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RESEARCH ARTICLE

Impact of different land-use systems on soil aggregate–associated organic carbon and nitrogen in Northeast India

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Abstract

This study investigated the effects of different land-use systems (LUS) and soil management practices (SMP) on soil aggregate stability and the distribution of soil organic carbon (SOC) and nitrogen (N) among aggregate size fractions. The long-term effects of plantation crops (tea and bamboo), horticultural systems (mango and lemon) and conventional agricultural cropping systems (rice–rice, wheat–millets and okra–onion) were evaluated in northeastern India. Soil organic carbon and total nitrogen (TN) were quantified within different aggregate size fractions to assess the influence of LUS and SMP on carbon and nitrogen stabilization. The results showed that uncultivated land exhibited the lowest mean weight diameter (MWD) of aggregates (0.69 mm), while mango land-use recorded the highest value (0.96 mm). Surface soil under tea plantations exhibited the highest TN concentration (1.31 g kg^{-1}), closely followed by mango plantations; both were significantly higher than the concentrations observed in agricultural systems. Across all LUS, macroaggregates were found to hold greater SOC than microaggregates. Notably, tea plantations had the highest SOC levels within microaggregates (13.2 g kg^{-1}), followed by bamboo, highlighting their superior capacity for stabilizing organic carbon. The distribution of total nitrogen within macroaggregates mirrored the pattern observed for SOC. Elevated clay-associated SOC under tree-based systems (tea, mango and bamboo) suggests enhanced long-term carbon stabilization due to the longer residence time of clay-bound organic matter.

Keywords: aggregate fractions; land-use; mean weight diameter; soil organic carbon; water-stable aggregate

Introduction

Soil aggregates represent fundamental structural components of soil, existing in various forms and dimensions. Typically, they are classified by size into macroaggregates (> 0.25 mm) and microaggregates (< 0.25 mm), with further subdivisions based on specific size ranges (1). Organic matter plays a crucial role in the formation and stabilization of these aggregates, serving as a key binding agent. In turn, soil aggregates provide physical protection to organic matter, thereby supporting the retention of carbon and essential nutrients. The distribution and stability of aggregate sizes are widely recognized as indicators of soil physical health, providing insights into the influence of land-use practices and management interventions on soil structure and degradation (2).

Changes in land-use, particularly the transformation of natural forest cover into croplands and plantations in tropical regions, can significantly influence soil carbon dynamics. As a result, soil organic carbon (SOC) content often serves as an indicator of soil ecological functioning and a historical record of land management interventions across both cultivated and uncultivated landscapes (3). According to a previous study, while average SOC levels may not exhibit substantial shifts across broader landscapes, site-specific alterations following forest-to-pasture conversion can be pronounced (4). The stabilization of SOC and total nitrogen (TN) in soil systems occurs through their temporary association with macroaggregates or through more persistent sequestration within microaggregates (5–7). Alterations in land-use significantly impact SOC stocks, playing a key role in determining whether soils function as carbon sinks or sources within the global carbon cycle (8, 9).

Land-uses involving tillage and soil disturbance (as in cultivation) break down soil aggregates and expose organic matter to oxygen, which accelerates microbial decomposition and releases carbon as CO_2. This increases SOC mineralization and lowers overall soil carbon stocks (10). Forest ecosystems are particularly efficient at sequestering carbon, thereby minimizing CO_2 emissions from soil systems (11). When agricultural systems include more biomass—especially from cover crops, perennial crops, or agroforestry mixtures—greater amounts of carbon are fixed from the atmosphere through photosynthesis and transferred to the soil as plant residues, roots and root exudates. These organic inputs are broken down by soil microbes and incorporated into the soil organic matter (SOM) pool, increasing SOC stocks over time (12). Within soil microaggregates, particularly toward the core of silt- and clay-sized aggregates, oxygen availability is substantially limited (13). This restricted oxygen diffusion impedes microbial access to SOM, leading to longer mean residence times for SOM bound within microaggregates and fine particles compared to that within macroaggregates (14, 15). The stabilization of SOC through its incorporation into microaggregates and the silt and clay fractions is recognized as an important pathway for long-term carbon sequestration (16).

Furthermore, the presence of SOC within microaggregates embedded in macroaggregates is considered an early and sensitive indicator of changes in SOC levels resulting from land management interventions (17). Land-use and soil management practices (SMP) play a crucial role in shaping soil properties such as pH, aggregate stability and the distribution of SOC and N across aggregate size classes—factors that serve as essential indicators of soil physico-chemical health. While land-use effects on bulk soil carbon and nitrogen are well studied, information on their stabilization within specific soil aggregate fractions under long-term LUS remains limited, particularly in northeastern India. The objective of this study was to evaluate the long-term effects of contrasting LUS and SMP on soil aggregate stability, soil aggregation and the distribution of aggregate-associated SOC and N across different aggregate size fractions in northeastern India.

Materials and Methods

Soil sampling and processing

The present study was conducted during 2021 and 2022 using soil samples collected from the Horticultural Research Complex (HRC), Nagicherra, Tripura (Latitude: 23.8116° N; Longitude: 91.3284° E). The perennial plantation crops evaluated included bamboo (5 years), tea (30 years), mango (11 years) and lemon (11 years). The agricultural cropping systems comprised rice–rice and wheat–millets (each under 14 years of continuous cultivation) and okra–onion (11 years).

Two sets of triplicate (three replications) undisturbed soil cores were collected from four depth intervals (0–15, 15–30, 30–60 and 60–100 cm) using a soil core sampler with a 5 cm internal diameter. Bulk density (BD) was determined from the first set by calculating the ratio of oven-dried soil mass to core volume. The second set of samples, collected from individual plots, was composited, air-dried and sieved through an 8 mm mesh before being stored in plastic bags at room temperature. These depth-specific samples were subsequently used to assess soil aggregation and total SOC. Soil pH and electrical conductivity (EC) were measured in a 1:2.5 soil–water suspension following previously described methods, using a calibrated pH meter and electrical conductivity meter with appropriate electrodes (18). For SOC analysis, all samples were further sieved through a 0.2 mm mesh and analyzed using a CHN elemental analyzer.

Soil aggregate separation

Aggregate size separation was accomplished using a dry sieving technique based on a previously described method (19). A 100 g subsample of soil aggregates (in duplicate) was placed on the uppermost sieve of a nested sieve set with mesh sizes of 5, 2, 1, 0.50 and 0.25 mm to isolate five distinct size classes: < 0.25 mm, 0.25–0.50 mm, 0.50–1 mm, 1–2 mm and 2–5 mm. The sieve stack was mounted in a bucket attached to a motorized apparatus. Water was added until it reached the base of the top sieve, allowing samples to soak for 3 min. Subsequently, the sieves were vertically oscillated (3 cm stroke length) at a rate of 16 strokes per minute for a total of 10 min. Any floating organic debris was carefully removed and the remaining aggregate fractions were collected, transferred to containers and oven-dried at 65 °C under vacuum conditions for 48 hr. The dry weights of each fraction were recorded.

The collected data were used to calculate water-stable aggregates following a previously described method (20), as well as mean weight diameter (MWD) (21) and geometric mean weight diameter (GMWD) (22). For the analysis of total SOC in both bulk soil and separated aggregate fractions, samples were finely ground to pass through a 0.2 mm sieve. Inorganic carbon was removed prior to analysis and SOC was quantified using a CHN analyzer following standard procedures (23).

Statistical analysis

Soil aggregates were classified into three size groups: macroaggregates (2–5 mm), mesoaggregates (0.25–2 mm) and microaggregates (< 0.25 mm). The proportion of each size class was calculated as a percentage of the total aggregate mass. To evaluate the effects of different land-use and SMP on aggregate distribution, statistical analysis was conducted using one-way analysis of variance (ANOVA) at a significance level of $p \leq 0.05$. The statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS 16.0) and RStudio.

Results and Discussion

Soil pH, electrical conductivity (EC) and bulk density (BD)

Table 1 represents the effect of various LUS on soil pH, which ranged from 4.38–5.64, with no statistically significant differences observed among treatments. Soil properties exhibited pronounced variability with depth across all LUS. Soil pH was highest in uncultivated land (5.64) and lowest under tea plantation systems (4.66), indicating that intensive cultivation and related management practices promote soil acidification. Comparable patterns were observed for soil EC (Table 1), which ranged from 0.30–0.44 dS m^{-1}, confirming non-saline conditions across all treatments.

The reduction in soil pH under vegetative cover corroborates the observations of previous researchers, who attributed similar acidification trends to organic acid inputs and enhanced leaching under vegetation—processes that can modify nutrient dynamics in the soil (24). Consistent with previous findings, these results highlight the significant impact of land-use practices on both the physical and chemical attributes of soil, which are key determinants of soil fertility and productivity (25, 26).

As shown in Table 2, BD exhibited marked differences across land-use types and soil depths, likely reflecting variations in soil compaction, organic matter accumulation and root activity.

Table 1. Effect of land-use systems (LUS) on soil pH (1:2.5) and electrical conductivity (EC) (dS m^{-1})

LUS	pH				EC (dS m^{-1})			
	0–15 cm	**15–30 cm**	**30–60 cm**	**60–100 cm**	**0–15 cm**	**15–30 cm**	**30–60 cm**	**60–100 cm**
Bamboo	5.02^{ab}	4.95^{abc}	4.92^{b}	4.79^{ab}	0.43^{ab}	0.41^{a}	0.42^{a}	0.39^{a}
Tea	4.66^{b}	4.63^{bc}	4.44^{c}	4.43^{b}	0.37^{d}	0.35^{c}	0.31^{d}	0.30^{c}
Mango	4.71^{b}	4.47^{c}	4.44^{c}	4.38^{b}	0.36^{d}	0.35^{c}	0.34^{cd}	0.34^{b}
Lemon	5.01^{ab}	4.97^{abc}	4.88^{bc}	4.82^{ab}	0.36^{d}	0.36^{c}	0.35^{c}	0.34^{b}
Rice–Rice	5.6^{a}	5.28^{ab}	4.82^{bc}	4.78^{ab}	0.39^{c}	0.37^{bc}	0.37^{bc}	0.36^{ab}
Wheat–Millet	5.02^{ab}	4.98^{abc}	4.87^{bc}	4.79^{ab}	0.42^{b}	0.41^{a}	0.41^{a}	0.39^{a}
Okra–Onion	4.97^{ab}	4.8^{bc}	4.47^{c}	4.65^{b}	0.44^{ab}	0.40^{ab}	0.39^{ab}	0.38^{a}
Uncultivated land	5.64^{a}	5.6^{a}	5.42^{a}	5.2^{a}	0.44^{a}	0.42^{a}	0.39^{ab}	0.38^{a}

*Means with different lowercase letters within a soil depth are significantly different at $p \leq 0.05$ according to Tukey's HSD test.

Table 2. Effect of land-use systems (LUS) on soil bulk density (BD) (g cm^{-3})

LUS	BD (g cm^{-3})			
	0–15 cm	**15–30 cm**	**30–60 cm**	**60–100 cm**
Bamboo	1.26^{bcde}	1.28^{bc}	1.47^{a}	1.53^{a}
Tea	1.21^{e}	1.26^{c}	1.48^{a}	1.51^{a}
Mango	1.24^{cde}	1.28^{bc}	1.48^{a}	1.52^{a}
Lemon	1.23^{de}	1.31^{abc}	1.47^{a}	1.51^{a}
Rice-Rice	1.35^{ab}	1.4^{ab}	1.51^{a}	1.53^{a}
Wheat-Millet	1.33^{abcd}	1.38^{abc}	1.5^{a}	1.54^{a}
Okra-Onion	1.34^{abc}	1.38^{abc}	1.5^{a}	1.53^{a}
Uncultivated land	1.38^{a}	1.42^{a}	1.52^{a}	1.55^{a}

* Means within a soil depth followed by different lowercase letters differ significantly at $p \leq 0.05$ (Tukey's HSD test)

Collectively, these results emphasize the critical role of sustainable land management strategies in preserving soil quality and supporting ecosystem functionality. Bulk density exhibited a consistent increase with soil depth across all LUS, with maximum values recorded in the 60–100 cm horizon. In the surface layer (0–15 cm), uncultivated land had the highest BD (1.38 Mg m^{-3}), whereas tea plantations showed the lowest BD (1.21 Mg m^{-3}). Agricultural systems, including rice–rice, wheat–millet and okra–onion rotations, displayed BD values comparable to those of uncultivated soils.

The tea-based system demonstrated an approximate 12 % reduction in BD relative to uncultivated land in the topsoil, likely due to greater organic matter inputs and elevated root activity associated with perennial tea cultivation. These factors enhance soil aggregation and porosity, thereby reducing compaction. In contrast, the elevated BD in uncultivated land may be linked to coarse-textured soil with higher sand content, reduced SOC concentrations, minimal soil disturbance and chronic compaction from grazing, as reported earlier (27, 28). These findings underscore the importance of vegetation type and land management practices in regulating soil physical properties, particularly BD. Given its direct influence on soil aeration, water infiltration and root penetration, understanding BD dynamics is vital for developing sustainable land-use strategies that safeguard soil health and optimize crop productivity.

Soil organic carbon (SOC)

As shown in Table 3, SOC declined progressively with increasing soil depth and was significantly influenced by both land-use type and soil depth strata. Across all examined LUS, SOC ranged from 2.35–17.55 g kg^{-1}. The tea plantation system consistently exhibited the highest SOC at all depths compared to other land-uses. In the surface layer (0–15 cm), SOC content peaked in the tea system (17.5 g kg^{-1}), followed by mango (16.0 g kg^{-1}), lemon (15.0 g kg^{-1}), bamboo (14.3 g kg^{-1}), rice–rice (13.8 g kg^{-1}), wheat–millets (13.1 g kg^{-1}), okra–onion (12.3 g kg^{-1}), with the lowest values observed in the uncultivated system (10.0 g kg^{-1}).

The SOC content in the topsoil (0–15 cm) was markedly higher than in subsoil layers (15–100 cm). The increase in SOC in the surface soil, relative to subsurface layers was quantified as follows: bamboo (47.3 %), tea (47.0 %), mango (49.3 %), lemon (51.6 %), rice–rice (54.4 %) and wheat–millets (52.4 %). Uncultivated land consistently showed the lowest SOC values across all depths, reflecting minimal organic inputs and disturbance. On average, the relative enhancement in SOC content compared to uncultivated soils was greatest in bamboo and tea systems (43 %), followed by mango (37.5 %), lemon (33.3 %), rice–rice (27.5 %), with the lowest increase observed in wheat–millets (23.7 %). The LUS were graded in terms of SOC accumulation as follows: plantation crops > horticultural systems > annual cropping systems (Table 3).

These findings highlight the crucial role of long-term perennial vegetation in promoting SOC sequestration, especially within the surface soil layers. Conversely, sub-humid tropical highland agroecosystems have experienced substantial declines in

Table 3. Effect of land-use systems (LUS) on soil organic carbon (SOC) (g kg^{-1})

LUS	SOC (g kg^{-1})			
	0–15 cm	**15–30 cm**	**30–60 cm**	**60–100 cm**
Bamboo	14.30^{cd}	10.30^{bc}	3.42^{c}	1.86^{cd}
Tea	17.5^{a}	13.40^{a}	4.03^{a}	2.17^{a}
Mango	16.01^{b}	11.40^{b}	3.75^{b}	2.04^{ab}
Lemon	15.02^{bc}	11.05^{bc}	3.59^{bc}	1.92^{bc}
Rice–Rice	13.8^{cd}	10.03^{c}	3.14^{d}	1.69^{d}
Wheat–Millet	13.11^{de}	10.09^{c}	2.97^{de}	1.85^{cd}
Okra–Onion	12.37^{e}	8.56^{d}	2.87^{e}	1.42^{e}
Uncultivated land	10.04^{f}	7.48^{d}	2.54^{f}	1.30^{e}

* Means within a soil depth followed by different lowercase letters differ significantly at $p \leq 0.05$ (Tukey's HSD test)

SOC and TN stocks, largely due to continuous cultivation and the removal of native vegetation (29). In line with earlier results, SOC concentrations consistently decline with increasing soil depth, regardless of vegetation type, soil texture, or clay content (30).

The pronounced depletion of organic carbon in bare and uncultivated lands is attributable to minimal organic inputs, limited vegetation cover and the breakdown of soil aggregates. These conditions, exacerbated by historical land degradation and reduced biological activity, foster an environment that enhances microbial decomposition and accelerates the mineralization of SOM. Over time, these processes contribute to the progressive depletion of the soil carbon pool (31).

The lower SOC concentrations recorded under the okra–onion cropping system likely reflect its high nutrient demand and frequent tillage, both of which are common features of smallholder farming practices (32). In contrast, soils under continuous vegetative cover, such as forests and grasslands, receive substantial organic inputs from litterfall, leading to greater SOC retention (33). Results from this study confirm significantly higher SOC stocks in plantation and horticultural LUS, where sustained carbon inputs from leaf litter and rhizodeposition enhance SOC stabilization. These processes are integral to long-term carbon sequestration in agroforestry and perennial horticultural systems (34).

Total nitrogen (TN) concentration of soil

Total nitrogen concentrations mirrored the trends observed for SOC, with significantly higher values recorded under the tea-based LUS compared to agricultural and horticultural systems. Across the studied land-uses, TN ranged from 0.84–1.46 g kg^{-1} (Table 4). In the surface layer (0–15 cm), mango and lemon orchards exhibited comparable TN levels, with no statistically significant difference between them. Notably, TN concentrations under tea plantations were 25 % and 42 % greater than those recorded in wheat–millet and uncultivated systems respectively. At the 15–30 cm depth, tea continued to maintain the highest TN content (1.21 g kg^{-1}), followed by lemon (1.13 g kg^{-1}) and mango (1.10 g kg^{-1}). In contrast, the wheat–millet, okra–onion and uncultivated plots displayed statistically similar TN levels in this subsurface layer.

At the 15–30 cm depth, TN concentration in the tea LUS was 41 % and 46 % higher than that in okra–onion and uncultivated systems respectively. In the 30–60 cm layer, tea and mango systems exhibited statistically similar TN levels, indicating comparable nutrient retention capacity. At the deepest soil layer (60–100 cm), bamboo, rice–rice, okra–onion and wheat–millet land-uses showed no significant differences and were grouped statistically at par. Earlier studies have reported that elevated soil nitrogen levels are often associated with increased organic matter inputs from litterfall in forested and mixed-tree plantation ecosystems (35). In agreement with this, earlier studies found that SOC and TN associated with sand fractions were generally higher under natural LUS, reflecting the influence of continuous organic matter inputs and minimal disturbance (36). The observed variability in SOC and TN stocks among different land-uses can be further explained by variations in land-use history, such as the duration of establishment, intensity of tillage, frequency of intercultural operations and patterns of fertilizer application, as highlighted by previous reports (37).

Table 4. Effect of land-use systems (LUS) on total nitrogen (TN) (g kg^{-1})

LUS	TN (g kg^{-1})			
	0–15 cm	15–30 cm	30–60 cm	60–100 cm
Bamboo	1.13^{c}	1.04^{c}	0.61^{c}	1.13^{c}
Tea	1.46^{a}	1.21^{a}	0.71^{a}	1.46^{a}
Mango	1.31^{b}	1.1^{bc}	0.68^{ab}	1.31^{b}
Lemon	1.27^{b}	1.13^{ab}	0.64^{bc}	1.27^{b}
Rice–Rice	1.1^{c}	0.91^{d}	0.49^{d}	1.1^{c}
Wheat–Millet	1.09^{c}	0.72^{e}	0.46^{de}	1.09^{c}
Okra–Onion	1.05^{c}	0.71^{e}	0.41^{e}	1.05^{c}
Uncultivated land	0.84^{d}	0.65^{e}	0.34^{f}	0.84^{d}

*Means within a soil depth followed by different lowercase letters differ significantly at $p \leq 0.05$ (Tukey's HSD test)

Soil organic matter (SOM) stability

Proportion of aggregates (%) within 0–15 cm soil depth

At the surface soil layer (0–15 cm), the mango LUS exhibited the highest proportion of large macroaggregates (9.35 %), followed by tea (8.11 %), which was statistically comparable to bamboo (7.55 %) (Fig. 1). The total macroaggregate content was significantly greater under tea (42.6 %) and bamboo (41.9 %) land-uses compared to rice–rice (34 %) and okra–onion (32.6 %) systems. On average, plantation land-uses contained approximately 6.7 % and 17 % higher macroaggregate proportions than horticultural and agricultural systems respectively, in the surface horizon. Similarly, horticultural land-uses exhibited about 12 % greater macroaggregate content than agricultural systems. In contrast to macroaggregates, the proportion of microaggregates was significantly higher in the okra–onion system (45.9 %), which was statistically comparable to the wheat–millet system (44.7 %) and lowest under mango plantations (34.8 %) (Fig. 1). These results indicate that perennial vegetation in plantation systems enhances soil structural stability by promoting macroaggregate formation, whereas intensive annual cropping favours aggregate breakdown and the dominance of finer soil fractions. On average, plantation systems exhibited approximately 15 % lower microaggregate proportions than agricultural systems. The silt + clay fraction was highest in the uncultivated LUS (18.1 %), followed by the rice–rice system (15.5 %), while the lowest values occurred under tea plantations (10.3 %), with an overall range from 10.3–18.1 %. The accumulation of leaf litter on plantation floors contributes to surface mulching, which enhances SOM content and creates favourable microhabitats for soil biota, thereby promoting aggregate formation and stability (38). The greater proportion of macroaggregates observed in plantation or forest systems, compared with cultivated lands, underscores the detrimental effects of frequent tillage on aggregate stability. Furthermore, the continuous input of organic residues and minimal soil disturbance characteristics of perennial systems such as plantations or pastures foster improved soil aggregation and enhance carbon sequestration potential relative to conventionally tilled croplands (39).

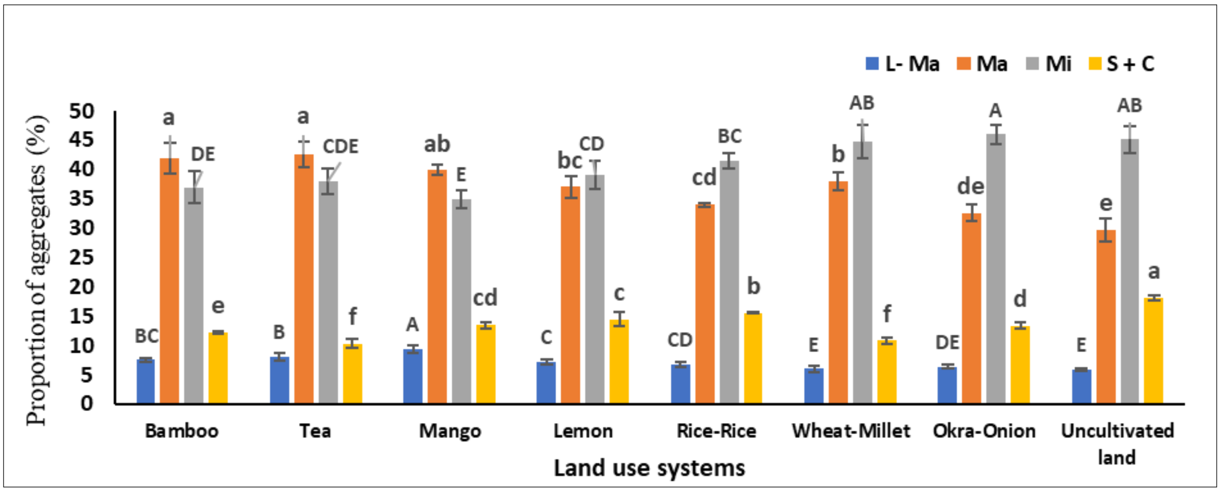

Fig. 1. Effect of land-use systems (LUS) on the proportion of soil aggregates (%) at 0–15 cm soil depth. Vertical bars represent the standard error (± SE). L-Ma - large macroaggregates; Ma- macroaggregates; Mi- microaggregates; S + C- silt + clay.

Mean weight diameter (MWD) and geometric mean diameter (GMD) in upper 0–15 cm soil depth

The mean weight diameter (MWD) of soil aggregates varied significantly among different LUS in the surface soil layer (0–15 cm) (Fig. 2). The highest MWD values were recorded under mango (0.97 mm) and tea (0.94 mm) land-uses, whereas the lowest occurred under the okra–onion system (0.75 mm). Specifically, MWD under mango land-use was 13 %, 19 % and 23 % greater than that observed under lemon, rice–rice and okra–onion systems respectively. Across all land-use types, MWD ranged from 0.70–0.97 mm.

Statistical analysis revealed no significant differences in MWD between the mango and tea systems, nor between the rice–rice and wheat–millet systems. In contrast, geometric mean diameter (GMD) did not differ significantly among the LUS (Fig. 3). The lower MWD values in intensively tilled agricultural systems can be attributed to the disruption of macroaggregates through continuous tillage operations, which compromise soil structural integrity (40). Moreover, the presence and decomposition dynamics of plant residues, along with SOM content, are key determinants of aggregate formation and stabilization (41).

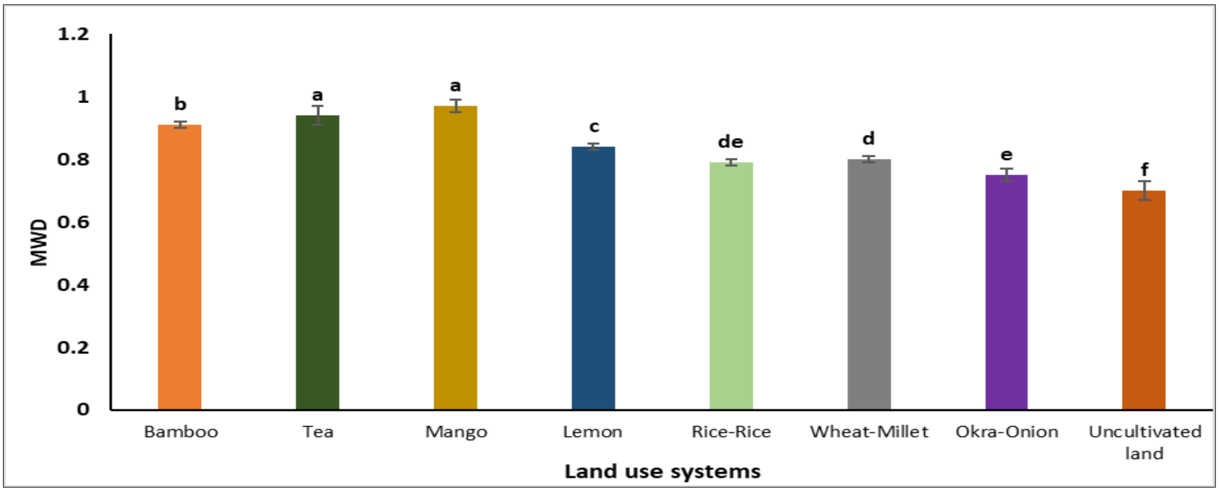

Fig. 2. Effect of land-use systems (LUS) on soil mean weight diameter (MWD).

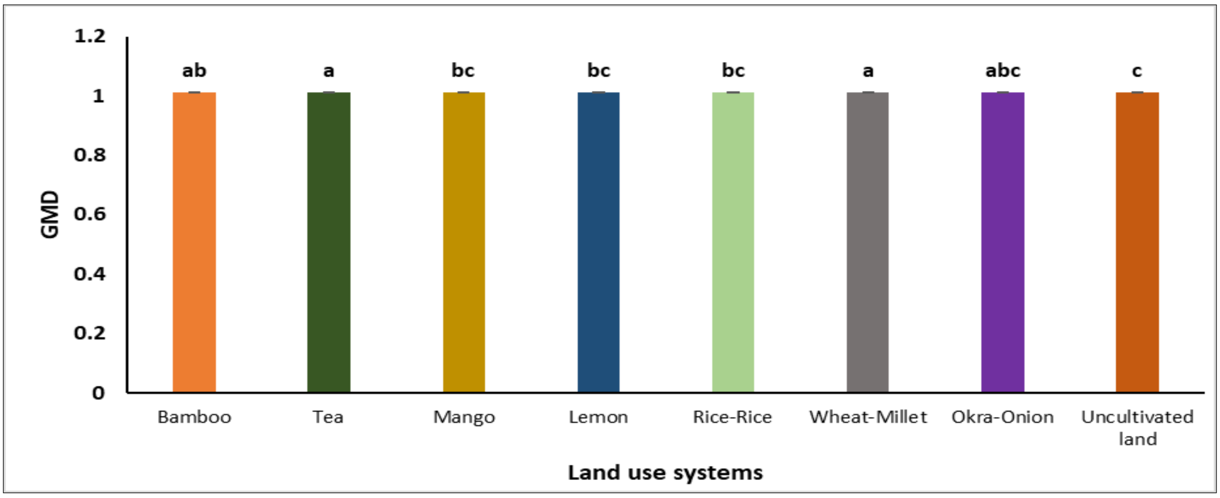

Fig. 3. Effect of land-use systems (LUS) on geometric mean diameter (GMD).

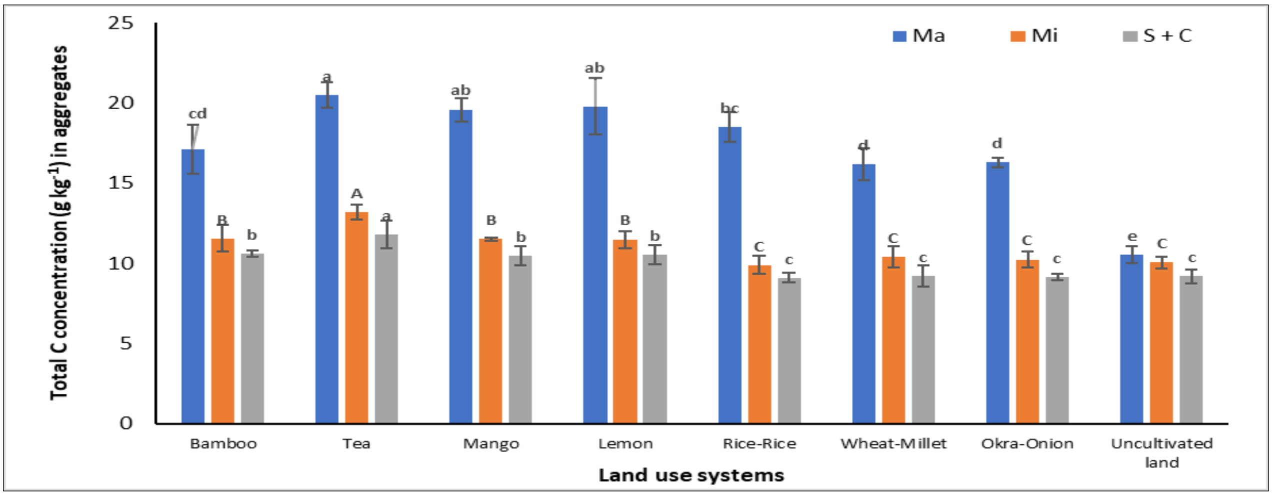

Fig. 4. Effect of land-use systems (LUS) on total carbon concentration (g kg^{-1}) in soil aggregates. Ma- macroaggregates; Mi- microaggregates; S + C- silt + clay.

Total carbon (TC) concentration in macro, micro and silt + clay aggregates

The concentration of TC associated with macroaggregates differed significantly across the various LUS (Fig. 4). The highest TC content was observed under the tea plantation (20.5 g kg^{-1}), which was statistically comparable to the lemon (19.8 g kg^{-1}) and mango (14.5 g kg^{-1}) systems. Across all land-uses, macroaggregate-associated TC ranged from 10.5–20.5 g kg^{-1}, with the lowest values recorded under uncultivated land. Agricultural systems such as wheat–millet (16.2 g kg^{-1}) and okra–onion (16.3 g kg^{-1}) exhibited significantly lower TC concentrations than plantation and horticultural systems. Notably, macroaggregates under tea land-use contained approximately 17 % and 49 % higher carbon than those under agricultural and uncultivated systems respectively. Comparable TC levels under mango and lemon land-uses further emphasize the role of perennial vegetation in enhancing organic carbon accumulation and stabilization within soil macroaggregates.

The concentration of carbon associated with microaggregates varied significantly among the different LUS (Fig. 4). The lowest microaggregate-associated carbon content was observed under agricultural systems (10.18 g kg^{-1}), whereas the highest concentration occurred in soils under tea cultivation (13.2 g kg^{-1}). Microaggregate-associated carbon in lemon (11.5 g kg^{-1}), mango (11.5 g kg^{-1}) and bamboo (10.56 g kg^{-1}) land-uses did not differ significantly, suggesting comparable levels of organic matter stabilization within this fraction. Among the agricultural systems, microaggregate-associated carbon concentrations were statistically similar across the different crop combinations, indicating a limited influence of crop type on carbon stabilization within microaggregates under conventional cultivation practices.

Similarly, the silt + clay fraction exhibited the highest TC concentration under tea land-use (11.8 g kg^{-1}), followed by bamboo (10.61 g kg^{-1}), which was statistically comparable to the lemon and mango systems (both 10.5 g kg^{-1}). In contrast, agricultural systems such as wheat–millet (9.2 g kg^{-1}), rice–rice (9.1 g kg^{-1}) and okra–onion (9.1 g kg^{-1}) showed significantly lower TC concentrations in the silt + clay fraction and were statistically similar to one another. Notably, the tea system exhibited approximately 11 % and 22 % higher silt + clay–associated carbon concentrations compared with horticultural and agricultural systems respectively. The absence of significant differences among bamboo, lemon and mango land-uses further underscores the stabilizing effect of perennial vegetation on soil carbon dynamics within the finer soil fractions. Previous studies have reported that, particularly in deeper soil layers, labile carbon fractions can become chemically stabilized through interactions with silt and clay particles, thereby contributing to the formation of more persistent soil organic carbon pools (42, 43). As noted earlier,

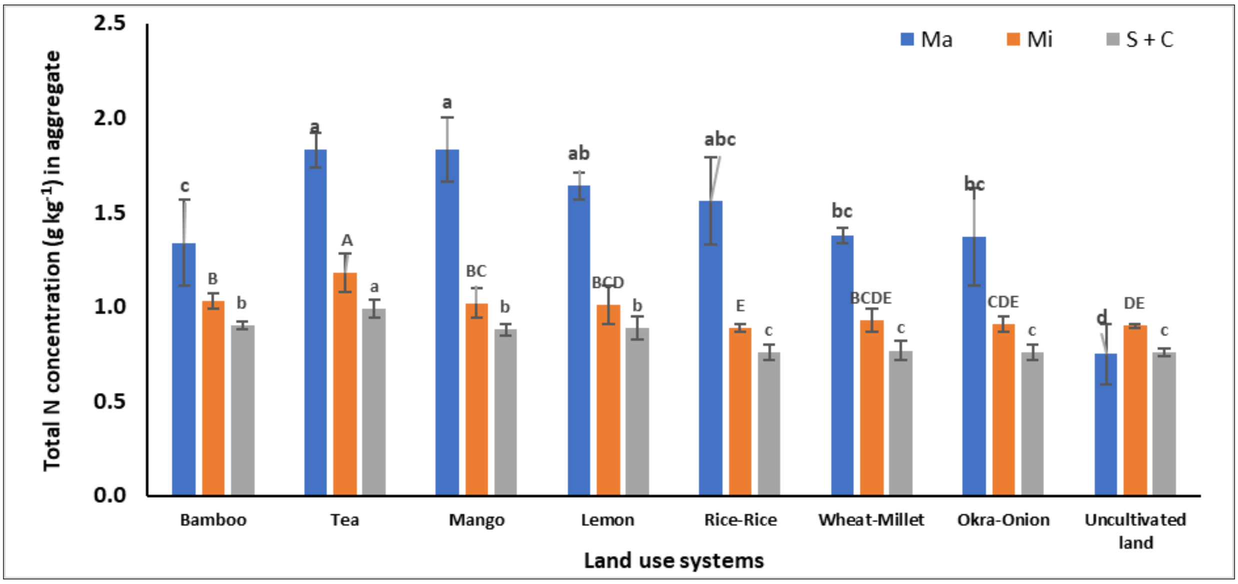

Fig. 5. Effect of land-stems (LUS) on total nitrogen (TN) concentration (g kg^{-1}) in soil aggregates.

macroaggregates typically contain higher concentrations of nutrients compared to microaggregates. Although macroaggregates are relatively less stable, they play a vital role in sustaining soil structure and contributing to short-term carbon sequestration. However, due to their limited biophysical and chemical protection, the carbon contained within macroaggregates is more susceptible to microbial decomposition and subsequent loss than that stabilized within microaggregates (44). In cultivated soils, a greater proportion of SOC is generally associated with microaggregates, whereas forest soils exhibit a higher proportion of SOC within macroaggregates (45).

Total nitrogen (TN) concentration in aggregates

Total nitrogen (TN) concentration within macroaggregates was highest under tea land-use (1.83 g kg^{-1}), which was statistically comparable to mango (1.83 g kg^{-1}) (Fig. 5). Across all LUS, macroaggregate-associated TN ranged from 0.75–1.83 g kg^{-1}, with the lowest concentration recorded in the uncultivated land. Agricultural systems such as wheat–millets (1.38 g kg^{-1}) and okra–onion (1.37 g kg^{-1}) exhibited significantly lower nitrogen concentrations, with no statistically significant difference between them. Compared with bamboo, agricultural and uncultivated systems, macroaggregates under tea cultivation had 22 %, 27 % and 59 % higher TN concentrations respectively. Similarly, macroaggregates under mango and lemon land-uses exhibited statistically similar nitrogen concentrations, suggesting that perennial and horticultural land-uses enhance nitrogen stabilization within aggregate fractions more effectively than annual cropping systems.

Microaggregate-associated nitrogen concentrations varied across LUS, with the lowest value recorded under rice–rice (0.89 g kg^{-1}) and the highest under tea (1.18 g kg^{-1}) (Fig. 5). Nitrogen concentrations in the microaggregates of lemon (1.01 g kg^{-1}), mango (1.02 g kg^{-1}) and bamboo (1.03 g kg^{-1}) land-uses were statistically similar. Among the agricultural LUS, no significant differences were observed in microaggregate-associated N concentrations across the crop combinations.

In the silt + clay fraction, tea land-use exhibited the highest TN concentration (0.99 g kg^{-1}), followed by bamboo (0.90 g kg^{-1}), which was statistically comparable to lemon (0.89 g kg^{-1}) and mango (0.88 g kg^{-1}) (Fig. 5). In contrast, wheat–millet (0.77 g kg^{-1}), rice–rice (0.76 g kg^{-1}) and okra–onion (0.76 g kg^{-1}) systems showed significantly lower N concentrations, with no statistical differences among them. Notably, tea land-use exhibited 11 % and 23 % higher nitrogen content in the silt + clay fraction than horticultural and agricultural systems respectively. However, silt + clay–associated N levels under bamboo, lemon and mango land-uses were statistically at par, reflecting the beneficial impact of perennial vegetation on nitrogen stabilization in finer soil fractions. Perennial and horticultural systems provide continuous root growth and sustained organic inputs, with deep root systems supplying carbon and nitrogen through root exudates and biomass turnover, thereby promoting microbial activity and aggregate stabilization. In contrast, annual crops have shorter growth periods and shallow roots, resulting in lower and less continuous nitrogen inputs for stabilization (46). In rice–rice and okra–onion systems, continuous cropping without rotation leads to high nitrogen removal through harvested biomass and limited residue return, resulting in a decline in soil total nitrogen as losses exceed natural replenishment.

Conclusion

The surface soils under tea and mango land-uses exhibited higher proportions of water-stable aggregates, highlighting the crucial role of litter input and decomposition in aggregate formation and stabilization. Reduced soil disturbance and increased crop residue retention in plantation systems promoted the formation of soil macroaggregates, thereby enhancing the physical protection and stabilization of SOC and TN within the soil matrix. Tea and bamboo land-uses supported greater macroaggregate formation, while intensively tilled agricultural systems such as okra–onion and wheat–millet had higher microaggregate content, likely due to macroaggregate breakdown and loss of associated SOC. Plantation and horticultural orchards (tea, mango and lemon) consistently showed higher SOC and TN concentrations across all aggregate fractions, indicating improved soil C and N dynamics under perennial land-use. Notably, clay-associated SOC was highest in tea, mango and bamboo systems, reflecting enhanced C stabilization due to the longer residence time of clay-bound organic matter. Overall, this study confirms that transitioning from annual cropping to perennial, tree-based systems promote SOC and TN accumulation and stability. These results highlight the potential of perennial and low-disturbance LUS to support long-term soil health and carbon sustainability in agroecosystems.

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Authors' contributions

SY conceptualized the study along with MB and KMM. The methodology was developed by SY and MB. Software support was provided by SK and SM. Validation of the data and methods was carried out by SY, DMM and KMM. Formal analysis was performed by RKY. The investigation was conducted by SY and MB. Resources were provided by MB and KMM. Data curation was undertaken by DMM, S and PS. The original draft of the manuscript was prepared by SY, MB and KMM. Review and editing of the manuscript were carried out by RKY and DMM. Visualization was performed by SY, MB and KMM, while supervision was provided by MB and KMM. All authors have read and agreed to the published version of the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

AI Declaration

No AI tools were used for data analysis, interpretation of results and generation of scientific content.

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