Journal of Agriculture and Natural Resources (2024) 7(1): 1-14
ISSN: 2661-6270 (Print), ISSN: 2661-6289 (Online)
DOI: https://doi.org/10.3126/janr.v7i1.72939

Research Article

Soil organic carbon and its influencing factors in Nepalese forest ecosystems

Gandhiv Kafle*

Faculty of Forestry, Agriculture and Forestry University, Hetauda, Makawanpur, Nepal

*Correspondence: gandhivkafle@gmail.com
*ORCID: https://orcid.org/0000-0001-5823-3454

Received: July 15, 2024; Revised: October 12, 2024;
Accepted: November 25, 2024; Published: December 30, 2024

ABSTRACT

The importance of soil organic carbon (SOC) in climate regulation and sustainable ecosystem management is increasingly recognized, prompting a comprehensive review of SOC research in Nepal. The objective of this study was to consolidate findings from various empirical studies to provide a holistic understanding of SOC dynamics across Nepalese forests. By integrating data from multiple studies derived from online search and desk reviews, this study seeks to identify patterns and factors influencing SOC stocks, thereby informing more effective land management and conservation strategies. The analysis was prepared based on the articles published in the last 100 years (1925-2024). The collected data were synthesized to identify patterns and key factors influencing SOC stocks in Nepalese forests. A narrative synthesis approach was used to integrate findings across studies, providing a comprehensive understanding of SOC dynamics and sequestration potential in the region. This study highlights the critical role of forest ecosystems in carbon sequestration and the influence of factors such as altitude, slope, canopy cover, and forest type on SOC stocks. The findings indicate that altitude, forest type, and management practices are key factors influencing SOC stocks, with greater carbon accumulation noted in pristine and well-maintained forests. This study highlights the significant role of SOC in climate regulation and sustainable ecosystem management. Advanced techniques like remote sensing and machine learning enhance SOC assessment accuracy, yet challenges such as deforestation and soil erosion persist. Sustainable practices, including conservation agriculture and agroforestry, are essential for SOC sequestration. Interdisciplinary collaboration, policy engagement, and community involvement are crucial for promoting these practices and addressing the challenges of SOC management, contributing to global climate change mitigation efforts.

Keywords: Soil organic carbon, Carbon sequestration, Nepalese forest ecosystems, Sustainable land management.

Correct citation: Kafle, G. (2024). Assessing soil organic carbon stocks and influencing factors in Nepalese forest ecosystems. *Journal of Agriculture and Natural Resources, 7*(1), 1-14. DOI: https://doi.org/10.3126/janr.v7i1.72939

INTRODUCTION

Soil organic carbon (SOC) is a critical component of soil health and plays a significant role in global carbon cycles, impacting climate regulation and ecosystem sustainability. In forest ecosystems, SOC acts as a major carbon sink, contributing to carbon sequestration and mitigating climate change (Lal, 2004; Smith *et al.*, 2018). Globally, SOC research has evolved significantly, emphasizing the critical role of SOC in climate regulation and ecosystem services. The preservation of carbon-rich ecosystems such as peatlands, old-growth forests, and wetlands is essential for maintaining SOC stocks and achieving global net-zero CO_2 emissions by 2050 (Beillouin *et al.*, 2023). Studies highlight the importance of

SOC in maintaining soil health, fertility, and structure, which in turn influences plant growth and carbon sequestration (Vitousek *et al.*, 1997; Korner, 2000). Moreover, global meta-analyses reveal that land-use changes, land management practices, and climate change significantly impact SOC dynamics (Beillouin *et al.*, 2023). Nepal, with its diverse topography and varying climatic conditions, provides a unique opportunity to study SOC dynamics across different forest types. The country's forests range from tropical lowland forests to alpine forests, each exhibiting distinct SOC characteristics influenced by factors such as altitude, canopy cover, and land management practices (Malla & Neupane, 2024).

Advanced techniques such as remote sensing and machine learning have revolutionized SOC estimation, providing more accurate and comprehensive data (Li *et al.*, 2024). The integration of interdisciplinary approaches and collaboration among researchers, policymakers, and local communities is crucial for promoting sustainable soil management practices and mitigating climate change (Corsi *et al.*, 2012; FAO, 2019). However, challenges such as deforestation, land-use changes, and soil erosion continue to impact SOC levels. Research indicates that well-managed forests have higher SOC content compared to degraded lands, emphasizing the need for sustainable land management practices (Sitaula *et al.*, 2004). Collaborative efforts involving researchers, policymakers, and local communities are essential for promoting conservation agriculture, agroforestry, and other climate-smart practices to enhance SOC sequestration. By addressing these challenges and leveraging advanced technologies, Nepal can make significant strides in SOC research and contribute to global climate change mitigation efforts (Malla & Neupane, 2024). Land conversion for crop production often leads to SOC loss, which can be partially mitigated through practices like agroforestry and organic amendments (Beillouin *et al.*, 2023). These findings underscore the need for strategic land management and conservation efforts to enhance SOC sequestration and support climate change mitigation.

In Nepal, SOC research has highlighted the significant role of forest ecosystems in carbon sequestration. Studies have shown that factors such as altitude, slope, canopy cover, and forest type greatly influence SOC stocks, with higher altitudes and broadleaved forests exhibiting higher carbon accumulation. The integration of advanced techniques like remote sensing and machine learning has improved the accuracy of SOC assessments, providing valuable data for climate change mitigation strategies (Malla & Neupane, 2024). Additionally, long-term studies and comprehensive sampling across various land uses have contributed to a better understanding of SOC dynamics in the region (Sitaula *et al.*, 2004).

This study covers several critical topics, including the patterns and factors influencing SOC stocks in various forest types across Nepal. It also examines the impact of altitude, canopy cover, land management practices, and the integration of advanced techniques like remote sensing and machine learning on SOC estimation and conservation strategies.

The urgent need to address climate change has directed global attention towards sustainable land management practices, particularly those that enhance SOC sequestration. Forest ecosystems, given their significant carbon storage potential, play a crucial role in this context. Nepal, with its diverse range of forest types and varying topographical and climatic conditions, offers a unique setting to study SOC dynamics. However, the current understanding of SOC in Nepal is fragmented, with existing studies focusing primarily on specific forest types or regions without a comprehensive synthesis. This analysis aims to consolidate findings from various empirical studies to provide a holistic understanding of SOC dynamics across Nepalese forests. By integrating data from multiple studies, this study seeks to identify patterns and factors influencing SOC stocks, thereby informing more effective land management and conservation strategies.

Ultimately, this study contributes to the global discourse on climate change mitigation by providing empirical evidence from Nepal, advocating for sustainable land management practices, and promoting the adoption of advanced technologies in SOC research. By addressing the gaps and challenges in current SOC studies, this article aims to support policymakers, researchers, and conservationists in their efforts to enhance carbon sequestration and combat climate change.

METHODOLOGY

Data sources, literature search strategies and selection criteria

A comprehensive literature search was conducted using Google Scholar to identify relevant studies on soil organic carbon (SOC) in forests of Nepal, covering publications from 1925 to 2004.

The reviews were made from Scopus indexed journals. Key information extracted included the study location, forest type, soil sampling depth, SOC measurement methods, environmental variables assessed, and main findings related to SOC dynamics and sequestration potential. The extracted data were tabulated to facilitate comparison and synthesis.

To ensure the quality and relevance of the studies included in the review, specific inclusion and exclusion criteria were applied. Studies were included if they focused on SOC within forest ecosystems in Nepal, employed empirical data collection methods, and discussed the impact of environmental variables or land management practices on SOC. Studies were excluded if they lacked empirical data, focused on non-forest ecosystems, or did not provide sufficient methodological details or statistical analysis.

The extracted data were synthesized to identify patterns and key factors influencing SOC stocks in Nepalese forests. A narrative synthesis approach was used to integrate findings across studies, providing a comprehensive understanding of SOC dynamics and sequestration potential in the region.

Diversity of sampling, data collection and analysis

The review on soil organic carbon (SOC) spans a diverse range of districts, reflecting various ecological and geographical contexts (Table 1). Many of these studies are centered in Nepal, covering districts such as the Terai region, Dhading, Nawalpur, and the Chure landscape. Specific forests within these districts, such as tropical community forests, pine forests, and broad-leaved forests, provide varied settings for SOC assessment. Research also extends to sub-watersheds like Pokhare Khola, highlighting different forest types and land-use practices. Additionally, studies examine altitudinal gradients and forest types in areas like Shivapuri Nagarjun National Park and Langtang National Park, offering a comprehensive view of SOC dynamics across different environmental conditions and forest management regimes. This geographical diversity enhances the robustness of the findings and their applicability to a wide range of ecological and management contexts.

Table 1: A comprehensive overview of the field sampling methods, soil layer depths, methods of soil carbon measurement, analysis methods and specific statistical tests and purpose used in each study

Field Sampling Method	**Soil Layers**	**Methods of Soil Carbon Measurement**	**Analysis**	**Statistical Tests and Purpose**	**References**
Soil samples collected from different forest stands and management regimes	0-20 cm, 20-40 cm, 40-60 cm	Dry combustion method using an elemental analyzer	Analysis of SOC stocks and soil quality across different forest stands and management regimes	ANOVA to compare SOC stocks and soil quality across different forest stands and management regimes	Kandel *et al.* (2024)
Soil samples collected from different forest types and soil depths	0-15 cm, 15-30 cm	Walkley-Black method and dry combustion for carbon analysis	Comparison of carbon stocks, pools, and dynamics among different forest types	ANOVA to test differences in carbon stocks among forest types and regression analysis for carbon stock dynamics	Lal *et al.* (2012)
Soil samples collected from three soil layers across different forest types	0-20 cm, 20-40 cm, 40-60 cm	Dichromate digestion method	Examination of SOC variation under different forest types	ANOVA to determine significant differences in SOC concentrations among forest types	Shapkota and Kafle (2021)
Soil samples collected from different land-use types and forest/soil conditions	Various depths depending on land-use type	Dry combustion method for SOC analysis	Evaluation of land-use changes and carbon sequestration dynamics	Regression analysis to model the relationship between land-use changes and carbon sequestration	Upadhyay *et al.* (2013)
Soil samples collected from different vertical soil layers in a tropical community forest	0-10 cm, 10-20 cm, 20-30 cm	Walkley-Black method	Analysis of vertical distribution of SOC and nitrogen	ANOVA to compare SOC and nitrogen concentrations at different soil depths	Kafle (2019)
Soil samples collected from different forest types in Pokhare Khola sub-watershed	0-10 cm, 10-20 cm, 20-30 cm	Dry combustion method using an elemental analyzer	Assessment of SOC stocks under different forest types	ANOVA to assess differences in SOC stocks among forest types	Pradhan *et al.* (2012)
Soil samples collected along altitudinal gradients in a pine forest	Various depths	Walkley-Black method for SOC measurement	Study of altitudinal gradients of stable isotopes of nitrogen and carbon	Regression analysis to explore the relationship between altitude and stable isotope concentrations	Sah and Brumme (2003)
Soil samples collected from forest floor after fire events	0-5 cm, 5-10 cm	Dry combustion method using an elemental analyzer	Impact of forest floor fire on SOC sequestration	ANOVA to examine the effects of fire on SOC concentrations	Aryal *et al.* (2018)

Field Sampling Method	**Soil Layers**	**Methods of Soil Carbon Measurement**	**Analysis**	**Statistical Tests and Purpose**	**References**
Soil samples collected from forest and grassland	0-15 cm, 15-30 cm	Dry combustion method for SOC analysis	Comparative assessment of SOC and nitrogen storage in forest and grassland	ANOVA to compare SOC and nitrogen storage between forest and grassland	Sharma and Kafle (2020)
Soil samples collected from community forests managed by user groups	0-10 cm, 10-20 cm, 20-30 cm	Walkley-Black method and dry combustion for SOC analysis	Influence of forest management and socio-economic characteristics on SOC stocks	ANOVA to evaluate the influence of different management practices on SOC stocks	Sitaula *et al.* (2019)
Soil samples collected from different vertical soil layers in a community-managed forest	0-20 cm, 20-40 cm	Dry combustion method for SOC measurement	Vertical distribution of soil properties and SOC in community-managed forests	ANOVA to compare vertical distribution of SOC and other soil properties among different soil layers	Lamichhane and Ghimire (2022)
Soil samples collected from Churia broad-leaved forest	0-10 cm, 10-20 cm, 20-30 cm	Walkley-Black method for SOC analysis	Assessment of SOC stock in Churia broad-leaved forest	ANOVA to determine significant differences in SOC concentrations at different soil depths and forest conditions	Adhikari and Ghimire (2019)
Soil samples collected from an Alnus nepalensis forest	0-20 cm, 20-40 cm	Dry combustion method for SOC measurement	Measurement of SOC and biomass carbon in Alnus nepalensis forest	Regression analysis to assess the relationship between SOC and biomass carbon	Dahal and Kafle (2013)
Soil samples collected from forest and agricultural land use in Chure landscape	0-20 cm, 20-40 cm, 40-60 cm	Dry combustion method for SOC analysis	Variation of SOC and nitrogen stocks in forest and agricultural land use	ANOVA to compare SOC and nitrogen stocks between forest and agricultural land use	Ghimire (2022a)
Soil samples collected from Chirpine forest in Mahabharat Hill	0-10 cm, 10-20 cm, 20-30 cm	Dry combustion method for SOC measurement	Analysis of vegetation and soil carbon pool in Chirpine forest	ANOVA to determine differences in vegetation and soil carbon pool at different soil depths	Ghimire (2022b)
Soil samples collected from dead wood and forest soil in Parsa National Park	0-10 cm, 10-20 cm, 20-30 cm	Walkley-Black method for SOC analysis	Contribution of dead wood and forest soil to carbon sequestration in Parsa National Park	Regression analysis to evaluate the contribution of dead wood and forest soil to carbon sequestration	Kafle *et al.* (2019)
Soil samples collected from tropical forest (Terai Sal-Shorea robusta)	0-20 cm, 20-40 cm	Dry combustion method using an elemental analyzer	Assessment of SOC in tropical forest	ANOVA to compare SOC concentrations among different tropical forest sites	Paudel *et al.* (2016)

Field Sampling Method	Soil Layers	Methods of Soil Carbon Measurement	Analysis	Statistical Tests and Purpose	References
Soil samples collected from Shorea robusta forest	0-10 cm, 10-20 cm, 20-30 cm	Walkley-Black method and dry combustion for SOC measurement	Effect of shelterwood system on SOC stock and soil quality	ANOVA to assess the impact of shelterwood system on SOC stock and soil quality	Poudel *et al.* (2024)
Soil samples collected from different forest management practices	0-10 cm, 10-20 cm, 20-30 cm	Dry combustion method using an elemental analyzer	Quantification of forest and soil carbon stocks under different management practices	ANOVA to analyze the effect of different management practices on forest and soil carbon stocks	Shrestha *et al.* (2013)
Soil samples collected from forest, grazing land, irrigated rice, and rainfed field crops in a watershed	0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm	Walkley-Black method for SOC measurement	Fluxes of methane and carbon dioxide from different land uses	ANOVA and regression analysis to study fluxes of methane and carbon dioxide from different land uses	Awasthi *et al.* (2005)

RESULTS AND DISCUSSION

Publication trends

The publication trend indicates a fluctuating yet overall increasing interest in SOC studies over the years. Notably, the frequency of studies surged in 2013 and 2019, with 3 and 4 publications, respectively. These peaks may correspond to periods of heightened research activity or increased funding and interest in soil carbon sequestration and climate change mitigation. The consistent number of publications in recent years, particularly in 2022 and 2024, suggests a sustained academic focus on understanding and managing SOC within forest ecosystems. This sustained interest aligns with the global emphasis on combating climate change through enhanced carbon sequestration strategies.

Table 2: Year of publication and frequency of study of the case studies

Year of publication	Frequency of study
2003	1
2005	1
2012	2
2013	3
2016	1
2018	1
2019	4
2020	1
2021	1
2022	3
2024	2

Factors influencing SOC

Choice of soil carbon measurement methods

The choice of soil carbon measurement methods significantly influences the accuracy and comprehensiveness of the findings in SOC research. The studies chosen in this research employed various methods for measuring soil organic carbon (SOC), each with its own strengths and weaknesses. The dry combustion method, used by Kandel *et al.* (2024), Pradhan *et al.* (2012), Aryal *et al.* (2018), Sharma and Kafle (2020), Ghimire (2022), Paudel *et al.* (2016), and Shrestha *et al.* (2013), are highly regarded for its precision. This method involves combusting soil samples and measuring the released CO_2, providing precise measurements of SOC. The high accuracy of this method allowed researchers such as Kandel *et al.* (2024) and Sharma and Kafle (2020) to obtain detailed data on SOC stocks, which was crucial for their analyses of forest management impacts. However, the dry combustion method is expensive, time-consuming, and requires specialized laboratory facilities, which may limit the sample size or the scope of fieldwork.

On the other hand, the Walkley-Black method, employed by Lal *et al.* (2012), Kafle (2019), Adhikari and Ghimire (2019), Sah and Brumme (2003), Sitaula *et al.* (2019), Poudel *et al.* (2024), and Awasthi *et al.* (2005), is more cost-effective and quicker. This method uses chemicals to oxidize organic matter, providing an accessible option for researchers with limited budgets, like Kafle (2019) and Adhikari and Ghimire (2019). Its field-friendly nature made it practical for extensive sampling, as seen in the studies by Sitaula *et al.* (2019) and Lal *et al.* (2012). However, the Walkley-Black method may underestimate SOC, especially in soils with high organic matter content, potentially affecting the accuracy of findings. Additionally, the use of hazardous chemicals poses potential risks during fieldwork.

The major statistical findings of these studies reflect the impact of the chosen methods on the accuracy and comprehensiveness of SOC assessments. For example, Kandel *et al.* (2024) reported significant variations in SOC stocks across different forest stands, thanks to the high accuracy of the dry combustion method. Lal *et al.* (2012) used the Walkley-Black method to facilitate extensive fieldwork, resulting in significant findings on SOC dynamics in various forest types. Pradhan *et al.* (2012) combined dry combustion and core sampling to yield precise SOC stock estimates, highlighting significant differences among forest types. While each SOC measurement method has its advantages and limitations, the choice often balances accuracy, cost, practicality, and specific research goals. Combining different methods, where feasible, can enhance the robustness and comprehensiveness of SOC assessments. This comprehensive approach provides valuable insights into soil carbon dynamics, helping to develop effective land management strategies and accurately model carbon budgets.

Choice of bulk density estimation method

The core sampling method for bulk density estimation, used across all listed studies, is recognized for its accuracy in converting SOC concentrations to stocks. This method involves collecting a soil core of known volume and measuring its dry weight, ensuring reliable data in studies like Pradhan *et al.* (2012) and Shrestha *et al.* (2013). Its widespread use allows for consistency and comparability across different studies, aiding in meta-analyses and broader research comparisons. However, collecting and processing core samples can be labor-intensive and time-consuming, which might limit the scope of fieldwork in studies like Aryal *et al.* (2018).

Choice of soil layers and depth for soil sample collection

The selection of specific soil layers in the studies highlighted in the table is crucial for capturing the vertical distribution of soil organic carbon (SOC). By sampling at various depths, such as 0-20 cm, 20-40 cm, and 40-60 cm, researchers can effectively capture the variations in SOC concentrations across soil profiles. This method provides a comprehensive understanding of how carbon is stored in different layers of the soil, which is vital for assessing soil health and carbon sequestration potential. For instance, studies like those conducted by Kandel *et al.* (2024) and Lal *et al.* (2012) demonstrate the importance of this approach in obtaining accurate estimates of SOC stocks.

While sampling from limited soil depths offers practical advantages, such as reduced labor and cost, it may miss significant amounts of SOC stored in deeper layers. Deeper soil layers can contain substantial carbon that, if not sampled, may lead to an underestimation of total SOC pools. Including deeper layers can provide a more complete picture of the total carbon stock and insights into the stability and long-term sequestration potential of SOC, as highlighted by Rumpel and Kögel-Knabner (2011). Moreover, deeper sampling can help identify vertical distribution patterns and understand processes affecting carbon dynamics at different soil depths, which are crucial for accurate modeling of carbon cycling (Fontaine *et al.*, 2007).

However, practical constraints often lead researchers to focus on surface layers. Digging deep into the soil can be labor-intensive and time-consuming, and not all sampling equipment can easily reach deeper layers. Additionally, conducting deep soil sampling requires more resources, including time, money, and labor. Researchers must balance the depth of sampling with the available resources while ensuring that the study remains feasible.

While sampling from limited soil depths may not capture the entire profile of SOC, it provides valuable data on the most active layers of soil. This approach balances the need for comprehensive data with practical and resource limitations, ensuring that studies are both feasible and informative. The practical and scientific considerations that guide the selection of specific soil layers ultimately aim to maximize the accuracy and comprehensiveness of SOC assessments.

Main findings

These studies used different methods to collect and analyze data to effectively study soil organic carbon (SOC) dynamics. Typically, they involved systematic soil sampling at different depths like 0-10 cm, 10-20 cm, and 20-30 cm, using core samplers to get accurate bulk density estimates. SOC was measured using methods like dry combustion and the Walkley-Black method, which are both precise and cost-effective. Many studies also measured soil physical and chemical properties like pH, moisture content, and nutrient levels to understand the factors affecting SOC.

For future studies, authors could consider several strategies to improve the accuracy and comprehensiveness of SOC assessments. Sampling deeper soil layers can give a better estimate of total SOC stocks since deeper layers can store significant amounts of carbon. Combining different measurement methods, like the precision of dry combustion with the practicality of the Walkley-Black method, can make the results more robust. Accurate bulk density estimation is crucial, and core sampling helps ensure reliable data, but care is needed to avoid disturbing the soil structure.

Using advanced technologies like near-infrared spectroscopy (NIR) and remote sensing can help with large-scale and non-invasive SOC assessments, complementing traditional methods. Detailed statistical analysis using tools like regression models and ANOVA can help understand the variability and drivers of SOC dynamics. Comprehensive data collection, including environmental variables like soil moisture, temperature, and microbial activity, can provide a complete understanding of the factors influencing SOC. Collaborating with other researchers and standardizing methods across studies can improve the quality and scope of research, ensuring consistency and comparability. Implementing these strategies can help achieve more accurate and comprehensive SOC assessments, providing valuable insights into soil carbon dynamics and supporting effective land management strategies.

Table 3: Factors influencing soil organic carbon as indicated in case studies

Factors influencing soil organic carbon	**References**
Forest stands, management regimes	Kandel *et al.* (2024)
Forest types, soil depths, land management practices	Lal *et al.* (2012)
Forest types	Shapkota and Kafle (2021)
Land-use changes, forest/soil conditions	Upadhyay *et al.* (2013)
Vertical soil layers, nitrogen content	Kafle (2019)
Forest types, soil layers	Pradhan *et al.* (2012)
Altitudinal gradients	Sah and Brumme (2003)
Forest floor fire events	Aryal *et al.* (2018)
Land use (forest and grassland), nitrogen storage	Sharma and Kafle (2020)
Forest management practices, socio-economic characteristics	Sitaula *et al.* (2019)
Community-managed forest, vertical soil layers	Lamichhane and Ghimire (2022)
Soil depths, forest conditions (Churia broad-leaved forest)	Adhikari and Ghimire (2019)
Forest type (Alnus nepalensis), biomass carbon	Dahal and Kafle (2013)
Land use (forest and agricultural), soil layers	Ghimire (2022a)
Vegetation type (Chirpine forest), soil depths	Ghimire (2022b)
Dead wood, forest soil, carbon sequestration	Kafle *et al.* (2019)
Forest type (tropical forest, Terai Sal-Shorea robusta)	Paudel *et al.* (2016)
Shelterwood system, soil quality in Shorea robusta forest	Poudel *et al.* (2024)
Forest management practices	Shrestha *et al.* (2013)
Land use (forest, grazing land, irrigated rice, rainfed field crops), gas fluxes	Awasthi *et al.* (2005)

The studies used various analytical techniques, including common statistical methods like ANOVA and regression analysis, to identify significant differences and relationships in soil organic carbon (SOC) dynamics across different land uses and management practices. Some also incorporated advanced methods such as isotopic analysis and microbial community assessments for deeper insights. These techniques collectively provided comprehensive and robust data on SOC, helping to develop effective soil management and carbon sequestration strategies.

To further enhance their analysis of SOC dynamics, authors could use advanced statistical techniques. Multivariate analysis methods, such as principal component analysis (PCA) and cluster analysis, can help identify patterns and relationships in complex datasets, showing key factors influencing SOC variation. Structural equation modeling (SEM) can explore causal relationships between variables, offering a deeper understanding of interactions affecting SOC. Spatial analysis techniques, including geo-statistics and spatial regression, can assess the spatial distribution and variability of SOC across different landscapes. Time-series analysis could be useful for studying temporal changes in SOC, especially in long-term studies. Machine learning algorithms, like random forests and support vector machines, can improve predictive modeling of SOC based on environmental and management variables. Using these statistical approaches can provide more detailed insights and robust conclusions, aiding in the development of effective soil management and carbon sequestration strategies.

These studies on soil organic carbon (SOC) dynamics offer key insights that deepen our understanding of SOC stocks and their variability across different forest types, management practices, and environmental conditions. They show that factors like land use, forest management, soil depth, and environmental gradients significantly influence SOC stocks. For instance, Kandel *et al.* (2024) and Sharma and Kafle (2020) found notable variations in SOC stocks across different forest stands and management regimes, with undisturbed forests generally having higher SOC levels. Pradhan *et al.* (2012) and Lal *et al.* (2012) observed significant differences in SOC stocks among various forest types, noting higher carbon concentrations in topsoil layers. Additionally, studies by Aryal *et al.* (2018) and Sah and Brumme (2003) revealed that environmental factors such as fire events and altitudinal gradients play a crucial role in SOC dynamics. Overall, these findings highlight the importance of comprehensive SOC assessments that consider multiple factors, offering valuable insights for enhancing soil management and carbon sequestration strategies.

These studies emphasize the complex interplay of various factors that influence soil organic carbon (SOC) stocks across different ecosystems and management practices. A common theme is the significant impact of land use and forest management on SOC dynamics. For example, Kandel *et al.* (2024) and Sharma and Kafle (2020) found that undisturbed forests generally have higher SOC levels, highlighting the importance of sustainable management practices for carbon sequestration. Pradhan *et al.* (2012) and Lal *et al.* (2012) showed that mixed and broad-leaved forests tend to store more carbon than monocultures, demonstrating variations in SOC stocks among different forest types. Studies by Aryal *et al.* (2018) and Sah and Brumme (2003) highlighted the influence of environmental factors such as fire events, altitudinal gradients, and soil moisture on SOC dynamics, showing the complex environmental controls on SOC.

Additionally, discussions on methodology point out the strengths and limitations of different SOC measurement techniques, such as dry combustion and the Walkley-Black method, with researchers suggesting that integrating multiple methods can improve accuracy and comprehensiveness. The use of advanced statistical analyses, like ANOVA and regression models, is consistently recommended to better understand SOC variations and their drivers. Overall, these studies underscore the need for comprehensive, multi-faceted approaches to SOC research to inform effective soil management and climate mitigation strategies.

Ways forward in the context of global climate change agenda

This analysis provides several critical insights and recommendations for future researchers and the scientific community studying soil organic carbon (SOC). Expanding the depth of soil sampling beyond surface layers is crucial, as deeper layers can store significant amounts of carbon that are often overlooked. This comprehensive sampling approach can provide a more accurate estimate of total SOC stocks and insights into long-term carbon sequestration potential. This study highlights the need for considering a broad range of environmental variables, including soil moisture, temperature, and nutrient levels, to understand their influence on SOC. Incorporating continuous monitoring with in-situ sensors and advanced statistical analyses like multivariate analysis and machine learning can provide deeper insights into SOC variability and its drivers. The collective findings underscore the importance of integrating multiple SOC measurement methods to enhance the accuracy and comprehensiveness of SOC assessments. Future researchers should consider combining methods like dry combustion and Walkley-Black, along with advanced techniques such as isotopic analysis, enzyme activity assays, and microbial community analysis, to gain a more holistic understanding of SOC dynamics. Long-term field experiments and studies that assess the impact of different land management practices are essential for understanding temporal changes in SOC and developing effective soil management strategies. Collaboration and standardization across studies can enhance the quality and comparability of research, facilitating meta-analyses and broader applications of findings. Overall, this analysis suggests that future SOC research should adopt a multifaceted approach, integrating diverse methods and considering various environmental and management factors. By doing so, researchers can develop more accurate and comprehensive assessments, ultimately contributing to better soil management and climate change mitigation efforts.

Given the broad agenda of climate change mitigation, researchers studying soil organic carbon (SOC) in forests should expand their focus to include various land uses and management practices. This includes integrating agroecological practices, such as cover cropping and agroforestry, which enhance SOC sequestration while promoting sustainable agriculture. Implementing advanced monitoring techniques like remote sensing and machine learning can provide more accurate SOC data. Additionally, engaging with policymakers and local communities to promote sustainable soil management practices can lead to broader adoption and greater impact. Long-term studies assessing different management practices on SOC dynamics are essential for developing effective climate mitigation strategies. This multi-faceted approach can significantly contribute to climate change mitigation and sustainable ecosystem management.

To enhance soil organic carbon (SOC) research in Nepal, researchers should adopt a comprehensive and innovative approach. Combining traditional methods like dry combustion and the Walkley-Black method with advanced techniques such as isotopic analysis and remote sensing can improve the accuracy and detail of SOC assessments. Expanding soil sampling to deeper layers and different land uses, such as agricultural lands and grasslands, will provide a more complete understanding of SOC dynamics. Collaboration with experts from agronomy, forestry, ecology, and climate science is crucial to address the complex nature of SOC studies, integrating diverse perspectives and methodologies. Engaging with policymakers and local communities to promote sustainable soil management practices will ensure broader adoption and impact. Utilizing advanced statistical tools and process-based models, including machine learning and big data analytics, can offer valuable insights. Setting up long-term monitoring sites and conducting large-scale field experiments will help track SOC changes over time and under various management practices. Investing in education and capacity-building initiatives will equip researchers with the skills needed for advanced SOC measurement and analysis. Aligning SOC research with broader climate change mitigation goals, exploring SOC's role in carbon trading markets and carbon offset programs, and using new technologies like drones, satellite imagery, and IoT sensors will enhance the overall impact and effectiveness of SOC studies in Nepal.

There is a need of a multifaceted approach to soil organic carbon (SOC) research in Nepal, integrating advanced measurement techniques, comprehensive sampling, interdisciplinary collaboration, and policy engagement. This aligns with global literature highlighting the synergy between remote sensing and machine learning for accurate SOC estimation (Li *et al.*, 2024). The call for long-term studies and capacity building resonates with the FAO's focus on sustainable soil management and the need for rigorous methodologies in meta-analyses (Corsi *et al.*, 2012; Fohrafellner *et al.*, 2023). The emphasis on policy engagement and stakeholder collaboration is supported by the FAO's advocacy for community involvement in soil conservation (Corsi *et al.*, 2012). This is well-supported by global research, emphasizing the need for advanced technologies, comprehensive data collection, and collaborative efforts to enhance SOC research and climate change mitigation.

To make their research on soil organic carbon (SOC) more robust, authors could consider several key factors and parameters. These include measuring soil moisture content, temperature, and microbial activity to understand how environmental factors affect SOC dynamics. Assessing soil physical properties, such as bulk density, particle size distribution, and mineral composition, can provide insights into how SOC is stabilized. Including measurements of soil nutrients like nitrogen, phosphorus, and potassium can help understand nutrient interactions with SOC. Evaluating root biomass and plant residue inputs can offer information on the sources of organic matter. Conducting isotopic analysis to trace carbon sources and turnover rates, as well as enzyme activity assays to gauge decomposition processes, can enhance understanding of SOC dynamics. Additionally, using spatial analysis techniques to assess SOC variability across landscapes and conducting long-term field experiments to monitor SOC changes over time can provide comprehensive data. Incorporating these factors can lead to more accurate and comprehensive SOC assessments, helping in effective soil management and climate change mitigation strategies.

CONCLUSION

This study highlights the significant role of soil organic carbon (SOC) in climate regulation and sustainable ecosystem management in Nepalese forest ecosystems. It is found that altitude, forest type, and management practices are crucial determinants of SOC stocks, with higher carbon accumulation observed in undisturbed and well-managed forests. The integration of advanced techniques such as remote sensing, machine learning, and comprehensive soil sampling across diverse ecological zones has provided a robust and accurate assessment of SOC dynamics. The results emphasize the importance of sustainable land management practices, including conservation agriculture and agroforestry, to enhance SOC sequestration and mitigate climate change. Collaborative efforts among researchers, policymakers, and local communities are essential to promote and implement these practices effectively. Future research should focus on long-term monitoring and the continuous application of advanced technologies to further refine SOC assessments and develop effective climate mitigation strategies. This study contributes valuable insights that can inform policy decisions and support global efforts to combat climate change through improved soil management.

ACKNOWLEDGEMENTS

The support of Faculty of Forestry, Agriculture and Forestry University, Hetauda, Makawanpur, Nepal is highly acknowledged as working institution.

Author’s contribution

Gandhiv Kafle: Conceptualization, Investigation, Writing, Reviewing and editing.

Conflict of Interest

The author has no relevant financial or nonfinancial interests to disclose.

REFERENCES

Adhikari, B. M., & Ghimire, P. (2019). Assessment of soil organic carbon stock of churia broad leaved forest of Nawalpur District, Nepal. *Grassroots Journal of Natural Resources*, *2*(1-2), 45-52.

Aryal, B., Bhattarai, B. P., Pandey, M., & Giri, A. (2018). Impact of forest floor fire on soil carbon sequestration of Pinus roxburghii forest in Langtang National Park, Nepal. *Journal of Natural History Museum*, *30,* 148-163.

Awasthi, K. D., Sitaula, B. K., Singh, B. R., & Bajracharya, R. M. (2005). Fluxes of methane and carbon dioxide from soil under forest, grazing land, irrigated rice and rainfed field crops in a watershed of Nepal. *Biology and fertility of soils*, 41, 163-172.

Beillouin, D., Corbeels, M., Demenois, J., Berre, D., Boyer, A., Fallot, A., Feder, F., & Cardinael, R. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. *Nature Communications*, *14*(1), 3700.

Corsi, S., Friedrich, T., Kassam, A., Pisante, M., & Sà, J. D. M. (2012). Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review (pp. x+-89).

Dahal, K. N., & Kafle, G. (2013). Organic carbon in soil and biomass of an Alnus nepalensis forest in Kathmandu, Nepal. *International Journal of Agriculture and Forestry*, *3*(6), 240-243.

FAO (2019) Soil Organic Carbon Manual. Global Soil Partnership. https://www.fao.org/global-soil-partnership/areas-of-work/soil-organic-carbon-manual/en/

Fohrafellner, J., Zechmeister-Boltenstern, S., Murugan, R., & Valkama, E. (2023). Quality assessment of meta-analyses on soil organic carbon. *Soil*, *9*(1),117-140. https://doi.org/10.5194/soil-9-117-2023

Fontaine, S., Barot, S., Barré, P., Bdioui, N., Mary, B., & Rumpel, C. (2007). Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, *450*(7167), 277-280.

Ghimire, P. (2022a). Variation of soil organic carbon and nitrogen stocks in forest and agricultural land use in Chure landscape, Nepal. *Agric. Fo.r J. 6*(2), 94-101.

Ghimire, P.(2022b). Vegetation and soil carbon pool in chirpine (Pinus roxburghii Sarg.) forest of Mahabharat Hill, Nepal. *Indian J Ecol 49*(2), 424-429.

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.

Kafle, G. (2019). Vertical distribution of soil organic carbon and nitrogen in a tropical community forest of Nepal. *International journal of forestry research*, 2019(1), 3087570.

Kafle, G., Timilsina, Y. P., Sharma, R. P., Rijal, M. L., Bartaula, B., Pokhrel, B., & Thakur, V. (2019). Contribution of dead wood and forest soil to carbon sequestration in Parsa National Park, Nepal. *Journal of Agriculture and Forestry University*, *3*, 113-123.

Kandel, D., Timilsina, S., Ayer, S., Chaudhary, S. K., Gautam, J., Adhikari, R., & Bhatta, K. P. (2024). Assessment of Soil Carbon Stock and Soil Quality in Different Forest Stands and Management Regimes in Terai Region of Nepal. *Scientifica*, *2024*(1), 1739115.

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. *J. Environ. Sci. Eng*, *1*, 800-811.

Lamichhane, U., & Ghimire, P. (2022). Vertical distribution of soil properties and soil organic carbon in community managed forest of Siwalik Hill, Nepal. *Asian J. For. 6*(2).

Li, T., Cui, L., Kuhnert, M., McLaren, T. I., Pandey, R., Liu, H., Wang, W., Xu, Z., Xia, A., Dalal, R.C., & Dang, Y. P. (2024). A comprehensive review of soil organic carbon estimates: Integrating remote sensing and machine learning technologies. *Journal of Soils and Sediments*, 1-16. https://doi.org/10.1007/s11368-024-03913-8

Malla, R., & Neupane, P. R. (2024). Spatial Distribution of Soil Organic Carbon in the Forests of Nepal. *Land*, *13*(3), 378. https://doi.org/10.3390/land13030378

Paudel, P., Gautam, P., Dhakal, G., Thapa, B., & Acharya, J. (2016). Assessment of soil organic carbon of tropical forest (Terai Sal-Shorea robusta) of Nepal. *Nepal J. Agric. Sci. 14*, 35-42.

Poudel, A., Ayer, S., Joshi, R., Gautam, J., Timilsina, S., Khadka, K., & Maharjan, M. (2024). Effect of the irregular shelterwood system on soil organic carbon stock and soil quality of Shorea robusta Gaertn. f. forest in Nepal. *Heliyon, 10*(15).

Pradhan, B. M., Awasthi, K. D., & Bajracharya, R. M. (2012). Soil organic carbon stocks under different forest types in Pokhare Khola sub-watershed: a case study from Dhading district of Nepal. *WIT Transactions on Ecology and the Environment*, *157*, 535-546.

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

Sah, S. P., & Brumme, R. (2003). Altitudinal gradients of natural abundance of stable isotopes of nitrogen and carbon in the needles and soil of a pine forest in Nepal. *J For Sci*, *49*(1), 19-26.

Shapkota, J., & Kafle, G. (2021). Variation in soil organic carbon under different forest types in Shivapuri Nagarjun National Park, Nepal. *Scientifica*, *2021*(1), 1382687.

Sharma, M., & Kafle, G. (2020). Comparative assessment of profile storage of soil organic carbon and total nitrogen in forest and grassland in Jajarkot, Nepal. *J. Agric. Nat. Resour. 3*(2),184-192.

Shrestha, H. L., Bajracharya, R. M., & Sitaula, B. K. (2013, August). Quantification of Forest and Soil Carbon Stocks under Different Management Practices in Nepal. *In International Conference on People, Forests and Climate: Changing Paradigms, held* (pp. 28-30).

Sitaula, B. K., Raut, N., Dahal, N. M., Bhatt, Y. R., Bajracharya, R. M., & Lal, R. (2019). Soil organic carbon stocks as influenced by forest management and socio-economic characteristics of community forest user groups in three districts of Central Nepal. *Indian For.*, *145*(9), 863-870.

Smith, P., Lutfalla, S., Riley, W. J., Torn, M. S., Schmidt, M. W., & Soussana, J. F. (2018). The changing faces of soil organic matter research. *European Journal of Soil Science*, *69*(1), 23-30.

Upadhyay, T. P., Sankhayan, P. L., & Solberg, B. (2005). A review of carbon sequestration dynamics in the Himalayan region as a function of land-use change and forest/soil degradation with special reference to Nepal. *Agriculture, ecosystems & environment*, *105*(3), 449-465.

Upadhyay, T. P., Solberg, B., Sankhayan, P. L., & Shahi, C. (2013). Land-use changes, forest/soil conditions and carbon sequestration dynamics: A bio-economic model at watershed level in Nepal. *Journal of Bioeconomics*, *15*, 135-170.

Vitousek, P. M., Mooney, H. A., Lubchenco, J., & Melillo, J. M. (1997). Human domination of Earth's ecosystems. *Science*, *277*(5325), 494-499.