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Soil Organic Carbon Stocks Across Land Cover Types in Segara Anakan, Central Java

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Abstract

Land cover change significantly affects soil organic carbon (SOC) storage, which is crucial for climate change mitigation. This study quantifies SOC stocks across five land cover types: mangrove forests, shrubs, settlements, plantations, and rice fields in the Segara Anakan Lagoon, Central Java, Indonesia. Soil cores were collected at three depth intervals (0–30 cm, 30–60 cm, and 60–100 cm) and analyzed for bulk density, organic carbon content, and carbon stocks using the loss on ignition (LOI) method. Principal component analysis (PCA) was employed to evaluate variations in soil characteristics across different land cover types. Mangrove forests exhibited the highest SOC stocks, with a peak value of 152.04 Mg C ha^{-1} at the 30–60 cm depth. Shrublands and settlement areas showed moderate SOC stocks (115–125 Mg C ha^{-1}), whereas plantations and rice fields recorded the lowest values (<90 Mg C ha^{-1}). Bulk density was highest in rice fields and plantations, indicating soil compaction, and lowest in mangrove soils due to high porosity. PCA results revealed clear separation between mangrove soils and agricultural or plantation soils, with the first principal component explaining 79.1% of the total variance. These findings underscore the significance of mangroves in storing blue carbon and promoting sustainable coastal land management.

Keywords: *soil organic carbon, mangrove ecosystem, land cover change, coastal restoration*

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Introduction

Climate change presents one of the most pressing global environmental challenges, demanding effective mitigation strategies grounded in nature-based solutions (Kalantari et al., 2023). Among these, the enhancement of soil carbon storage through sustainable land cover management has been recognized as a key pathway to reduce atmospheric carbon levels (Kafy et al., 2023; Nazir et al., 2024). Land cover changes, such as deforestation, agricultural intensification, and urban expansion, can significantly alter the soil's capacity to function as a carbon sink, thus affecting greenhouse gas (GHG) dynamics and influencing global climate systems (Telo da Gama, 2023).

Soil organic carbon (SOC) is a critical component of terrestrial carbon pools. Its quantity and distribution are largely determined by vegetation type, land use practices, and biophysical conditions (Sahu et al., 2023). Forests, croplands, peatlands, and coastal wetlands each exhibit different capacities for carbon accumulation. Several studies have emphasized that appropriate land management, including the restoration of degraded lands, can enhance SOC sequestration while improving soil fertility and ecosystem functioning (Food and Agriculture Organization, 2022; Lal, 2004; Rodrigues et al., 2023).

Coastal ecosystems, especially mangroves, are among the most effective carbon sinks due to their high productivity, sedimentation rates, and anaerobic soil conditions (Alongi, 2015). In Indonesia, the Segara Anakan region in Cilacap, Central Java, is a dynamic coastal zone characterized by diverse land covers, including mangrove forests, settlements, rice fields, and plantations. This area is ecologically significant and has considerable potential for climate change mitigation through blue carbon sequestration. However, increasing anthropogenic pressures, such as deforestation and land conversion, threaten the carbon storage potential of these ecosystems (Donato et al., 2011; Wang et al., 2024).

Previous studies have identified significant variation in soil carbon stocks depending on land cover type and degree of disturbance (Azizah et al., 2013). Nonetheless, empirical data that simultaneously integrates field-based soil carbon measurements across multiple depths and land cover types with landscape-level spatial analysis remain limited, particularly in coastal areas such as Segara Anakan (Yulianti et al., 2024). Moreover, while research has often focused on forest or agricultural systems, mangrove-dominated coastal landscapes have not been comprehensively assessed for their carbon storage potential using a combined biophysical and geospatial approach. To address this gap, the present study evaluates the influence of land cover types on soil carbon stocks across various depths in the Segara Anakan region. The research aims to 1) quantify soil carbon storage across five dominant land cover types: mangroves, shrubs, settlements, plantations, and rice fields; 2) identify statistical differences and key soil parameters using principal component analysis (PCA); and 3) derive implications for coastal land use planning and climate mitigation strategies. By integrating ecological measurements with spatial insights, this study contributes to evidence-based policymaking for sustainable land and ecosystem management in vulnerable coastal zones.

Methods

Study area and sampling design This research was conducted in August 2024 in the Segara Anakan coastal wetland, coordinates E108°45'11"–E109°2'54" and S7°3722–7°47'37" located in Cilacap Regency, Central Java Province, Indonesia (Figure 1). This region is characterized by a mosaic of land covers, including mangroves, rice fields, plantations, settlements, and shrubs. These categories were selected based on their dominance in the landscape and their potential influence on belowground carbon dynamics. A total of 45 soil samples were collected using random sampling across five land cover types in Segara Anakan mangrove, with three replicates per land cover type. Sampling targeted three depth intervals: 0–30 cm, 30–60 cm, and 60–100 cm.

The five land cover types in Segara Anakan have contrasting characteristics that affect total carbon stocks. Estate refers to commercial plantations on alluvial sediments, where tree biomass can be relatively high but carbon stock is reduced by harvesting and intensive management. Mangrove forest is dominated by mangrove species (e.g., Rhizophora, Avicennia, and Nypa) with organically rich sediments, thus storing the largest carbon stocks in both biomass and soil. Rice fields result from the conversion of mangroves into irrigated paddy fields, but plowing and drainage accelerate organic matter decomposition, leading to lower soil carbon stocks. Settlement includes dense residential areas and built-up zones on sediment-derived land; total carbon stock can be higher than in estates because soil carbon and accumulated organic materials (residual mangrove sediments, organic waste, wooden structures) dominate despite the low tree cover. Shrubs represent shrubland on accretion areas or abandoned land with low vegetation density and slow growth and therefore generally have the lowest carbon stocks among these land cover types (Ardli & Wolff, 2008).

Soil sampling and laboratory analysis At each sampling point, soil cores were collected using a standard soil corer to a depth of 100 cm and separated into three depth intervals: 0–30 cm, 30–60 cm, and 60–100 cm. Each core was segmented using a hacksaw and composited per layer to obtain one sample per depth per point. A total of 135 composite samples were obtained (45 points × 3 depths), placed in labeled Ziploc bags, and transported to the Integrated Biogeochemical Carbon Center (IBCC) in Bogor for analysis.

Organic carbon content was determined using the loss on ignition (LOI) method following standard procedures. Samples were oven-dried at 105 °C to obtain constant weight, followed by combustion at 550 °C for 4–5 hours in a muffle furnace. The difference in weight before and after combustion was used to estimate organic matter content, which was subsequently converted to carbon content using a

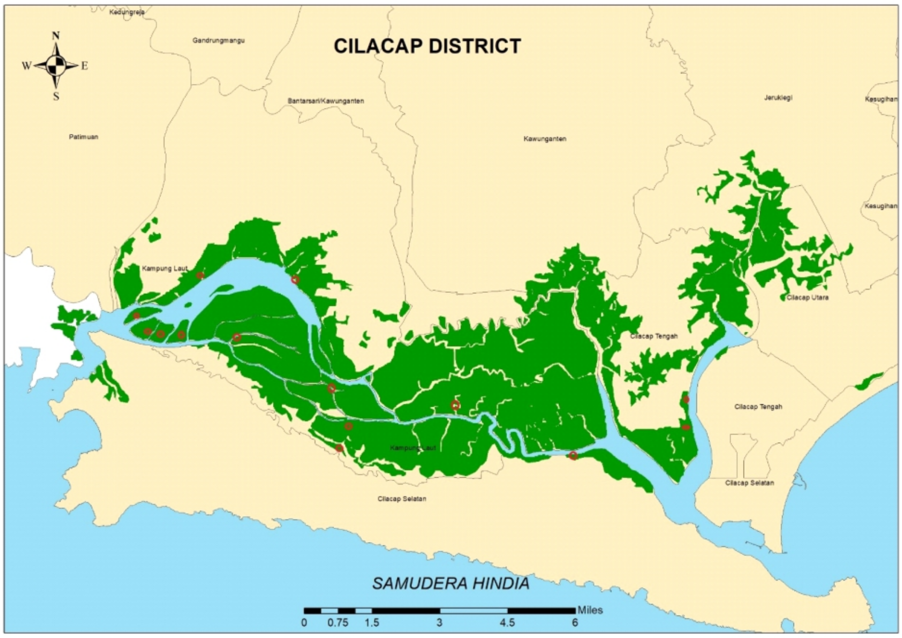

Figure 1 Location sampling.

conversion factor (a conversion factor of 0.58 was applied) based on relevant standards (Agus et al., 2011; Standar Nasional Indonesia, 2011). Soil bulk density (g cm^{-3}) was calculated as the ratio of oven-dried weight to the volume of the soil core using Equation *[1]*.

$$\text{Bulk density} = \text{Dry weight (g)}/\text{Volume (cm}^3\text{)} \qquad [1]$$

Estimation of soil carbon stock Soil carbon stock (Mg C ha^{-1}) for each depth interval and land cover was calculated using Equation *[2]*.

$$\text{C-stock (Mg C ha}^{-1}\text{)} = \text{Bulk density (g cm}^{-3}\text{)} \times \text{Depth (cm)} \times \text{(\% Organic C/100)} \times \text{Conversion factor} \qquad [2]$$

The appropriate conversion factor was applied to adjust the unit to Mg C per hectare, following national and international guidelines (Donato et al., 2011; Badan Standardisasi Nasional, 2011) .

Land cover mapping and GIS integration Field-based data were integrated with satellite imagery using geographic information systems (GIS) to spatially map soil carbon stocks across the landscape. This integration allowed for the identification of spatial trends and supported the estimation of total carbon storage within each land cover class (Donato et al., 2012).

Statistical analysis To evaluate the effects of land cover and soil depth on carbon stock, a two-way ANOVA was performed using R software (R Core Team, 2023). Before to analysis, normality and homogeneity of variance assumptions were tested using the Shapiro–Wilk and Levene's tests, respectively (p-value > 0.05 for both). Upon detecting significant differences (p-value < 0.05), Tukey's honestly significant difference (HSD) test was conducted for pairwise comparisons among groups.

PCA To explore the multivariate relationships between soil parameters and land cover types, PCA was performed following the procedures outlined by Mestiri (2023). PCA was used to reduce data dimensionality and identify the main components explaining variation in bulk density, organic matter content, and organic carbon concentration. The analysis produced biplots with factor axes (e.g., F1 and F2) to visualize clustering patterns across land covers and soil depths, allowing interpretation of dominant factors influencing carbon storage patterns.

Results

Soil bulk density Bulk density (BD) varied across land use types and depths (Table 1). At the 0–30 cm depth, the highest BD was observed in rice fields (0.84 g cm^{-3}), while the lowest was recorded in settlement areas (0.50 g cm^{-3}). In deeper layers (60–100 cm), the BD tended to increase across all land covers, with plantations reaching up to 1.06 g cm^{-3}. Mangrove soils consistently exhibited lower bulk density values (0.60–0.88 g cm^{-3}), indicating a higher porosity and potential for organic matter retention.

Organic carbon content The organic carbon content (C-org) was highest in mangrove ecosystems at all depth intervals, peaking at 9.25% in the topsoil (0–30 cm). Shrubs and settlements also showed elevated C-org values (above 7%), while the lowest C-org was observed in rice fields (4.13% at 0–30 cm). Organic carbon levels declined slightly with depth but remained relatively high in mangroves (6.27% at 60–100 cm), suggesting strong long-term sequestration.

Carbon stock in soil Carbon stock (Mg C ha^{-1}) followed similar patterns to C-org, with mangrove sites exhibiting the highest values across all depths. The maximum carbon stock was recorded at 30–60 cm in mangroves (59.27 Mg C ha^{-1}), nearly double that of rice fields (32.71 Mg C ha^{-1}) at the same depth. Shrubs and settlements also showed relatively high carbon storage (42.98 Mg C ha^{-1}), especially in subsurface layers.

The comparative distribution of soil parameters across land use types is illustrated in Figures 2–4. Figure 2 highlights the differences in bulk density at depths of 0–30

Tabel 1 Potential land cover (g cm^{-3})

	Bulk density (g cm^{-3})		C-org (%)		C-stock (Mg C ha^{-1})	
Land use	Mean	Std. err	Mean	Std. err	Mean	Std. err
Depth: 0–30 cm						
Estate	0.67	0.17	5.24	0.51	30.60	2.84
Mangrove forest	0.60	0.10	9.25	2.62	45.71	4.53
Ricefield	0.84	0.11	4.13	0.66	32.20	7.40
Settlement	0.50	0.13	8.16	2.10	32.72	1.41
Shrubs	0.68	0.10	7.42	1.27	44.21	2.84
Depth: 30–60 cm						
Estate	1.06	0.24	4.84	1.36	40.89	1.56
Mangrove forest	0.91	0.14	7.56	1.45	59.27	4.53
Ricefield	0.65	0.16	4.33	0.77	23.39	1.29
Settlement	0.60	0.04	8.06	2.75	43.06	13.97
Shrubs	0.67	0.06	7.09	0.34	42.98	1.56
Depth: 60–90 cm						
Estate	1.06	0.28	5.55	1.27	155.10	6.30
Mangrove forest	0.88	0.20	6.27	0.98	154.07	3.31
Ricefield	0.67	0.13	4.55	0.82	90.40	7.77
Settlement	0.63	0.21	7.23	1.77	122.93	10.93
Shrubs	0.76	0.28	6.31	1.11	124.44	6.30

cm, 30–60 cm, and 60–100 cm. Estate areas consistently recorded the highest values (reaching up to 1.2 g cm⁻³), suggesting compacted soils, potentially due to mechanized land use. Conversely, mangrove soils had significantly lower bulk densities (0.60–0.88 g cm⁻³), indicating higher porosity and organic matter accumulation. Organic carbon content (Figure 3) followed an opposite trend, with mangrove forests consistently exhibiting the highest C-org values across all depths, peaking at 9.25% in the surface layer. This reinforces the role of mangrove ecosystems in long-term carbon sequestration. Settlement and shrub areas also maintained elevated carbon contents (>7%), while rice fields and estate land showed lower percentages (<5%). Total carbon stock across all depths (Figure 4) further confirmed the dominance

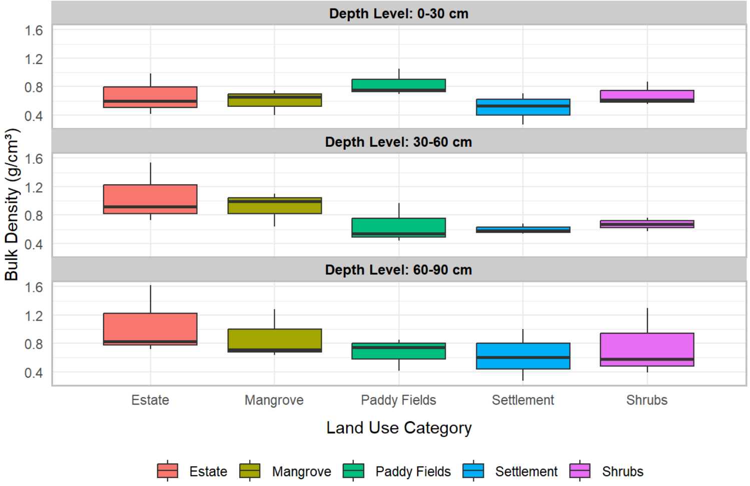

Figure 2 Soil bulk density (g cm^{-3}) by land use category and depth level.

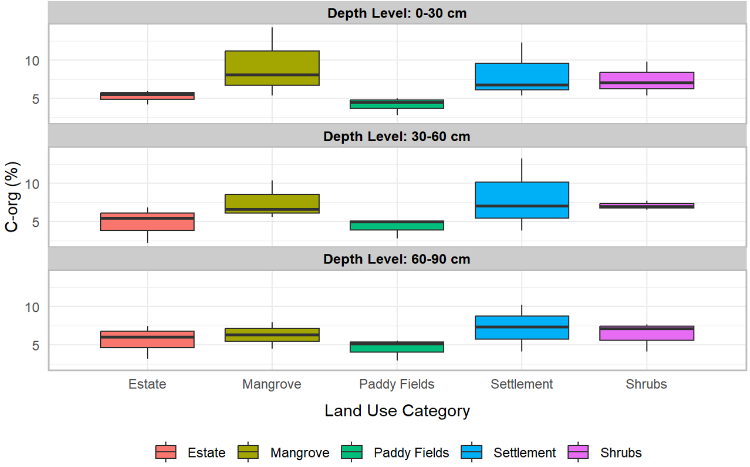

Figure 3 Organic carbon content (C-org, %) across land use types and soil depths.

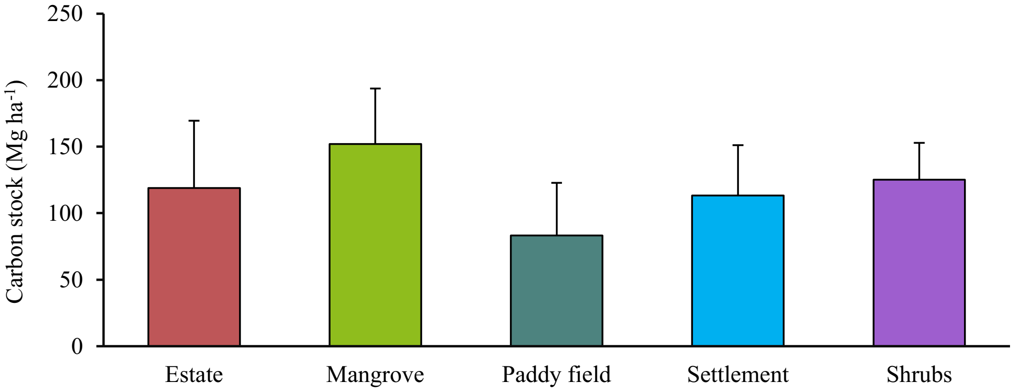

Figure 4 Total carbon stock up to 90 cm depth by land use category (Mg C ha^{-1}).

of mangrove land cover in soil carbon storage, with over 152 Mg C ha^{-1} recorded. Shrubs and settlements also contributed substantial stocks (115–125 Mg C ha^{-1}), reflecting vegetative input and organic material retention. In contrast, paddy fields–despite having extensive root systems–showed the lowest carbon accumulation (under 85 Mg C ha^{-1}), likely due to high disturbance and less organic input.

PCA To further explore the relationships among land use types based on soil parameters, a PCA was conducted using two main variables: BD and C-org. The PCA results are illustrated in Figure 5 (individual PCA plot) and Figure 6 (PCA biplot with vectors).

The first principal component (Dim1) accounted for 79.1% of the total variance in the dataset, while the second component (Dim2) explained 20.9%. This indicates that nearly all variation among soil samples can be meaningfully summarized along these two axes. In the individual PCA plot (Figure 5), there is a clear spatial separation between samples from Estate (red) and Mangrove Forest (yellow) areas. Estate samples tend to cluster toward the left side of the Dim1 axis, while Mangrove samples appear on the right. This separation reflects significant differences in soil characteristics between these two land uses. Conversely, other land use types, including Rice Fields (green), Settlements (blue), and Shrubs (purple), appear to overlap more substantially, particularly around the center of the PCA space. This suggests that these land covers share more similar soil characteristics, possibly due to common management practices, anthropogenic disturbances, or transitional vegetation structures. The PCA biplot (Figure 6) shows that BD has a strong negative correlation with Dim1, while C-org is strongly positively associated. This indicates an inverse relationship between the two variables: samples with high BD (e.g., Estate) are characterized by low C-org, while those with high C-org (e.g., Mangrove Forest) tend to have low BD. This trade-off is consistent with soil ecological theory, where high organic matter inputs in mangrove environments result in looser, carbon-rich soils, while compacted plantation soils tend to have reduced organic content. Some data points, such as samples 26, 34, and 45, lie farther from their respective group centroids, suggesting localized conditions or micro-variation in soil properties, potentially driven by microtopography, specific vegetation types, or historical land use. These outliers can offer useful insight into site-specific processes that may warrant further field investigation.

Discussion

Differences in soil carbon stocks across land covers Our results demonstrate clear contrasts in SOC stocks among mangroves, shrubs, settlements, plantations, and rice fields in Segara Anakan, and these values can be meaningfully positioned relative to other tropical coastal landscapes. Mangrove forests exhibited the highest SOC stocks, consistent with global and regional studies identifying mangroves as among the most carbon-rich ecosystems. However, the SOC values observed in Segara Anakan mangroves fall within a moderate range when compared to large, relatively undisturbed deltaic mangroves in Indonesia and Southeast Asia, where soil carbon stocks commonly exceed 300–500 Mg C ha^{-1} (Sasmito et al., 2019; Murdiyarso et al., 2021). In contrast, land covers such as settlements and plantations display substantially lower soil carbon levels, owing to intensive land management and degradation of natural ecosystems (Yuen et al., 2013; Castillo, 2017). Research from the Mahakam Delta and Segara Anakan further confirms that converting mangroves to ponds or agricultural fields can reduce soil carbon stocks by over 50% (Arifanti, 2017; Jennerjahn et al., 2022). Shrublands and secondary vegetation in Segara Anakan store moderate SOC stocks, which are relatively high compared to shrublands in other parts of Southeast Asia, where SOC commonly ranges between 60 and 110 Mg C ha^{-1} (Lasco, 2002). This suggests that shrublands in Segara Anakan benefit from continuous sediment inputs and organic matter accumulation in the lagoonal environment. Settlement areas exhibit lower SOC stocks than mangroves and shrubs, yet their values are higher than many urban soils reported globally, which often store less than 80 Mg C ha^{-1} unless supported by extensive green spaces (Pouyat et al., 2002b; Pouyat et al., 2006). Plantation areas show SOC stocks comparable to or slightly higher than intensively managed plantations elsewhere in the tropics,

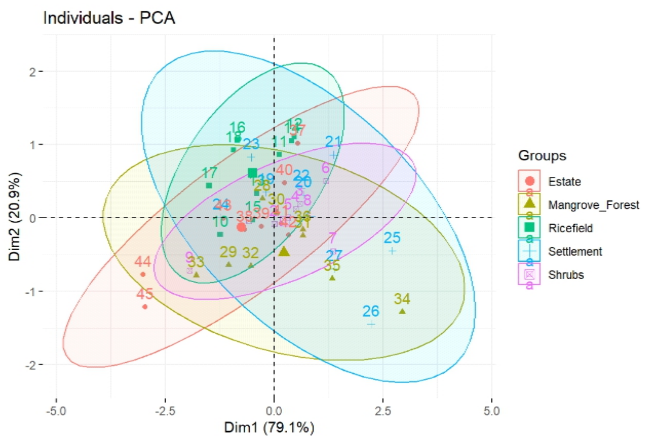

Figure 5 PCA individual plot showing sample grouping by land use.

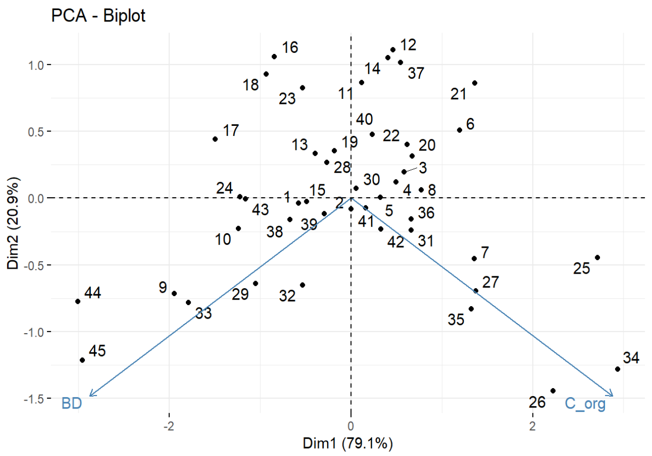

Figure 6 PCA biplot showing variable loadings of bulk density (BD) and organic carbon content (C-org).

where forest-to-plantation conversion typically reduces SOC to 60–120 Mg C ha^{-1} (Guo & Gifford, 2002). Rice fields display the lowest SOC stocks in Segara Anakan, consistent with global evidence that frequent tillage, flooding, and chemical inputs limit long-term soil carbon accumulation in paddy systems (Hapsari et al., 2020).

Although soil sampling at 0–30 cm depth is commonly applied in terrestrial systems (Food and Agriculture Organization, 2022), this approach is inadequate for mangrove ecosystems where substantial soil organic carbon (SOC) is stored below 30 cm due to anaerobic conditions and continuous sediment burial (Intergovernmental Panel on Climate Change, 2019). Therefore, it recommends soil carbon sampling in mangroves to a depth of at least 1 m to avoid underestimation of total carbon stocks. The higher C-org observed in settlement areas at the 30–60 cm and 60–100 cm depths (Table 1; Figure 3) is likely a legacy effect of past land use, where organic-rich subsurface horizons remain preserved despite surface disturbance. Additional inputs from household organic residues may also contribute to deeper C-org accumulation. In contrast, mangrove subsurface layers may be dominated by mineral sediments due to hydrodynamic processes, resulting in lower C-org concentrations at intermediate depths (Alongi, 2014; Donato et al., 2011). Limiting sampling to surface layers alone risks underestimating actual carbon stocks.

Curiously, our findings indicate that C-org content in settlement areas surpassed that in mangroves between 30 and 90 cm depths. This could arise from older soil horizons enriched with organic matter from previous agricultural or paddy field uses (Kaye, 2014), coupled with the accumulation of household organic waste (Kumar et al., 2023). By contrast, the mangroves here likely contain subsurface layers dominated by sand or mineral content, resulting in comparatively lower C-org at intermediate depths (Marchand et al., 2006).

The difference in land cover influences the ecological balance of SOC content, which results from the interaction of plant residues and microbial decomposition (Zhang et al., 2024). Mangroves occupy the first position in soil carbon storage due to their high organic productivity, litter accumulation, and anaerobic conditions that slow decomposition. These unique conditions make mangroves important carbon sinks both above and below ground (Donato et al., 2011). In addition, mangroves have the ability to sequester carbon over long periods, supporting their critical role in climate change mitigation (Alongi, 2014). Shrubs rank second in SOC accumulation. Their dense and diverse vegetation results in abundant litter input and a more stable decomposition process. Although lower than mangroves, shrublands remain essential in storing carbon, especially in landscapes lacking natural forest cover (Gibbs et al., 2007). Settlements came next, with lower soil carbon than mangroves and shrubs. Urban activities such as infrastructure development reduce soil organic content; however, vegetation like ornamental trees and organic residues from domestic sources still contribute to SOC (Pouyat et al., 2002b). Despite this, impervious surfaces in settlements limit organic matter infiltration and carbon retention.

Plantation areas, though vegetated, often experience disturbances from tillage, fertilization, and pesticide use, which reduce SOC accumulation. Short life cycles of cultivated plants also limit biomass contribution to the soil (Guo & Gifford, 2002). Lastly, rice fields exhibited the lowest carbon stocks. Frequent tillage, inundation, and chemical use enhance decomposition of organic material and prevent effective carbon sequestration. Rice cultivation with homogeneous vegetation and short growing cycles adds minimal organic matter to the soil (Zuo et al., 2023).

Ecological impacts of land cover on soil carbon and sequestration potential Significant differences were found in SOC content and carbon sequestration potential across different land cover types and soil depths. Vertically, SOC content was highest in topsoil layers (0–30 cm) and gradually decreased with depth. This is attributed to higher biological activity and organic inputs in surface soils (Jobbagy & Jackson, 2000; Schmidt et al., 2011). Mangrove and shrub areas maintained relatively high SOC content at deeper depths, suggesting better long-term storage conditions supported by lower oxygen levels, consistent soil temperatures, and lower decomposition rates (Peros et al., 2008). Mangrove ecosystems can store three to five times more carbon than tropical upland forests (Donato et al., 2011; Alongi, 2014). Conservation efforts are vital, as emphasized by Murdiyarso et al. (2015), who noted that mangrove loss accelerates atmospheric CO_2 emissions.

Shrubs, though secondary vegetation, contribute meaningfully to SOC, especially in regenerating or transitional landscapes (Syam'ani et al., 2012). Settlements, particularly those with urban greening efforts, have demonstrated moderate carbon stocks. Studies from urban environments indicated that green spaces and urban vegetation (e.g., shade trees) can store measurable (Pouyat et al., 2002a; Nowak et al., 2013). Conversely, rice fields and plantations generally exhibited lower carbon storage. Land conversion from forests to agriculture or plantation significantly reduces biomass and disrupts soil carbon pools (Guo & Gifford, 2002). For instance, Irsan and Izdihaar (2024) reported a 91,708-ton carbon stock loss in Paloh due to forest conversion to agriculture and settlements between 2018 and 2023.

Policy implications and landscape carbon management These findings emphasize the critical role of conserving high-carbon ecosystems like mangroves. Land-use change remains a major source of global carbon emissions (Intergovernmental Panel on Climate Change, 2019). Protecting and restoring natural vegetation types—especially mangroves and secondary forests—offers a nature-based solution for enhancing soil carbon stocks and mitigating climate change (Kalantari et al., 2023).

Landscape-level strategies should prioritize the maintenance of ecosystems in later succession stages where SOC accumulation is higher and more stable. Forest ecosystems represent a carbon saturation point, where further natural succession contributes marginally to SOC (Zhang et al., 2024). This illustrates the value of succession-aware planning in reforestation and rehabilitation programs. Urban ecosystems, while limited in spatial extent, can contribute through green infrastructure. Urban greening, tree planting, and sustainable landscape planning can enhance SOC in residential zones (Nowak et al., 2013). Integrating SOC indicators into national climate accounting systems and land management policy frameworks could improve the accuracy and effectiveness of emissions reduction targets. SOC mapping in diverse ecological zones should be expanded to support ecosystem-based mitigation strategies.

Conclusion

This study confirms that land cover type plays a crucial role in controlling soil organic carbon storage across different depth layers in the Segara Anakan landscape. Among the five land cover categories examined mangroves, shrubs, settlements, plantations, and rice fields mangrove ecosystems consistently exhibit the highest organic carbon content and soil carbon stocks, particularly at the 30–60 cm depth. Shrublands store moderate levels of soil carbon, while settlements show slightly lower but still notable carbon stocks, likely reflecting residual organic matter in vegetated urban areas. In contrast, plantations and rice fields exhibit the lowest soil carbon stocks, which is associated with frequent soil disturbance, short vegetation life cycles, and limited organic matter inputs. Vertically, soil carbon stocks generally decrease with increasing depth; however, vegetated and less-disturbed land covers retain relatively higher carbon levels in deeper soil layers, emphasizing the importance of subsurface carbon storage. Principal component analysis further reveals distinct differences in soil characteristics among land cover types, particularly between mangrove forests and estate lands in terms of bulk density and organic carbon. Overall, these findings highlight the dominant role of mangroves in belowground carbon storage and underscore the importance of land cover in shaping long-term soil carbon dynamics.

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