International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 7, 2025
https://theaspd.com/index.php

Spatial and Depth-Wise Variability of Bulk Density, Cation Exchange Capacity, And Soil Organic Carbon Pools in Different Land Uses of Tehsil Ramnagar

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Abstract
This study investigates the variation of soil properties and carbon pools across different land uses in Tehsil Ramnagar, with a focus on microbial biomass carbon (MBC), water-soluble organic carbon (WSOC), and soil organic carbon (SOC). The analysis reveals significant differences in soil characteristics among forest, grassland, orchard, and agricultural systems. Grassland soils exhibited the highest MBC, followed by forest, orchard, and agricultural soils, with agricultural soils showing the lowest microbial biomass. The study also observed a general decrease in WSOC with increasing soil depth, particularly in agricultural soils, indicating higher organic carbon degradation. The SOC content varied across villages, with grasslands consistently showing the highest SOC levels, particularly in villages like Dalsar and Dehari, whereas agricultural soils exhibited the lowest SOC. Additionally, orchards and forests were found to store more carbon than grassland and agricultural systems. These findings highlight the importance of land use management in influencing soil health and carbon sequestration, with forest and orchard systems providing critical contributions to soil organic matter and microbial activity. Sustainable land management practices, particularly in agricultural systems, are necessary to enhance soil carbon storage and improve soil fertility.
Keywords: *Soil carbon pools, microbial biomass carbon, water-soluble organic carbon, soil organic carbon, land use management.*

INTRODUCTION:

Soil is a fundamental component of terrestrial ecosystems, influencing agricultural productivity, hydrological cycles, and global biogeochemical processes. The assessment of soil physical and chemical properties, such as bulk density (BD), cation exchange capacity (CEC), and soil organic carbon (SOC) pools, provides essential insights into soil health and its response to land-use changes. These properties exhibit considerable spatial and depth-wise variability, primarily driven by differences in land management practices, vegetation cover, and soil-forming processes. Understanding these variations is crucial for implementing sustainable land management strategies that optimize soil quality and ecosystem resilience.

Bulk density is a key indicator of soil compaction, influencing root penetration, water infiltration, and nutrient availability. It varies considerably among land-use types, with forest soils generally exhibiting lower BD due to high organic matter content and improved soil aggregation, while agricultural soils tend to have higher BD due to mechanical compaction and reduced organic inputs. Studies suggest that BD tends to increase with depth as organic matter content declines and compaction from overlying soil layers intensifies. Changes in BD significantly affect soil porosity and aeration, thereby influencing microbial activity and nutrient cycling.

Cation exchange capacity is a fundamental soil property that governs nutrient retention and availability. It is primarily controlled by soil texture, organic matter content, and mineral composition. Soils with high clay and organic matter content generally exhibit higher CEC, enhancing their ability to retain essential cations such as potassium (K), calcium (Ca), and magnesium (Mg). However, land-use changes such as deforestation and intensive agriculture can alter soil CEC by affecting soil structure and organic matter dynamics. A decline in CEC due to land degradation can lead to increased nutrient leaching, reducing soil fertility and productivity.

Soil organic carbon is a crucial determinant of soil fertility, structure, and water-holding capacity, playing a significant role in carbon sequestration and climate regulation. SOC pools vary considerably with land use, with forest soils typically storing higher SOC due to continuous litter input and minimal disturbances, whereas cultivated lands experience SOC depletion due to intensive tillage, erosion, and residue removal. The depth-wise distribution of SOC is influenced by soil type, climate, and land management practices, with the majority of SOC concentrated in surface layers due to microbial activity and organic matter accumulation. Loss of SOC not only affects soil fertility but also contributes to atmospheric CO_2 emissions, emphasizing the need for sustainable soil management practices.

Different land-use systems, including forests, croplands, and pastures, exhibit distinct spatial and depth-wise variations in BD, CEC, and SOC pools. Forest soils generally maintain better physical and chemical properties due to reduced disturbances and continuous organic matter input. In contrast, agricultural soils often show increased BD, reduced CEC, and lower SOC due to mechanical compaction, erosion, and organic matter depletion. Pasture lands may exhibit intermediate characteristics, depending on grazing intensity and soil management practices. A comprehensive evaluation of these variations is essential for devising land-use policies that enhance soil sustainability and ecosystem stability.

Although extensive research has been conducted on soil properties in different land-use systems, there is a lack of region-specific studies focusing on the spatial and depth-wise variability of BD, CEC, and SOC in Tehsil Ramnagar. The absence of localized data hinders the implementation of targeted soil conservation and management strategies. Therefore, a systematic investigation is required to assess the impact of different land uses on these key soil properties, providing empirical evidence to support sustainable land management practices. It is hypothesized that land-use changes significantly influence BD, CEC, and SOC pools, with forested areas exhibiting superior soil properties compared to agricultural and pasture lands. Additionally, these properties are expected to exhibit pronounced depth-wise variability due to differential organic matter accumulation and soil-forming processes. This study aims to assess the spatial variability of BD, CEC, and SOC across different land-use types in Tehsil Ramnagar, evaluate their depth-wise distribution, and establish relationships between land management practices and soil property variations to support sustainable soil conservation strategies.

METHODOLOGY

Study Area and Site Selection

The study was conducted in Tehsil Ramnagar, which represents diverse land-use types, including forest, agricultural land, and pastureland. The area was systematically stratified to ensure adequate representation of different land-use systems. A grid-based sampling approach was employed to minimize spatial bias, ensuring comprehensive coverage of soil variability. The geographic coordinates of each sampling location were recorded using a GPS device to facilitate spatial mapping and analysis.

Soil Sampling and Depth Intervals

Soil samples were collected from selected sites within each land-use type at three standard depth intervals: 0–10 cm, 10–30 cm, and 30–60 cm. These depth intervals were chosen to assess the impact of surface processes, root activity, and subsurface changes in soil properties. Undisturbed soil cores were obtained using a stainless-steel core sampler (5 cm diameter and 5 cm height) for bulk density determination, while composite samples were collected for cation exchange capacity (CEC) and soil organic carbon (SOC) analysis.

Bulk Density Determination

Bulk density (BD) was measured using the core method, which provides a direct estimation of soil compaction and porosity. The collected soil cores were oven-dried at 105°C for 24 hours to remove moisture content. BD was calculated using the formula:

This parameter is critical for understanding soil structure, aeration, and water retention capacity. Higher BD values indicate compaction, reducing root penetration and water infiltration, while lower BD values suggest better soil aggregation and organic matter content.

Cation Exchange Capacity Analysis

Cation exchange capacity (CEC) was determined using the ammonium acetate extraction method at pH 7.0. This technique quantifies the soil's ability to retain and exchange essential cations, which directly influences nutrient availability. Soil samples were air-dried, ground, and passed through a 2-mm sieve before analysis. A 1 M ammonium acetate solution was used to saturate the exchange sites, followed by displacement with 1 M sodium chloride (NaCl). The extracted ammonium was quantified using the Kjeldahl distillation method, and CEC was expressed in cmol (+) kg^{-1} of soil. Higher CEC values indicate greater nutrient retention capacity, which is typically associated with high clay and organic matter content.

Soil Organic Carbon Analysis

Soil organic carbon was quantified using the Walkley-Black wet oxidation method, a widely used procedure for estimating organic carbon content in soils. The soil samples were digested with potassium dichromate ($K_2Cr_2O_7$) in the presence of sulfuric acid (H_2SO_4), and the unreacted dichromate was titrated with ferrous sulfate ($FeSO_4$). SOC content was expressed as a percentage of soil weight. To estimate soil organic matter (SOM), the conversion factor of 1.724 was applied, assuming that organic matter consists of approximately 58% organic carbon. This analysis provides insights into carbon sequestration potential and soil fertility.

Statistical and Spatial Analysis

All soil analyses were performed in triplicate to enhance accuracy and reliability. The data were statistically analyzed using Analysis of Variance (ANOVA) to evaluate significant differences in BD, CEC, and SOC among different land-use types and soil depths. Post-hoc tests were used to identify specific variations between land-use categories. Pearson correlation analysis was conducted to determine the interrelationships between BD, CEC, and SOC. Additionally, geostatistical techniques in GIS were employed to map spatial variability and generate interpolation models using Kriging or Inverse Distance Weighting (IDW).

Quality Control and Data Validation

To ensure data accuracy and reproducibility, standardized protocols were followed for sample collection and laboratory analysis. Equipment was calibrated before each measurement, and control soil samples with known properties were analyzed alongside test samples. Data validation was performed by cross-checking results with established reference values.

RESULTS AND INTERPRETATIONS

Figure 1 showed the variation of mean bulk density at different depths (0-15 cm, 15-30 cm and 30-60 cm) in various land uses within tehsil Ramnagar. Forest soil exhibit lowest bulk density and Agriculture soils have the highest bulk density (1.54 g/cm³). Horticulture and Grassland soils fall between the extremes, with Horticulture at 1.36 g/cm³ and Grassland at 1.43 g/cm³. Top soil layer has the lowest bulk density ranging between 1.0-1.2 gm/cm³ however sub surface layer has moderate values ranging between 1.2-1.6 gm/cm³. Subs soil layer has the highest bulk density value between 1.4-1.8 gm/cm³.

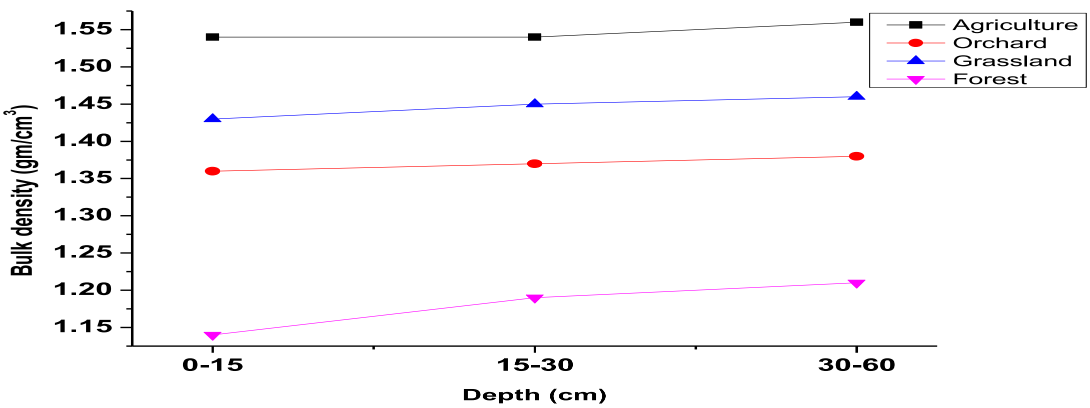

Fig. 1: Bulk density under different depth for different land uses in different villages of tehsil Ramnagar. Bars are standard deviation bars (n=7)

Depth-wise variation of mean value of CEC in soil samples extracted from various land uses Agriculture, Horticulture, Grassland and Forest within different villages of tehsil Ramnagar is shown in fig. For agriculture and horticulture CEC values at 30-60 cm are well up to 22.11 meq/100g and 22.3 meq/100g respectively revealing the nutrient and organic matter richness probably due to leaching from above. For top soil layer (0-15 cm) CEC values are generally high in this layer and for sub surface soil layer (15-30 cm) CEC slightly decreases or remains stable in many sites.

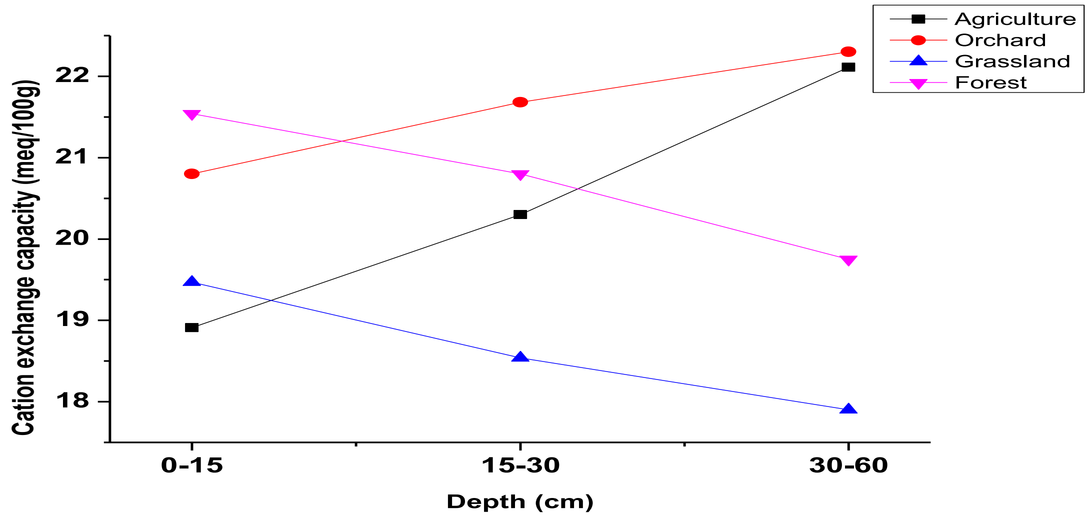

Fig. 2: Cation exchange capacity under different depth for different land uses in different villages of tehsil Ramnagar. Bars are standard deviation bars (n=7)

The variation of KOC (potassium permanganate oxidizable carbon) in mg/kg with soil depth (0-15 cm, 15-30 cm, 30-60 cm) for different land uses: Agriculture, Orchard, Grassland, and Forest studied in different villages of tehsil Ramnagar is described in Fig. 3. Forest has the highest KOC values at all soil depths compared to other land uses, with a significant decrease from the surface (0-15 cm) to deeper layers (30-60 cm). Grassland follows Forest in terms of KOC levels, with a moderate decline in KOC as depth increases. Orchard and Agriculture have lower KOC values compared to Grassland and Forest, but Orchard shows consistently higher KOC than Agriculture across all depths, indicating less organic carbon content in the soil.

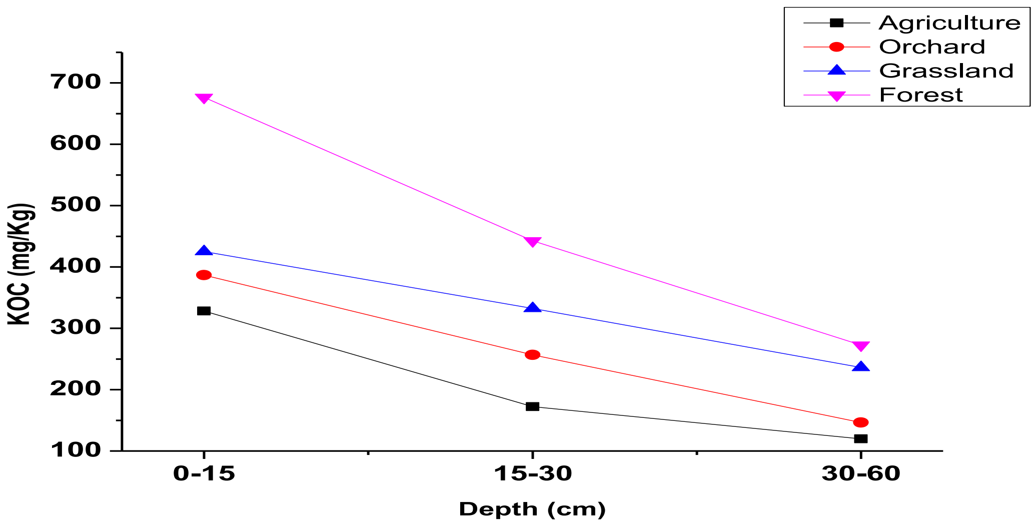

Fig. 3: Potassium permanganate oxidizable carbon under different depth for different land uses in different villages of tehsil Ramnagar. Bars are standard deviation bars (n=7)

The variation of mean bulk density of soil samples extracted from various depths across different villages under study for targeted land uses is shown in Fig. 4. Agriculture has the highest bulk density among the four land uses, indicating more compacted soil. Grassland also shows a relatively high bulk density, similar to Agriculture but slightly lower. Horticulture has a lower bulk density compared to Agriculture and Grassland. Forest has the lowest bulk density, suggesting that forest soils are less compacted and have higher porosity.

Fig. 4: Bulk density (gm/cm^3) in top layer soil under different land uses in different villages of tehsil Ramnagar. Bars are standard deviation bars (n=7)

In Figure 5 the distribution of KOC (potassium permanganate oxidizable carbon) in mg/kg across different land uses: Agriculture, Horticulture, Grassland, and Forest in different villages of tehsil Ramnagar. Forest has the highest overall KOC, with substantial contributions from all three depth layers, particularly the 15-30 cm and 30-60 cm layers. Grassland shows a notable increase in KOC compared to Horticulture, particularly in the deeper soil layers. Horticulture has a slightly higher total KOC than Agriculture, with a more significant contribution from the 15-30 cm layer. Agriculture has the lowest overall KOC values among the four land uses.

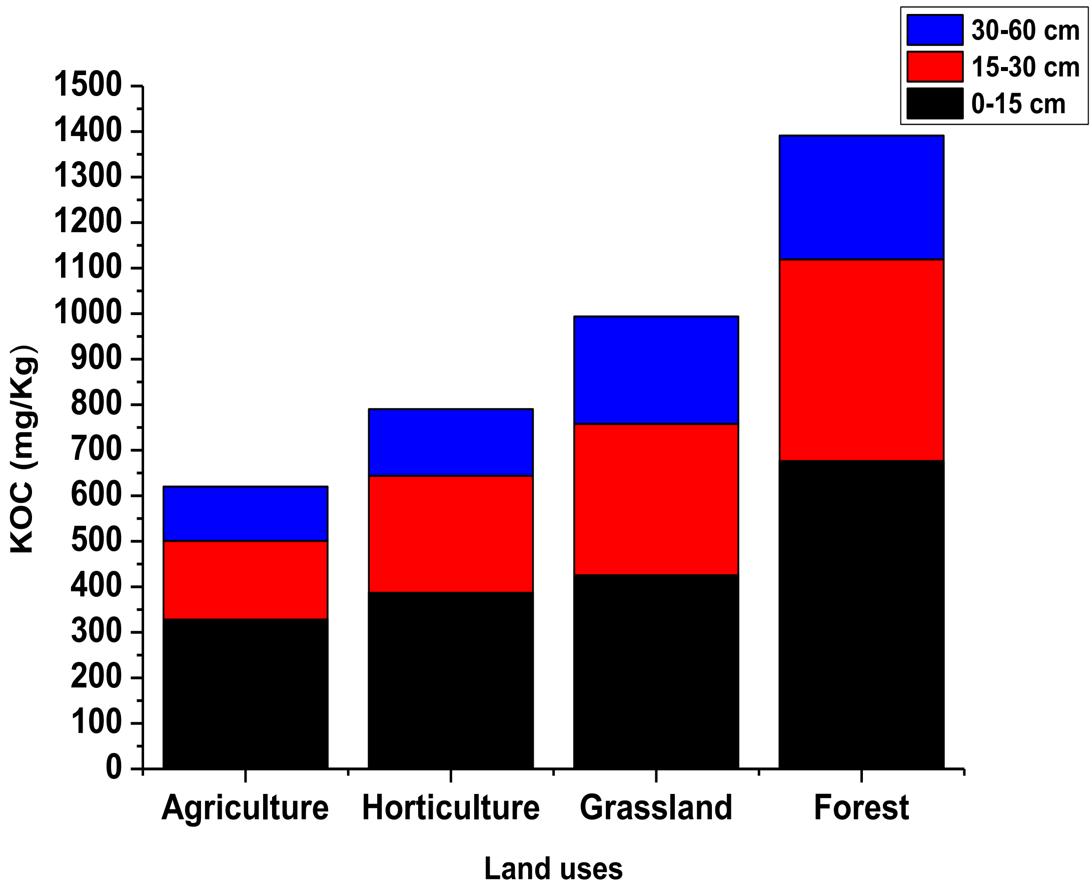

Fig. 5: KOC (mg/Kg) in different depth under different land uses for different villages of tehsil Ramnagar. Bars are standard deviation bars (n=7)

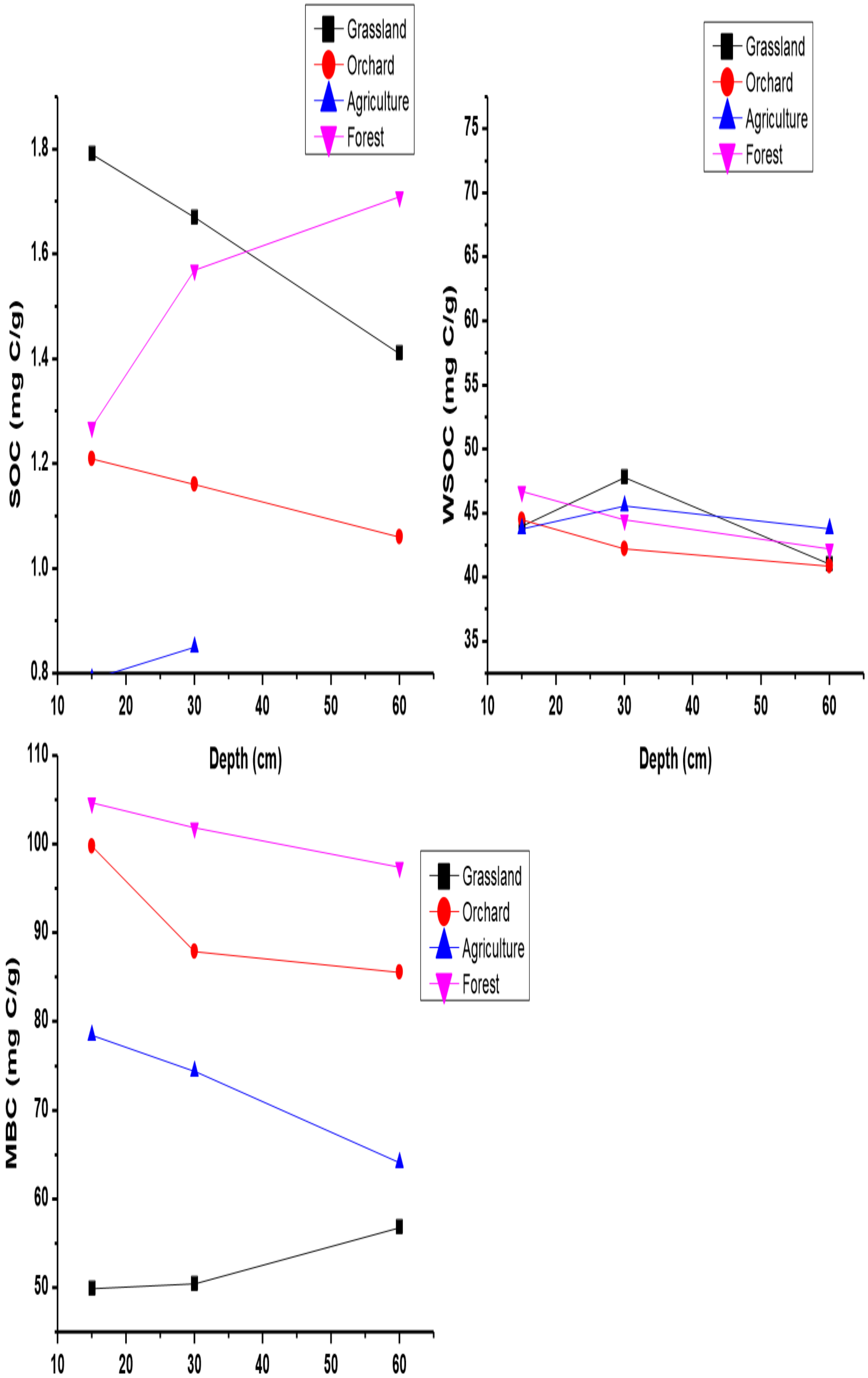

Fig 6: Variation of Soil organic carbon pools at different depth in different land uses for village Dalsar.

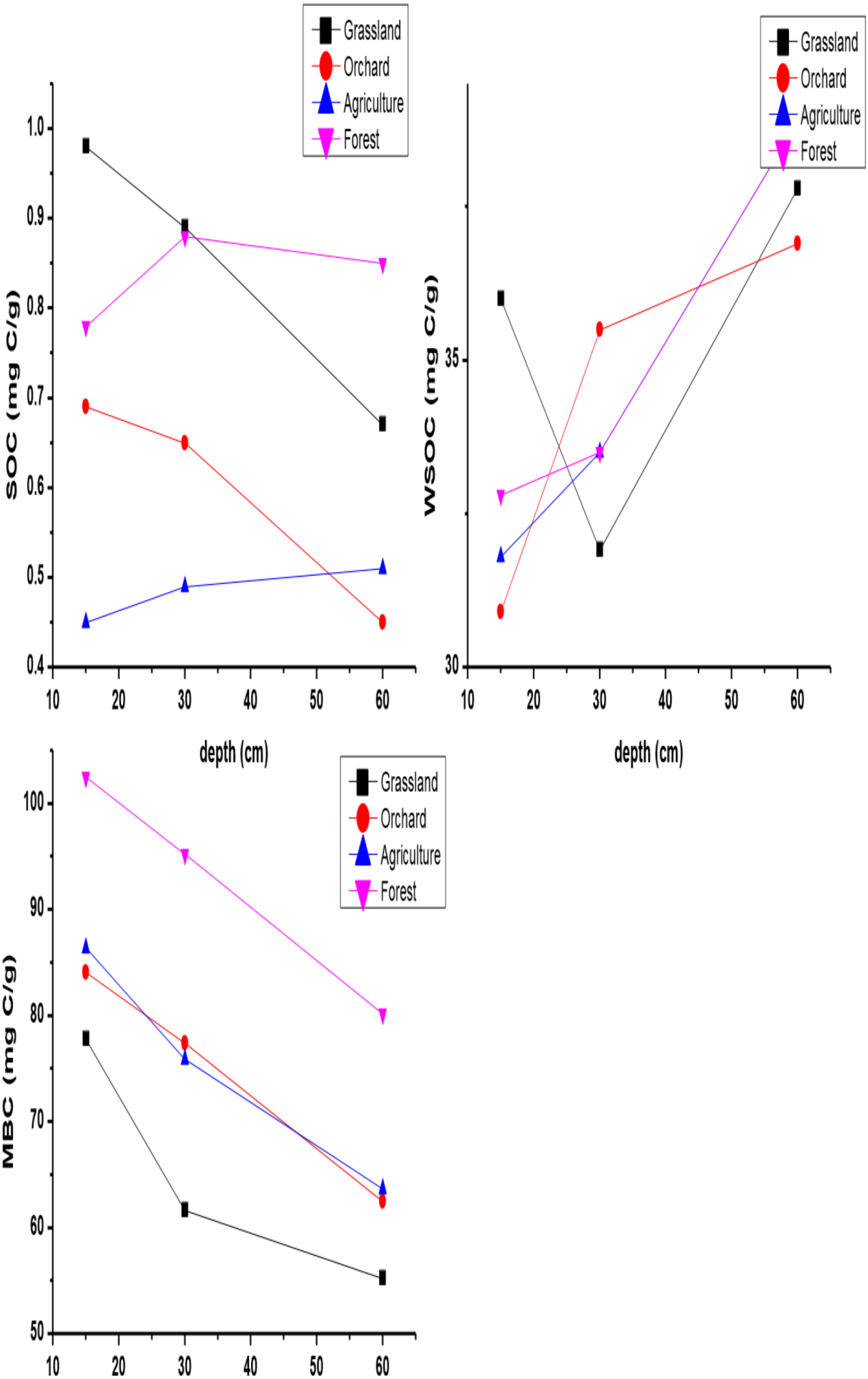

Fig 7: Variation of soil organic carbon pools at different depths in different landuses of village Dehari.

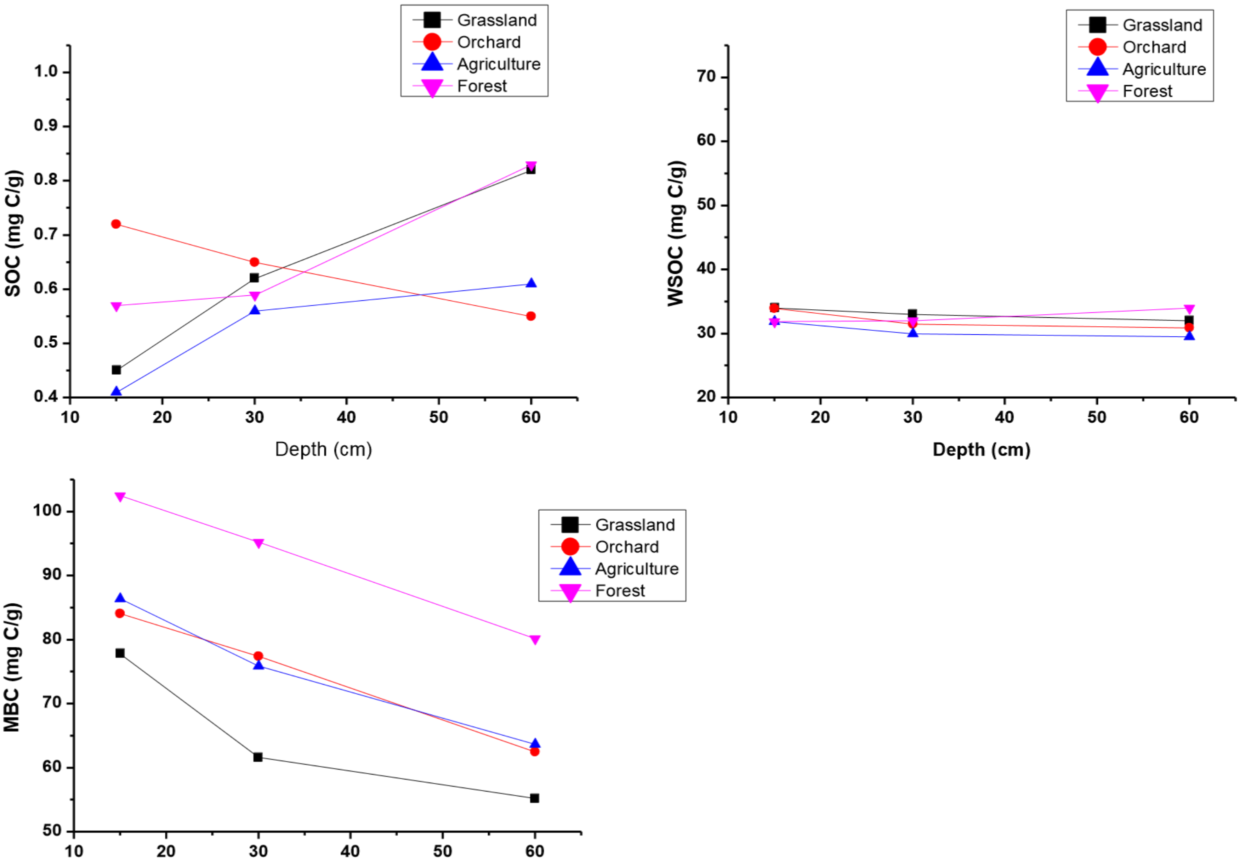

Fig 8: Variation of soil organic carbon pools at different depths in different land uses in village Khagote

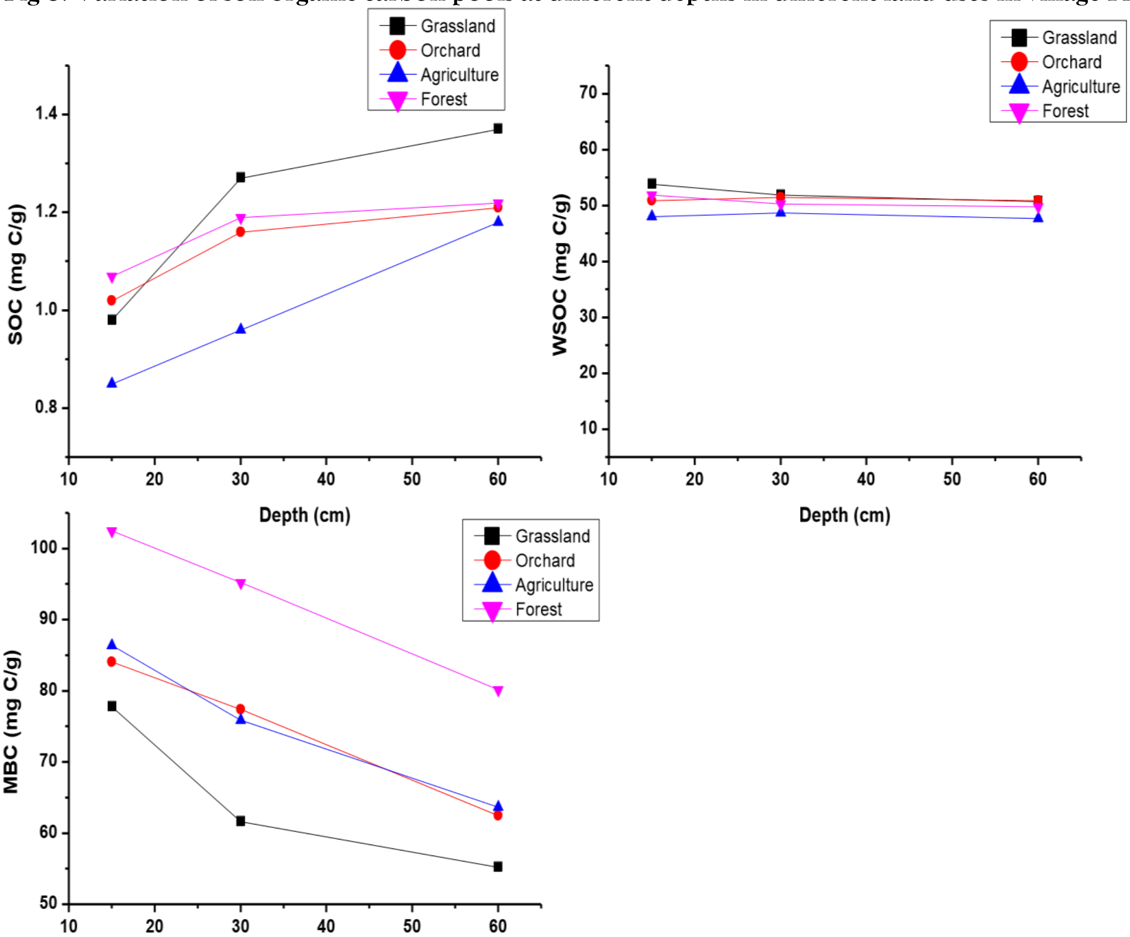

Fig 9: Variation of soil organic carbon pools at different depths in different landuses of village Kulwanta.

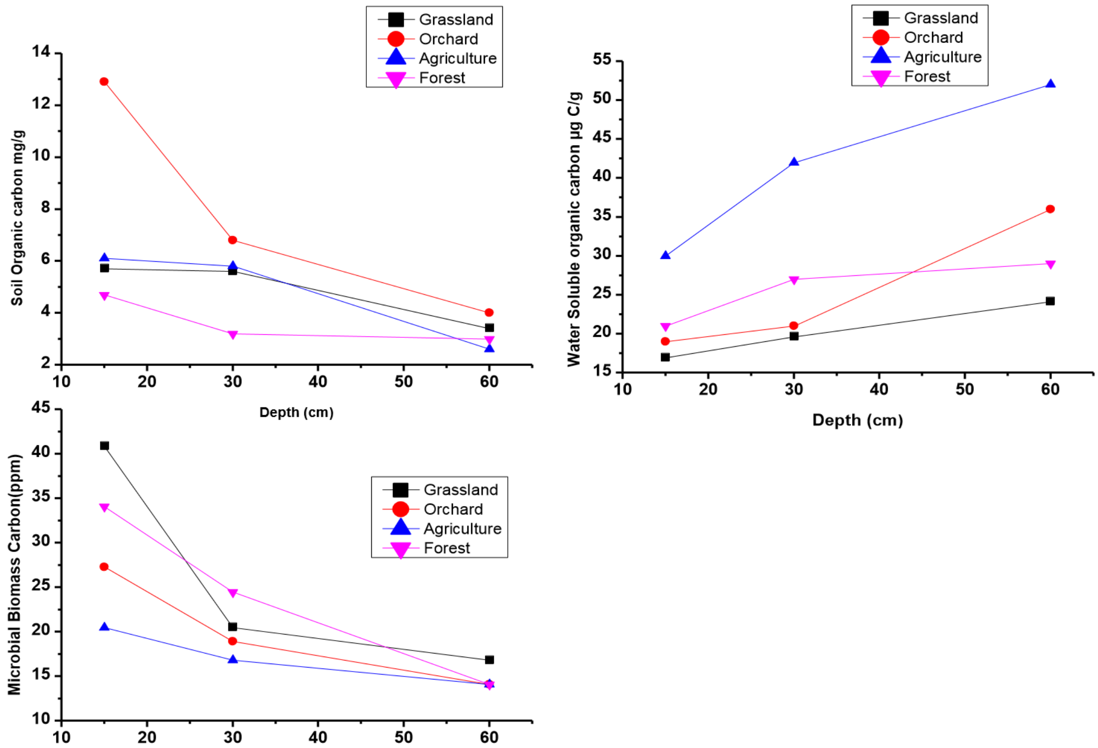

Fig 10: Variation of Soil organic carbon pools at different depth in different land uses for village Thaplal

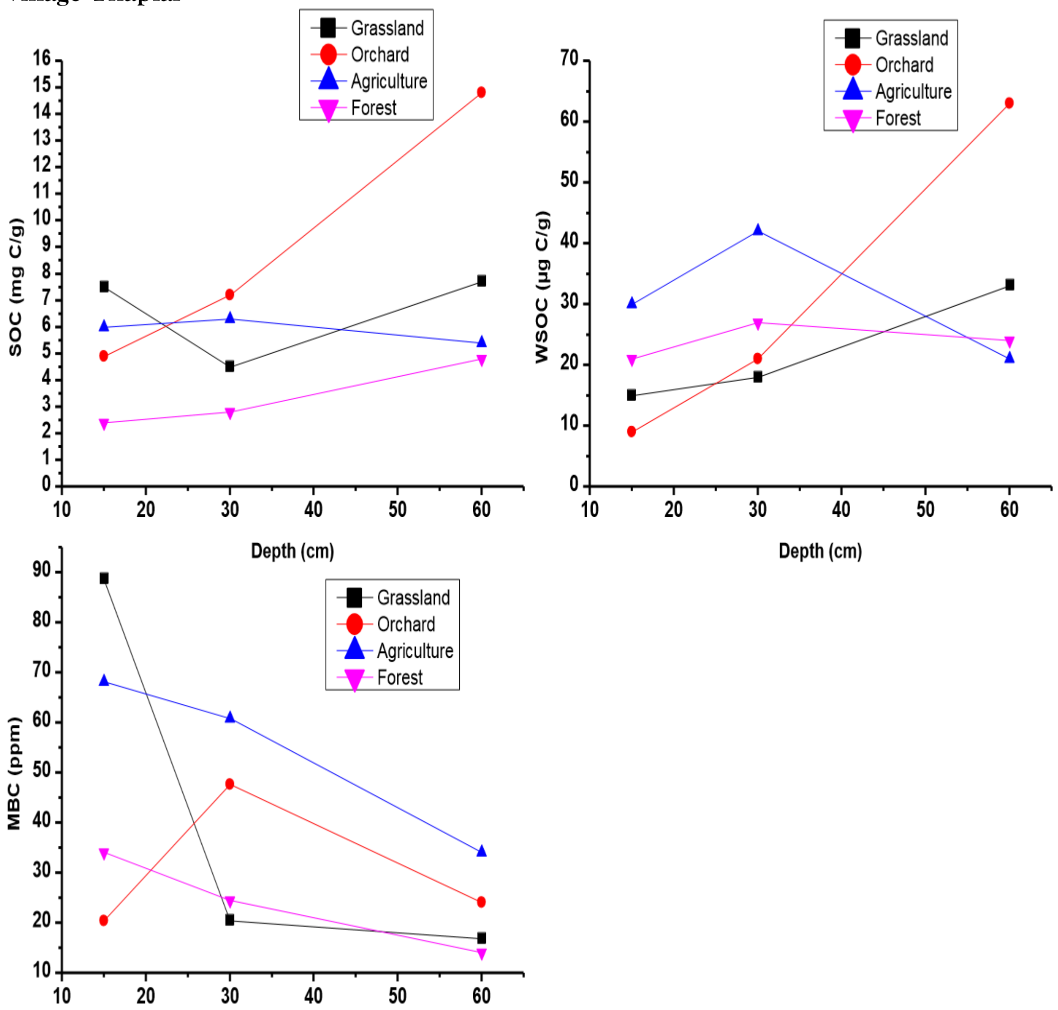

Fig 11: Variation of Soil organic carbon pools at different depth in different land uses for village Marta

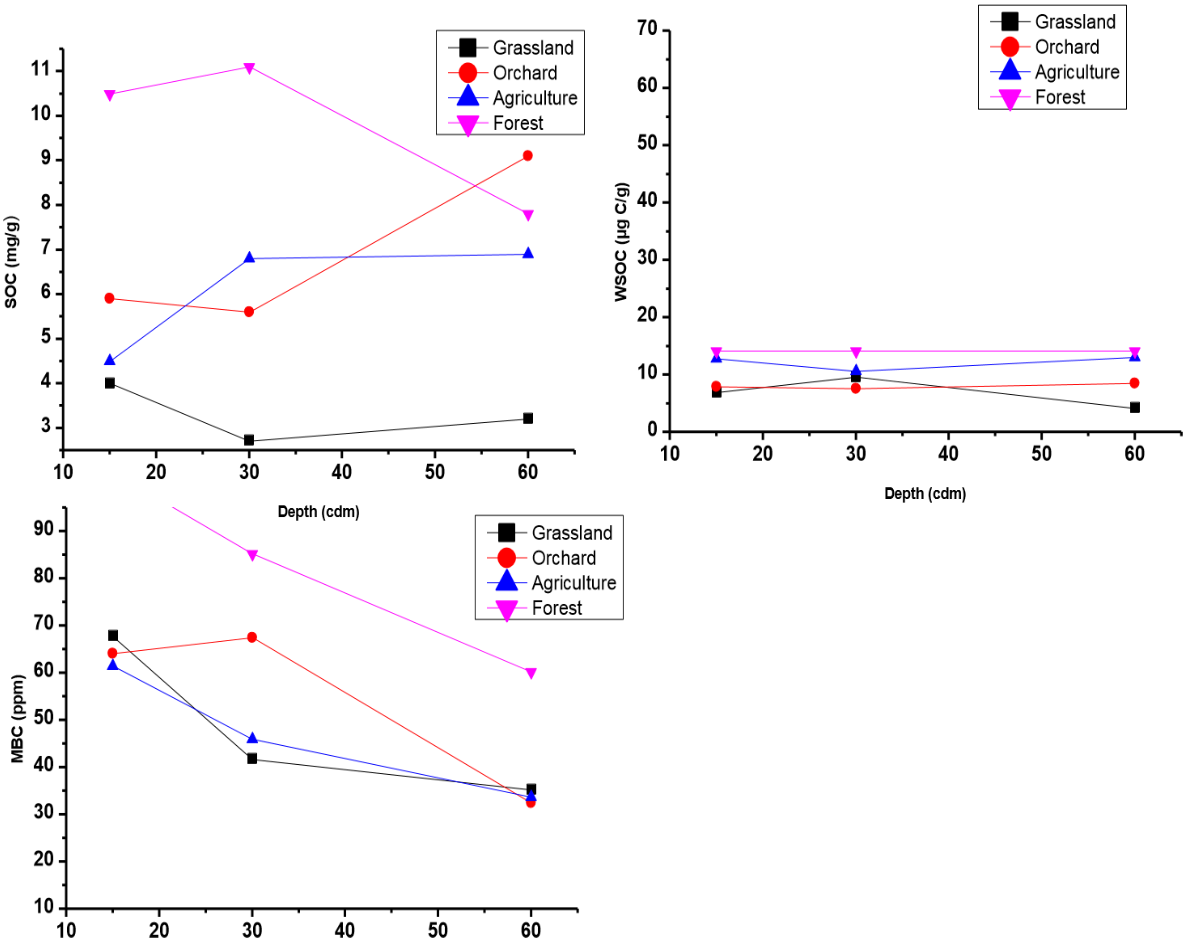

Fig 12: Variation of soil organic carbon pools at different depths in different landuses of village Kirmoo

The soil carbon pool characteristics, as illustrated in Graphs 5, 6, 7, 8, and 9, show a clear trend in the distribution of microbial biomass carbon (MBC) across different land uses and soil depths. Microbial biomass carbon (MBC) content was highest in grassland soils, followed by forest soils, orchard soils, and the lowest content in agricultural soils. The order of MBC content, from highest to lowest, is Grassland > Forest > Orchards > Agriculture. This trend indicates that grasslands, with their rich organic matter input and diverse vegetation, support higher microbial populations, while agricultural soils, often impacted by intensive tillage and reduced organic matter, have the lowest microbial biomass. This finding is consistent with existing research which shows that agricultural systems, particularly those subjected to heavy mechanization, generally exhibit lower microbial biomass compared to more natural or less disturbed ecosystems such as grasslands and forests.

Further examination of the water-soluble organic carbon (WSOC) across the different soil depths revealed a general decrease in WSOC with increasing soil depth across most land uses. However, agricultural soils showed the most significant decline in WSOC levels, suggesting that intensive farming practices may lead to the leaching or degradation of easily soluble organic carbon, making it less available in deeper layers. In contrast, no major variation was observed in WSOC content across different land uses at all soil depths, except for the pronounced reduction in agricultural soils.

The soil organic carbon (SOC) content also demonstrated varying trends across different villages in Tehsil Ramnagar. In villages such as Dalsar and Dehari, the SOC content followed the order: Agriculture < Orchards < Forest < Grassland. This indicates that grasslands have the highest SOC content, likely due to their perennial vegetation and relatively undisturbed nature, while agricultural soils have the lowest SOC, which can be attributed to farming practices that deplete organic matter over time. On the other hand, villages like Khagote and Kulwanta displayed a slightly different pattern: Agriculture < Grassland < Orchards < Forest. The higher SOC content in orchards and forests compared to agriculture and grasslands reflects the ability of these land uses to sequester carbon through better organic matter management and the slower decomposition rates typical in forested environments.

In Graphs 10, 11, and 12, the trends for MBC, WSOC, and SOC further reinforce the pattern that microbial biomass carbon decreases with soil depth, with grassland soils consistently exhibiting the

highest MBC content across all depths, followed by forests and orchards. Agricultural soils continue to show the lowest microbial biomass carbon content, which suggests that the soil under agriculture might be experiencing microbial stress due to factors like reduced organic matter and frequent disturbances.
While WSOC showed minimal variation among land uses at different depths, the general trend of SOC content being higher in orchard and forest soils compared to agricultural and grassland soils underscores the importance of these land uses in storing carbon. Orchards and forests, with their higher organic matter inputs and slower decomposition rates, maintain higher SOC levels, making them crucial for carbon sequestration efforts. Conversely, the lower SOC content in agriculture and grassland soils highlights the need for more sustainable land management practices to enhance soil carbon storage and support soil fertility.

Bulk Density:

From Fig. 1 it was observed that mean bulk density was greatest for agriculture soil (1.54 gm/cm^3), followed by grassland (1.43 gm/cm^3) horticulture (1.36 gm/cm^3) and forest soil (1.14 gm/cm^3) for the surface soil (0-15 cm). Forest soil exhibit lowest bulk density which may be due to undisturbed soil structure and presence of thick layer of organic matter. From the observed data it was found that bulk density increases with depth for all land uses. Top soil layer has the lowest bulk density ranging between 1.0-1.2 gm/cm^3 however sub surface layer has moderate values ranging between 1.2-1.6 gm/cm^3. Subs soil layer has the highest bulk density value between 1.4-1.8 gm/cm^3. Also it was observed that bulk density varies with the agro climatic regions. Temperate regions like Kulwanta and Marta were observed to have higher soil bulk density than that of sub-tropical regions like Dehari, Kirmoo, Khagote and Dalsar. Temperate zones were founds to have clay rich soil which are more compact and hence have higher bulk density than sub-tropical zones having loamy and alluvial soils.

Cation Exchange Capacity (CEC):

For top soil layer (0-15 cm) CEC values are generally high in this layer, reflecting the influence of organic matter and biological activity. For instance, horticulture sites often exhibit higher CEC (e.g., Marta 23.8 meq/100g, Kulwanta 22.4 meq/100g). For sub surface soil layer (15-30 cm) CEC slightly decreases or remains stable in many sites. However, some horticulture and agricultural soils maintain higher CEC levels, possibly due to nutrient and organic matter leaching from above. CEC values generally decrease across all land uses, particularly in grasslands and forest soils, as organic matter reduces and CEC is more dependent on clay minerals for the deepest soil layer. CEC values vary with respect to the land uses under considerations as follows: agriculture >Horticulture >Grassland >Forest (Fig 4.2). Agricultural soil has high CEC values across all depths, likely due to soil amendments and farming practices that increase organic matter and nutrient levels. Whereas horticulture soils show consistently high CEC across depths, with the top layers being especially rich, such as in Kulwanta and Marta. This might be due to organic inputs and decaying plant material. Grassland soils tend to show moderate CEC, with values generally decreasing with depth, indicating lesser organic matter and nutrient input. Forest soils exhibit higher CEC in the top 15 cm, attributed to leaf litter and decomposing organic matter. Deeper layers show a gradual decrease, although some locations like Kulwanta maintain relatively high CEC.

Potassium Permanganate oxidizable carbon (KOC):

The mean value of $KMnO_4$ oxidizable carbon (KOC) in the surface layer was observed as 328.35, 386.71, 425.35 and 676.44 mg/Kg for agriculture, horticulture, grassland and forest soils respectively (Table 4.4). KOC was highest for forest soil followed by grassland, horticulture and agriculture lands for top soil layer (Fig 3). Forest soils are found to have higher KOC values compared to other land uses may be due to rich organic matter from litter and low disturbance. The sub surface KOC values was highest in forest soil followed by horticulture and then agriculture soil. The deepest soil has the lowest KOC values for all Land uses as compared to surface and sub-surface soils. The depth wise decrease was nearly 50% from surface soil to 15-30cm in case of agriculture soil but not too sharp but a clear decrease was observed for forest, horticulture and grassland soils. This may be attributed to reduced plant root biomass and microbial activity.

Variation of BD values in top layer soil for different land uses:

In Fig.4 the bulk density values under different land uses highlight how land management practices impact soil structure and compaction. Forest soils, with the lowest bulk density, suggest a healthier, less compacted soil environment. In contrast, agricultural soils exhibit higher compaction, potentially limiting soil function and requiring management practices to enhance structure and porosity. Horticulture and Grassland represent intermediate conditions, with reasonable porosity and moderate compaction. Forest soils have the lowest bulk density (1.14 g/cm^3), indicating less compacted soil, Agriculture soils have the highest bulk density (1.54 g/cm³), suggesting more compacted soil, Horticulture and Grassland soils fall between the extremes, with Horticulture at 1.36 g/cm³ and Grassland at 1.43 g/cm³.

Variation of KOC values under different depth for different land uses:

Fig. 5 shows that land use type significantly influences the distribution of potassium oxidizable organic carbon with depth. For all land uses KOCdecreases as depth increases, indicating that organic carbon content generally diminishes with soil depth. **Agriculture** has the highest relative decrease (about 64%), implying more rapid labile carbon depletion with depth. **Horticulture** and **Grassland** fall in between, with Grassland showing a moderate reduction. **Forest** shows the smallest relative decrease (about 60%), suggesting a slower reduction in organic carbon with depth. Agriculture's rapid reduction in KOCwith depth suggests that organic carbon is more concentrated near the surface, possibly due to tillage and crop harvesting, which may not support long-term soil health. Forest and Grassland soils maintain higher organic carbon content at greater depths, which can support better soil structure, moisture retention, and nutrient cycling. **Forest** consistently has the highest KOCvalues across all depths, followed by Grassland, Horticulture, and Agriculture.

Correlation between KOC (labile carbon pools) and CEC and BD (physical properties) of soil samples under different depth for different land uses:

For agriculture land uses a strong positive correlation exists between CEC and BD. This could mean that as soil becomes denser, it gains more cation exchange sites. There is a strong **negative correlation** between KOC and CEC, meaning as soil organic carbon retention (KOC) increases, the cation exchange capacity (CEC) tends to decrease. For horticulture soil samples it is observed that there is a very strong **negative correlation** between **KOC** and **CEC**. This suggests that as the soil's ability to retain organic compounds (KOC) increases, its ability to hold and exchange cations (CEC) decreases. Similarly, there's a very strong **negative correlation** between **KOC** and **BD.** This means that as the soil's organic carbon retention increases, bulk density tends to decrease. A strong **positive correlation** exists between **CEC** and **BD,** suggesting that higher bulk density is associated with a greater cation exchange capacity. Table 4.5 suggested that for grassland and forest sample sites it was observed that there is a very strong **positive correlation** between **KOC** and **CEC**. This indicates that as the soil's ability to retain organic compounds (KOC) increases, its cation exchange capacity (CEC) also tends to increase. A very strong **negative correlation** exists between **KOC** and **BD and CEC and BD**, meaning that as the soil's organic matter content (KOC) increases, bulk density (BD) decreases and higher bulk density is associated with a lower cation exchange capacity.

DISCUSSION

'The study presented significant insights into the variation of soil properties such as bulk density, cation exchange capacity (CEC), potassium permanganate oxidizable carbon (KOC), microbial biomass carbon (MBC), water-soluble organic carbon (WSOC), and soil organic carbon (SOC) across various land uses in Tehsil Ramnagar. These parameters are essential for understanding soil health, fertility, and carbon sequestration potential, providing a comprehensive overview of soil dynamics in agriculture, horticulture, grassland, and forest systems. The bulk density of soil, a crucial indicator of soil compaction and porosity, exhibited distinct patterns across the studied land uses. Forest soils exhibited the lowest bulk density, followed by horticulture and grassland soils, while agriculture soils showed the highest bulk density (1.54 g/cm³). The trend observed here aligns with earlier studies, which indicate that natural ecosystems like forests maintain lower bulk density due to higher organic matter content and soil structure complexity (Blume et al., 2010; Batjes, 2014). On the other hand, the higher bulk density observed in agricultural soils is indicative of soil compaction, often a result of tillage and heavy machinery use (Pikul et al., 2009). This finding is particularly important, as increased bulk density restricts root penetration, reduces water infiltration, and hampers overall soil fertility, leading to reduced crop yields in agricultural systems (Rutgers et al., 2020).

The depth-wise variation of bulk density further highlights the soil compaction effect across different layers. The topsoil layer (0-15 cm) consistently exhibited the lowest bulk density, which may be attributed to better soil aggregation and organic matter content. In contrast, the subsurface and subsoils (15-30 cm and 30-60 cm) displayed higher bulk density, especially in agricultural and grassland soils. This suggests a gradual increase in compaction with depth, consistent with findings by Schjønning et al. (2002), who noted that deeper soil layers in intensively managed agricultural systems tend to be more compacted due to mechanical stress and lack of organic matter.

CEC is a critical indicator of soil fertility, reflecting the soil's ability to retain essential nutrients. In the study, CEC values were highest in the subsurface layers (30-60 cm) of agricultural and horticultural soils, indicating the accumulation of nutrients due to leaching from the surface. These findings are consistent with those of Allen and Dendy (2016), who reported high CEC values in deeper layers of agricultural soils, likely due to organic matter leaching from the upper soil horizon. In contrast, forest soils exhibited lower CEC values, possibly due to differences in soil organic matter composition, which influences the exchange capacity (Fleissner et al., 2019).

The CEC trend observed in this study also aligns with previous research showing that natural ecosystems such as forests and grasslands tend to have lower CEC compared to agricultural systems (Marschner, 2012). This difference could be attributed to the accumulation of organic materials like decomposed plant roots and microbial residues in forest and grassland soils, which results in higher cation exchange capacity, thus improving nutrient retention (Malik et al., 2018). The lower CEC values in forest soils may also reflect nutrient limitations, as forest ecosystems typically have low nutrient leaching and rely more on nutrient cycling processes.

The variation in KOC, which provides an estimate of the active organic carbon pool in the soil, indicated a clear disparity in the organic carbon content among the different land uses. Forest soils exhibited the highest KOC values across all depths, followed by grassland, horticulture, and agricultural soils. This pattern is consistent with previous studies, which have shown that forest ecosystems generally have higher KOC due to greater organic matter input from leaf litter, root exudates, and decomposing plant material (Chenu et al., 2000; Nair et al., 2017).

Grassland soils, while showing moderate KOC levels, also demonstrated a slight decline from surface to deeper layers, suggesting some degree of organic matter decomposition and leaching. In contrast, the KOC levels in horticultural and agricultural soils were notably lower, with agriculture soils showing the lowest KOC values. This suggests that intensive agricultural practices, including tillage and the use of chemical fertilizers, may deplete the active organic carbon pool, thereby reducing the soil's carbon storage potential (Ghosh et al., 2021).

The microbial biomass carbon (MBC) content demonstrated a clear decrease with soil depth, with the highest MBC found in grassland soils, followed by forest and orchard soils, while agricultural soils exhibited the lowest MBC content. This trend is consistent with the literature, which highlights the role of organic matter inputs in supporting microbial populations in soils (Bardgett et al., 2008). Grasslands, due to their diverse vegetation and organic matter inputs, provide a conducive environment for microbial life. Forests, though having slightly lower MBC compared to grasslands, still maintain a higher microbial biomass than agricultural soils, as natural ecosystems support a more diverse soil microbiota (Zak et al., 2003).

The lower MBC content in agricultural soils is often linked to the depletion of organic carbon reserves and the use of pesticides or fertilizers that can adversely affect soil microorganisms (van der Heijden et al., 2008). These findings support the idea that organic farming practices or agroforestry systems that encourage higher organic matter inputs may improve microbial biomass and soil health (Saha et al., 2020).

The water-soluble organic carbon (WSOC) exhibited minimal variation across land uses, except for a significant decrease in agriculture soils. This is consistent with the fact that WSOC represents the labile fraction of organic carbon, which is readily available to soil microbes and contributes to nutrient cycling. The decline in WSOC in agricultural soils reflects the loss of easily available organic carbon, which could result from intensive tillage practices and the degradation of organic matter over time (Zhu et al., 2017).

The SOC content in the soils of different villages within Tehsil Ramnagar revealed that forest and orchard lands exhibited higher SOC levels compared to agriculture and grassland soils, highlighting the role of forest management and agroforestry in carbon sequestration. These findings are aligned with studies indicating that well-managed forest and orchard soils tend to accumulate more SOC than agricultural and grassland soils due to slower rates of organic matter decomposition and more efficient carbon cycling processes (Lal, 2004).

This study reinforces the growing body of literature emphasizing the significant role of land use in determining soil properties, particularly in relation to carbon sequestration. Forest soils, with their low bulk density, high CEC, high KOC, and greater microbial biomass, stand out as key reservoirs of soil organic carbon, contributing to enhanced carbon storage. On the other hand, agricultural systems, characterized by higher bulk density, lower KOC, and microbial biomass, have been shown to experience soil degradation and organic carbon depletion, as indicated in previous studies (Jiang et al., 2021).

CONCULSIONS

The findings suggest that land management practices play a crucial role in shaping soil health and carbon dynamics. Forests, with their low compaction and high organic matter, are ideal for maintaining soil fertility and storing carbon. In contrast, agricultural systems need to adopt more sustainable practices such as reduced tillage, organic amendments, and agroforestry to improve soil quality and enhance carbon sequestration. The results also underscore the need for deeper, site-specific studies to optimize land use practices for soil conservation and carbon management.

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