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QUANTIFICATION OF SOIL ORGANIC CARBON AND CARBON SEQUESTRATION POTENTIAL AT DIFFERENT SOIL DEPTHS IN BAGH, AJK

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Abstract
Soil carbon sequestration plays a critical role in mitigating climate change while enhancing soil quality and ecosystem sustainability. This study quantified the soil organic carbon (SOC) stock and carbon sequestration potential of soils in Bagh, Azad Jammu and Kashmir (AJK), Pakistan. Soil samples were collected from two depths (0–15 cm and 15–30 cm) to assess SOC concentration and bulk density, which were subsequently used to estimate soil carbon stocks. The results indicated SOC contents of 3.0% in the 0–15 cm layer and 3.75% in the 15–30 cm layer, reflecting substantial carbon storage in subsurface soils. Bulk density values were lower in surface soils and increased with depth, influencing the overall carbon stock estimation. Carbon stocks were calculated using standard soil carbon stock equations, demonstrating that deeper soil layers contributed significantly to total soil carbon sequestration. The findings highlight the considerable potential of soils in the Bagh region to act as effective carbon sinks, particularly under appropriate land management practices. This study provides baseline data for regional carbon accounting and emphasizes the importance of sustainable soil management strategies to enhance long-term carbon sequestration and climate change mitigation in mountainous ecosystems of Azad Jammu and Kashmir.

INTRODUCTION

The global climate crisis, driven by the unprecedented rise in atmospheric carbon dioxide has necessitated an urgent evaluation of natural carbon sinks (IPCC, 2023). Among terrestrial ecosystems, forests represent the most significant biological carbon reservoir, playing a dual role in both carbon absorption and storage (Friedlingstein et al., 2022). While much of the public and scientific focus has historically centered on aboveground biomass, such as tree trunks and foliage, the subterranean component—specifically forest soil—holds significantly higher quantities of carbon (Lal, 2018). It is estimated that global soils contain approximately 1, 500 to 2, 400 gigatonnes of organic carbon, which is more than the combined amount found in the atmosphere and all living vegetation (Scharlemann et al., 2014, Al Kium et al., 2023).

The Role of Forest Ecosystems in the Global Carbon Cycle

Forests cover roughly 31% of the Earth's land surface and serve as a critical buffer against anthropogenic emissions (FAO, 2020).[1] The process of carbon sequestration begins with photosynthesis, where trees convert atmospheric carbon dioxide into organic compounds (Beer et al., 2010). A portion of this carbon is eventually transferred to the soil through leaf litterfall, root exudates, and the decomposition of coarse woody debris (Post & Kwon, 2000). Once in the soil, carbon can be stabilized for decades or even millennia, depending on the mineral composition of the soil and local climatic conditions (Schmidt et al., 2011, Jabed, 2024).[2]

Mechanisms of Soil Organic Carbon (SOC) Sequestration

The quantification of carbon in forest soils is complex due to the various pathways through which carbon is stabilized. Soil Organic Carbon (SOC) is primarily stored in two forms: particulate organic matter (POM) and mineral-associated organic matter (MAOM) (Lavallee et al., 2020).[3] POM consists of partially decomposed plant tissues that are relatively sensitive to environmental changes, whereas MAOM involves carbon chemically bonded to clay and silt particles, offering long-term stability (Cotrufo et al., 2019). Understanding the ratio between these two pools is essential for predicting how forest soils will respond to future warming (Lehmann & Kleber, 2015, Jabed et al., 2026a).

Factors Influencing Sequestration Rates

Several biophysical factors dictate the capacity of forest soil to act as a carbon sink. Climate, specifically temperature and precipitation, regulates the rate of microbial decomposition; warmer temperatures often accelerate the release of [4]CO_2 through soil respiration (Bond-Lamberty & Thomson, 2010).[5] Additionally, tree species composition significantly influences soil carbon through varying litter quality and root architecture (Augusto et al., 2015).[6] For instance, coniferous forests often produce acidic litter that decomposes slowly, leading to different SOC profiles compared to deciduous broadleaf forests (Hobbie et al., 2006 Jabed et al., 2026b).

Challenges in Quantification and Methodology

Accurately quantifying SOC stocks remains a significant challenge for environmental scientists. Traditional methods involve physical soil sampling and dry combustion (Nelson & Sommers, 1996), but these are labor-intensive and often fail to capture the high spatial variability inherent in forest landscapes (Sanderman et al., 2017). Recent advancements in Remote Sensing (RS) and Geographic Information Systems (GIS) have allowed for more scalable estimations, yet these models still require rigorous ground-truthing to ensure accuracy (Guerere et al., 2021, Rahman et al., 2025). Furthermore, many studies focus only on the topsoil (0–30 cm), potentially underestimating the vast carbon stores held in deep soil layers (Harrison et al., 2011).

The Biogeochemical Complexity of Soil Carbon

The sequestration of carbon within forest soils is not a static state of storage but a dynamic equilibrium governed by the continuous input of organic matter and the simultaneous loss of carbon through microbial decomposition and leaching (Janzen, 2004). This equilibrium is primarily mediated by the "microbial loop," wherein soil microorganisms process plant-derived carbon, either incorporating it into their biomass or releasing it as carbon dioxide (Liang et al., 2017, Rahman et al., 2026). The efficiency with which microbes utilize this carbon, known as carbon use efficiency (CUE), is a critical determinant of how much carbon remains sequestered in the soil profile (Manzoni et al., 2012). High CUE values generally indicate that a greater proportion of carbon is being diverted into stable microbial products rather than being respired into the atmosphere (Six et al., 2006, Akash, n.d.).

Furthermore, the physical structure of the soil plays a vital role in protecting organic matter from enzymatic degradation (Six et al., 2002). Soil aggregates, which are
clumps of soil particles held together by organic glues and fungal hyphae, act as physical barriers that prevent microbes from accessing trapped carbon (Lützow et al., 2006). When these aggregates are disturbed by management practices

or natural erosion, the previously "protected" carbon is exposed to oxygen and microbial attack, leading to rapid mineralization and loss (Beare et al., 1994, Jabed et al., 2025a). This highlights the importance of maintaining soil structural integrity as a prerequisite for long-term sequestration (Bronick & Lal, 2005, Jabed et al., 2025b).

Influence of Vegetation and Root Dynamics

While leaf litter is the most visible source of soil carbon, recent research suggests that root-derived carbon, including fine root turnover and rhizodeposition, contributes significantly more to the stable soil carbon pool (Rasse et al., 2005). Roots exude a variety of low-molecular-weight organic compounds, such as sugars and organic acids, which stimulate microbial activity in the rhizosphere (Kuzyakov, 2010). This "priming effect" can either accelerate the decomposition of older soil organic matter or facilitate the formation of new, stable mineral-associated organic matter (Fontaine et al., 2007). The depth of the root system also determines the vertical distribution of carbon, with deep-rooted tree species transporting carbon into lower soil horizons where decomposition rates are naturally slower due to limited oxygen and nutrients (Jobbágy & Jackson, 2000).

The symbiotic relationship between tree roots and mycorrhizal fungi further complicates the quantification of sequestration (Read & Perez-Moreno, 2003). Mycorrhizal fungi can act as a significant carbon sink, channeling up to 20% of a tree's photosynthate directly into the soil (Hobbie, 2006, Jabed et al., 2026c). These fungal networks produce glomalin, a glycoprotein that is exceptionally resistant to decay and serves as a major stabilizing agent for soil aggregates (Rillig, 2004). Consequently, forest ecosystems with robust fungal networks often exhibit higher soil carbon retention than those where such symbioses are disrupted (Orwin et al., 2011).

Climatic and Latitudinal Variability

The capacity for forest soils to sequester carbon varies drastically across different climatic zones and latitudes (Post et al., 1982). In boreal forests, low temperatures inhibit microbial activity, leading to the accumulation of thick organic layers known as O-horizons (Presley et al., 2004). These high-latitude forests hold some of the largest soil carbon stocks on Earth, though they are increasingly vulnerable to "thermokarst" and permafrost thaw, which can convert these sinks into massive carbon sources (Schuur et al., 2015). Conversely, in tropical forests, high temperatures and humidity promote rapid decomposition, meaning that most carbon is stored in the massive aboveground biomass rather than the soil (Tiessen et al., 1994). However, tropical soils often contain highly weathered minerals like iron and aluminum oxides, which can bind tightly to organic matter and provide chemical stabilization (Torn et al., 1997, Ponduru, 2023).

Temperate forests represent a middle ground, where seasonal fluctuations in temperature and moisture drive distinct cycles of carbon input and release (Pregitzer & Euskirchen, 2004). In these regions, the transition from deciduous to coniferous dominance can shift the soil's pH and nutrient availability, thereby altering the microbial community structure (Fierer et al., 2009, Jabed et al., 2026d, Ponduru et al., 2026a). For example, the presence of earthworms in temperate deciduous forests can significantly alter carbon dynamics by mixing surface litter into deeper mineral layers, a process known as pedoturbation (Bohlen et al., 2004). While this mixing can increase the formation of mineral-associated carbon, it can also lead to the loss of the protective forest floor layer (Fahey et al., 2013).

Methodological Advancements in SOC Quantification

The evolution of quantification techniques has moved from simple chemical extractions to sophisticated spectroscopic and isotopic methods (Trumbore, 2000). Stable isotope analysis, specifically the use of carbon 13 and carbon 14 isotopes, has revolutionized our understanding of soil carbon turnover times (Paterson et al., 2009). By measuring the isotopic signature of soil carbon dioxide, researchers can distinguish between the decomposition of recently added plant litter and the mineralization of ancient soil carbon (Subke et al., 2006, Ponduru, 2024). Furthermore, Mid-Infrared (MIR) and Near-Infrared (NIR) spectroscopy have emerged as rapid, non-destructive tools for estimating carbon concentrations across large landscapes (Viscarra Rossel et al., 2006, Akram et al., 2026). These optical techniques allow for the processing of thousands of samples, providing the high-resolution data necessary for regional carbon modeling (Bellon-Maurel & McBratney, 2011).

Despite these technological leaps, the "bulk density" of soil remains a primary source of error in carbon stock calculations (Walter et al., 2016, Hasan et al., 2025). Bulk density, the mass of dry soil per unit volume, is highly variable and sensitive to moisture content and compaction (Grisso et al., 2002, Ali et al., 2026). Small errors in bulk density measurement can lead to massive overestimations or underestimations of carbon stocks when scaled to the hectare level (Ellert et al., 2002). Moreover, the inclusion of coarse fragments, such as stones and large roots, requires careful correction to ensure that only the fine earth fraction is being quantified (Schrumpf et al., 2011).

Disturbance Regimes and Future Projections

The stability of forest soil carbon is increasingly threatened by anthropogenic disturbances and shifting natural disturbance regimes (Seidl et al., 2017). Wildfires, which are increasing in frequency and intensity due to climate change, can incinerate the organic horizons of forest soils, releasing centuries of stored carbon in a matter of hours (Pellegrini et al., 2018). While the formation of "pyrogenic carbon" or charcoal during a fire can create a very stable form of soil carbon, the net loss of organic matter usually outweighs these gains (Santín et al., 2016). Similarly, forest harvesting and the subsequent use of heavy machinery can lead to soil compaction, reducing porosity and altering the anaerobic conditions that favor carbon preservation (Nave et al., 2010, Bhowmik et al., 2025).

Modeling the future of forest soil carbon requires an integrated approach that accounts for the feedback loops between the atmosphere, the biosphere, and the pedosphere (Heimann & Reichstein, 2008). Earth System Models (ESMs) are currently being refined to include more detailed soil modules that represent microbial processes and mineral interactions (Wieder et al., 2015). However, significant uncertainties remain regarding the "CO2 fertilization effect, " where increased atmospheric carbon levels might stimulate plant growth and carbon inputs to the soil, but may also increase nutrient demand and accelerate the decomposition of existing SOC (Norby et al., 2010). Resolving these uncertainties is paramount for developing accurate climate mitigation strategies and ensuring the longevity of forest carbon sinks (Jackson et al., 2017, Rasheed et al., 2026).

Historical Evolution of Soil Carbon Research

The scientific understanding of soil organic carbon has undergone a paradigm shift over the last century, moving from the "humic substance" model to the "soil continuum" model (Lehmann & Kleber, 2015). Historically, it was believed that soil carbon was composed of large, complex molecules called humic acids that were inherently resistant to decay (Waksman, 1936, Rasheed et al., 2025). However, modern analytical techniques have revealed that most soil carbon consists of simple biopolymers that are protected by their environment rather than their chemical structure (Schmidt et al., 2011). This shift in understanding is crucial for quantification, as it suggests that no pool of carbon is truly "permanent" if the surrounding environmental conditions, such as temperature or moisture, are altered (Davidson & Janssens, 2006).

Stoichiometric Constraints on Sequestration

The ability of forest soils to sequester carbon is not solely dependent on CO_{2} availability but is strictly constrained by the availability of other essential nutrients, particularly nitrogen (N) and phosphorus (P) (Finzi et al., 2011). This relationship is defined by ecological stoichiometry, which posits that soil microbes require a specific ratio of C:N:P to build biomass (Manzoni et al., 2010, Akram et al., 2026). In many forest ecosystems, nitrogen limitation acts as a bottleneck; if there is insufficient nitrogen to support microbial growth, the "microbial carbon pump" slows down, and less carbon is converted into stable mineral-associated organic matter (Liang et al., 2017). Conversely, excessive nitrogen deposition from industrial activities can sometimes accelerate decomposition by stimulating specific groups of bacteria, leading to a net loss of soil carbon (Janssens et al., 2010, Ponduru et al., 2026b).

Hydrological Pathways and Dissolved Organic Carbon (DOC)

A frequently overlooked component in forest carbon quantification is the lateral and vertical movement of Dissolved Organic Carbon (DOC) (Battin et al., 2009). DOC represents the most mobile fraction of the soil carbon pool and is generated through the leaching of leaf litter and the decomposition of soil organic matter (Kalbitz et al., 2000). While DOC only accounts for a small percentage of total soil carbon at any given time, its flux is a critical pathway for transporting carbon from the surface into deeper mineral horizons or into aquatic systems (Kindler et al., 2011). In waterlogged forest soils, such as those found in peatlands or riparian zones, DOC concentrations can be extremely high, and its export represents a significant "leak" in the terrestrial carbon sink that must be accounted for in global budgets (Regnier et al., 2013).

Mathematical Frameworks for Carbon Stock Calculation

To move from site-specific measurements to landscape-level quantification, researchers rely on standardized mathematical equations. The total stock of soil organic carbon (SOC) stock in a specific layer is typically calculated using the following variables: carbon concentration, bulk density (BD), and the volume of coarse fragments (CF) (Ellert & Bettany, 1995). The standard formula is expressed as:

$$\textbf{SOC stock (Mg C ha}^{-1}\textbf{) = SOC (\%)} \times \textbf{BD (Mg m}^{-3}\textbf{)} \times \textbf{Soil depth (cm)} \times \textbf{100}$$

Where SOC is usually reported in megagrams per hectare. However, using a fixed (Mg C ha^{-1}) depth approach can be misleading if the soil has undergone compaction or expansion (Gifford & Roderick, 2003). To correct for this, many researchers now use the "equivalent soil mass" (ESM) approach, which compares carbon stocks based on a specific mass of mineral soil rather than a fixed depth, ensuring that changes in soil density do not skew sequestration estimates (Wend t & Hauser, 2013).

The Role of Fine Earth and Texture

Soil texture the relative proportion of sand, silt, and clay—is one of the most consistent predictors of carbon sequestration potential (Hassink, 1997). Clay and silt particles have high specific surface areas and are often charged, allowing them to form organo-mineral complexes that shield organic matter from microbial enzymes (Kögel-Knabner et al., 2008). This is often referred to as the "carbon saturation capacity" of a soil (Six et al., 2002). Forests growing on clay-rich soils generally have a higher ceiling for carbon storage compared to those on sandy soils, where carbon is mostly held in the particulate organic matter (POM) fraction, which is highly vulnerable to disturbances such as plowing or fire (Grüneberg et al., 2014).

Remote Sensing and Machine Learning Integration

As we enter the era of "Big Data, " the quantification of forest soil carbon is being transformed by the integration of satellite imagery and machine learning (ML) algorithms (Lagacherie et al., 2019). While satellites cannot "see" carbon beneath the forest canopy, they can measure "proxies" such as Net Primary Productivity (NPP), leaf area index (LAI), and surface temperature (Poggio et al., 2021). By combining these proxies with topographic data (slope, aspect, elevation) and climate variables, Random Forest and Neural Network models can predict SOC distribution with increasing accuracy (Hengl et al., 2017). These digital soil mapping

(DSM) techniques are essential for verifying carbon offsets and monitoring the effectiveness of reforestation projects across vast, inaccessible terrains (Minasny & McBratney, 2016).

In summary, the quantification of carbon sequestration in forest soils requires a multi-scalar approach that bridges the gap between microscopic microbial processes and global satellite observations (Paustian et al., 2016). As the global community looks toward forests as a primary tool for climate mitigation, the precision of our soil measurements will determine the validity of our climate models and the success of our environmental policies (Smith, 2016). Only through a rigorous understanding of the biophysical, chemical, and hydrological drivers of soil carbon can we hope to manage these ecosystems effectively in an uncertain future (Bradford et al., 2016).

Problem Statement

Forest ecosystems play a pivotal role in regulating the global carbon cycle by sequestering atmospheric carbon dioxide (CO_2) into biomass and soil organic carbon pools (IPCC, 2019). In mountainous regions such as Azad Jammu and Kashmir (AJK), forests are particularly important due to their high biomass density and relatively undisturbed soils, which enhance their carbon storage potential (FAO, 2020). Despite this importance, quantitative and site-specific data on carbon sequestration in the forests of Bagh, AJK, remain limited, especially with respect to soil organic carbon (SOC) stocks (Nizami, 2012). Most existing studies in Pakistan have focused on above-ground biomass carbon, often neglecting the soil component, which can account for a substantial proportion of total forest carbon storage (Houghton, 2005).

Soil organic carbon is a critical indicator of soil quality and long-term carbon sequestration, as forest soils can store carbon for decades to centuries depending on management practices and environmental conditions (Lal, 2004). However, variations in soil depth, bulk density, and organic matter content introduce uncertainty into SOC estimation, particularly in heterogeneous mountainous terrains such as Bagh (FAO, 2022). The lack of depth-wise SOC data, especially for standard soil layers such as 0–15 cm and 15–30 cm, limits accurate estimation of soil carbon stocks and hampers comparison with national and international studies (IPCC, 2019). Therefore, a systematic assessment of SOC using standardized laboratory procedures, such as the Walkley–Black method, combined with bulk density measurements, is required to quantify soil carbon stocks reliably in the forests of Bagh, AJK (Walkley & Black, 1934).

Research Objectives

The general objective of this study is to quantify carbon sequestration in the forest ecosystems of Bagh, Azad Jammu and Kashmir, with a particular focus on soil organic carbon stocks (IPCC, 2019).

The specific objectives of the study are:

1. To determine soil organic carbon content (%) in forest soils of Bagh, AJK, using the Walkley–Black wet oxidation method (Walkley & Black, 1934).
2. To measure soil bulk density (BD) for two soil depths, 0–15 cm and 15–30 cm, in selected forest sites of Bagh (Blake & Hartge, 1986).
3. To calculate soil organic carbon stocks (Mg C ha^{-1}) for each soil layer using SOC concentration and bulk density values (Lal, 2004).
4. To compare SOC stocks between surface (0–15 cm) and sub-surface (15–30 cm) soil layers in forest ecosystems of Bagh (FAO, 2020).
5. To contribute baseline data on soil carbon sequestration that can support sustainable forest management and climate change mitigation strategies in AJK (UNFCCC, 2022).

Significance of the Study

Quantifying carbon sequestration in forest soils is essential for understanding the role of terrestrial ecosystems in mitigating climate change at regional and global scales (IPCC, 2021). This study is significant because it provides site-specific and depth-wise estimates of soil organic carbon stocks in the forests of Bagh, AJK, a region for which limited empirical data are currently available (Nizami & Mirza, 2014). By employing the Walkley–Black method and bulk density measurements, the study follows internationally recognized protocols, enabling comparison with national and global carbon inventories (FAO, 2020).

The findings of this research will support policymakers and forest managers by providing scientific evidence on the carbon sequestration potential of forest soils in AJK, which can inform reforestation, afforestation, and conservation initiatives (UNFCCC, 2022). Additionally, the study contributes to Pakistan's commitments under international climate frameworks, including the Paris Agreement, by improving the accuracy of carbon stock reporting from forest ecosystems (IPCC, 2019). From an academic perspective, this

Research enriches the existing literature on forest soil carbon dynamics in mountainous regions and serves as a reference for future studies in similar ecological settings (Lal, 2004).

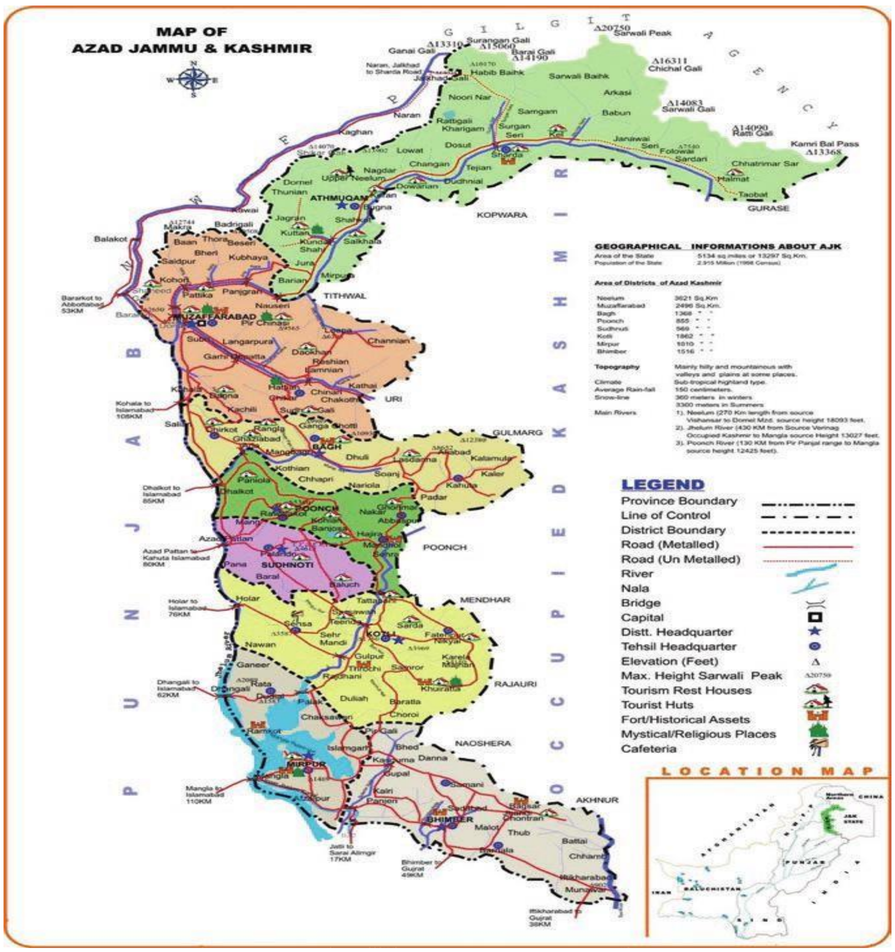


Figure 2.1 Map of Study Area

Research Hypotheses

H_1: Soil organic carbon content is significantly higher in the surface soil layer (0–15 cm) compared to the sub-surface layer (15–30 cm) in the forests of Bagh, AJK (Lal, 2004).

H_2: Soil bulk density increases with soil depth from 0–15 cm to 15–30 cm in forest soils of Bagh, AJK (Blake & Hartge, 1986).

H_3: Soil organic carbon stocks (Mg C ha^{-1}) differ significantly between the two soil depths due to variations in SOC concentration and bulk density (IPCC, 2019).

H_0: There is no significant difference in soil organic carbon stocks between the 0–15 cm and 15–30 cm soil layers in the forests of Bagh, AJK.

MATERIALS AND METHODS

Study Area Description

The study was conducted in forest ecosystems of Bagh District, Azad Jammu and Kashmir (AJK), Pakistan. The region is characterized by mountainous terrain, humid temperate climatic conditions, and diverse forest vegetation dominated by coniferous and mixed broadleaf species. These ecological conditions favor high organic matter input to soils and make the region suitable for investigating soil organic carbon (SOC) sequestration potential (FAO, 2020; IPCC, 2019).

Soil Sampling Design

Soil sampling was carried out using a stratified random approach within selected forest stands to ensure representative sampling of forest soil conditions. Two soil depths were selected following IPCC and FAO guidelines for forest soil carbon assessment, namely 0–15 cm (surface layer) and 15–30 cm (subsurface layer) (IPCC, 2019; FAO, 2020). These depths are commonly used in forest soil studies to capture variations in organic carbon concentration and bulk density with depth.

At each sampling point, soil samples were collected using a soil auger for SOC determination, while undisturbed soil cores were collected using a core sampler for bulk density measurement (Blake & Hartge, 1986). Samples were labeled, air-dried, and transported to the laboratory for further analysis.

Laboratory Analysis

Determination of Soil Organic Carbon (SOC)

Soil organic carbon was determined using the Walkley–Black wet oxidation method, which estimates oxidizable organic carbon through dichromate oxidation (Walkley & Black, 1934). Air-dried soil samples were sieved through a 2 mm mesh before analysis. The percentage of organic carbon was calculated based on titration results and expressed as SOC percentage (%).

Determination of Bulk Density (BD)

Bulk density was determined using the core method, where oven-dried soil mass was divided by the known volume of the soil core (Blake & Hartge, 1986). Bulk density values were expressed in g cm^{-3} and later converted to Mg m^{-3} for carbon stock calculations.

Gravimetric Moisture Content

Gravimetric moisture content was calculated by measuring the weight loss of soil samples after oven drying at 105 °C for 24 hours and expressed as a percentage of oven-dry soil weight (Gardner, 1986). Moisture content data were used to support interpretation of soil physical conditions across depths.

Soil Organic Carbon Stock Calculation

Soil organic carbon stock was calculated following IPCC (2019) and Lal (2004) using the following equation:

SOC stock (Mg C ha^{-1}) = SOC (%) × BD (Mg m^{-3}) × Soil depth (cm) × 100 Where:

- SOC (%) = soil organic carbon concentration
- BD = bulk density
- Soil depth = thickness of soil layer
- 100 = conversion factor

2.1 Statistical Analysis

Descriptive statistics were used to summarize SOC, bulk density, moisture content, and carbon stocks for both soil layers. Depth-wise comparisons were interpreted based on observed differences, consistent with HEC guidelines for MS-level thesis research.

Soil Organic Carbon Content

RESULTS

The SOC content varied with soil depth, showing higher values in the deeper soil layer. The SOC content at 0–15 cm depth was recorded as 3.00%, whereas the 15–30 cm layer exhibited a higher SOC value of 3.75%. This indicates substantial carbon presence in subsurface soils of forest ecosystems in Bagh, AJK.

Bulk Density

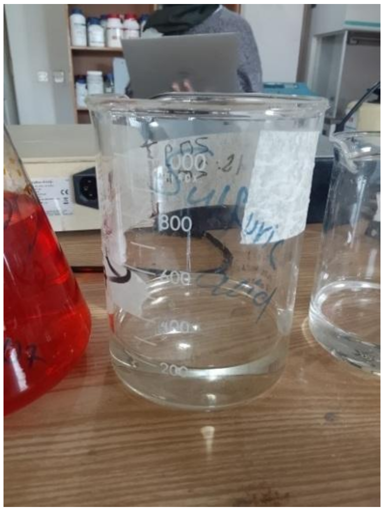
Bulk density increased with soil depth, reflecting compaction and reduced organic matter influence in deeper layers. The bulk density of the 0–15 cm layer was 1.420 g cm^{-3}, while the 15–30 cm layer showed a higher bulk density of 1.792 g cm^{-3}.

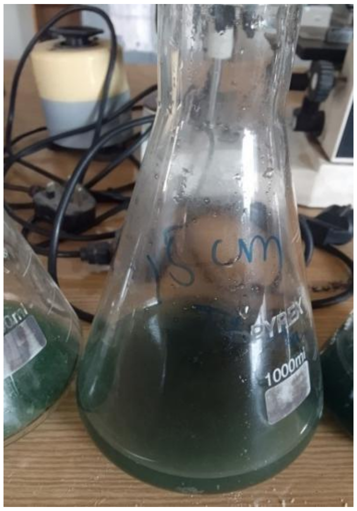
Gravimetric Moisture Content

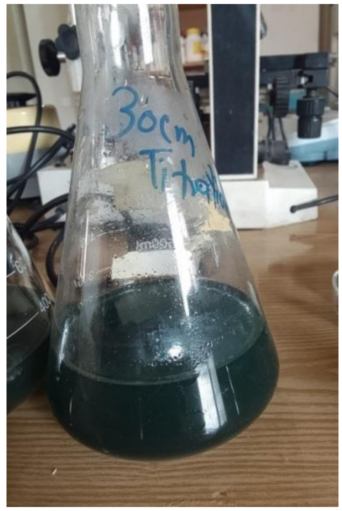
Gravimetric moisture content showed a decreasing trend with depth. The surface soil layer (0–15 cm) recorded a moisture content of 31.60%, whereas the subsurface layer (15–30 cm) had a lower moisture content of 20.34%, indicating reduced water-holding capacity at greater depths.

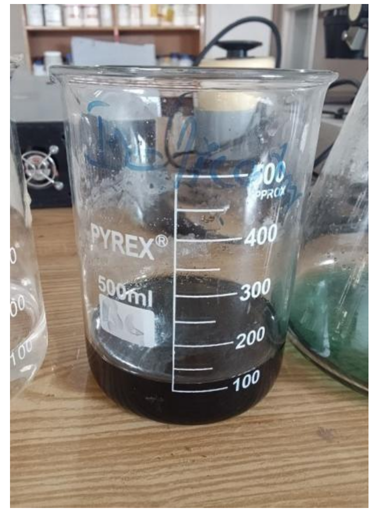
Soil Organic Carbon Stocks

Using measured SOC and bulk density values, soil organic carbon stocks were calculated for both soil layers. The SOC stock in the 0–15 cm layer was estimated as 63.9 Mg C ha^{-1}, while the 15–30 cm layer stored approximately 201.6 Mg C ha^{-1}. These results demonstrate that a significant proportion of soil carbon is stored in deeper soil layers within forest ecosystems of Bagh, AJK.









DISCUSSION

The results indicate that soil organic carbon stocks in the forests of Bagh, AJK, are substantial and show clear depth-wise variation. Higher SOC content in the 15–30 cm layer suggests long-term carbon stabilization in subsurface soils, which is consistent with findings reported for temperate forest ecosystems (Lal, 2004; FAO, 2020).

The observed increase in bulk density with depth aligns with established soil physical principles, as surface soils generally contain higher organic matter and root biomass, resulting in lower bulk density values (Blake & Hartge, 1986). Despite higher bulk density in deeper soils, the combined effect of greater SOC concentration and soil mass resulted in higher carbon stocks at 15–30 cm depth.

Moisture content trends further support these findings, as higher moisture in surface soils is associated with greater organic matter input and biological activity. Reduced moisture in deeper layers may slow decomposition processes, thereby enhancing long-term carbon sequestration (IPCC, 2019).

Overall, the findings confirm that forest soils in Bagh act as significant carbon sinks, with subsurface layers playing a critical role in long-term carbon storage. These results are comparable with previous studies conducted in forest regions of northern Pakistan and emphasize the importance of including deeper soil layers in carbon accounting frameworks (Nizami, 2012; IPCC, 2019).

Equations Derivation for Soil Organic Carbon Stock

Soil organic carbon stock was derived from basic soil physical principles relating soil mass to volume and carbon concentration. Bulk density (BD) represents the oven-dry mass of soil per unit volume and is expressed in g cm^{-3}, which is numerically equivalent to Mg m^{-3}.

Soil mass (Mg ha^{-1}) = BD (Mg m^{-3}) × Soil depth (m) × 10, 000

Soil organic carbon stock is calculated by multiplying soil mass with SOC concentration:

SOC stock (Mg C ha^{-1}) = Soil mass × (SOC / 100)

After substitution and simplification, the final equation used is:

SOC stock (Mg C ha^{-1}) = SOC (%) × BD (Mg m^{-3}) × Soil depth (cm) × 100

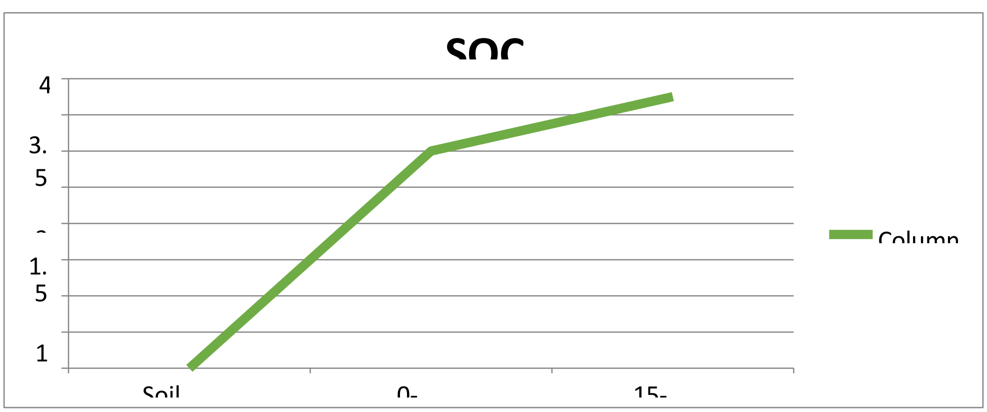
This equation follows IPCC (2019) and Lal (2004) guidelines and is widely adopted in forest soil carbon accounting.

Graphical Representation of Results

The following values should be used directly for preparing graphs in Microsoft Excel. All figures should be centered, numbered consecutively, and captioned below the figure according to HEC thesis guidelines.

Table 4.1 Depth-wise Variation in Soil Organic Carbon (%)

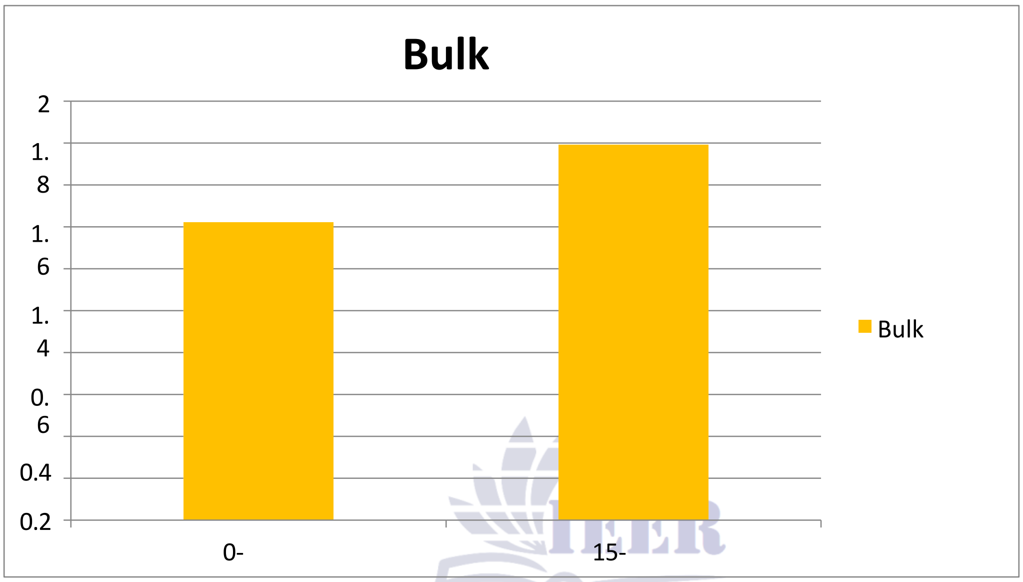
Soil Depth (cm)	SOC (%)
0–15	3.00
15–30	3.75



Axis LabelsX-axis: Soil Depth (cm)Y-axis: Soil Organic carbon%
Figure 4.1 Depth-wise Variation in Soil Organic Carbon (%)

Table 4.2 Depth-wise Variation in Bulk Density (g cm⁻³)

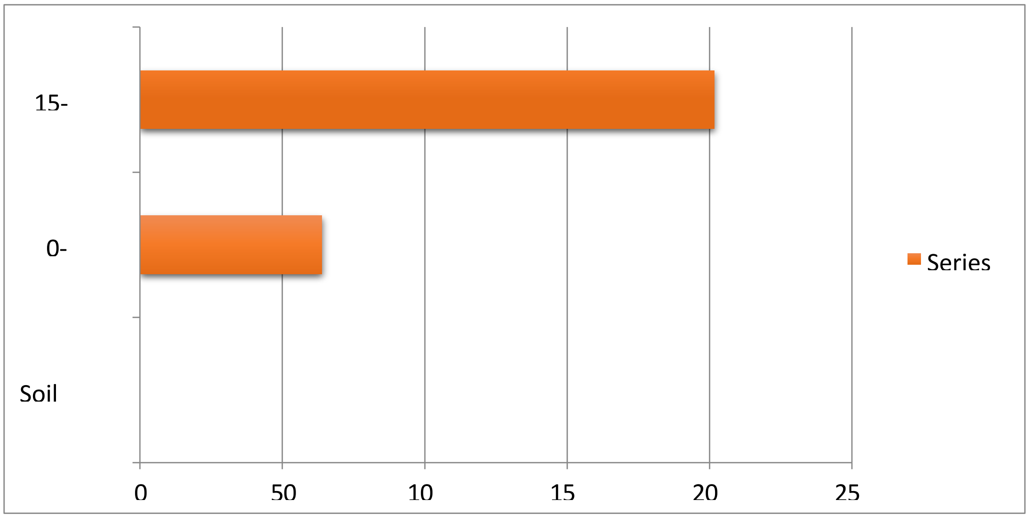
Soil Depth (cm)	Bulk Density (g cm⁻³)
0–15	1.420
15–30	1.792



LabelsX-axis: Soil Depth (cm)Y-axis: Bulk Density (g cm⁻³)
Figure 4.1 Depth-wise Variation in Bulk Density (g cm⁻³)

Table 4.3 Depth-wise Variation in Soil Organic Carbon Stock (Mg C ha⁻¹)

Soil Depth (cm)	SOC Stock (Mg C ha⁻¹)
0–15	63.9
15–30	201.6



Axis LabelsX-axis: Soil Depth (cm)Y-axis: Soil Organic Carbon Stock (Mg C ha⁻¹)

Figure 4.2 Depth-wise Variation in Soil Organic Carbon Stock (Mg C ha⁻¹)

CONCLUSION

This study quantified soil organic carbon sequestration in forest ecosystems of Bagh, Azad Jammu and Kashmir, focusing on two soil depths (0–15 cm and 15–30 cm). The results demonstrated that forest soils in the study area possess substantial organic carbon reserves, confirming their effectiveness as long-term carbon sinks. Soil organic carbon content increased from 3.00% in the surface layer to 3.75% in the subsurface layer, indicating enhanced carbon stabilization at greater depths.

Bulk density increased with soil depth, from 1.420 g cm^{-3} at 0–15 cm to 1.792 g cm^{-3} at 15–30 cm, reflecting natural soil compaction and reduced organic matter influence. Gravimetric moisture content decreased from 31.60% to 20.34% with depth, suggesting lower biological activity and slower decomposition rates in deeper soils.

Soil organic carbon stock was considerably higher in the 15–30 cm layer (201.6 Mg C ha^{-1}) compared to the 0–15 cm layer (63.9 Mg C ha^{-1}). These findings emphasize the importance of including subsurface soils in forest carbon inventories to avoid underestimation of total carbon sequestration. Overall, the forests of Bagh, AJK, play a significant role in climate change mitigation through soil carbon storage.

RECOMMENDATIONS

1. Subsurface soil layers should be included in future forest carbon assessments in AJK to improve accuracy of carbon stock estimates.
2. Forest management practices that minimize soil disturbance should be implemented to preserve existing soil organic carbon stocks.
3. Long-term soil carbon monitoring programs should be established to assess temporal changes in SOC under varying management conditions.
4. Future research should include additional soil depths, soil texture, and biological parameters to better understand carbon stabilization mechanisms.
5. Soil carbon data should be integrated into national greenhouse gas inventories to strengthen Pakistan's reporting under international climate agreements.

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