaton, S. L. Tisdale, and W. L. Nlson, *Soil Fertility and Fertilizers: An Introduction to Nutrient Management* (Pearson Education, Upper Saddle River, NJ, 2005).
26. J. L. McIntosh, "Bray and Morgan soil test extractants modified for testing acid soils from different parent materials," *J. Agron.* **61**, 259–265 (1969).
27. J. Lehmann, D. Kern, J. German, G. C. Martins, and A. Moreira, "Soil fertility and production potential," in *Amazonian Dark Earths*, Ed. by J. Lehmann, D. Kern, B. Glaser, and W.I. Woods (Springer-Verlag, Dordrecht, 2003), pp. 105–124.
28. J. M. Anderson and J. S. L. Ingram, *Tropical Soil Biology and Fertility: A Handbook of Methods* (CAB International, Wallingford, 1993).
29. J. Wu, "Carbon accumulation in paddy ecosystems in subtropical China: evidence from landscape studies," *Eurasian Soil Sci.* **46**, 579–586 (2011).
30. K. Coleman and D. S. Jenkinson, "RothC-26.3—A model for the turnover of carbon in soil," in *Evaluation of Soil Organic Matter Models* (Springer-Verlag, Berlin, 1996).
31. K. F. Baker, "The determination of organic carbon in soil using a probe-colorimeter," *Lab. Pract.* **25**, 82–83 (1976).
32. K. Y. Chan and D. P. Heenan, "Lime-induced loss of soil organic carbon and effect on aggregate stability," *Soil Sci. Soc. Am. J.* **63**, 1841–1844 (1999).
33. L. Weng, E. J. Temminghoff, S. Lofts, E. Tipping, and W. H. Riemsdijk, "Complexation with dissolved organic matter and solubility control of heavy metals in a sandy soil," *Environ. Sci. Technol.* **36**, 4804–4810 (2002).
34. L. B. Guo and R. M. Gifford, "Soil carbon stocks and land use change: a meta-analysis," *Glob. Change Biol.* **8**, 345–360 (2002).
35. M. Gao, J. Yang, Y. Li, L. Ning, L. Na, H. Yuqian, L. Peiyu, and H. Xiaori, "Characteristics of organic carbon changes in brown Earth under 37-year long-term fertilization," *Eurasian Soil Sci.* **51**, 1172–1180 (2018).
36. M. Kumari, D. Chakraborty, M. K. Gathala, H. Pathak, B. S. Dwivedi, R. K. Tomar, and J. K. Ladha, "Soil aggregation and associated organic carbon fractions as affected by tillage in a rice–wheat rotation in North India," *Soil Sci. Soc. Am. J.* **75**, 560–567 (2011).
37. M. T. Barral, M. Arias, and J. Guerif, "Effects of iron and organic matter on the porosity and structural stability of soil aggregates," *Soil Tillage Res.* **46**, 261–272 (1998).
38. N. C. Brady and R. R. Weil, "Nitrogen and sulfur economy of soils," in *Elements of the Nature and Properties of Soils* (Prentice Hall, Upper Saddle River, NJ, 2002), pp. 584–662.
39. *National Atlas for Sri Lanka*, Survey Department of Sri Lanka (Colombo, 2007).
40. P. A. Shary and D. L. Pinskii, "Statistical evaluation of the relationships between spatial variability in the organic carbon content in gray forest soils, soil density, concentrations of heavy metals, and topography," *Eurasian Soil Sci.* **46**, 1076–1087 (2013).
41. P. M. Soltanpour and A. P. Schwab, "A new soil test for simultaneous extraction of macroand micronutrients in alkaline soils," *Commun. Soil Sci. Plant Anal.* **8**, 195–207 (1977).
42. R. Derpsch and K. Moriya, "Implications of no-tillage versus soil preparation on sustainability of agricultural production," *Adv. Geocol.* **31**, 1179–1186 (1998).
43. R. J. Haynes, "Labile organic matter fractions as central components of the quality of agricultural soils: an overview," *Adv. Agron.* **85**, 221–268 (2005).
44. R. Lal, "Agroforestry systems and soil surface management of a tropical alfisol," *Agr. Syst.* **8**, 1–6 (1989).
45. R. Lal, "Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands," *Land Degrad. Dev.* **17**, 197–209 (2006).
46. R. Lal, "Soil carbon sequestration to mitigate climate change," *Geoderma* **123**, 1–22 (2004).
47. R. Lal, "Soil management and restoration for C sequestration to mitigate the accelerated greenhouse effect," *Prog. Environ. Sci.* **1**, 307–326 (1999).
48. R. Lal and J. P. Bruce, "The potential of world cropland soils to sequester C and mitigate the greenhouse effect," *Environ. Sci. Policy* **2**, 177–185 (1999).
49. R. Leemans, *Land-Use Change and the Terrestrial Carbon Cycle* (International Council of Scientific Unions, Paris, 1999), pp. 24–26.
50. R. Mageswaran and S. Mahalingam, "Nitrate nitrogen content of well water and soil from selected areas in Jaffna peninsula," *J. Natl. Sci. Found. Sri Lanka* **11**, 269–275 (1983).
51. R. R. Ratnayake, B. M. A. C. Perera, R. P. S. K. Rajapaksha, E. M. H. G. S. Ekanayake, R. K. G. K. A. Kumara, and H. M. A. C. Gunaratne, "Soil carbon sequestration and nutrient status of tropical rice based cropping systems: rice-rice, rice-soya, rice-onion and rice tobacco in Sri Lanka," *Catena* **150**, 17–23 (2017).
52. R. R. Ratnayake, G. Seneviratne, and S. A. Kulasooriya, "Effect of soil carbohydrates on nutrient availability in natural forests and cultivated lands in Sri Lanka," *Eurasian Soil Sci.* **46**, 579–586 (2013).
53. R. R. Ratnayake, T. Kugendren, and N. Gnanavelrajah, "Changes in soil carbon stocks under different agricultural management practices in North Sri Lanka," *J. Natl. Sci. Found. Sri Lanka* **42**, 37–44 (2014).
54. R. R. Weil, K. R. Islam, M. A. Stine, L. B. Gruver, and S. E. Samson-Liebig, "Estimating active carbon for soil quality assessment, A simplified method for laboratory and field use," *Am. J. Altern. Agric.* **18**, 1–16 (2003).
55. R.B. Mapa, S. Somasiri, and A. R. Dassanayake, *Soils of the Dry Zone of Sri Lanka*, Special Publication no. 9 (Soil Science Society of Sri Lanka, Peradeniya, 2010).

56. S. B. Karunaratne, T. F. A. Bishop, J. S. Lessels, J. A. Baldock, and I. O. A. Odeh, "A space time observation system for soil organic carbon," *Soil Res.* **53**, 647–661 (2015).
57. S. Lenore, L. E. Clesceri, A. E. Greenberg and R. R. Trussell, *Standard Methods for the Examination of Water and Waste Water* (American Public Health Association, Washington, 1989).
58. S. Nagarajah, B. N. Emerson, V. Abeykoon, and S. Yogalingam, "Water quality of wells in Jaffna and Kilinochchi districts," *Trop. Agric.* **144**, 15–20 (1988).
59. S. P. Sohi, E. Krull, E. Lopez-Capel, and R. Bol, "A review of biochar and its use and function in soil," in *Advances in Agronomy*, Ed. by D. L. Sparks (Elsevier, San Diego, 2010), **Vol. 105**, Chap. 2, pp. 47–82.
60. *Procedures in the SAS/STAT Guide for Personal Computers, Version 6* (SAS Institute Cary, NC, 1999).
61. *Soil Taxonomy*, Agriculture Handbook no. 436 (Soil Conservation Service, US Department of Agriculture, Washington, DC, 1978).
62. W. D. Kemper and R. C. Rosenau, "Aggregate stability and Size distribution," in *Methods of Soil Analysis*, Part 1: *Physical and Mineralogical Methods*, SSSA Book Series 5.1, Ed. by A. Klute (American Society of Agronomy, Madison, 1986), pp. 434–435.
63. W. M. Post and K. C. Kwon, "Soil carbon sequestration and land-use change: processes and potential," *Global Change Biol.* **6**, 317–327 (2000).
64. W. R. Hogg, "The photoproduction of charged pions from deuterium," *Proc. Phys. Soc.* **80**, 729 (1992).
65. W. Burghardt, D. Heintz, and N. Hocke, "Soil fertility characteristics and organic carbon stock in soils of vegetable gardens compared with surrounding arable land at the Center of the Urban and Industrial Area of Ruhr, Germany," *Eurasian Soil Sci.* **51**, 1067–1079 (2018).