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Soil Organic Carbon to Clay Ratio as an Indicator of Structural Soil Quality: A Case Study of South Bihar, India

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Abstract: *Soil is a valuable and non-renewable resource for agricultural production, and it is essential to establish indicators to monitor its condition. Soil organic carbon (SOC) is a key indicator of soil quality and health since it regulates important physical, chemical, and biological soil properties. Hence, a simple measure of appropriate levels of soil organic matter is needed for soil evaluation, management and monitoring, based on readily measurable soil properties. In this study, an index of soil organic matter based on the SOC to clay ratio, defined by thresholds of SOC/clay ratio for specified levels of soil structural quality, was tested. We assess the index using data from the land resource inventory of WDC2.0/III/Gaya watershed under agricultural land, forest land and open scrub. The results showed that SOC was ranged between 2.40 to 10.40 g kg^{-1} (surface) and 0.70 to 6.10 g kg^{-1} (sub-surface) for agriculture; 1.80 to 12.90 g kg^{-1} (surface) and 1.0 to 5.10 g kg^{-1} (sub-surface) for forest and for the open scrub, it ranged from 1.30 to 10.20 g kg^{-1} (surface) and 0.70 to 5.90 g kg^{-1} (surface). Mean clay content increased in the order of agriculture > forest > open scrub in the surface layer and increased in sub-surface layer across the LULC. Thresholds of SOC/clay ratio of 1/8, 1/10 and 1/13 indicated the boundaries between "very good", "good", "moderate" and "degraded" levels of structural condition. On this scale, 92.0, 77.8 and 71.4% of agricultural land, open scrub and forest sites, respectively, were degraded. The index gives a method to assess and monitor soil organic matter at national, regional or sub-regional scales based on two routinely measured soil properties.*

Keywords: SOC/clay ratio; Soil function; Structural soil quality; Mapping; Spatial variability

The functional qualities of soil, including water-holding capacity, aggregate stability, compactibility and erodibility, nutrient storage, cation exchange capacity, and acid buffering capacity, are all positively impacted by soil organic carbon (SOC) in a variety of ways (Murphy, 2015). Hence, SOC is a crucial indicator of soil quality and health since all of those characteristics are closely related to the services that soils offer, such food security, water security,

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or biodiversity protection (Bünemann *et al.,* 2018; Kopittke *et al.,* 2022). However, an index to assess the amount of soil organic matter under specific conditions must take these factors into consideration because soil organic matter varies with land use, soil type, location, and other factors.

Clay content is a key factor because of its effects on SOC protection, including adsorption on mineral surfaces and within soil aggregates (Six *et al.,* 2002; Dungait *et al.,* 2012). Soils have a tendency to stabilize their SOC content as a function of clay content when land management and organic matter inputs are continuous (Hassink, 1997; Hassink and Whitmore, 1997; Six *et al.,* 2002; Stewart *et al.,* 2007). Dexter *et al.* (2008) observed that the relative amounts of SOC and clay content in relation to another, rather than their combined levels, could better describe the physical qualities of soil (bulk density, water retention characteristics, and clay dispersibility). They observed that the SOC/clay ratio provided a general demarcation between the various land uses and was a good indication of soil physical characteristics. Other scholars later confirmed these findings (de Jonge *et al.,* 2009; Schjønning *et al.,* 2012; Jensen *et al.,* 2019). De Jonge *et al.* (2009) found that soils with SOC:clay > 1:10 showed favorable tilth conditions, contrary to soils with SOC:clay < 1:10. Dupla *et al.* (2021) referred to the SOC:clay ratio as the "structure vulnerability indicator" and calculated the amount of SOC necessary to reach the ratio of 1:10. The approach was further improved by Johannes *et al.* (2017), who established SOC/clay thresholds of 1/ 8, 1/10, and 1/13 as delineating the limits between ″very good,″ ″good,″ ″suggest improvement,″ and ″poor″ levels of structural state.

Bihar, is a state of India, there is an issue of land degradation which had a negative impact on Gaya district. Many of the current land degradation issues in the current study area, such as gullied and ravenous land, degraded forest area, and an increase in sandy areas, have been brought on by inadequate information on soil resources linked to inappropriate land use design. This has a negative impact on crop productivity, among other issues. In the Gaya district, anthropogenic activities such as the conversion of native vegetation into crop and grazing land or deforestation, which leaves soil cover prone to land degradation, are among the major causes of land degradation. The rise in gullied/ravenous and badland) is a result of these unsustainable land management techniques (Ghosh and Maiti, 2021). Hence, in this paper, we assess the three SOC/clay thresholds of Johannes *et al.* (2017) to obtain the degradation level of agricultural land, forest land and open scrub of WDC2.0/III of Gaya district, Bihar. The study will aid to restore the soil fertility status by taking proper management practices and to manage the land easily.

Materials and Methods

Study Area

The study was carried out in the WDC2.0/IV watershed of the Gaya district, Bihar, India (24°28′01″ to 24°39′57″ N latitude and 85°12′26″ E and 85°20′26″ E longitude), covering an area of 9725 ha (Fig. 1). The home of Jharkhand borders the southern limit, and the Dhadhar river, which began from the Jharkhand tablelands, flows in the northeastern direction within the southern extent of the study area. A continental monsoon with a hostile environment affects the whole study area. Summer months are characterized by blistering westerly winds with maximum temperatures up to 46° C and as low as 4° C. Geomorphologically, the study area has three distinct units: (i) residual hills of outcrops of the Chotanagpur plateau consisting of shales, compact sandstones, mica schist, quartzite, and siltstone; (ii) pediments and pedi plains consisting of major land areas covered by residual soil and slope and sheet wash deposits from bordering

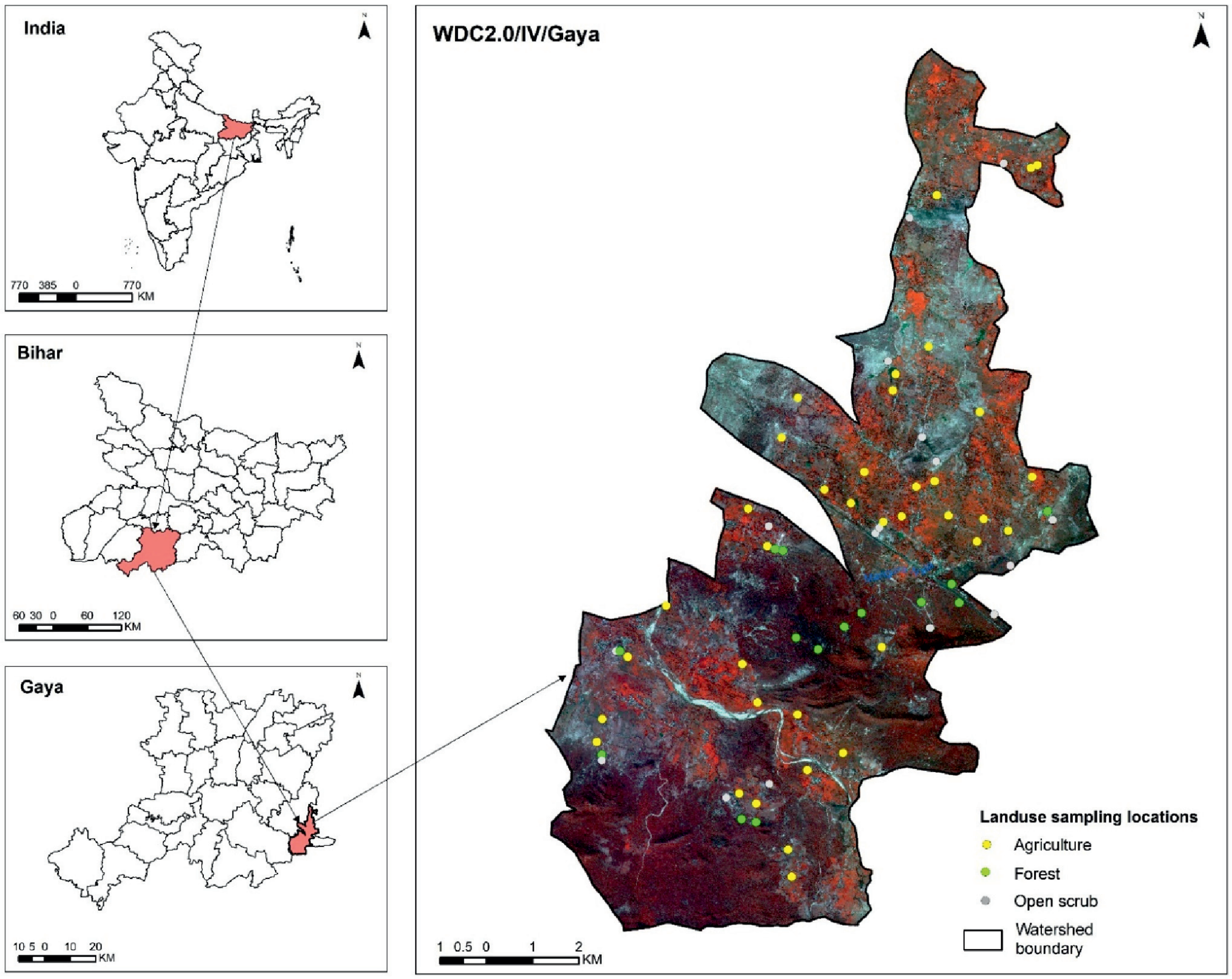

Fig. 1. Location map of the study area

hills and inliers; and (iii) valleys. The undulating uplands and gullied lands having alluvium of the river in the southern and southeastern part of the study area (Reza *et al.,* 2024). The major soil types of the watershed are Typic Haplustalfs (33.1%), Typic Haplusteps (31.96%), Lithic Ustorthents (11.46%), and Typic Endoaquepts (2.51%) (Reza *et al.,* 2024).

Soil Sampling and Analysis

KOMPSAT-3A of 27th January, 2024) were georeferenced using WGS 84 datum, Universal Transverse Mercator (UTM) projection, and ground control points (GCPs). The Standard False Color Composite (SFCC) was used for delineation of land use/land cover classes (LULC), and the boundaries were verified and corrected wherever found necessary (Fig. 2). Three land classes (agricultural land, forest land, and open scrub) were selected for this study, and a total of 68 soil samples (37 from agricultural, 13 from forest, and 17 from open scrub land) were collected from a depth of 0-15 and 15-30 cm. Soil samples were air-dried, ground, and sieved to pass through a 2 mm sieve. Particle size analysis was carried out by the international pipette method (Piper, 1966). SOC was estimated by the Walkley-Black method (Walkley and Black, 1965). SOC/clay ratios were estimated for all surface and sub-surface layers and grouped into three soil structural classes, *i.e.,* very good (>1:8), good (1:8-1:10),

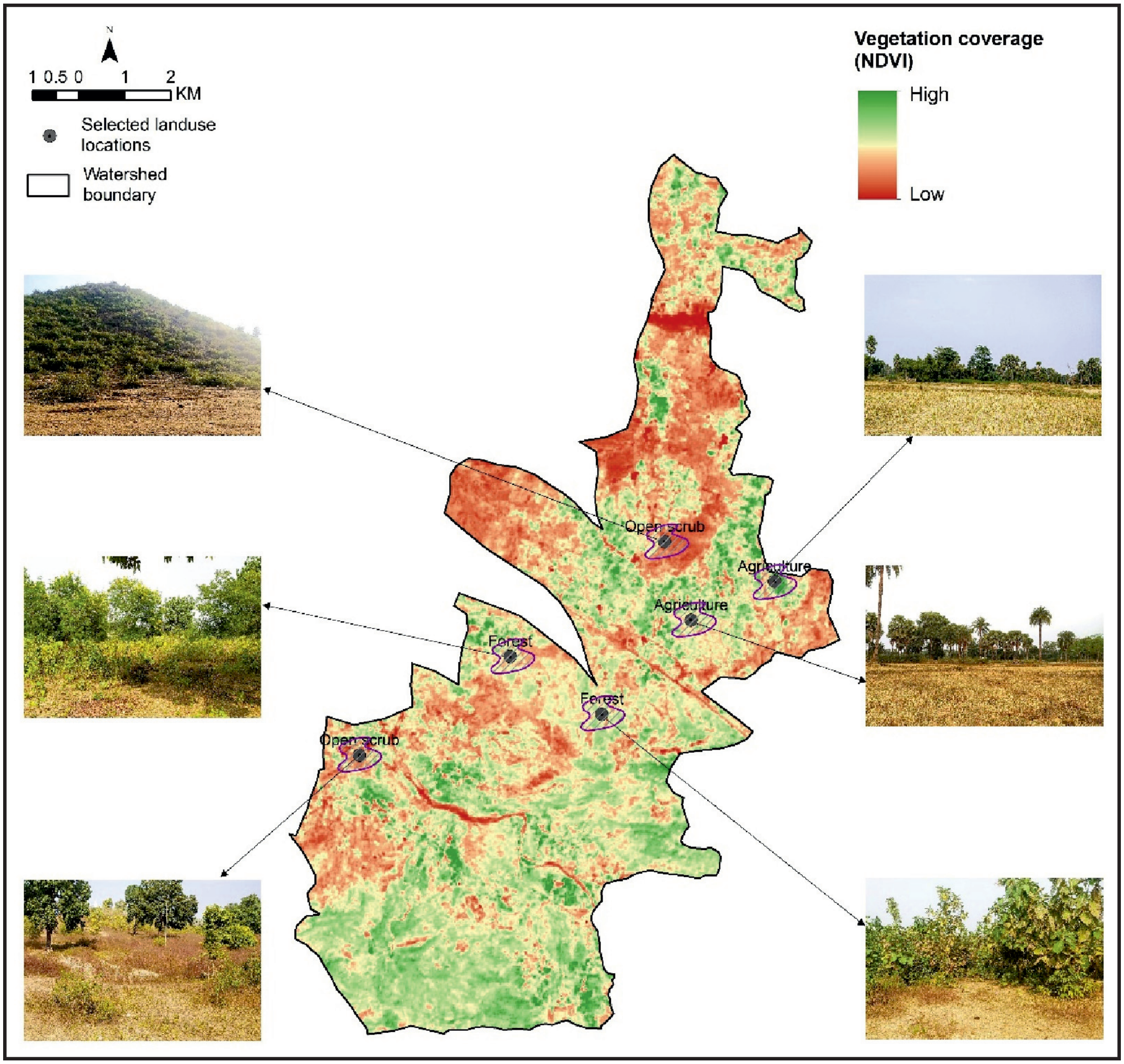

Fig. 2. Ground-truth verified LULC map of WDC2.0/IV/Gaya

moderate (1:10-1:13), and degraded (<1:13) (Johannes *et al.,* 2017).

Using the Inverse Distance Weighted (IDW) interpolation method, which is included in the ArcGIS Geostatistical Analyst toolbar (ver. 10.8), the spatial interpolation was carried out. SOC, clay content, and SOC/clay ratio were mapped in time and space using the IDW interpolation technique, which is the best continuous, unbiased analyzer for extrapolating missing data in difficult-to-reach places (Reza *et al.,* 2010; Vatandoos *et al.,* 2018; Rizwan *et al.,* 2021; Badar *et al.,* 2024). IDW interpolation relies on two statistical and mathematical techniques to generate surfaces and compute the predictions of unmeasured locations. Several researchers (Reza *et al.,* 2013, 2015; Emadi *et al.,* 2016) mapped the spatial variability of soil properties for both surface and sub-surface soils effectively by using IDW method.

Results and Discussion

Variation of SOC, Clay Content and SOC/Clay Ratio in Different LULC

The mean SOC contents increased in the order of open scrub > agriculture > forest in surface layer and were similar for the sub-surface layer except for the open scrub. The SOC was ranged between 2.40 to 10.40 g kg^{-1} (surface) and 0.70 to 6.10 g kg^{-1} (sub-surface) for agriculture; 1.80 to 12.90 g kg^{-1} (surface) and 1.0 to 5.10 g kg^{-1} (sub-surface) for forest and for the open scrub, it ranged from 1.30 to 10.20 g kg^{-1} (surface) and 0.70 to 5.90 g kg^{-1} (surface) (Table 1). The surface layer tended to be richer in SOC than the sub-surface layer in all LULC. This may be attributed to the contribution made by litter fall (Panwar *et al.,* 2011; Reza *et al.,* 2011). Jha *et al.* (2012) and Reza *et al.* (2014) had also reported that soils under horticulture and forest systems showed greater amounts of soil SOC than agricultural lands.

Mean clay content increased in the order of agriculture > forest > open scrub in the surface layer and increased in sub-surface layer across the LULC. The clay content ranged from 60 to 588 g kg^{-1} (surface) and 71 to 569 g Kg^{-1} (sub-surface) for agriculture; 82 to 427 g kg^{-1} (surface) and 65 to 425 g kg^{-1} (sub-surface) for forest and for the open scrub it ranged from 31 to 344 g kg^{-1} (surface) and 19 to 391 g kg^{-1} (sub-surface) (Table 1). The increase in clay content in the sub-surface layer in all the LULC may be due to weathering of soil and vertical movement of clay from the surface to the subsurface horizon. This showed that the pedogenic processes of eluviation and illuviation are prevalent in the study area (Reza *et al.,* 2022, 2024).

Box plot is a standardised way of displaying the distribution of data based on a five summary; minimum, first quartile (Q1), median, third quartile (Q3), and maximum. It was depicted in Fig. 3 showed the variation of SOC, clay and SOC/clay ratio. The distribution of indicators of soil quality was identified as uniform. The plot gives a visual summary of the spread and central tendency of each parameter, indicating how variable the parameters are.

Relation between Structural Quality and SOC/Clay Ratio

The LULC were classified as good, moderately degraded and degraded by using the threshold values of degradation based on the SOC/clay ratio (Johannes *et al.,* 2017). The major proportion of the three LULC were degraded as the ratio of SOC/clay was less than the 1/13 threshold value (Table 2). About 92% of surface soil samples of agricultural land was degraded, whereas 5.6% (SOC/clay <1/10≥1/13) were moderately degraded and only 2.4% (SOC/clay <1/8≥1/10) was in good condition. The percentage of degradation of forest surface samples was 71.4%, and the percentage for open scrub was 77.8%, which are less than the agricultural land. The results showed that the

Table 1. Soil organic carbon (SOC) and clay content in different land use/land cover (LULC)

LULC		LayersSOC content (g kg^{-1})				Clay content (g kg^{-1})			
		Mean	Median	Minimum	Maximum	Mean	Median	Minimum	Maximum
Agriculture	Surface	5.39	5.20	2.40	10.40	270	273	60	588
	Sub-surface	2.49	2.20	0.70	6.10	292	287	71	569
Forest	Surface	6.55	6.05	1.80	12.90	252	254	82	427
	Sub-surface	2.97	3.00	1.00	5.10	272	262	65	425
Open scrub	Surface	5.13	4.90	1.30	10.20	196	205	31	344
	Sub-surface	2.63	2.35	0.70	5.90	230	244	19	391
All LULC	4.20	3.95	0.70	12.9	252	258	31	588	

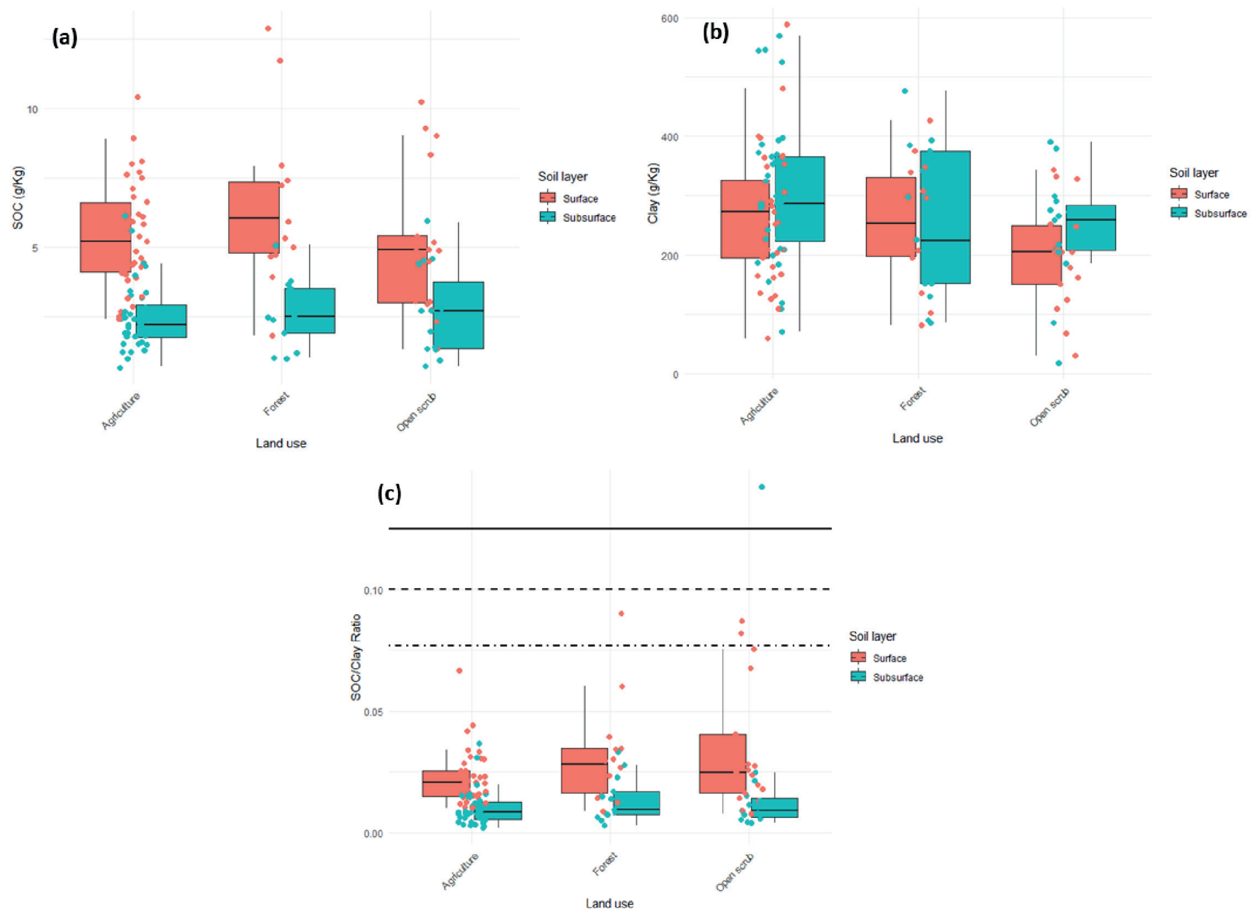

Fig. 3. Box-plots of (a) SOC, (b) clay and (c) SOC/clay ratio for each LULC. Horizontal lines are SOC/clay thresholds: Solid = 1/8, dashed = 1/10, dot-dash = 1/13

Table 2. Percentage of soil samples of agricultural, forest and open scrub land classified as good, moderate and degraded land based on SOC/Clay ratio

LULC	Soil layers	Degraded (<1/13)	Moderate (<1/10≥1/13)	Good (<1/8≥1/10)
Agriculture	Surface	92.0	5.6	2.4
	Sub-surface	100	0	0
Forest	Surface	71.4	14.3	14.3
	Sub-surface	100	0	0
Open scrub	Surface	77.8	22.20	-
	Sub-surface	94.12	0	5.88

agricultural land was mostly degraded (SOC/clay ratio below 1/13), which indicated that these lands are prone to erosion. Regardless of climate, the distribution of particle sizes can control the amount of SOC. Because clays have a protective effect on organic components, an increase in clay content within a climatically homogeneous area results in an increase in SOC (Burke *et al.,* 1989; Buschiazzo *et al.,* 1991; Matus, 2021).

The forest and open scrub were relatively high in SOC, and the clay content was uniformly distributed in surface and sub-surface layers.

Forest and open scrub are the natural systems having SOC/clay ratios <1/10≥1/13 for some percentage of soil samples, indicating that some of these lands were moderately degraded. There were 14.3% of soil samples of forest land that had SOC/Clay ratios <1/8≥1/10, indicating that the highly concentrated SOC was present as a top layer. Since clay concentration is a major determinant of SOC protection and stability, the SOC/clay ratio gives a more definitive separation between different managements, climates and other factors within a land use category than SOC alone. Hence the percentage of land under good condition, *i.e.,* above the 1/10 threshold value of degradation suggests that the clay content protects the SOC whereas, the arable lands H" agriculture land, which undergo the SOC/clay ratio >1/10 threshold value, recommend that the SOC is independent of clay content.

The major proportion of sub-surface layers of three LULC had SOC/clay <1/13 (Fig. 4) which suggested that all the sub-surface layers of the three LULC are depleted in SOC and enriched in clay parentage. SOC percentage was very much influenced by the soil layers ($P < 0.001$) as the SOC level was decreased from surface to sub-surface layers. Clay percentage was independent of surface layer ($P < 0.01$). SOC/clay ratio was not independent of soil layer ($P < 0.001$) as the ratio is highly influenced by SOC percentage. The ranges of SOC/clay ratio for agriculture, forest and open scrub varied from 0.1 to 0.01 (Table 3).

Spatial Distribution of SOC/Clay Ratio (Structural Quality)

Predicted SOC/clay ratio (structural quality) maps through IDW for two soil depths were

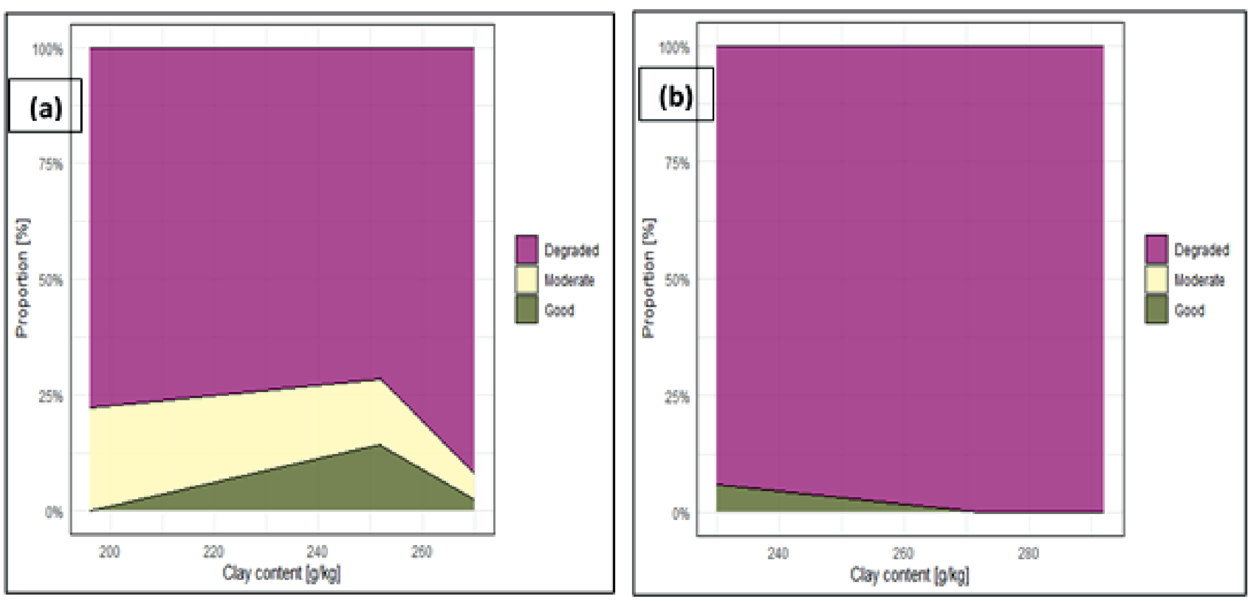

Fig. 4. The proportion of LULC in each class as a function of clay content (a) surface layer and (b) sub-surface layer

Table 3. Summary of SOC/Clay ratio values calculated for each LULC

LULC	Mean	Median	Maximum	Minimum
Agriculture	0.02	0.02	0.10	0.01
Forest	0.04	0.03	0.10	0.01
Open scrub	0.04	0.02	0.10	0.01

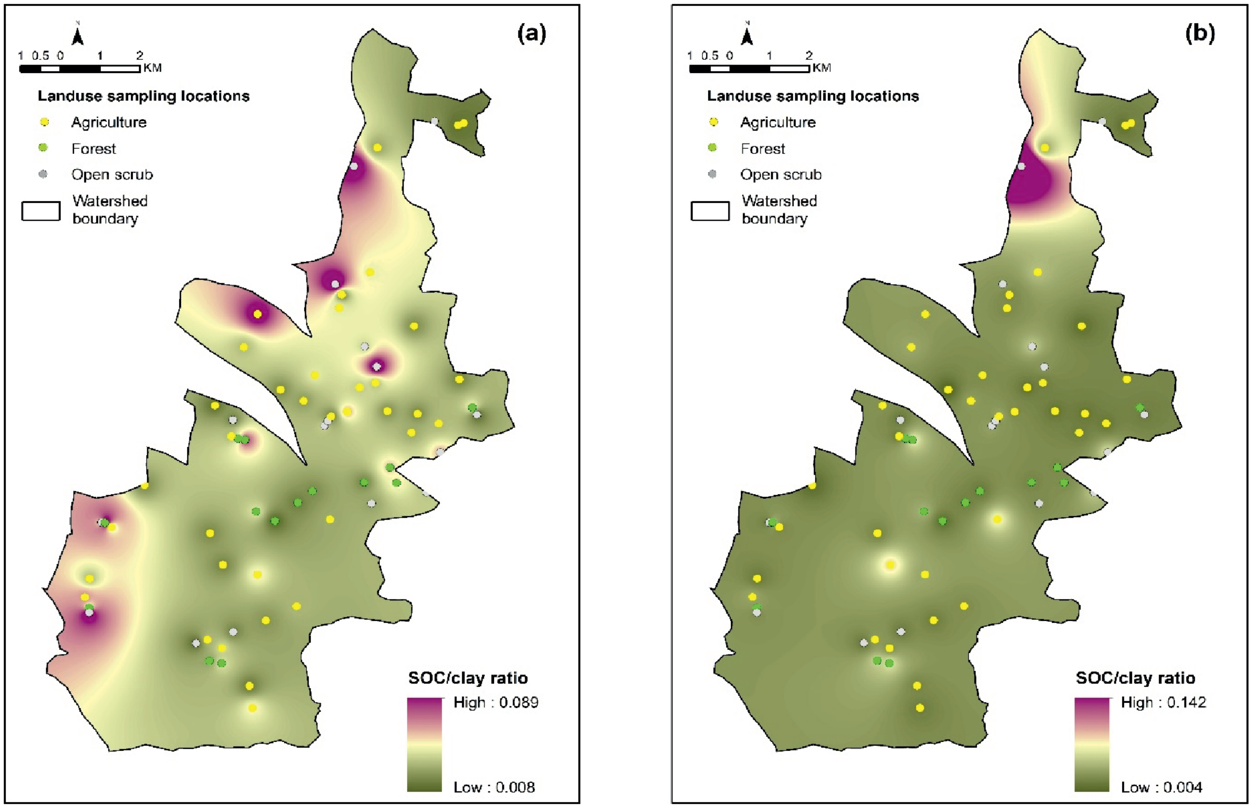

Fig. 5. Spatial distribution map of soil organic carbon (SOC)/clay ratio (a) surface layer and (b) sub-surface layer

shown in Fig. 5. The spatial distribution map for the surface layer showed a scattered distribution pattern and increased towards the north-western and south-western parts, whereas for the sub-surface layer showed an increased in northern part of the study area.

The SOC/clay index is a simple measure to evaluate the SOC status of any given soil. It will therefore be meaningful for experts and non-experts and have consequences for many soil functions beyond agricultural uses. It could allow farmers to identify degraded soils on their farms and adjust their management accordingly. It could also be used to monitor and understand the state of soils at a national scale to inform decision-making and policy.

Conclusions

An index of soil organic matter with threshold SOC/clay ratios of 1/8, 1/10 and 1/13 satisfactorily separates the soils into good, moderate and degraded classes of SOC content and physical structure condition. The study reveals that agricultural lands were highly prone to degradation, with a majority having an SOC/clay ratio below 1/13, making them susceptible to erosion, particularly in areas with low precipitation. The SOC/clay ratio serves as a more effective indicator of soil health and management impacts than SOC alone. While clay content protects SOC in certain lands, agricultural land with SOC/clay ratios exceeding the 1/10 threshold highlighted that SOC levels in these cases may be less dependent on clay content. By using SOC/clay threshold values, *i.e.,* 1/8, 1/10 and 1/13, the lands under consideration, the agricultural lands were highly degraded and need more management practices, as indicated by the SOC/clay ratio below 1/13 in a larger proportion of these areas. So, this ratio parameter can be very useful to detect the soil health, whether it is degraded or not, which helps to restore the soil fertility.

Conflicts of Interest

The authors declare no competing interests;

Contribution of Authors

S.K. Reza: Conceptualization, Methodology, Sampling, Data interpretation, Preparation of the original draft, Writing-review & editing.

N. Dey, Sk. Md. Asif and S. Bandyopadhyay: Preparation of the original draft, Writing-review & editing.

J. Chakraborty: Mapping, Writing-review & editing.

S. Chattaraj: Statistical analysis and Mapping.

R. Das: Writing-review & editing.

F.H. Rahman: Coordination, Writing-review & editing, Preparation of the final manuscript.

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