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ORIGINAL PAPER

Structural stability and organic carbon stock of soils under three land use systems from semi-arid area of northern Ethiopia

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Abstract

To monitor soil and land degradation and identify climate-resilient land management practices, it is pertinent to understand land use influences on soil structure and soil organic carbon (SOC). This study was aimed to evaluate land use impacts on aggregate stability and soil organic carbon (SOC) stock to the upper 30 cm depth of shrub land (SL), grass land (GL) and cultivated land (CL) in northern Ethiopia. Dry and wet sieving approaches were applied to fractionate aggregates into coarse macro-aggregates (> 2 mm), meso-aggregates (2–0.25 mm) and micro-aggregates (< 0.25 mm). The size distribution of soil aggregates showed distinct variations across land uses: coarse macro-aggregates were higher in SL soils, meso-aggregates in GL, but micro-aggregates in CL soils. Percent by weight of dry stable aggregates, water stable aggregates, mean weight diameter, geometric mean diameter, aggregation ratio and structural stability index followed the increasing sequence of SL > GL > CL, while aggregate deterioration index displayed the reverse order of SL < GL < CL. Soils in shrub land followed by those in grass land had greater potential to store carbon than soils in cultivated land. The mean SOC stock estimated to top 30 cm depth of the area was 49.06 Mg ha^{-1}. Overall, land use types had plausible influences on structural stability and carbon sequestration potential of soils in the study area. Cultivated lands had poorly structured soils with low SOC stock, thus asking proper management measures.

Keywords Aggregate fractions · Aggregate stability · Dry sieving · Land uses · SOC stock · Wet sieving

Introduction

Soil structure, which is defined as the organization of primary soil particles and organic components into larger units called aggregates (Horn and Smucker 2005), is measured quantitatively by analyzing the stability of aggregates. Aggregate stability influences several biochemical and physical soil processes including porosity (Wang and Hu 2023), water (Boix-Fayos et al. 2001) and nutrient retention (Wang et al. 2019, 2020a, b) and erodibility (Gan et al. 2023). Added to this, aggregate stability controls soils' carbon storage capacity and stability through its influence on shielding (through occluding and organo-mineral complexation) organic molecules against attacks by microbes and enzymes (Yang et al. 2022). The nature and characteristics of pores between aggregates (structural pores), by altering oxygen supply and concentration, closely controls the susceptibility to erosion and decomposition of soil carbon (Liu et al. 2023).

Based on their size and formation processes, soil aggregates can be divided in to micro- (< 250 μm diameter) and macro-aggregates (> 250 μm diameter) (Six and Paustian 2014). Micro-aggregates are formed through binding of flocculated clay and fine silt grains with organic molecules within macro-aggregates (Almagro et al. 2021), whereas macro-aggregates are accumulations of micro-aggregates, minerals and particulate organic carbon loosely held together by sticky networks of fine roots and fungal hyphae (Li et al. 2019). The distribution and amount of micro-aggregates is closely impacted by the concentration of recalcitrant carbon

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pools and hence are responsible to keep the durability of stable soil organic carbon (Liu et al. 2023). Thus, micro-aggregates can be used for diagnosing carbon sequestration efficiency of soil management activities (Pan et al. 2021). On the other hand, the content of macro-aggregates is closely associated with easily-decomposing (labile) carbon pools such as roots and hyphae and the coarse organic carbon. Compared to micro-aggregates, macro-aggregates are more sensitive to anthropogenic (physical) disturbances and their stability is responsible for increasing the residence time of labile carbon fraction and lessening water and wind erosion rates (Nunes et al. 2020). This stresses on the fact that aggregate fractions respond differently against management changes associated with differences in their size and stability.

Soil organic carbon (SOC) strongly determines the quality and ecosystem functions of soils (Lorenz et al. 2019) as it is responsible for biochemical and physical soil fertility. It is critical to maintain aggregate stability (Halder et al. 2022) and water holding capacity (Sekucia et al. 2020), regulate heat and temperature (Cotching 2018), control the size and distribution of soil pores (Lorenz et al. 2019), filter and denature soil pollutants (Adhikari et al. 2019) and is a nutrient reservoir for crops and a food source for soil biota (Rabbi et al. 2018; Dhaliwal et al. 2019). SOC affects aggregate stability through its influence on modifying the bond between mineral particle fractions, amount and concentration of aromatic compounds and polysaccharides, aggregate wetness and mechanical strength. Also, SOC impacts the rate of emissions in carbon dioxide from soil to atmosphere which consequently affects climate change (Altieri and Nicholls 2017). This indicates that the dynamics in SOC concentration in soils are potential to induce carbon dioxide concentration discrepancies within the atmosphere (Lal 2020), making improving the potential to sequester carbon of soils a burning and global issue for improving the overall soil health and curbing the increase in anthropogenic carbon emissions.

In areas with uniform climate, the quantity and quality, fluxes into and out of the soil system and the spatial distribution of SOC, aggregate size and stability responds sensitively to anthropogenic activities explained by land use systems (Okolo et al. 2020). Magnified by their impacts on the quantity and quality of organic carbon inputs (Eze et al. 2023), their distribution and turnover rates (He et al. 2022), flux and availability of water and air (Santos et al. 2021), activity and diversity of biota (Conrado et al. 2023) and soil erosion (Chen et al. 2023), land utilization activities may exert profound impacts on soil aggregation and the stock and sequestration dynamics of soil carbon (Table 1). Apart from this, land use practices have been regarded as among the potential factors contributing substantial (reaching up to 35%) greenhouse gas emissions (Foley et al. 2005). Land use change-induced soil carbon losses can be evident over fast periods of time, whereas decades up to centuries time is needed for its accumulation (Ostle et al. 2009), which underlines the pertinence to carryout frequent investigations on its spatial and temporal distribution which are critical

Table 1 Review of papers on land use influence to soil structural stability and soil organic carbon

Author	Study area	Objectives addressed
Abegaz et al. (2016)	Ethiopian highlands	Spatial and temporal dynamics of SOC in Ethiopian highlands
Wang et al. (2018)	Loess Plateau (China)	Aggregate stability and associated organic carbon and nitrogen as impacted by soil erosion and vegetation rehabilitation
Wang et al. (2019)	western Sichuan (China)	Distribution of SOC, total nitrogen (TN), available phosphorus and exchangeable cations across aggregate fractions with plantation chronosequences
Abebe et al. (2020)	Ethiopian highlands	Effects of land use and topographic position on SOC and TN stocks
Abegaz et al. (2020)	Ethiopian highlands	Land-use change impacts on SOC dynamics
Gessesse et al. (2020)	Northern Ethiopia	Land use type impacts on SOC stocks
Okolo et al. (2020)	Northern Ethiopia	SOC accumulation in various soil aggregate sizes under different land use systems
Li et al. (2020)	Northern China	Response of SOC, N and AP to land-use change and erosion
Redmile-Gordon et al. (2020)		SOC, extracellular polymeric substances, and soil structural stability as affected by previous and current land-use
Cheng et al. (2023)	Loess Plateau (China)	Contribution of soil aggregate particle sizes to organic carbon as influenced by land use
Eze et al. (2023)	Global coverage	Changes in SOC stock following land use change
Okolo et al. (2023)	Northern Ethiopia	Soil organic carbon, total nitrogen stocks and CO_2 emissions in top-and subsoils with contrasting land uses
Wang et al. (2023a)	Loess Plateau (China)	Effects of vegetation restoration on soil aggregates, SOC and TN
Wang et al. (2023b)	Loess Plateau (China)	Variations in soil organic carbon storage and stability with vegetation restoration stages

inputs for prioritizing land uses for management intervention. Stemmed from those facts, there have been upsurge of researches on understanding soil aggregate size and stability and carbon stock responses to changes in land use (Table 1).

Northern Ethiopia has high population size and greater land fragmentation which have led to the predominance of integrated crop-livestock farming practices making cultivated land and grass land and partly open shrub land among the major land use systems. It has been considered as a potential farming area for cereal and livestock production (MoFED (Ministry of Finance and Economic Development) 2003). The area has a semi-arid climate, which reportedly accelerates soil organic matter decomposition (Leirós et al. 1999), and thus leads to reduced SOC storage. On top of this, small holder farmers practicing continuous and low input extensive cultivation, over grazing and deforestation activities are dominant (Okolo et al. 2023), which may have significant implications to increase SOC losses (Tilahun et al. 2022) and induce physical damages including crusting, soil erosion, structural degradation (Tamene and Vlek 2007). Given the greater sensitivity of soil structural stability and SOC to land use/management activities (Redmile-Gordon et al. 2020), understanding land use-induced changes in aggregate size compartments and their stability in such like areas can be paramount to evaluate whether a soil under specific management practice is being degraded or aggraded and thus identify and adopt the best promising land uses. Through investigating the storage capacity of soils to carbon, it is possible to quantify carbon fluxes which will further help to identify climate-resilient land use practices and forecast climate response to carbon flux (Shibabaw et al. 2023). This could in turn assist government policies and decision makers for designing context-specific land use plans and climate change adaptation and mitigation measures. Nevertheless, effects of land use activities on soil structural stability and SOC stock and the contribution of SOC to aggregate stability in northern Ethiopia have got an insufficient attention. Simultaneous use of multiple sieving approaches (particularly dry and wet sieving methods) can help us to advance assessment of land use/management impacts to aggregation and structural stability of soils in arid and semi-arid areas (Franzluebbers 2022). To the best of our knowledge, there is however only one study which evaluated aggregate size distribution and structural stability of soils using both dry and wet sieving approaches in the area (Okolo et al. 2020). For addressing this research gap, this study was aimed: i) to evaluate whether land use type controls aggregate size distribution (using both dry and wet sieving methods) and their stability; ii) to explore the relationship between dry and wet structural stability indices and structural stability indices with SOC; iii) to investigate the dynamics of SOC stock under different land use types; iv) to map the spatial distribution of aggregate and structural stability indices and carbon stock and sequestration rates. Thus, we hypothesized that (1) aggregate size fractions and stability indices would significantly differ with land use type (2) shrub land and grass land soils would have more stable structure relative to those of CL (3) differences in aggregate fractions and stability indices could potentially be attributed to SOC changes, in which coarser aggregates would better be explained by SOC than finer aggregates and (4) soils of cultivated land would sustain less carbon compared to those of grass land and shrub land. Specifically, the study was conducted to address the following questions: (a) how do land use activities (cultivated land, grass land and shrub land) affect structural stability and SOC storage capacity of soils? (b) are soil aggregate fractions and stability indices related to SOC (c) how does SOC stock vary with land use, and (d) how much SOC is stored in top 30 cm depth of the soils under different land uses?

Materials and methods

The study area

The study site (12° 55′–13° 20′N, 39° 20′–39° 55′E) is found in Hintalo Wajerat district of Tigray region, northern Ethiopia (Fig. 1). Altitude varies from 2000 to 3500 m a.s.l., with plateau, plains, hills and mountain terrain. The climate is dry semi-arid with mean precipitation and temperature totals 531 mm and 19 °C respectively. Cultivated land, grass land and shrub land covering 555 Km^2 (57.42% of the total land area), 262 Km^2 (27.08%) and 150 Km^2 (15.49%) respectively are typical land use systems (Fig. 1). Cropping of wheat (*Triticum aestivum* L.), *teff* (*Eragrostis tef* (Zucc.) Trotter), barley (*Hordeum vulgare* L.), maize (*Zea* mays L.), sorghum *(Sorghum bicolor* L.), lentil (*Lens culinaris* L.) and faba bean (*Vicia faba* L.) is prevalent. Much of the crop leftovers are used for animal feed. Livestocks are integral parts of the farming systems. Grass lands located on wetlands and hill sides both communally owned and government protected are used for grazing. *Juniperus procera, Olea africana, Tarchonanthus camphoratus, Maytenus senegalensis, Acacia etbaica and Euclea schimperi* are the dominant shrub stands. The lithology there is dominated by limestone, shale, sandstone, basalt and dolerite (Fig. 1). Moisture and temperature regimes of soil are Ustic and Isohyperthermic respectively. Soils are black (10YR2/1, moist) to yellow (10YR7/6, moist), well-drained (containing granular to blocky-shaped aggregates), dominantly sandy loam, clay loam and clayey in texture, salt-free, calcareous and alkaline, classified as Leptosols, Cambisols, Vertisols, and Calcisols (IUSS working group WRB 2015).

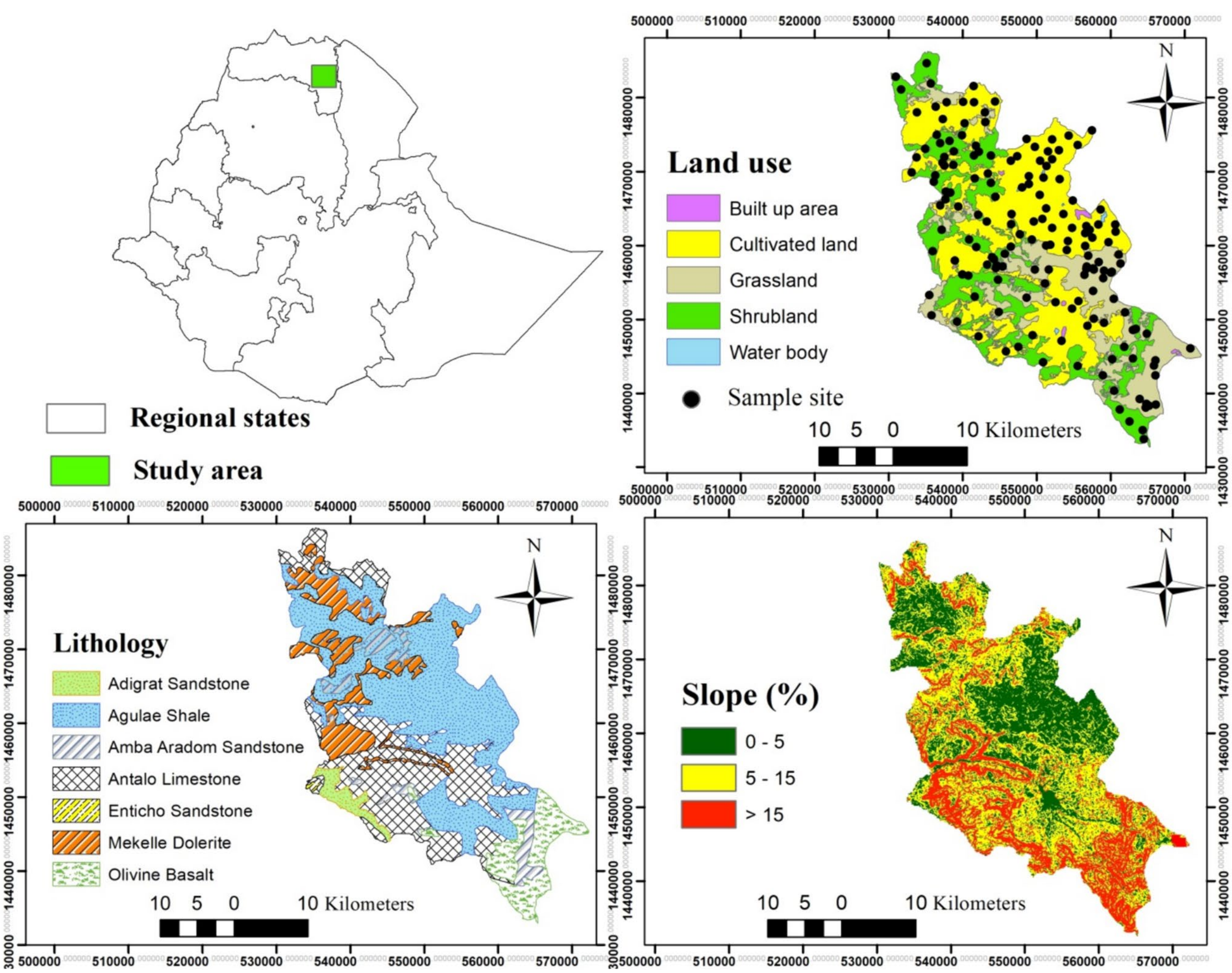

Fig. 1 Location of study area in Ethiopia, land use, lithology and slope maps with spatial distribution of sampling sites

Soil sampling and analysis

Preliminary field survey was carried out with the help of topographic maps for comprehending the biophysical features of the area which in turn serves as a clue for judging location of sampling sites. Soil sampling was made across three land uses (number of samples per land use was guided by the area proportion of land uses and diversities in lithology and geomorphology): (1) cultivated land (CL, n = 97), (2) grass land (GL, n = 44) and shrub land (SL, n = 39). A 0–30 cm depth was considered according to the assumption that the labile carbon fraction which actively responds to management changes is mostly concentrated in top soils. Also, this depth range is considered as a minimum depth-limit for quantifying land use impacts on soil properties (Richter et al. 1999). Samples were gathered from a sampling plot area of 48 m^2 (6 m × 8 m). Five to six samples were bulked to make a composite sample (1 kg weight) within each sampling site. Also, undisturbed samples were gathered using metallic cores for bulk density determination. Soil samples were crushed gently by hand, air-dried, homogenized, purified from undecomposed plant and root materials and coarse fragments and were partitioned into two: one was sieved to fine earth fraction (< 2 mm) for determining soil properties, while the second portion was passed through an 8 mm mesh for aggregate fractionation. Standard procedures were followed for analysis of soil properties. Soil texture was determined by Bouyoucus hydrometer method (Bouyoucos 1962); bulk density (BD) by core method (Black and Hartge 1986); soil pH in 1:2.5 soil-water suspension by pH meter (van Reeuwijk 1993); calcium carbonate by Acid neutralization method (Jackson 1970); soil organic carbon by Walkley–Black oxidation method (Walkley and Black 1934).

Aggregate fractionation

Soil subsamples collected from each land use type were air-dried for aggregate analysis. Separate sub-samples were prepared from composite samples for aggregate size fractionation of both dry and wet sieving techniques. Air-dried soil samples were broken gently by hand along planes of natural weakness and were passed through an 8 mm mesh to exclude stones and plant materials. For dry aggregate separation, the sieved sample (100 g weight) was spread on a set of five sieves (with 4.75, 2, 1, 0.5 and 0.25 mm openings) and was subjected to shaking using electromagnetic sieve-shaker for two minutes. The soil material partitioned to each sieve was weighed to calculate aggregate proportions of > 2, 2–1, 1–0.5, 0.5–0.25 and < 0.25 mm size ranges. Wet aggregate size fractionation was determined following Cambardella and Elliott (1993) methodology. A 100 g air-dried soil was soaked for 10 min to remove aggregate-entrapped air. Moist soil samples were immersed in water on a stack of sieve sizes used for dry aggregate separation and sieved mechanically by oscillating the sieve stack 3 cm up and down 50 times over 2 min period. Water-floating materials were subjected to dredging and discarding. Aggregates left on each sieve were transferred into pre-weighed beakers, oven-dried for 72 h and weighed to calculate mass of stable aggregates. Finally, Eqs. (1) to (4) were applied to calculate the percent stable aggregates, mean weight diameter and geometric mean diameter in both dry and wet conditions (Oades and Waters 1991; Cambardella and Elliott 1993).

$$\text{DSA}\ (\%) = \left(\frac{\text{Mass of dry aggregates on each sieve size}}{\text{Tatal mass of aggregates}}\right) \text{x } 100 \tag{1}$$

$$\text{WSA}\ (\%) = \left(\frac{(\text{Weight of resistant aggregates} + \text{sand}) - (\text{Weight of sand})}{(\text{Total weight of sieved sample} - \text{Weight of sand})}\right) \text{x } 100 \tag{2}$$

$$\text{dMWD or wMWD (mm)} = \sum_{i=1}^{n} \text{XiWi} \tag{3}$$

$$\text{dGMD or wGMD (mm)} = \exp\left(\sum_{i=1}^{n} \text{WilogXi}\right) \tag{4}$$

where, DSA is dry stable aggregates, WSA is water stable aggregates, dMWD is dry mean weight diameter, wMWD is wet mean weight diameter, dGMD is dry geometric mean diameter, wMWD is wet geometric mean diameter, i = 1 to n, n represents to number of sieves, Xi is aggregate mean diameter (mm) of the ith size class, and Wi is proportional weight of aggregate class retained on ith sieve size relative to the total weight.

The weighed aggregates were clustered into: (i) > 2 mm (coarse macro-aggregates) (ii) 2–0.25 mm (meso-aggregates) and (iii) < 0.25 mm (micro-aggregates) (Kurmi et al. 2020).

For estimating aggregate ratio (AR), Eq. (5) was employed and Eq. (6) was applied to determine aggregate deterioration index (ADI) (Oades and Waters 1991):

$$\text{AR} = \left(\frac{\%\ \text{Water stable aggregates} > 0.25\ \text{mm}}{\%\ \text{Water stable aggregates} < 0.25\ \text{mm}}\right) \tag{5}$$

$$\text{ADI} = \left(\frac{(\text{Dry stable macroaggregates}\ (> 0.25\ \text{mm}) - \text{Water stable macroaggregates}\ (> 0.25\ \text{mm}))}{\text{Dry stable macroaggregates}\ (> 0.25\ \text{mm})}\right) \tag{6}$$

Soil structural stability index (SSI), a criteria used for evaluating degradation status of soil and efficiency of SOC and textural fractions for structural stability assessment, was calculated using Eq. (7) (Reynolds et al. 2009):

$$\text{SSI} = \left(\frac{1.724\text{SOC}}{\text{Silt} + \text{Clay}}\right) \tag{7}$$

A SSI value ≤ 5 represents a structurally degraded soil with sever SOC loss, 5 < SSI < 7 represents to soils with high risk of structural degradation, 7 < SSI < 9 indicates soils with low risk of structural degradation and a SSI > 9 represents stable structural stability (Reynolds et al. 2009).

SOC stock measurement

Coarse fraction (cf) content was quantified during soil sample preparation after gentle crushing and grinding, air-drying and sieving (by 2 mm sieve). The coarse fractions left on the 2 mm sieve were weighed separately for individual sample and its fractional weight (%) was calculated via Eq. (8) (Zhang et al. 2008).

$$\text{cf}\ (\%) = \left(\frac{\text{Weight of fraction} > 2\ \text{mm}}{\text{Total weight}}\right) \text{x } 100 \tag{8}$$

Thus, SOC stock (Mg ha^{-1}) for a specified depth was calculated by considering the soil organic carbon (SOC), bulk density (BD) and cf values (Eq. 9):

$$\text{SOC stock (Mg ha}^{-1}) = \left(\frac{\text{SOC}\ (\%)}{100}\right) \text{x BD (Mg m}^{-3}) \text{ x d (m) x } \left(1 - \frac{\text{cf}\ (\%)}{100}\right) \text{x } 10^4\ (\text{M}^2\ \text{ha}^{-1}) \tag{9}$$

where, d stands for depth of soil layer which is 30 cm in our case and 10^4 is unit conversion factor from hectare to M^2. To determine the total storage potential to organic carbon of each land use, SOC stock was multiplied by area of respective land uses. In addition, SOC stock was multiplied by 3.67 (ratio of molecular mass of carbon dioxide/atomic mass of carbon) to quantify the carbon sequestration rate (Mg ha^{-1}) (Penman et al. 2003).

Statistical analysis

A one-way analysis of variance was performed to examine the overall differences in physicochemical properties, aggregate fractions and stability indices and SOC stock attributable to changes in land use. The means for land use types were separated using the least significant difference (LSD) test. The level of statistical significance was set at $p = 0.05$. To explore correlations between measured aggregate stability indices and SOC, Pearson's correlation coefficient and linear regression equations were generated. Redundancy analysis was adopted to characterize soil structural attributes related to land use variation. Statistical analyses were performed using SPSS 26.0 for windows package and PAST analysis package. Mapping of SOC stock and sequestration rate, MWD and SSI was carried out using kriging interpolation approach in ArcGIS10.4.

Results and discussion

Basic soil characteristics

The basic soil properties of the three land use types are presented in Table 2. Land use type did not bring notable effects on coarse fraction (cf) content ($p = 0.86$), although its value was slightly greater for CL than that for GL and SL. The sand, silt and clay fractions in CL differed significantly from those in GL and SL, while they exhibited non-significant variations between GL and SL. Sand content increased by 77.1% in GL and 72.7% in SL, while silt decreased by 24.6% in GL and 28.7% in SL relative to CL. Soils in CL were with the highest clay fraction followed by those in SL and GL respectively. The BD for CL soils was significantly lower than those for SL and GL (10% smaller than that for SL and GL), but values between SL and GL were statistically at par. Soils of the three land uses were alkaline and calcareous, with mean pH and calcium carbonate ($CaCO_3$) contents of soils in CL being significantly exceeding those in GL and SL, though measurements between the later two did not differ significantly. The SOC content was highest in SL followed by GL, while it was lowest in CL (variation significant).

Land use influences on aggregate size distribution and stability

Influences of land use variation on distribution of aggregate fraction

Under dry sieving analysis, the differences in mass distribution by percent of aggregate size fractions across the land uses prevailing in the area were significant (Fig. 2). When comparing the three land uses, there was 5 times and 11 times increase in percent of coarse macro-aggregates (> 2 mm) in SL relative to GL and CL respectively. The percentage of meso-aggregates (2–0.25 mm) was highest in GL with the lowest being in CL. Micro-aggregates were higher in CL (26.29 ± 0.88%) (mean ± standard error) than in GL (13.86 ± 0.85%) and SL (14.60 ± 0.88) (variation significant), with no significant change between GL and SL. The percent by weight of dry stable aggregates (DSA) was highest in SL (92.25 ± 0.81%) followed by GL (74.3 ± 1.80%), being CL (54.67 ± 1.26%) with the lowest (variation significant). Results from wet sieving analysis also showed distinct variations of land use systems related to mass of coarse macro-aggregates by percent ($p < 0.0001$), being higher in SL soils than those on GL (2.4-fold lower) and CL (11.6-fold lower) (Fig. 3). On the other hand, the fraction by mass of meso-aggregates under wet condition were significantly highest for GL soils (40.62 ± 1.59%), followed by those for SL (34.43 ± 1.59%) and CL (21.39 ± 0.79%) ($p < 0.0001$). At the expense of coarse- and meso-aggregates, micro-aggregates were observed to increase in CL soils relative to those in SL and GL. Micro-aggregates were 44% and 34% higher in CL than in GL and SL respectively. The mass proportion of water stable aggregates (WSA) significantly increased from CL (43.89 ± 1.14%) to GL (68.45 ± 1.95%) to SL (88.38 ± 0.94%) ($p < 0.0001$).

Influences of land use variation on aggregate stability indices

The MWD and GMD records determined by dry and wet stability analysis methods are presented in Fig. 4. The distributions in dry mean weight diameter (dMWD) and geometric mean diameter (dGMD) were significantly

Table 2 General physicochemical characteristics of soils for cultivated land (CL), grass land (GL) and shrub land (SL)

LU	cf (%)	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density	pH-H_2O	$CaCO_3$ (%)	SOC (%)
CL	13.98 (0.10)a	32.51 (2.22)b	31.07 (1.10)b	36.52 (1.93)a	Clay loam	1.23 (0.02)b	7.73 (0.12)a	14.97 (1.25)a	0.380 (0.05)c
GL	13.42 (0.84)a	57.57 (3.59)a	23.43 (1.78)a	19.00 (3.13)b	Sandy loam	1.37 (0.03)a	6.79 (0.19)b	7.91 (2.02)b	1.78 (0.08)b
SL	13.10 (1.14)a	56.14 (4.05)a	22.14 (2.01)a	21.72 (3.54)b	Sandy clay loam	1.37 (0.03)a	6.74 (0.21)b	5.96 (2.29)b	4.38 (0.09)a

Parenthesis indicate standard errors. Values with the same lowercase letters within columns (land uses) are not significantly different at $p < 0.05$

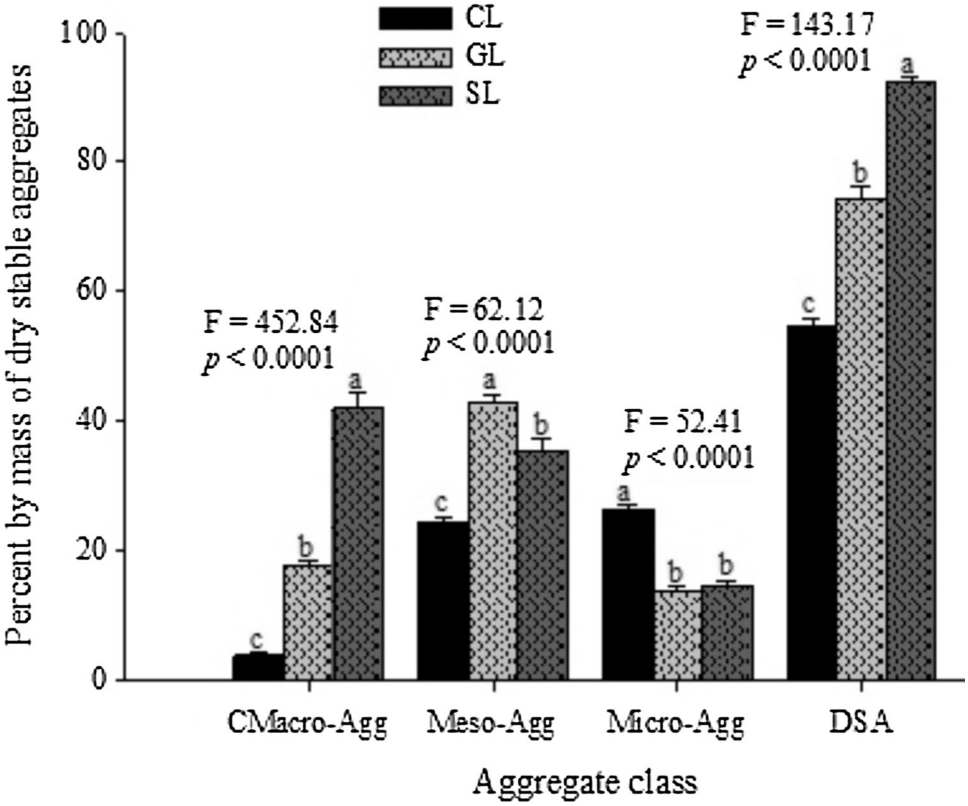

Fig. 2 Mass distribution by percent of dry stable aggregates as influenced by land use type. The bars represent standard errors. F and p values represent to the results of ANOVA test. *CMacro-Agg* coarse macro-aggregates; *Meso-agg* meso-aggregates; *Micro-agg* micro-aggregates; *DSA* dry stable aggregates; *CL* cultivated land; *GL* grass land; *SL* shrub land

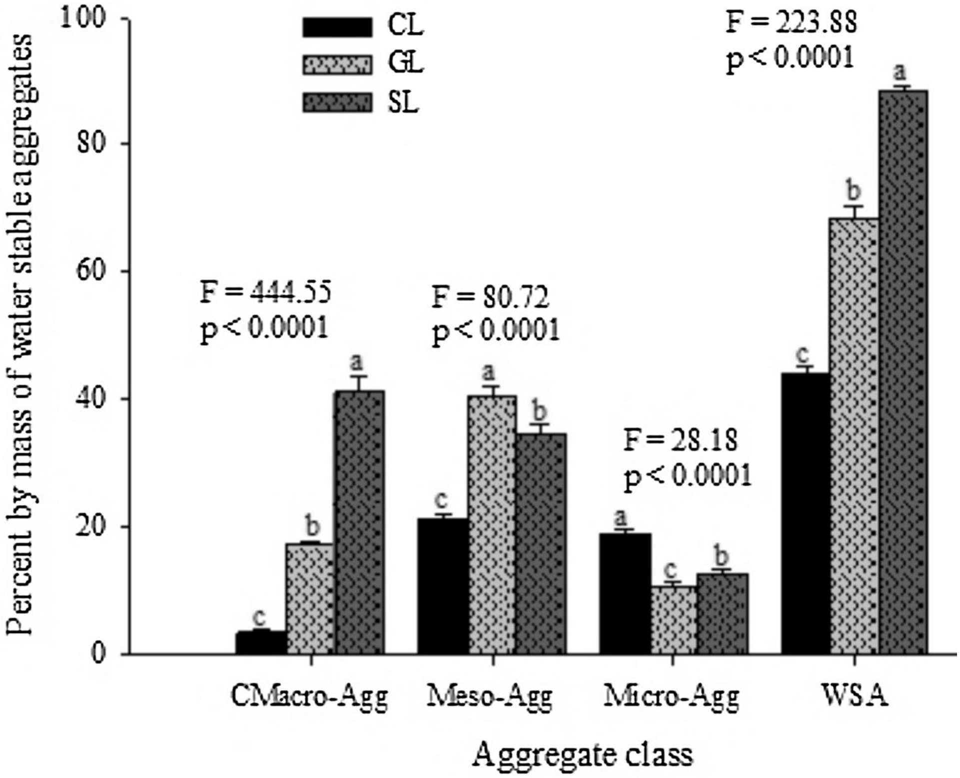

Fig. 3 Mass distribution by percent of water stable aggregates as influenced by land use type. The bars represent standard errors. F and p values represent to the results of ANOVA test. See Fig. 2 for other abbreviations

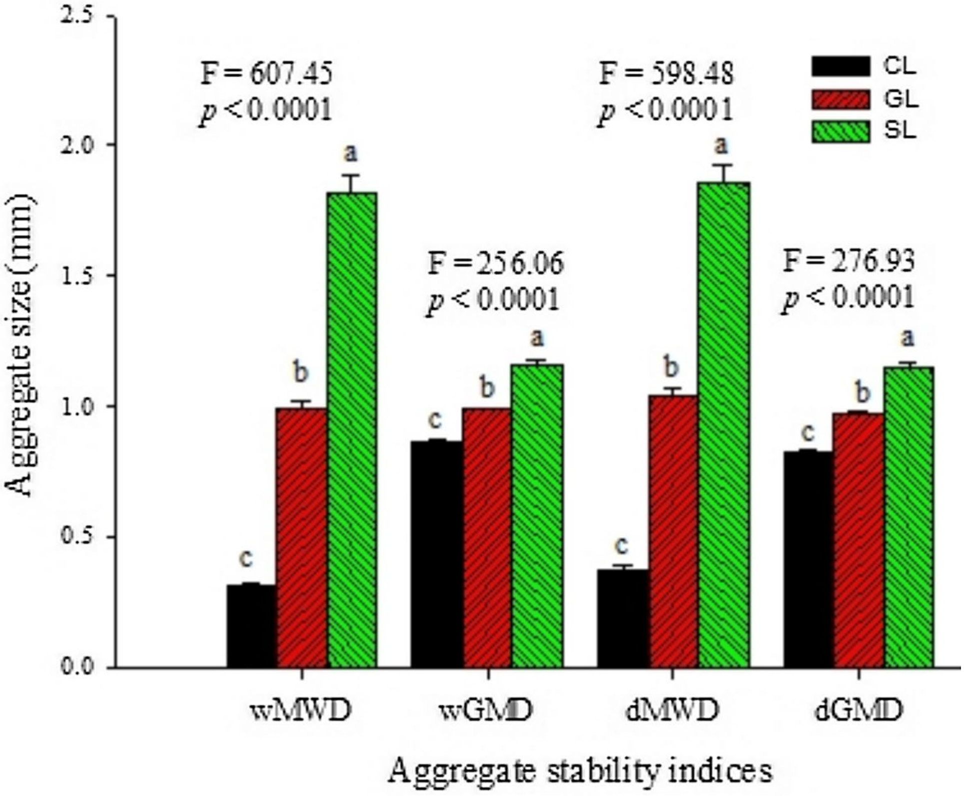

Fig. 4 Mean weight diameter and geometric mean diameter of dry (dWMD and dGMD) and water (wMWD and wGMD) stable aggregates across different land uses. The bars represent standard errors. F and *p* values represent to the results of ANOVA test. *CL* cultivated land; *GL* grass land; *SL* shrub land

differentiated by land use ($p < 0.0001$). On average, dMWD was lowest in CL (0.37 ± 0.02) mm, compared to its respective values in GL (1.04 ± 0.03 mm) and SL (1.86 ± 0.07 mm). Mean dGMD values increased from 0.83 ± 0.005 mm to 1.15 ± 0.02 mm and followed the sequence SL > GL > CL. Significantly more wet mean weight diameter (wMWD) and geometric mean diameter (wGMD) were corresponded to SL relative to GL and CL ($p < 0.0001$). Soils in CL contained 3.1 to 5.69 and 1.13 to 1.3 times lower wMWD and wGMD over those in GL and SL respectively. The aggregation ratio under CL was significantly different from that for GL and SL, whereas its difference between GL and SL was not statistically apparent (Table 3). Its values ranged between 1.59 ± 0.10% (CL) and 11.88 ± 5.45% (SL) which indicates the predominance of large-sized aggregates (coarse + meso-aggregates, > 0.25 mm diameter) accounting for more than 65% of the total aggregated masses of soil. In terms of macro-aggregate concentration, CL and GL soils demonstrated higher percentage of meso-aggregate than coarse macro-aggregates, while the reverse was true for those of SL. The variation in aggregate deterioration index (ADI) was statistically perceptible, which displayed an ascending order of SL < GL < CL (an opposite trend to aggregation ratio). The ADI value measured in CL soils was 2.3 and 4.8 times that in GL and SL soils respectively. Variations in structural stability index (SSI) were highly explained by differences in land use, with soils in SL appeared to show significant increases over those in GL and CL (22.6 and 2.4 times greater when compared to CL and GL respectively).

Table 3 Land use impacts on aggregation ratio, aggregate deterioration index (ADI) and structural stability index

Land use	Aggregation ratio	ADI (%)	Structural stability index (%)
CL	1.59 (0.10)b	11.27 (1.02)a	1.01 (0.01)c
GL	7.41 (1.53)a	4.85 (0.66)b	9.4 (0.01)b
SL	11.88 (5.45)a	2.36 (0.27)c	22.8 (0.01)a
F-value	7.92	18.02	118.58
p-value	0.001	< 0.0001	< 0.0001

Results are shown as mean (SE). Values with the same lowercase letters within columns (land uses) are not significantly different at $p < 0.05$

Correlation among structural stability indices and other soil properties

Pearson's correlation and linear regression analysis between dry and wet aggregate stability indices and

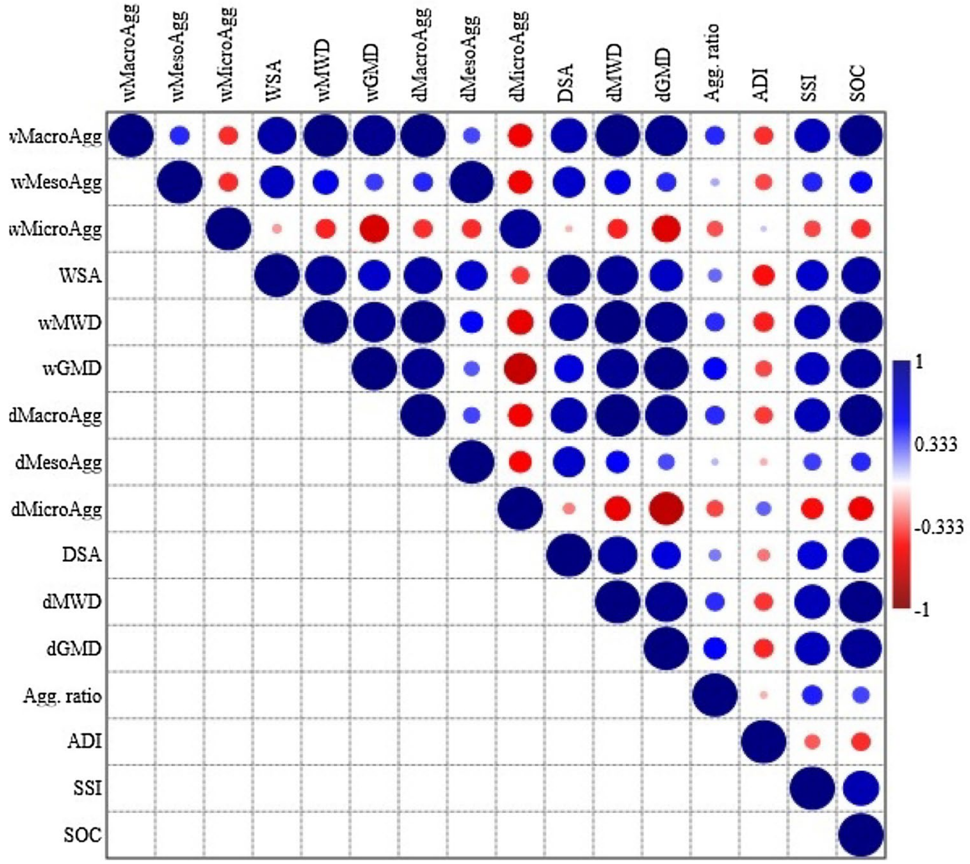

Fig. 5 Pearson's correlation coefficients between aggregate stability indices. *wMacroAgg* wet coarse macro-aggregates; *wMesoAgg* wet meso-aggregates; *wMicroAgg* wet micro-aggregates; *WSA* water stable aggregates; *wMWD* wet mean weight diameter; *wGMD* wet geometric mean diameter; *dMacroAgg* dry coarse macro-aggregates; *dMesoAgg* dry meso-aggregates; *dMicroagg* dry micro-aggregates; *DSA* dry stable aggregates; *dMWD* dry mean weight diameter; *dGMD* dry geometric mean diameter; *Agg.ratio* aggregation ratio; *ADI* aggregate deterioration index; *SSI* structural stability index; *SOC* soil organic carbon

Table 4 Results of linear regression between dry and wet aggregate stability indices and soil organic carbon (SOC)

Equation[a]	R^2	r	*p*
dCMacro-Agg = 1.01 (wCMacro-Agg) + 0.38	0.998	0.99	< 0.001
dMeso-Agg = 0.97 (wMeso-Agg) + 3.31	0.95	0.98	< 0.001
dMicro-Agg = 1.18 (wMicro-Agg) + 2.54	0.82	0.91	< 0.001
DSA = 0.86 (WSA) + 16.52	0.92	0.96	< 0.001
dMWD = 0.99 (wMWD) + 0.05	0.996	0.998	< 0.001
dGMD = 1.09 (wGMD) + 0.12	0.98	0.99	< 0.001
dCMacro-Agg = 9.51 (SOC) + 0.46	0.93	0.95	< 0.001
dMeso-Agg = 3.17 (SOC) + 26.12	0.18	0.42	< 0.001
dMicro-Agg = − 3.27 (SOC) + 26	0.30	− 0.54	< 0.001
DSA = 9.4 (SOC) + 52.57	0.63	0.81	< 0.001
dMWD = 0.37 (SOC) + 0.27	0.93	0.97	< 0.001
dGMD = 0.08 (SOC) + 0.81	0.83	0.91	< 0.001
wCMacro-Agg = 9.43 (SOC) + 0.11	0.92	0.95	< 0.001
wMeso-Agg = 3.65 (SOC) + 22.94	0.24	0.49	< 0.001
wMicro-Agg = − 1.92 (SOC) + 18.61	0.17	− 0.42	< 0.001
WSA = 11.16 (SOC) + 41.65	0.73	0.86	< 0.001
wMWD = 0.37 (SOC) + 0.21	0.93	0.97	< 0.001
wGMD = 0.07 (SOC) + 0.85	0.83	0.91	< 0.001

R^2 = coefficient of determination; r = Pearson's correlation coefficient; *p* = statistical level of significance

[a] See Fig. 2 for abbreviations

SOC were detailed in Fig. 5 and Table 4. The aggregate stability indices (both in dry and wet conditions) exhibited significant positive correlation among each other ($R^2 = 0.91–0.99$, r = 0.91–0.99, $p < 0.001$). The proportion of micro-aggregates by mass was negatively related with other aggregate stability indices and SOC. On the other hand, a strong and positive correlation of SOC with aggregate stability indices was captured. The correlation of SOC with coarse macro-aggregates was much stronger ($R^2 = 0.92–0.93$, r = 0.95, $p < 0.001$), than with meso-aggregates ($R^2 = 0.18–0.24$, r = 0.42–0.49, $p < 0.001$). Correlations of DSA, WSA, dMWD, wMWD, dGMD and wGMD with SOC were positive and significant ($R^2 = 0.63–0.93$, r = 0.81–0.97, $p < 0.001$). The relations between aggregate stability indices, besides using Pearson's' and linear regression correlations, were elaborated by using redundancy analysis (RDA) (Fig. 6). The ordination diagram explained for 72.93% of the variations related to soil aggregate stability indices. The first axis (axis 1) explained 65.65% of the variation which separated CL from SL and GL, while axis 2 explained 7.28% of the variation in which GL and SL had the largest share. Axis 1 was primarily contributed by dry micro-aggregates and ADI, while axis 2 was principally contributed by dry coarse macro-aggregates, aggregation ratio, WSA, DSA

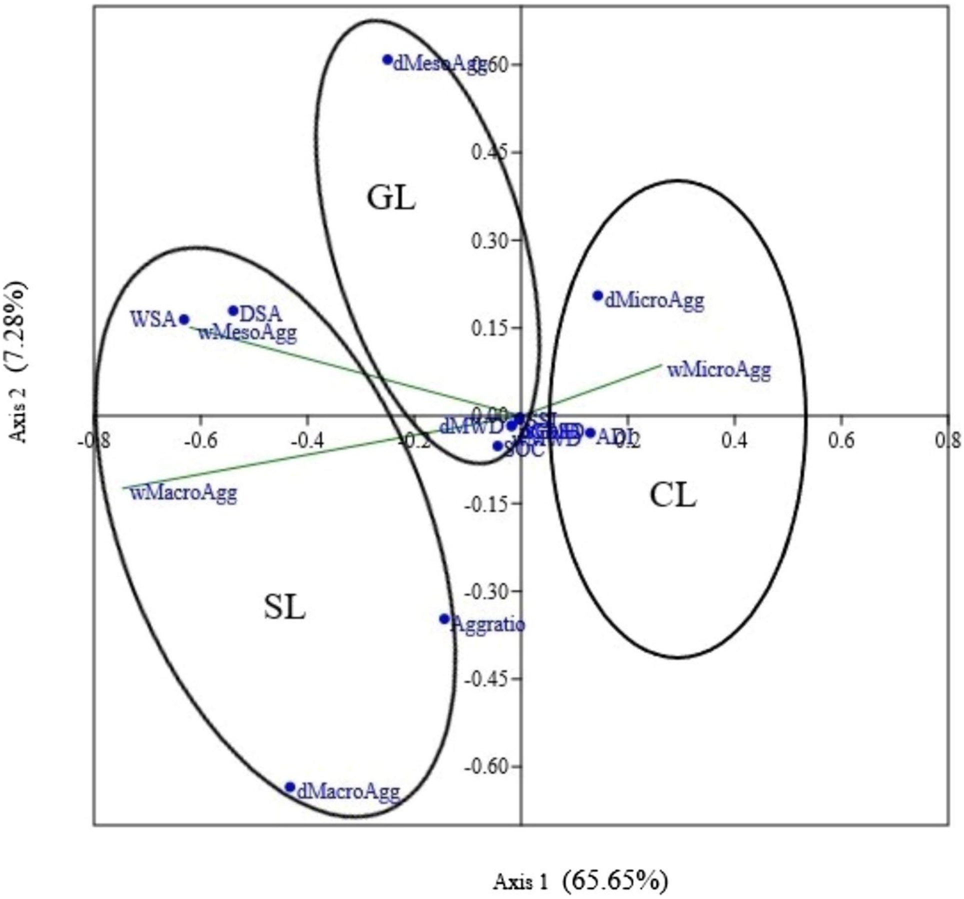

Fig. 6 Odination diagram produced by redundancy analysis illustrating relationships among aggregate stability indices recorded under different land uses. See Fig. 5 for abbreviations

and dry meso-aggregates. The stable aggregate fractions in dry condition were particularly the key indicators separating the three land use systems.

Land use influences on soil organic carbon stock

The one way ANOVA and LSD test results presented in Fig. 7 witnessed that the SOC stock

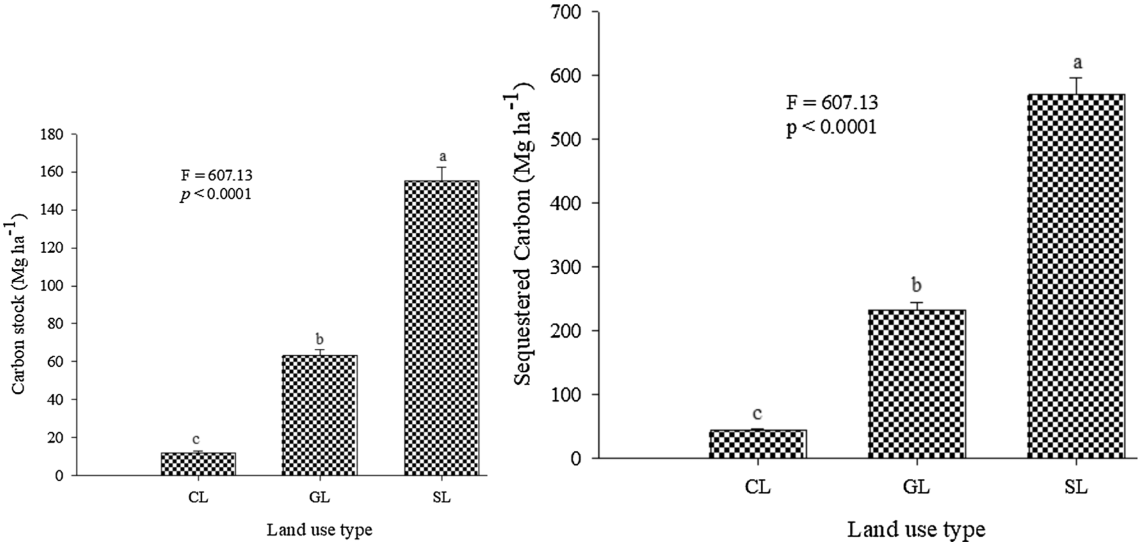

Fig. 7 Stock and sequestration dynamics of soil organic carbon as affected by land use type. The bars represent standard errors. F and *p* values represent to the results of ANOVA test. *CL* cultivated land; *GL* grass land; *SL* shrub land

displayed significantly varied records with changes in land use. The mean SOC stock was lowest in CL (11.79 ± 0.86 Mg ha^{-1}), tracked by a degree towards denser carbon value in GL (63.35 ± 3.22 Mg ha^{-1}, 5.4-fold greater than in CL), and the highest accumulation was in SL (155.48 ± 7.13 Mg ha^{-1}, 13.19-fold greater relative to CL). In GL, SOC stock was almost less than half of that in SL, but five times more than that in CL (variation significant). The total SOC stored to top 30 cm depth was estimated to be 4644.33 Gg (Table 5). SL (14,986 ha) and GL (26,196 ha) soils stored 2330.02 Gg and 1659.52 Gg of SOC which were amounted to be 50% and 36% of the total SOC, while that for CL soils (55,538 ha) was 654.79 Gg which accounted for 14% of the total. The average SOC stock in the area was estimated to be 49.06 Mg ha^{-1}. There was a significant difference in carbon sequestration rate (SOC mitigation potential) among land uses, being peaked in SL (570.62 ± 26.18) followed by GL (232.49 ± 11.80) and CL (43.25 ± 3.16).

Table 5 Total SOC stock estimated to top 30 cm depth of soils under different land uses

Land use	Area (ha)	Mean SOC stock (Mg ha^{-1})	Total SOC stored (Gg)
Cultivated land	55,538	11.79	654.79
Grass land	26,196	63.35	1659.52
Shrub land	14,986	155.48	2330.02
Total			4644.33

Spatial distribution of aggregate stability indices and SOC stock

The spatial distributions of structural stability indices (mainly MWD and SSI) and SOC stock and sequestration rate are presented in Fig. 8. Structurally unstable and very unstable soils shared largest part of the area, while those

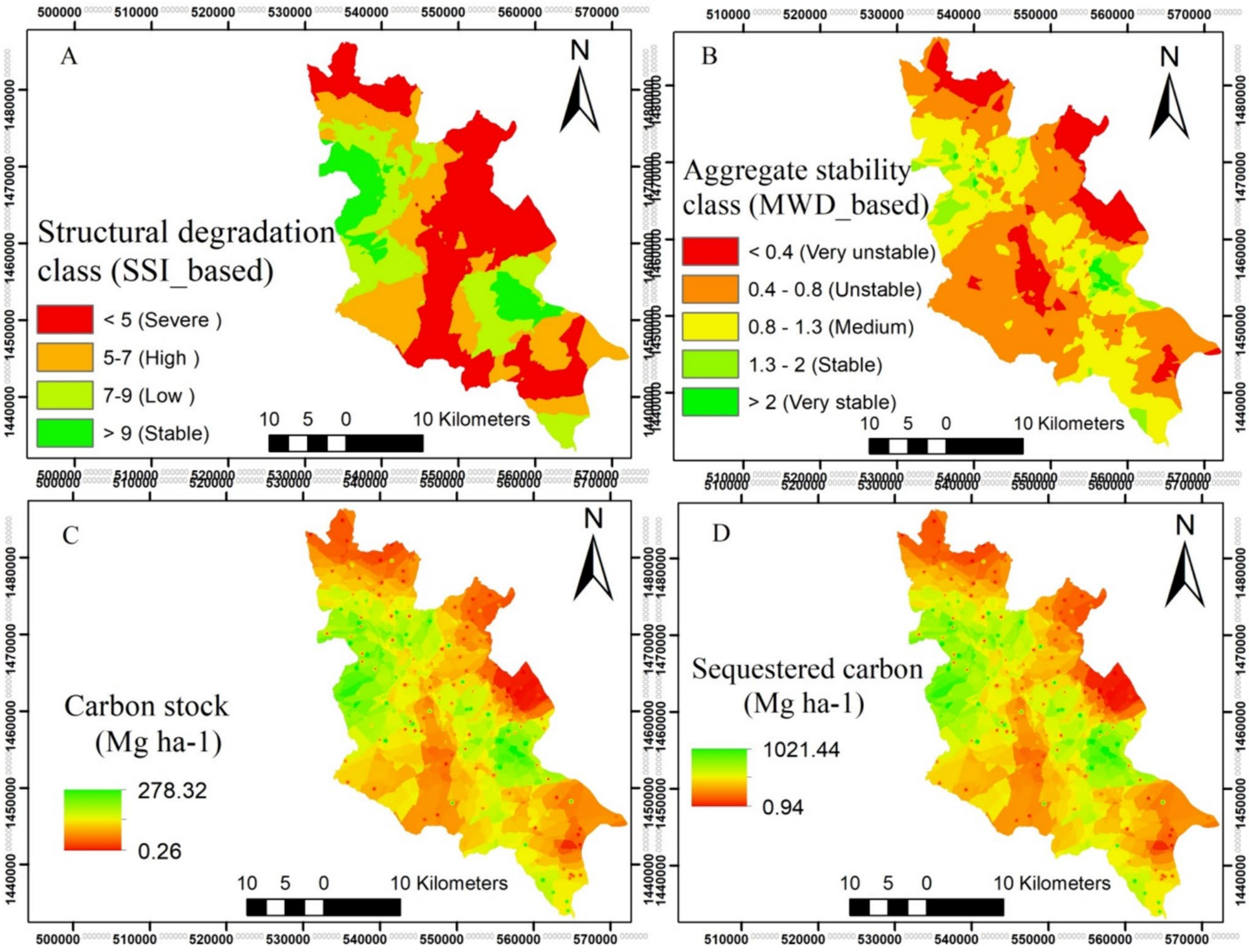

Fig. 8 Spatial distribution of structural degradation (**A**) and aggregate stability (**B**) classes, carbon stock (**C**) and sequestration rate (**D**) predicted by ordinary kriging

with medium to very stable structure covered very limited area towards its southern, eastern and northwestern parts. The greater stock and sequestration potential to carbon of the area occurred on its eastern and northwestern patches. Their lower quantities, on other hand, were concentrated on its southern, central, eastern and northern tips.

Discussion

Influences of land use variation on aggregate fraction distribution and their stability

Coarse macro-aggregates (both in dry and wet conditions) were dominant in SL soils compared to those in CL and GL, likely associated with the increased litter and root biomasses which release considerable SOC and cementing compounds to form large aggregates (Kurmi et al. 2020; Wang et al. 2021) and create micro-climates conducive for micro-and meso-fauna generating aggregation encouraging compounds (Rashid et al. 2016). The influence of SOC on macro-aggregates was described by the linear regression and Pearson's correlation analysis (Fig. 6 and Table 4). Similar findings were reported by Okolo et al. (2020), who found higher proportion of macro-aggregates (> 0.25 mm) in soils covered by natural vegetation and grasses than those covered by crop land. Soils in GL had higher meso-aggregate fractions relative to those in SL and CL which was in line with research results of Emadi et al. (2009), who observed increased meso-aggregate fractions in grass land soils than those of forest and crop lands in northern Iran. Macro-aggregates were observed to decrease, while micro-aggregates were increasing in CL soils which probably corresponded with their increased clay and calcium carbonate ($CaCO_3$) contents (Table 2). Exchangeable calcium when released from $CaCO_3$ up on dissolution, through its contribution to bridging clay and organic particle surfaces, can substantially enhance the formation and stability of micro-aggregates (Pihlap et al. 2021). Apart from this, the higher proportion of micro-aggregates for CL soils over those of GL and SL could further suggest the cultivation disturbance and the vulnerability to erosion impacts due to limited plant coverage, which contributes to macro-aggregate weakness and in turn increases concentration of carbon-poor small-sized aggregates (Celik 2005). Compared to micro-aggregates, the formation of macro-aggregates primarily from oxidation-prone temporary and transient binding agents which are sensitive to cultivation disturbances (Cheng et al. 2023), also accounted for the higher micro-aggregate masses in CL (Fig. 7). This confirms our first hypothesis. Those results are in line with observations that cultivation-induced aggregate disintegration resulted in an increased mass of micro-aggregates (Wolka et al. 2021). Our observation could partly support the fact that "micro-aggregates are more stable and resistant to management changes than macro-aggregates" (Oades and Waters 1991). Generally, SL soils exhibited more stable aggregates (both DSA and WSA) than those of GL and CL (Fig. 7). Soils on GL relative to those on CL showed greater records likely attributable to their greater root and residue leftovers along with cattle depositions which encourage particle-enmeshment and serve as food sources for microbes secreting aggregating compounds. Similarly, a study in northern Ethiopia has reported more stable aggregates in soils of grass land (72%) relative to those of crop land (41%) (Delelegn et al. 2017). This is consistent with our second hypothesis, which stated that shrub land and grass land soils have more stable structure relative to those of CL.

In the study, SL soils had higher MWD, GMD, SSI and aggregation ratio relative to those of GL and CL, which finding was in line with Kalhoro et al. (2017). The higher value of those structural stability indices in SL is mainly explained by the increase in above- and below-ground biomasses which increases SOM accumulation (Yang et al. 2023), and thus enhances soil aggregation. Soils in GL were with higher values of those stability indices compared to soils under CL attributable to their relatively higher plant biomass and SOC. Those results are supported by Wang et al. (2023a), who reported higher aggregate stability for soils of grass land compared to those of cultivated land. In contrast, CL soils exhibited higher ADI values but lower MWD, GMD, SSI and aggregation ratio than those of GL and SL which may indicate the plowing influences to aggregate disruption by modifying aeration, temperature and microbial activities and decreasing and redistributing SOC. Attributable to the negative effects of tillage on aggregation, soils in CL were generally characterized by poor structural conditions.

The dry and wet sieved aggregate fractions and stability indices were significantly and positively correlated ($R^2 = 091–0.99$, Table 4), which implies the possibility to use of dry sieving instead of wet sieving attributable to its simplicity and ease of application. The correlation of SOC with coarse macro-aggregates was positive and stronger ($R^2 = 0.92–0.93$) compared with that of meso-aggregates ($R^2 = 0.18–0.24$), but it was negative with micro-aggregates. This supports the fact that the stability of large aggregates is closely related with the amount of coarse organic carbon, while micro-aggregation tended to be explained more by other factors (not covered by the study) including clay and cation type, wet-dry cycles and $CaCO_3$ content (Amézketa 1999). This supports our third hypothesis, which stated that the correlation of SOC with coarser soil aggregates is stronger than that with finer aggregate fractions. The study findings also indicated that 63% to 93% of the variations in soil aggregation and stability were contributed by SOC content (Table 4), which suggests as SOC is a prime factor explaining structural stability of soils in the study area.

Effects of land use on SOC sequestration

The variation in land use significantly influenced SOC stock and sequestration. Soils in CL, relative to those of SL and GL, stored and sequestered lower SOC. The least SOC reserve in CL could be associated with the fact that tillage exposes SOM to oxidation through aggregate disruption, modifying aeration, temperature, moisture and biological processes. On top of this, the low SOC for CL soils might probably be triggered by crop uptake, limited nutrient supply and residue removal upon crop harvesting for animal feed (Zhang et al. 2017), along with its loss by tillage-promoted erosion (Kirkels et al. 2014). A study by Sun et al. (2015) examined land use change impacts on SOC stock, and reported lesser SOC in crop land than in grass land and shrub land. This concords with our fourth hypothesis that soils under continuous cultivation store less SOC compared to those under grass land and shrub land. On the other side, the leaf and root litter accumulations (which release recalcitrant carbon pools) together with the mulching contribution of plant leftovers to reduce soil temperature (which slows oxidization of SOM) along with the minimal disturbance and reduced runoff may led to SOC build up in SL soils (Wang et al. 2021). The physical shielding served by larger aggregates for SOC along with the longer rooting behavior of trees which explore nutrients from deeper soils (this exerts positive impacts on SOC content through enhancing plant biomass) could also lead to SOC gains for soils in SL (Deng et al. 2018). This finding reaffirms results of earlier studies in Ethiopian highlands (Abegaz et al. 2016; Abebe et al. 2020), who found higher SOC stock in soils of shrub land compared to those in crop land. For GL soils, the carbon inputs from animal droppings and dense fine and easily decomposable roots along with the small residues left on surface soil seem probable reasons for their high SOC stock next to those in SL. Similar to our finding, in a cross-site study in northern Ethiopia, grass land soils have been observed to contain significantly higher SOC stock than those of crop land (Okolo et al. 2023). Likewise, a 36.5 Mg ha^{-1} more SOC was stored in grass land soils relative those of cropland in Mindae watershed of northern Ethiopia (Gelaw et al. 2014). However, SOC stocks for GL soils were not comparable with those for SL which might be associated with grazing impacts on reducing biomass inputs, modifying temperature conditions and pore networks and increasing erosion (Nie et al. 2023). The mean carbon stock records measured for different land uses in this study were found closely comparable with the amount quantified for different soils in Ethiopia (Gelaw et al. 2014; Feyisa et al. 2017; Tesfaye and Negash 2018; Gessesse et al. 2020; Okolo et al. 2023). In addition, the mean SOC stock estimated for the study area was 49.06 Mg ha^{-1}, which was 20–25% higher than the estimated average for East African soils (37–39 t ha^{-1}) (Bajtes 2004), but more than four times as low as that for tropical areas (216 t ha^{-1}) (Lal 2004). However, it appeared to be within the ranges of the global average (30–410 t ha^{-1}) (Bajtes 1996).

Future research outlooks

The sensitivity of total SOC to land use activities was investigated in this study. However, SOC when fractionated into aggregate sizes can have important implications on showing particle size contributions to stability and storage of carbon (Cheng et al. 2023; Wang et al. 2023b). Particularly quantifying the distribution of SOC pools (labile and non-labile fractions rather than the bulk SOC) across aggregate fractions can further our understanding of the short- and long-term land use change impacts on aggregate-carbon pool interactions and track turnover time dynamics (sequestration, loss and stability) of SOC as rate of mineralization and responses of SOC pools can vary with differences in structural grades and gluing materials (Eze et al. 2023; Liu et al. 2023). In further research work, it would, thus, be preferable to account separation of carbon pools and investigate their distribution across aggregates to gain deeper understandings regarding soil degradation and restoration processes. The study was limited to top soil (the plough layer). However, sub-soils may contain considerable amount of SOC with longer residence time (Hunter et al. 2023; Okolo et al. 2023). This suggests as analysis and quantification of SOC in relation to major soil pedogenic processes (considering deeper soil layers) potentially advances assessments of soil carbon storage potential.

Conclusion

Assessment of changes in soil aggregate size distribution and stability and carbon stock related to land use variation in Hintalo Wajerat district of northern Ethiopia was made by this study. The size and stability of soil aggregates and dynamics of soil organic carbon stock were susceptible land use variation. Shrub land soils had more stable aggregates (greater concentration of coarse-macro-aggregates, D(W)SA, MWD, GMD, aggregation ratio and SSI, but lower percent by mass of micro-aggregates and ADI) relative to those in grass land and cultivated land. Aggregate stability indices were strongly associated with SOC indicating the prime contribution of SOC for soil aggregation. Soils in shrub land followed by those in grass land had greater potential to sequester carbon than soils in cultivated land. The greater stability of aggregates and carbon storage capacity of soils in shrub land were likely associated with the increased litter and root biomasses which increase SOC and microbial diversity and release aggregation-promoting cementing compounds. From the study, it is possible to conclude that land use types had plausible influences on structural stability and carbon sequestration potential of soils in the study area. The results further demonstrated that crop lands had poorly structured soils with low SOC stock. Management technologies including balanced fertilizer supplies, improved surface cover and integrated-cropping system involving crops of diverse rooting depths capable of yielding recalcitrant organic compounds should be encouraged to improve soil structure, carbon sequestration and climate resilience for soils in cultivated land.

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Declarations

Conflict of interest The authors declare that they have no competing interests regarding publication of this paper.

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