Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2025.v30i3.175-188

Influence of Land Use and Land Cover Variations on Soil Carbon Sequestration Potential in the Northern Madhupur Tract, Bangladesh

Nishat Tasnim, Rehana Khatun, Aslam Ali, Sadiqur Rahman and Murad Ahmed Farukh*

Department of Environmental Science, Bangladesh Agricultural University, Mymensingh, 2202, Bangladesh
e-mail: farukh_envsc@bau.edu.bd

Received 02 Mei 2025 Revised 16 August 2025; Accepted 24 August 2025

ABSTRACT

This study examines the effects of diverse land use and land cover (LULC) types on soil physico-chemical properties and carbon sequestration potential in the northern Madhupur Tract, Bangladesh. Soil samples were collected from seven LULC types – sal forest, social forest, orchard, bare land, agricultural land, protected area, and built-up area across three depths (0–15 cm, 16–40 cm, and 41–70 cm) between April and September 2022. Key parameters analyzed included texture, bulk density, pH, electrical conductivity (EC), total nitrogen, available phosphorus, exchangeable potassium, available sulfur, organic carbon (OC), and soil organic carbon (SOC). Soil texture ranged from clay loam to clay. Bulk density was the lowest in built-up areas (1.57–1.62 g cm^{-3}) and the highest in protected areas (1.97–2.20 g cm^{-3}). Orchard soils had the highest surface moisture (23.26%). Surface soils showed the highest EC (0.82 dSm^{-1}), total N (0.11%), available P (118.6 ppm), and OC (1.07%), while pH increased with depth, peaking at 6.15. SOC stock differed significantly among land uses ($F = 6.56$, $p < 0.05$), highest in social forests (138.67 Mg ha^{-1}) and built-up areas (134.04 Mg ha^{-1}). Corresponding CO_2 mitigation potentials were 508.93 Mg C ha^{-1} and 491.34 Mg C ha^{-1}. Agricultural land had the lowest SOC stock (85.31 Mg ha^{-1}). Enhancing carbon storage through better land management is vital for sustainability and climate resilience.

Keywords: Carbon stock dynamics, land use change, madhupur tract ecosystem, soil carbon sequestration

INTRODUCTION

Carbon sequestration in terrestrial ecosystems refers to the net removal of atmospheric carbon dioxide (CO_2) or the prevention of its release from land-based systems, a process central to climate change mitigation (IPCC, 2000). Globally, soils represent a significant carbon sink, storing an estimated 2,300–2,500 gigatonnes (Gt) of carbon, making them the third-largest reservoir after oceans and fossil fuels (Matovic, 2011; Lal, 2008). Soil organic carbon (SOC) is a pivotal component of this pool, containing nearly twice as much carbon as the atmosphere (Rahman et al., 2021). Beyond its climate-regulating role, SOC supports soil fertility, water retention, and nutrient cycling, thereby underpinning agricultural productivity and food security (Bünemann et al., 2018). Because soils can function as both sources and sinks of greenhouse gases (GHGs), their management strongly influences global carbon budgets (Smith et al., 2015; FAO, 2020).

Land use and land cover (LULC) change is one of the primary drivers of SOC variability. The conversion of forests and grasslands to croplands typically reduces SOC stocks, whereas practices such as agroforestry, residue retention, and reduced tillage can enhance them (Don et al., 2011; Chenu et al., 2019; Lal, 2021). In tropical regions, where land pressures are particularly intense, understanding SOC dynamics across different LULC types is essential for developing climate-smart land management strategies (Post & Kwon, 2000; Kooch et al., 2020).

In Bangladesh, soils are distributed across diverse physiographic units, among which the Madhupur and Barind tracts represent distinctive Pleistocene terraces. The Madhupur Tract is especially important for its Sal (*Shorea robusta*) forests, which account for approximately one-third of the nation's forest land (BBS, 2005; Rahman, 2015). However, this region is under severe anthropogenic pressure due to population growth, agricultural expansion, deforestation, and infrastructure development linked to its proximity to Dhaka (Alamgir et al., 2021). These transformations threaten both biodiversity and ecosystem services, including soil carbon storage, with potential implications for Bangladesh's national GHG inventories and climate commitments (Hossain et al., 2020; IPCC, 2021).

Despite its importance, research on carbon in the Madhupur TracMg has primarily concentrated on aboveground biomass carbon (Karim et al., 1994; Rahman, 2015; Saha et al., 2021), with relatively little attention given to soil carbon pools. Where SOC has been examined, studies have either been broad-scale (Rahman et al., 2021; Hossain et al., 2020) or limited to single land-use categories. Systematic, depth-resolved assessments of SOC stocks across the heterogeneous land uses of the Tract, ranging from natural and social forests to orchards, agricultural land, bare land, protected areas, and built-up areas, are virtually absent. It represents a critical knowledge gap, particularly given the region's rapid land transformation.

This study addresses that gap by conducting a comparative, multi-depth (0–70 cm) assessment of soil physico-chemical properties and SOC stocks across seven LULC types in the northern Madhupur Tract. By quantifying not only SOC but also the associated CO_2 mitigation potential, this work moves beyond descriptive analysis to evaluate the climate-regulating services of soils under contrasting land management regimes. Importantly, our findings reveal that social forests and even certain built-up areas retain higher SOC than intensively cultivated croplands, challenging conventional assumptions about land-use effects on soil carbon.

Thus, the novelty of this study lies in (i) providing the first integrated, depth-specific SOC dataset across multiple LULC systems in the Madhupur Tract, (ii) identifying land-use patterns that either deplete or enhance soil carbon storage, and (iii) linking SOC stocks with CO_2 mitigation potential in a rapidly transforming Pleistocene terrace ecosystem. These insights will support the design of sustainable land management practices, inform Bangladesh's climate mitigation policies, and contribute to global discussions on soil-based natural climate solutions (Paustian et al., 2016; Jones et al., 2018).

MATERIALS AND METHODS

Site Selection

The study was conducted in the northern part of the Madhupur Tract, which lies within the greater Mymensingh and Tangail districts. The Madhupur Sal Forest (MSF) is a tropical, moist, deciduous forest that represents one of Bangladesh's distinctive forest ecosystems. Geographically, the MSF is

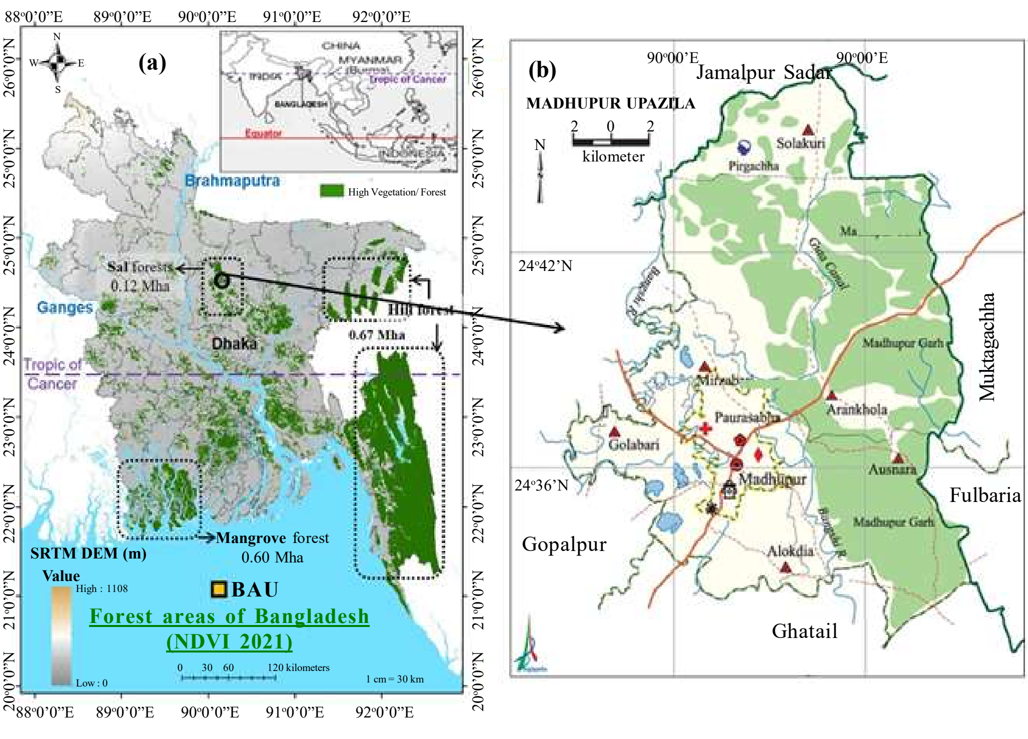

Figure 1. Map of the study area (**a**) Map of the forest areas of Bangladesh, compiled from MODIS Terra/ Aqua 16-day normalized difference vegetation index (NDVI) for 2021 (adapted from Farukh et al., Atmosphere, 2023, 14, 97; https://doi.org/10.3390/atmos14010097, (b) research location

located at 24°45' N latitude and 90°05' E longitude (Figure 1). The MSF spans 18,453.90 hectares, of which 1,022.63 hectares are designated as reserved forest. An additional 1,743.12 hectares are currently undergoing the process of being declared a reserved forest. To support biodiversity conservation, the Government of Bangladesh designated the Madhupur Garh region as the Madhupur National Park (MNP) (Ahmed, 2008). According to IPAC (2009), MNP is divided into four administrative ranges and ten beats. The four ranges are: i) National Park Range, ii) Dokhola Range, iii) Madhupur Range, and iv) Arankhola Range. For this study, three ranges — National Park, Dokhola, and Arankhola — were selected as sampling sites.

Broadly, the study area was categorized into seven distinct land use types: forest land (both natural Sal and social forests), agricultural land, orchard land, bare land, protected area, and built-up area. In recent decades, deforestation within the Madhupur Fores Mg has been primarily driven by expanding agricultural practices, including the cultivation of cash crops such as corn. Local communities have also increasingly established commercial pineapple and banana orchards within the forest. Areas of bare land have been observed, indicating further land degradation. Currently, the Madhupur Sal Forest covers approximately 45,564.18 acres, of which 2,525.14 acres are officially designated as a reserved forest (protected area). Historically, a significant portion of this foresMg has been encroached upon by local settlers, contributing to the expansion of built-up areas. Consequently, the forested area has been diminishing over time. Misguided policy decisions and corruption have further exacerbated the degradation of the forest, severely threatening this unique habitat for flora and fauna.

Soil Sample Collection And Preparation

To conduct the study, a stratified random sampling method was employed following the approach of Wu et al. (2016). The initial sampling point was selected at random. Within each of the seven LULC types, sampling plots were first identified using recent land use maps and ground-truthing surveys. To minimize edge effects and local heterogeneity, sampling was restricted to relatively homogeneous patches of at least 0.5 ha with minimal disturbance. Within each patch, sampling points were randomly chosen, with three replications per LULC type across the three administrative ranges (National Park, Dokhola, and Arankhola). In total, 63 soil samples were collected, representing three soil depths: 0–15 cm, 16–40 cm, and 41–70 cm. GPS coordinates were recorded for all sampling points to ensure reproducibility.

All samples were collected once during the peak dry season (April–May 2022), which minimized temporal variability in soil moisture and management activities. Although the study period covered April–September 2022, the sampling itself was confined to this dry-season window, making the dataset a single-season baseline assessment.

The collected samples were transported to the laboratory for subsequent physical and chemical analyses. In preparation, the samples were air-dried at room temperature, thoroughly mixed, crushed, and sieved through a 20-mesh screen, then stored in plastic bags. All laboratory analyses were conducted at the Bangladesh Institute of Nuclear Agriculture (BINA) in Mymensingh.

Analysis of Soil Sample

Soil Texture

Soil texture was determined using the Feel method (Arshad et al., 1997), and soil classes were identified based on the USDA soil textural classification system.

Soil Moisture Content

Soil moisture (SM) content is a key component of the soil water budget. It plays a vital role in agriculture, hydrology, and water resources management, particularly in determining crop water requirements. SM content was determined using the following equation:

$$\%\,Moisture = \frac{Wet\ soil\ (g) - Dry\ soil\ (g)}{Dry\ soil\ (g)} \times 100$$

Soil Bulk Density

Soil bulk density was determined using the core sampling method (Blake & Hartge, 1986). Oven-dry (at 105°C) soil samples were used for moisture correction. The following formula calculates bulk density:

Bulk density (g cm^{-3}) = (Oven dry weight of soil in gm)/ (Volume of the soil in cm^3)

where, Volume of the soil = Volume of core – Volume of the stone.

Soil pH

The soil pH was determined electrochemically as described by Jackson (1962).

Soil electrical conductivity (EC)

The electrical conductivity of soil was measured by the EC meter (Biswas & Mukherjee, 1987).

Organic carbon

Organic carbon of soil was determined by the wet oxidation method of Walkey and Black (1934).

Soil Organic Carbon (SOC)

Soil organic carbon (SOC) was analyzed using the Walkley-Black wet oxidation method (Walkley & Black, 1934). Total SOC was estimated using the following formula, as described by Donato et al. (2011) and Sahu et al. (2016), and the amounts were converted into tonnes per hectare.

SOC= Organic carbon content % × soil bulk density (g cm^{-3}) × thickness of horizon

Total Nitrogen

Total nitrogen content in soil was determined by the semi-micro-Kjeldahl method (Bremner & Mulvaney, 1982).

Available Phosphorus

Available P was extracted from soil samples using the Olsen method (Olsen et al., 1954).

Exchangeable Potassium (K)

Exchangeable potassium (K) was determined using a flame photometer and calibrated with a standard K curve (Black, 1965).

Available Sulphur

Available Sulphur was determined by Williams and Steinberg (1959).

CO_2 mitigation potential in different land use types through sequestration

CO_2 mitigation potential is calculated using the formula of Bhandari and Bam (2013). CO_2 mitigation potentialŠ§ SOC × 3.67.

Statistical Analysis

The effects of land use type and soil depth on soil physical and chemical parameters were tested

Table 1. Physical properties of the soil under different land use and land cover.

Land use types	Soil depth (cm)	Textural class	Moisture content (%)	BD (gm cm^{-3})
Sal forest	0-15	Clay loam	20.02	1.70
	16-40	Clay loam	19.98	1.85
	41-70	Clay loam	19.73	1.93
Social forest	0-15	Loam	22.25	1.73
	16-40	Clay loam	21.05	1.95
	41-70	Loam	19.88	2.02
Orchard	0-15	Clay	23.26	1.80
	16-40	Clay loam	21.89	1.87
	41-70	Clay loam	21.56	1.96
Bare land	0-15	Clay loam	18.76	1.65
	16-40	Loam	18.25	1.71
	41-70	Clay loam	18.03	1.70
Agriculture land	0-15	Loam	20.46	1.66
	16-40	Clay	19.91	1.65
	41-70	Loam	18.35	1.78
Protected Area	0-15	Loam	21.24	1.97
	16-40	Clay loam	20.18	2.02
	41-70	Clay loam	20.24	2.20
Build up Area	0-15	Clay loam	19.57	1.57
	16-40	Clay loam	19.32	1.51
	41-70	Clay loam	19.04	1.62

using one-way ANOVA. Where significant differences were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was used as a post hoc procedure to identify pairwise differences among treatments. All statistical analyses were performed using SPSS version 25.0 (IBM Corp., Armonk, NY, USA).

RESULTS AND DISCUSSION

Physical properties of soil

Soil texture

Table 1 summarizes the textural classification of the soil samples. Of the 63 samples analyzed, 38 were classified as clay loam, nine as loam, and six as clay.

Moisture content of soil

In the present study, the mean moisture content was observed to follow the descending order: orchard (22.24%) > social forest (21.06%) > protected area (20.55%) > sal forest (19.91%) > agricultural land (19.57%) > built-up area (19.31%) > bare land (18.35%) (Table 1).

Bulk density (BD) of soil

Bulk density (BD) across different depths varied by land use type, ranging from 1.70–1.93 g cm^{-3} in sal forest, 1.73–2.02 g cm^{-3} in social forest, 1.80–1.96 g cm^{-3} in orchard, 1.65–1.71 g cm^{-3} in bare land, 1.66–1.78 g cm^{-3} in agricultural land, 1.97–2.20 g cm^{-3} in protected areas, and 1.57–1.62 g cm^{-3} in built-up areas (Table 1). A statistically significant variation in bulk density was observed across soil depths under different land use types ($P < 0.05$). Bulk density ranged from 1.57 to 1.97 g cm^{-3} at 0–15 cm, 1.51 to 2.02 g cm^{-3} at 16–40 cm, and 1.62 to 2.20 g cm^{-3} at 41–70 cm depths. The highest bulk density (2.20 g cm^{-3}) was recorded in protected areas at 41–70 cm depth, while the lowest (1.57 g cm^{-3}) was observed in built-up areas at 0–15 cm depth.

Chemical properties of soil

Soil pH

Soil pH across all land use types ranged from 4.00 to 6.15 (Figure 2). The highest pH value (6.15) was recorded in agricultural land at a depth of 41–70 cm, while the lowest (4.00) was observed in orchard soils at the 0–15 cm depth. Soil pH varied significantly among land use types ($P < 0.05$) and across soil depths. Specifically, pH ranged from 4.10 to 6.15 at 0–15 cm, 4.00 to 6.00 at 16–40 cm, and 4.10 to 5.15 at 41–70 cm.

Electrical Conductivity (EC)

The electrical conductivity (EC) of soils varied across different land use types, ranging from 0.37–0.50 dS m^{-1} in sal forest, 0.32–0.64 dS m^{-1} in social forest, 0.53–0.82 dS m^{-1} in orchard, 0.37–0.41 dS m^{-1} in bare land, 0.24–0.39 dS m^{-1} in agricultural land, 0.18–0.33 dS m^{-1} in protected areas, and 0.58–0.70 dS m^{-1} in built-up areas (Figure 3). The results indicated significant variation in EC values across

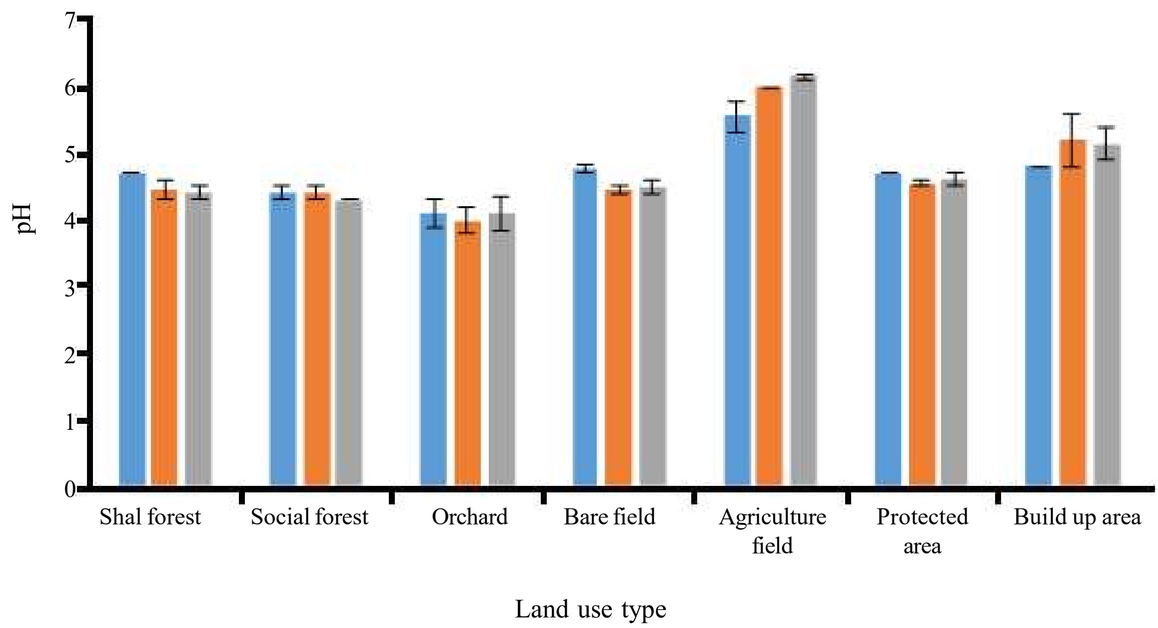

Figure 2. pH of soils under different land use types. ■: 0-15 cm, ■:16-40 cm, ■: 41-70 cm.

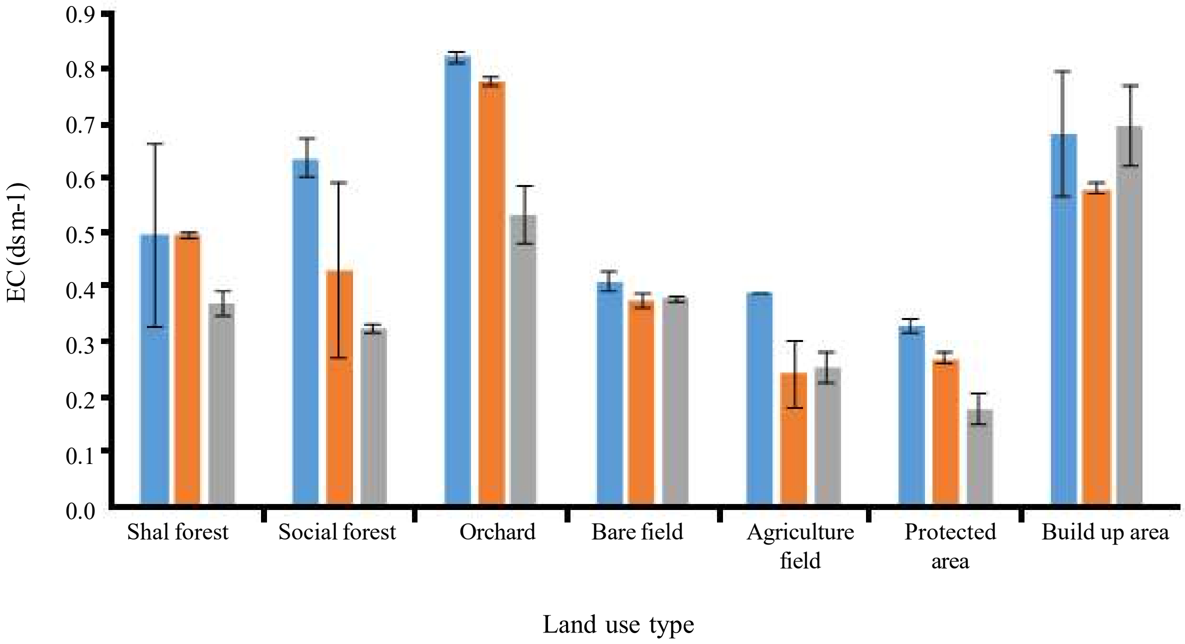

Figure 3. Electrical conductivity of soils under different land use types. ■ : 0-15 cm, ■ :16-40 cm, ■ : 41-70 cm.

both land use types and soil depths (P < 0.05). At the 0–15 cm depth, EC ranged from 0.33 to 0.70 dS m^{-1}, with an average of 0.54 dS m^{-1}. At 16–40 cm, it varied from 0.24 to 0.78 dS m^{-1} (mean: 0.45 dS m^{-1}), and at 41–70 cm, it ranged from 0.18 to 0.70 dS m^{-1}, with an average of 0.39 dS m^{-1}. The highest EC value (0.82 dS m^{-1}) was recorded in orchard land at the 0–15 cm depth, while the lowest value (0.18 dS m^{-1}) was observed in the protected area at 41–70 cm depth.

Total Nitrogen Content (N)

The total nitrogen content across all land use types ranged from 0.035% to 0.111% (Figure 4). The highest concentration was observed in the surface soil (0–15 cm depth) of bare land (0.111%), followed by orchard land (0.104%). In contrast, the lowest value (0.035%) was recorded in the subsoil (41–100 cm) of the sal forest. Total nitrogen content varied significantly (P < 0.05) among different land

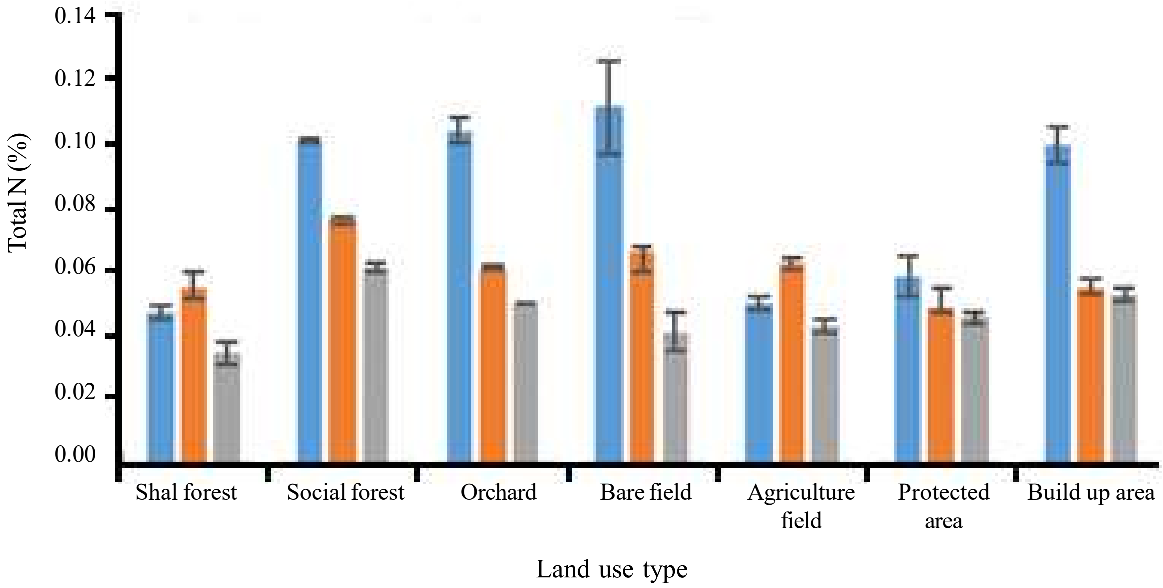

Figure 4. Nitrogen content of soils under different land use types. ■ : 0-15 cm, ■ :16-40 cm, ■ : 41-70 cm.

use types. Nitrogen content also showed significant variation with soil depth ($P < 0.05$). The highest concentration was found in the topsoil layer (0–15 cm), with a mean value of 0.082%. At 16–40 cm depth, total nitrogen ranged from 0.050% to 0.076%, averaging 0.061%, while at 41–70 cm depth, it ranged from 0.035% to 0.076%, with a mean value of 0.047%.

Available Phosphorus Content (P)

The available phosphorus content across all land use types ranged from 2.2 to 118.59 ppm (Figure 5). The highest mean available phosphorus was observed in surface soils (0-15 cm depth), and it decreased with increasing soil depth. The maximum available phosphorus, 118.59 ppm, was found in the orchard at a depth of 0-15 cm, while the lowest, 2.2 ppm, was recorded in agricultural land at a depth of 41-70 cm. The available phosphorus ranged from 3.68 to 118.59 ppm in the 0-15 cm depth, 2.65 to 24.64 ppm in the 16-40 cm depth, and 2.2 to 20.75 ppm in the 41-70 cm depth. ANOVA results revealed significant differences between land use types and depths ($P < 0.05$).

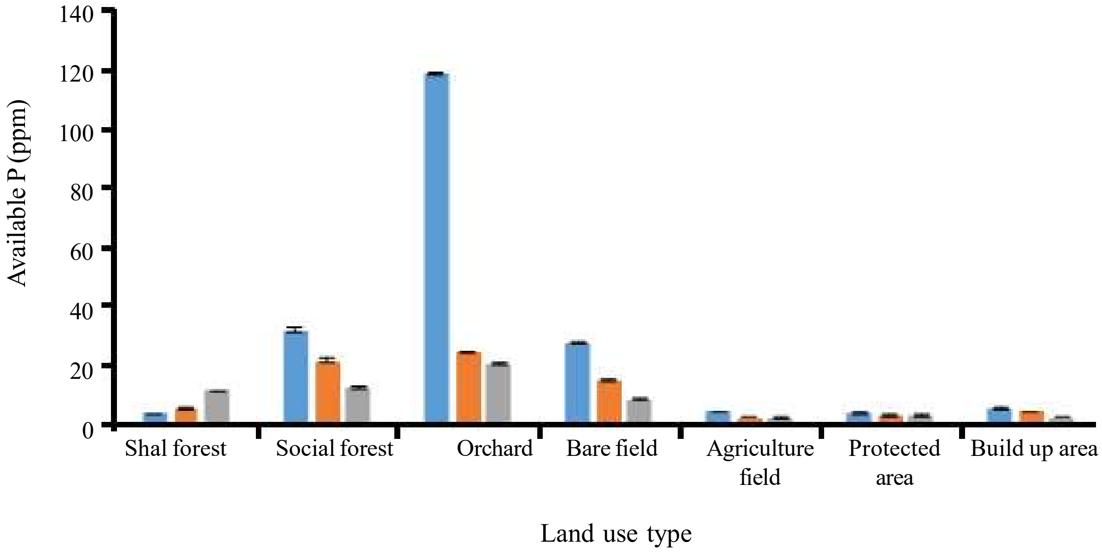

Figure 5. Available phosphorus of soils under different land use types. ■: 0-15 cm, ■:16-40 cm, ■: 41-70 cm.

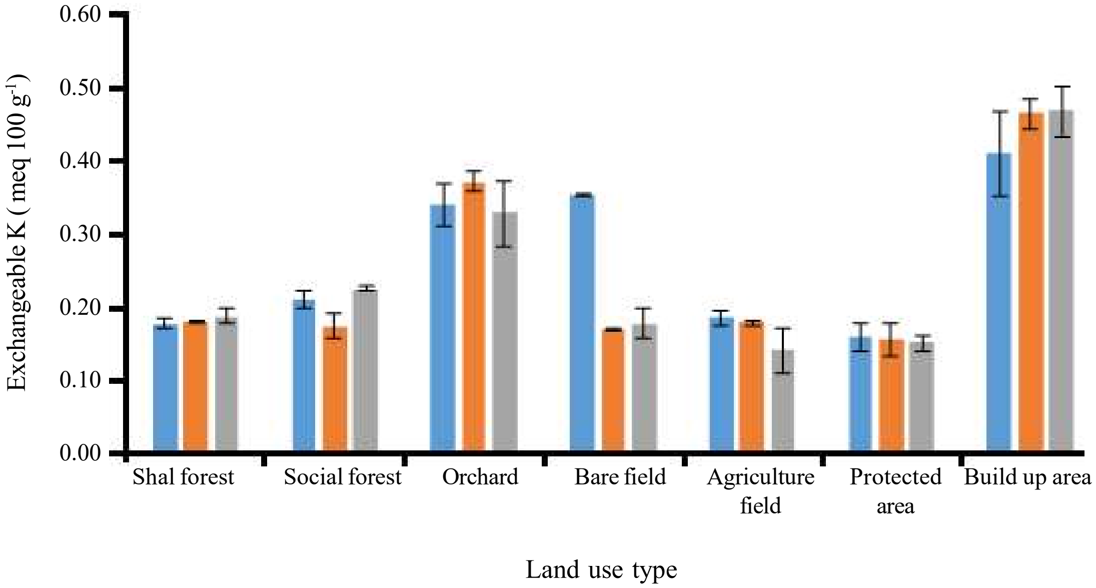

Figure 6. Exchangeable potassium of soils under different land use types. ■: 0-15 cm, ■:16-40 cm, ■: 41-70 cm.

Exchangeable Potassium Content (K)

The exchangeable potassium (K) content across all land use types ranged from 0.142 to 0.470 meq $100g^{-1}$. The highest value, 0.470 meq $100g^{-1}$, was observed in the built-up area at a depth of 41-70 cm, while the lowest value, 0.142 meq $100g^{-1}$, was recorded in agricultural land at the same depth (Figure 6). The exchangeable K content was significantly affected by land use type ($P < 0.05$). At the 0-15 cm soil depth, the exchangeable K content ranged from 0.161 to 0.412 meq $100g^{-1}$, with a mean of 0.264 meq $100g^{-1}$, indicating a medium status of exchangeable K in the soil samples. For the 16-40 cm soil depth, exchangeable K ranged from 0.157 to 0.468 meq $100g^{-1}$, with a mean value of 0.243 meq $100g^{-1}$. At 41-70 cm, the extractable potassium content ranged from 0.142 to 0.470 meq $100g^{-1}$, with a mean of 0.241 meq $100g^{-1}$ (Figure 5). Additionally, the extractable potassium content varied significantly by soil depth ($P < 0.05$).

Available sulfur content (S)

The available sulfur across different land-use and land-cover types ranged from 18.39 to 38.01 ppm (Figure 7). The highest value, 38.01 ppm, was observed in the built-up area at a depth of 16-41 cm, while the lowest value, 18.39 ppm, was recorded in the protected area at the same depth. The distribution of sulfur followed the order: built-up area > orchard > bare land > social forest > protected area > sal forest > agricultural land in the Madhupur tract. The range of available sulfur was 32.02 to 34.38 ppm at a depth of 0-15 cm, 18.38 to 38.01 ppm at 16-40 cm, and 25.63 to 33.22 ppm at 41-70 cm.

Organic Carbon Content (OC)

The organic carbon content of soil samples from various land use types in the northern part of the Madhupur tract ranged from 0.47% to 1.07% (Figure 8). Among the different soil types in the Madhupur tract, organic carbon in the sal forest ranged from 0.49% to 0.97%, in the social forest from 0.65% to 0.96%, in the orchard from 0.45% to 1.06%, in bare land from 0.47% to 1.07%, in agricultural land from 0.43% to 0.63%, in protected areas from 0.50% to 0.64%, and in built-up areas from 0.81% to 1.05%. At the 0-15 cm depth, organic carbon content ranged from 0.97% to 1.05%, with a mean of 0.90%. At a depth of 16-40 cm, it ranged from 0.45% to 0.81%, with a mean of 0.63%. At the 41-70 cm depth, the organic carbon content ranged from 0.43% to 0.81%, with a mean value of 0.57% (Figure 7). The highest organic carbon content (1.07%) was observed in the orchard at the 0-15 cm depth, while the lowest (0.43%) was recorded in agricultural land at the 41-70 cm depth.

Soil Organic Carbon (SOC)

The organic carbon stock in soil samples from different land use types in the northern part of the Madhupur tract ranged from 13.20 to 78.73 Mg ha^{-1} (Table 2). The total soil organic carbon (SOC) stock was recorded as 108.41 Mg ha^{-1} in sal forest,

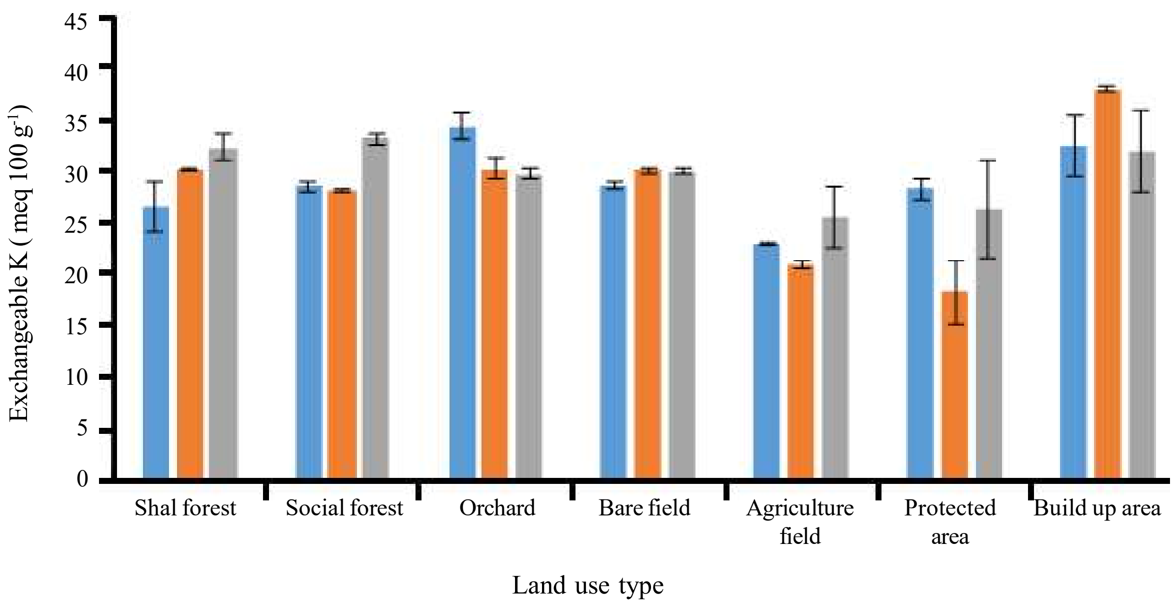

Figure 7. Available Sulphur of soils under different land use types. ■ : 0-15 cm, ■ :16-40 cm, ■ : 41-70 cm.

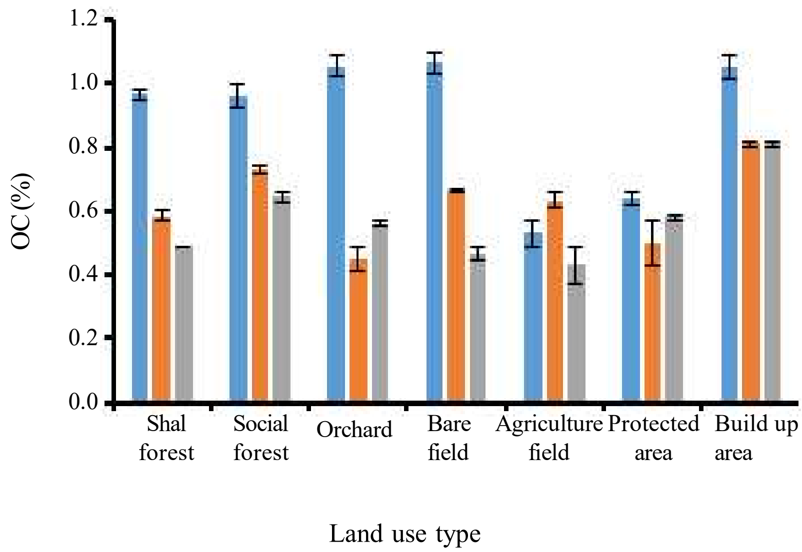

Figure 8. Organic carbon of soils under different land use types. ■: 0-15 cm, ■: 16-40 cm, ■: 41-70 cm.

138.67 Mg ha^{-1} in social forest, 115.38 Mg ha^{-1} in orchard, 102.77 Mg ha^{-1} in bare land, 85.31 Mg ha^{-1} in agricultural land, 120.72 Mg ha^{-1} in protected area, and 134.04 Mg ha^{-1} in built-up areas (Table 2). The highest total SOC was found in the social forest (138.67 Mg ha^{-1}), while the lowest was in agricultural land (85.31 Mg ha^{-1}). Land use types significantly influenced the SOC stock in the current study, with changes in land use causing substantial alterations in SOC density ($P < 0.05$). The results also revealed that SOC varied by soil depth: from 13.20 to 28.49 Mg ha^{-1} at 0-15 cm, with a mean of 23.03 Mg ha^{-1}; from 21.04 to 35.59 Mg ha^{-1} at 16-40 cm, with a mean of 27.73 Mg ha^{-1}; and from 45.92 to 78.73 Mg ha^{-1} at 41-70 cm, with a mean of 64.27 Mg ha^{-1}. The total SOC stock also exhibited significant variation with soil depth ($P < 0.05$).

CO_2 mitigation potential in different land use types through C sequestration

The CO_2 mitigation potential was 397.85 C Mg ha^{-1} (13%), 508.93 C Mg ha-^{1} (17%), 423.44 C Mg ha^{-1} (14%), 377.16 C Mg ha^{-1} (13%), 313.11 C Mg ha^{-1} (11%), 443.05 C Mg ha^{-1} (15%), and 491.92 C Mg ha^{-1} (17%) for sal forest, social forest, orchard, bare land, agricultural land, protected area, and built-up area (Figure 9). The present study demonstrated that social forests and built-up areas had significantly ($p < 0.05$) higher potential to sequester atmospheric carbon dioxide than other land-use types.

DISCUSSION

The observed variation in SOC and CO, mitigation potential across LULC types can be explained by underlying ecological and management processes. Forest-based systems (social forestry, sal forest, and protected forest) consistently exhibited the highest SOC levels. Mechanistically, this is attributable to higher litterfall, root biomass inputs, and minimal soil disturbance, all of which enhance organic matter accumulation and stabilization through aggregate formation and organo-mineral interactions. In contrast, agricultural lands are subjected to continuous tillage, crop residue removal, and intensive fertilizer application. These practices accelerate SOC mineralization, disrupt soil structure, and ultimately lower carbon storage capacity. Built-up areas demonstrated intermediate SOC values, which may appear counterintuitive, but can be explained by reduced erosion and organic inputs from homestead vegetation, domestic waste deposition, and limited soil turnover.

Statistical analyses further support these mechanistic interpretations. SOC was significantly and positively correlated with soil moisture ($r = 0.62$, $p < 0.01$), total nitrogen ($r = 0.71$, $p < 0.01$), and organic carbon percentage ($r = 0.83$, $p < 0.001$), while being negatively correlated with bulk density ($r = –0.54$, $p < 0.05$). Regression models indicated that organic carbon percentage and total nitrogen are the strongest predictors of SOC, explaining over 65% of the variance. These findings highlight that SOC is not only a product of land use type but also of specific soil physicochemical properties shaped by land management practices.

The implications for carbon management and climate policy in Bangladesh are significant. Enhancing SOC stocks through targeted land management can provide a practical, locally appropriate pathway for climate change mitigation. For instance, promoting social forestry programs not only boosts SOC sequestration but also supports rural livelihoods, aligning with Bangladesh's Nationally Determined Contributions (NDCs) under the Paris Agreement. Similarly, shifting from conventional to conservation agriculture by adopting reduced tillage, residue retention, and crop diversification could help slow SOC depletion in croplands. Integrating SOC monitoring into national greenhouse gas inventories would strengthen the accuracy of carbon accounting and inform adaptive land-use planning.

Overall, these results underscore the ecological and policy relevance of LULC transitions. By explicitly linking SOC dynamics to underlying soil processes and regional climate strategies, our study provides a framework for managing land resources to enhance carbon sinks and support sustainable development in the Meghna Basin and beyond.

CONCLUSIONS

This study investigated the impact of land-use and land-cover changes on soil physical and chemical properties and carbon sequestration potential in the northern part of the Madhupur Tract. The physico-chemical analysis showed that all soil samples from various land use types in the region were acidic, with medium to high clay content, indicative of highly weathered soils. Significant variations were observed in bulk density, moisture content, soil pH, electrical conductivity (EC), total nitrogen (N), available phosphorus (P), exchangeable potassium (K), available sulfur (S), organic carbon (OC) content (%), total organic carbon (Mg ha^{-1}), and CO, mitigation potential across different soil depths. The surface layer exhibited the highest concentrations of most soil parameters. Among the essential nutrients, organic carbon content ranged from low to medium, total nitrogen from very low to low, available phosphorus from very low to optimum, exchangeable potassium was predominantly very low, and available sulfur ranged from very low to medium. Overall, the results suggest that soil organic carbon (OC) was influenced by land-use type, with cultivation leading to OC depletion. However, this does not necessarily imply a loss of stable organic carbon. Less disturbed native soils do not always result in enhanced OC storage, as this depends on factors such as vegetation cover, management practices, and soil type. Both land use and soil depth significantly influenced SOC. The total SOC followed this order: social forest > built-up area > protected area > orchard > sal forest > bare land > agricultural land, with SOC values of 138.67, 134.04, 120.72, 115.38, 108.41, 102.77, and 85.31 Mg ha^{-1}, respectively. Bulk density (BD) increased with soil depth for all land uses, while the percentage of soil organic carbon decreased with increasing soil depth. It indicates that BD governs the quantity of organic carbon stored in soil, and that land use influences this quantity. Therefore, implementing appropriate land-use strategies and sustainable soil management practices is crucial for enhancing SOC storage capacity across different land-use systems.

The study also showed that soils in social forests and built-up areas had significantly ($p < 0.05$) higher CO_2 sequestration potential than those in other land-use types. It suggests that conditions favorable to increased vegetative cover, with minimal anthropogenic disturbance, promote greater soil carbon sequestration. In conclusion, land-use changes significantly affect soil carbon storage by altering vegetation, which, in turn, affects carbon inputs and outputs. Efforts should focus on implementing appropriate land-use management practices, such as applying biofertilizers and organic manure, to enhance SOC content. Converting agricultural land to managed perennial plantations can further increase soil carbon stocks. Effective land use management is critical for preserving existing soil carbon, and forest regions, in particular, have a great capacity to sequester carbon. This capacity can be further expanded through effective land-use management, helping these areas contribute to CO_2 mitigation.

ACKNOWLEDGEMENTS

The authors are highly thankful to the Ministry of Science and Technology, Bangladesh, for granting the National Science and Technology Fellowship, which partially supported the study.

REFERENCES

Ahmed, B., & Dewan, A. (2022). *Land use and land cover changes and their impact on environment in Bangladesh*. Springer.

Alamgir, M., Campbell, M. J., Sloan, S., Goosem, M., Clements, G. R., Mahmoud, M. I., & Laurance, W. F. (2021). Infrastructure expansion challenges sustainable development in Bangladesh. *npj Sustainable Urbanization*, *1*(1), 1–9. https://doi.org/10.1038/s42949-021-00017-9

Ali, S., Begum, F., Hayat, R., & Bohannam, B. J. M. (2017). Variation in soil organic carbon stock in different land uses and altitudes in Bagrot Valley, Northern Karakoram. *Acta Agriculturae Scandinavica, Section B — Soil and Plant Science*, *67*(6), 551–561.

Altrell, D. (2007). *National forest and tree resources assessment 2005–2007, Bangladesh*. Bangladesh Forest Department, Ministry of Environment and Forest.

Amelung, W., Bossio, D., de Vries, W., Kögel-Knabner, I., Lal, R., Lehmann, J., & Pan, G. (2020). Towards a global-scale soil climate mitigation strategy. *Nature Communications*, *11*(1), 1–10. https://doi.org/10.1038/s41467-020-18887-7

Arshad, M. A., Lowery, B., & Grossman, B. (1997). Physical tests for monitoring soil quality. In J. W. Doran & A. J. Jones (Eds.), *Methods for assessing soil quality* (pp. 123–141). Soil Science Society of America.

Bai, Y., Ma, L., Degen, A. A., Rafiq, M. K., Kuzyakov, Y., Zhao, J., Zhang, R., Zhang, T., Wang, W., Li, X., Long, R., & Shang, Z. (2020). Long-term active restoration of extremely degraded alpine grassland accelerated turnover and increased stability of soil carbon. *Global Change Biology*, *26*(12), 7217–7228. https://doi.org/10.1111/gcb.15361

Bajracharya, R. M., Lal, R., & Kimble, J. M. (2004). Erosion effects on carbon dioxide concentration and carbon flux from an Alfisol in Central Ohio. *Soil and Tillage Research*, *81*(2), 237–252.

Bajracharya, R. M., Sitaula, B. K., Shrestha, B. M., Awasthi, K. D., Balla, M. K., & Singh, B. R. (2004). Soil organic carbon status and dynamics in the central Nepal Middle Mountains. *Journal of the Institute of Forestry*, *12*, 28–44.

Bangladesh Bureau of Statistics. (2005). *Statistical yearbook of Bangladesh 2004*. Ministry of Planning, Government of Bangladesh.

Begum, K., Sikder, A. H. F., Khanom, S., Hossain, M. F., & Parveen, Z. (2015). Nutrient uptake by plants from different land types of Madhupur soils. *Bangladesh Journal of Scientific Research*, *28*(2), 113–121.

Berhanu, H. (2015). *Evaluation of selected soil physicochemical properties across land use types and soil depth in Sum Be sub-watershed of West Showa Zone, central Ethiopia* [Master's thesis, Haramaya University].

Bewket, W., & Stroosnijder, L. (2003). Effects of agroecological land use succession on soil properties in the Chemoga watershed, Blue Nile basin, Ethiopia. *Geoderma*, *111*(1–2), 85–98.

Bhandari, S., & Bam, S. (2013). Comparative study of soil organic carbon (SOC) under forest, cultivated and barren land: A case of Chovar Village, Kathmandu. *Nepal Journal of Science and Technology*, *14*(1), 103–108.

Bhat, Z. A., Akther, F. A., Ganaie, A. Q., Rehman, H. U., Dar, N. A., & Gill, R. K. (2017). Nutrient status of grape orchard soils of Jammu and Kashmir, India. *MOJ Ecology & Environmental Sciences*, *2*(5), 1–8.

Biswas, T. D., & Mukherjee, S. K. (1987). *A textbook of soil science*. Tata McGraw-Hill.

Black, C. A. (Ed.). (1965). *Methods of soil analysis, Part 2*. American Society of Agronomy.

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis: Part 1. Physical and mineralogical methods* (2nd ed., pp. 363–375). Soil Science Society of America.

Bossio, D. A., Cook-Patton, S. C., Ellis, P. W., Fargione, J., Sanderman, J., Smith, P., & Griscom, B. W. (2020). The role of soil carbon in natural climate solutions. *Nature Sustainability*, *3*(5), 391–398. https://doi.org/10.1038/s41893-020-0491-z

Bremner, J. M., & Mulvaney, C. S. (1982). Nitrogen—Total. In A. L. Page, R. H. Miller, & D. R. Keeney (Eds.), *Methods of soil analysis, Part 2: Chemical and microbiological properties* (2nd ed., pp. 595–624). American Society of Agronomy.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125. https://doi.org/10.1016/j.soilbio.2018.01.030

Chaudhari, P. R., Ahire, D. V., Ahire, V. D., Chkravarty, M., & Maity, S. (2013). Soil bulk density as related to soil texture, organic matter content and available total nutrients of Coimbatore soil. *International Journal of Scientific and Research Publications*, *3*(2), 1–8.

Chen, L., Gong, J., Fu, B., Huang, Z., Huang, Y., & Gui, L. (2007). Effect of land use conversion on soil organic carbon sequestration in the loess hilly area, loess plateau of China. *Ecological Research*, *22*(4), 641–648.

Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., & Balesdent, J. (2019). Increasing organic carbon stocks in agricultural soils: Knowledge gaps and potential innovations. *Global Food Security*, *20*, 9–17. https://doi.org/10.1016/j.gfs.2019.01.001

Chung, H., Kim, S., & Lee, D. (2019). Impacts of land use change on climate: A review of current understanding and future challenges. *Remote Sensing*, *11*(6), 706. https://doi.org/10.3390/rs11060706

Davood, A. D., Bhawana, P., & Fulekar, M. H. (2014). Assessment of soil organic carbon stock of temperate coniferous forests in Northern Kashmir. *International Journal of Environment*, *4*(1), 161–178.

Denboba, A. (2021). *Acidity status and lime requirement of soils of Ameya district, southwest showa, Ethiopia* [Doctoral dissertation, Haramaya University].

Dhakal, S., Koirala, M., Sharma, E., & Subedi, N. R. (2010, June). *Effect of land use change on soil organic carbon stock in Balkhu Khola watershed southwestern part of Kathmandu Valley, central Nepal* [Conference paper]. International Conference on Environmental Science and Development, Cairo, Egypt.

Dhakhwa, G. B., Campbell, C. L., Jones, J. W., & Daniels, R. B. (1997). Estimating carbon sequestration in agroecosystems using a modified CENTURY model. *Agricultural Systems*, *54*(3), 435–450.

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land use change on soil organic carbon stocks–a meta analysis. *Global Change Biology*, *17*(4), 1658–1670. https://doi.org/10.1111/j.1365-2486.2010.02336.x

Donato, D. C., Kauffman, J. B., Murdiyarso, D., Kurnianto, S., Stidham, M., & Kanninen, M. (2011). Mangroves among the most carbon-rich forests in the tropics. *Nature Geoscience*, *4*(5), 293–297.

Egashira, K., Aramaki, K., Yoshimasa, M., Takeda, A., & Yamasaki, S. (2004). Rare earth elements and clay minerals of soils of the floodplains of three major rivers in Bangladesh. *Geoderma*, *120*(1–2), 7–15.

Fageria, N. K., Baligar, V. C., & Bailey, B. A. (2015). Role of cover crops in improving soil and row crop productivity. *Communications in Soil Science and Plant Analysis*, *46*(22), 2733–2755. https://doi.org/10.1080/00103624.2015.1089275

Farukh, M. A., Rani, K., Nashif, S. M., Khatun, R., Toma, L. T., Hyakumura, K., & Islam, K. K. (2023). Carbon stock mapping utilizing accumulated volume of sequestrated carbon at Bangladesh Agricultural University, Bangladesh. Sustainability, *15*(5), 4300. https://doi.org/10.3390/su15054300

Food and Agriculture Organization. (2020). *Soil pollution: A hidden reality*.

Ganai, A. Q., Dar, M. A., Chesti, M. H., Bhat, Z. A., Khanday, M., & Dar, N. A. (2018). Macronutrients status of apple (cv. red delicious) orchard soils of Jammu and Kashmir India. *International Journal of Chemical Studies*, *6*(2), 3314–3319.

Genxu, W., Jian, S., Qi, W., & Shiqiang, W. (2002). Soil organic carbon pool of grassland soils on the Qinghai–Tibetan Plateau and its global implication. *Science of the Total Environment*, *291*(1–3), 207–217.

Gray, J. M., Bishop, T. F., & Wilson, B. R. (2015). Factors controlling soil organic carbon stocks with depth in eastern Australia. *Soil Science Society of America Journal*, *79*(6), 1741–1751.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., & Woodbury, P. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Haridjaja, O., Sabiham, S., & Dai, J. (2012). Soil carbon and nitrogen stocks under different land uses in tropical mountainous area. Journal of Tropical Soils, *17*(2), 105-112.

Heluf, G., & Wakene, N. (2006). Impact of land use and management practices on chemical properties of some soils of Bako area, Western Ethiopia. *Ethiopian Journal of Natural Resources*, *8*(2), 177–197.

Hossain, M. F., Chen, W., & Zhang, Y. (2020). Land use change and its impact on soil organic carbon storage in the coastal areas of Bangladesh. *Science of the Total Environment*, *726*, 138500. https://doi.org/10.1016/j.scitotenv.2020.138500

Huq, S., Islam, M. A., & Adnan, M. S. G. (2021). Monitoring deforestation and forest degradation using remote sensing in the Madhupur Sal Forests of Bangladesh. *Environmental Challenges*, *5*, 100252. https://doi.org/10.1016/j.envc.2021.100252

Integrated Protected Area Co-management Project. (2009). *Site-level field appraisal for forest co-management: IPAC Madhupur site*. International Resource Group.

Intergovernmental Panel on Climate Change. (2000). *Land use, land-use change, and forestry: A special report of the IPCC*. Cambridge University Press.

Intergovernmental Panel on Climate Change. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://doi.org/10.1017/9781009157896

Islam, M. S. (2008). Soil fertility history, present status and future scenario in Bangladesh. *Bangladesh Journal of Agriculture and Environment*, *4*, 129–151.

Jackson, M. L. (1962). *Soil chemical analysis*. Prentice Hall.

Jemal, K., & Tesfaye, H. (2020). Soil physico-chemical property characterization along with different land use system in Gurage Zone, Southern Ethiopia. *Modern Chemistry*, *8*(3), 40–48.

Jin, Z., Shah, T., Zhang, L., Liu, H., Peng, S., & Nie, L. (2020). Effect of straw returning on soil organic carbon in rice–wheat rotation system: A review. *Food and Energy Security*, *9*(2), e200.

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423–436.

Jones, R., Smith, A., & Taylor, L. (2018). Soil carbon management in broader climate policy frameworks: Aligning national development with global climate targets. *Environmental Policy and Climate Change*, *15*(3), 345–358. https://doi.org/10.1016/j.envpol.2018.04.009

Karim, A., Rahman, M. M., & Hoque, A. (1994). Carbon storage in Sal (Shorea robusta) forest in Bangladesh. *Forest Ecology and Management*, *68*(3–4), 201–209.

Karltun, E., Lemenih, M., & Tolera, M. (2013). Comparing farmers' perception of soil fertility change with soil properties and crop performance in Beseku, Ethiopia. *Land Degradation & Development*, *24*(3), 228–235.

Khan, M. A. S. A., Hoque, M. A., & Huda, M. K. (1997). *Toposequences and soils of Madhupur tract*. Soil Resources Development Institute (SRDI).

Khanday, M., Wani, J. A., Ram, D., & Kumar, S. (2018). Depth wise distribution of available nutrients of soils of horticultural growing areas of Ganderbal district of Kashmir valley. *Journal of Pharmacognosy and Phytochemistry*, *7*(1), 19–22.

Kiflu, A., & Beyene, S. (2013). Effects of different land use systems on selected soil properties in south Ethiopia. *Journal of Soil Science and Environmental Management*, *4*(5), 100–107.

Kooch, Y., Hosseini, S. M., & Mohammadi, J. (2020). Impacts of land use change on soil organic carbon and other soil properties: A review. *Catena*, *187*, 104396. https://doi.org/10.1016/j.catena.2019.104396

Kumar, U., Rashid, H., Tithi, N. H., & Mia, M. Y. (2019). Status of soil properties in relationship with soil pH in Madhupur tract of Tangail district in Bangladesh. *Progressive Agriculture*, *30*(3), 282–287.

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1492), 815–830.

Lal, R. (2009). Agriculture and climate change: An agenda for negotiation in Copenhagen; the potential for carbon sequestration. *IFPRI Vision 2020 for Food, Agriculture, and the Environment, Focus 16, Brief S*, 1–2.

Lal, R. (2021). Soil organic matter content and crop yield. *Journal of Soil and Water Conservation*, *76*(2), 37A-42A. https://doi.org/10.2489/jswc.2021.0204A

Lal, S. H., Bajracharya, R. M., & Sitaula, B. K. (2012). Forest and soil carbon stocks, pools and dynamics and potential climate change mitigation in Nepal. *Journal of the Institute of Forestry*, *12*, 800–811.

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Liefeld, J., Bassin, S., & Fuhrer, J. (2005). Carbon stock in Swiss agriculture soils predicted by land use soil characteristics and altitude. *Agriculture, Ecosystems & Environment*, *105*(1–2), 225–266.

Mallick, S. R., Proshad, R., Islam, M. S., Sayeed, A., Uddin, M., Gao, J., & Zhang, D. (2019). Heavy metals toxicity of surface soils near industrial vicinity: A study on soil contamination in Bangladesh. *Archives of Agriculture and Environmental Science*, *4*(4), 356–368.

Matovic, D. (2011). Biochar as a viable carbon sequestration option: Global and Canadian perspective. *Energy*, *36*(4), 2011–2016.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., & Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma*, *292*, 59–86. https://doi.org/10.1016/j.geoderma.2017.01.002

Olsen, S. R., Cole, C. U., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of available phosphorus in soils by extraction with sodium bicarbonate* (Circular No. 939). U.S. Department of Agriculture.

Ostle, N. J., Levy, P. E., Evans, C. D., & Smith, P. (2009). UK land use and soil carbon sequestration. *Land Use Policy*, *26*, S274–S283.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49–57. https://doi.org/10.1038/nature17174

Portch, S., & Islam, M. S. (1984). Nutrient status of some of the more important agricultural soils of Bangladesh. In *Proceedings of the International Symposium on Soil Test Crop Response Studies* (pp. 97–106). Bangladesh Agricultural Research Council and Soil Science Society of Bangladesh.

Post, W. M., & Kwon, K. C. (2000). Soil carbon sequestration and land-use change: Processes and potential. *Global Change Biology*, *6*(3), 317–328.

Rahman, M. M., Jahan, S., & Haque, A. (2021). Land use change and its impact on soil organic carbon: A case study from the Madhupur Tract, Bangladesh. *Journal of Environmental Management*, *289*, 112487. https://doi.org/10.1016/j.jenvman.2021.112487

Rahman, M. S. (2015). Assessment of biomass and carbon stock in the Sal forests of Bangladesh. *Forest Science and Technology*, *11*(4), 211–216.

Ratul, A. A., Hoque, T. S., Islam, M. R., & Hoque, M. A. (2021). Physico-chemical properties of acid soils from Madhupur Tract and Northern and Eastern Piedmont Plains of Bangladesh. *Asian Journal of Medical and Biological Research*, *7*(1), 12–20.

Rumpel, C., & Kögel-Knabner, I. (2011). Deep soil organic matter—a key but poorly understood component of terrestrial C cycle. *Plant and Soil*, *338*(1), 143–158.

Saha, S., Islam, M. S., & Khatun, M. (2021). Estimation of soil organic carbon stock in Sal forest ecosystems of Bangladesh. *Environmental Monitoring and Assessment*, *193*(7), 1–13.

Sahu, S. C., Kumar, M., & Ravindranath, N. H. (2016). Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. *Current Science*, *110*(12), 2252–2260.

Saikh, H., Varadachari, C., & Ghosh, K. (1998). Effects of deforestation and cultivation on soil CEC and contents of exchangeable bases: a case study in Simplipal National Park, India. *Plant and Soil*, *204*(1), 67–75.

Sakin, E., Deliboran, A., & Tutar, E. (2011). Bulk density of the Harran Plain soils in relation to other soil properties. *African Journal of Agricultural Research*, *6*(7), 1750–1757.

Sartaj, S. S., Atkinson, L., Alawi, R. M., & Azhar, E. (2017). Viral infection and obesity: current status and future prospective. *Current Drug Metabolism*, *18*(9), 798–807.

Sartori, F., Lal, R., Ebinger, M. H., & Eaton, J. A. (2007). Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. *Agriculture, Ecosystems & Environment*, *122*(3), 325–339.

Shil, N. C., Saleque, M. A., Islam, M. R., & Jahiruddin, M. (2016). Soil fertility status of some of the intensive crop growing areas under major agro-ecological zones of Bangladesh. *Bangladesh Journal of Agricultural Research*, *41*(4), 735–757.

Shrestha, B. P., Singh, G. K., & Niraula, S. R. (2008). Work related complaints among dentists. *Journal of Nepal Medical Association*, *47*(170), 77–81.

Singh, D., Singh, A. K., Singh, A. K., & Gupta, S. K. (2020). Characterization of rice growing soil of Nagara block of Ballia District (U.P.), India. *International Journal of Current Microbiology and Applied Sciences*, *9*(4), 575–581.

Smith, P., Soussana, J. F., Angers, D., Schipper, L., Chenu, C., Rasse, D. P., & Lal, R. (2020). How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. *Global Change Biology*, *26*(1), 219–241.

Takkar, P. N. (1998). Sulphur status of Indian Soils. In *Proceedings of TSIFAI Symposium on Sulphur in Indian Agriculture* (pp. 1–31). The Sulphur Institute.

Tshewang, J., & Sridith, K. (2022). Valley bottom wetland plant communities and their relationship with soil factors in the Gangtey-Phobji Wetland, WangdiPhodrang, Himalayan, Bhutan. *Science, Technology and Engineering Journal*, *44*(3).

Utami, S. N. H., & Kurniawan, S. (2019). The dynamics of soil organic carbon in relation to land use changes and soil management practices in the humid tropics. Journal of Tropical Soils, *24*(1), 1-10.

Walkley, A., & Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science*, *37*(1), 29–38.

Whitebread, A. M., Lofroy, R. B. D., & Blair, G. J. (1998). A survey of the impact of cropping on soil physical and chemical properties in north-eastern New South Wales. *Soil Research*, *36*(4), 669–681.

Wiesmeier, M., Hübner, R., & Kögel-Knabner, I. (2019). Degradation and rehabilitation of arable land — A global perspective. *Global Sustainability*, *2*, e8. https://doi.org/10.1017/sus.2019.8

Williams, C. H., & Steinbergs, A. (1959). Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. *Soil Research*, *10*(2), 340–352.

Wu, P., Xiang, X., Xu, Z., Lu, C., Cheng, H., Lyu, X., Zhang, J., He, W., Deng, W., Lyu, Y., Lou, Q., & Hong, Y. (2016). Bacterial communities in rhizospheres of three mangrove tree species from Beilun estuary, China. *PLOS ONE*, *11*(11), e0164082.

Zhang, P., Chen, X., Wei, T., Yang, Z., Jia, Z., Yang, B., & Zhang, X. (2018). Effects of land use change on soil carbon storage and sequestration rate in the arid region of Northwest China: A meta-analysis. *Global Ecology and Conservation*, *16*, e00463. https://doi.org/10.1016/j.gecco.2018.e00463

Zhu, P., Saadati, H., & Khayatnezhad, M. (2021). Application of probability decision system and particle swarm optimization for improving soil moisture content. *Water Supply*, *21*(8), 4145–4152.

Zomer, R. J., Bossio, D. A., Sommer, R., & Verchot, L. V. (2017). Global sequestration potential of increased organic carbon in cropland soils. *Scientific Reports*, *7*(1), 1–8. https://doi.org/10.1038/s41598-017-15794-8