Wiley
International Journal of Forestry Research
Volume 2025, Article ID 6694454, 9 pages
https://doi.org/10.1155/ijfr/6694454

WILEY

Research Article

Variations in Soil Organic Carbon Accumulation Between *Pinus kesiya* and *Pinus oocarpa* at Viphya Plantations in Malawi

Eda Munthali,[1] **Faides Mwale**,[1] **Estiner Katengeza**,[1] **Francis Kamangadazi**,[2] **Edward Missanjo**,[3] **and Henry Kadzuwa**[4]

[1]*Department of Physics and Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi*
[2]*Department of Forestry, Mzuzu University, Luwinga, Mzuzu, Malawi*
[3]*Department of Environmental Sciences, University of Namibia, Ogongo Campus, Omusati Region, Windhoek, Namibia*
[4]*Department of Planning and Land Surveying, Malawi University of Business and Applied Sciences, Blantyre, Malawi*

Correspondence should be addressed to Eda Munthali; mepm20-emunthali@mubas.ac.mw

Received 8 December 2024; Accepted 27 May 2025

Academic Editor: Poulami Jha

Copyright © 2025 Eda Munthali et al. International Journal of Forestry Research published by John Wiley & Sons Ltd. This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

This study pioneers the assessment of soil organic carbon (SOC) accumulation in *Pinus kesiya* and *Pinus oocarpa* at Viphya Plantations, addressing a critical gap in carbon sequestration research in Malawi. Unlike the well-studied Miombo woodlands, Pine plantations, despite their prominence, have received limited attention. The findings offer novel insights with significant implications for Malawi's contribution to global net-zero targets and REDD + commitments. Therefore, this study estimated SOC accumulation variations and annual soil carbon sequestration between *P. kesiya* and *P. oocarpa* at the age of 16 years at Viphya plantations, Malawi. A total of 40 composite samples of soil were collected and analyzed for SOC using the Walkley–Black method. The results revealed that *P. kesiya* accumulates higher SOC (32.37 ± 2.75 tC/ha) compared with *P. oocarpa* (28.85 ± 1.22 tC/ha). Furthermore, *P. kesiya* had a higher annual soil carbon sequestration (7.41 ± 1.12 tCO_2e/ha/yr) as compared to the annual soil carbon sequestration of *P. oocarpa* plantation (6.62 ± 0.46 tCO_2e/ha/yr). Although the results are not statistically significant, this trend suggests a potential difference that may be biologically or environmentally relevant. Further research with longer observation periods may help clarify these differences and their implications. Therefore, this study's findings underscore species-specific characteristics as key determinants in carbon accumulation and annual soil carbon sequestration in *Pinus* tree species. The findings further show that the uncertainties were low (< 2.0%) and fit within the IPCC's recommended range (< 15.0%). This suggests potential for carbon trading in Malawi using *P. kesiya* or *P. oocarpa* plantations.

Keywords: carbon credit; carbon sequestration; climate mitigation; plantation forestry; REDD+ strategy

1. Introduction

Forests play a crucial role in the terrestrial carbon cycle, significantly contributing to carbon sequestration and climate change mitigation [1]. Compared with agricultural and grassland ecosystems, forests store the highest carbon per unit area, accounting for approximately 80% of aboveground and over 70% of soil organic carbon (SOC) in terrestrial ecosystems [2]. However, land-use changes and forest degradation threaten this capacity, necessitating sustainable management [3]. Among forest types, *Pinus* plantations are widely established for timber production, yet their carbon storage potential and contribution to climate goals require further investigation [4]. This study examines carbon dynamics in *Pinus* plantations to enhance their role in climate mitigation.

Forest carbon emissions are a result of the decomposition and burning processes that happen

subsequently impacting the carbon stored in both biotic and abiotic components. Nevertheless, this most important carbon sink is threatened by population growth, shrinking farm sizes, and declining soil fertility [5]. The subsequent landcover and land-use changes emanating from the actualization of the threats mostly leading to deforestation account for about one third of the emissions of greenhouse gasses [6]. The Amazon rain forest continues to face pressure, and it is estimated to experience a 43.26% reduction by 2050 [7]. In Colorado, transformation of forests to other land use was estimated at 3.4% between 2017 and 2020 [4].

Widespread deforestation in Sub-Saharan Africa, driven by agricultural expansion, threatens forest-based livelihoods and carbon storage [6, 8, 9]. In Malawi, rising forest loss underscores the need for studies like this one, which estimates SOC accumulation and annual carbon sequestration to support emission monitoring and inform restoration and climate mitigation strategies.

Even with availability of policy frameworks and instruments, landscape restoration interventions fall short of holistic integration into the governance systems, lacking critical governance interactions and proper coordination and thus leading to insufficient implementation [10]. Agroforestry and climate-smart agriculture promote the integration of trees with crops and sustainable farming practices, which enhance soil health, increase carbon sequestration, and improve water retention. These practices reduce emissions by minimizing reliance on chemical inputs and tillage while restoring degraded farmlands through improved biodiversity and ecosystem resilience [11]. The interventions are implemented across the African continent with a focus on local smallholder farmers [11, 12]. In central Malawi, it is estimated that about 0.5 of a hectare of the farmland per household is subjected to climate-resilient agroforestry and agriculture. Farmers diversify restoration patterns by adopting multiple landscape restoration technologies, selecting those that complement their specific livelihoods, food security, and ecological restoration goals, while also considering labor and input requirements [12].

Diminishing land holding capacities, land tenure secured zones are apt to be exposed to landscape restoration interventions. In addition, women's inadequate access and control over product resources issues affect their level of adoption and implementation of the efforts [12]. Even though adoption of climate smart agriculture and agroforestry seems higher in central Malawi, the level of adoption across Africa and similarly in Malawi is low. Issues of inadequate extension workers, most of the climate smart agriculture technologies are supported by nonstate actors which are location specific and implement under time restrictions [11]. However, there was an upsurge in acceptance of farmland restoration at the household level to 2.24 in 2019 from 2.05 in 2016. The change indicates increased intensification of the farmland restoration over time. The noted increase translated to rise in the socioeconomic status of the families, affecting the food intake mark to shift from 43.19 in 2016 to 47.43 in 2019. Correlating with the observations, the authors in [12] reported positive trends in adoption of farmland land restoration technologies between 2012 and 2022 in Malawi. Issues of land productivity status, topography, and farmer perceptions affect individual farmer's participation. In addition, short- and long-term incentives attached to adoption of the technologies act as a motivation.

Carbon markets epitomize strides toward linking policy initiatives with poverty reduction considering that to a certain extent, forest degradation and GHG emissions arise from poverty. Wholistic targeting is thus paramount in a bid to reverse the current rate of GHG emissions. Managing forest for REDD+ and carbon-trading purposes offers potential financial empowerment to poverty-stricken communities, as well as other investment opportunity for business ventures [13]. Africa remains marginalized in global carbon markets despite significant mitigation opportunities in agriculture and forestry [14]. Malawi and Zambia have, to this effect, implemented several carbon management projects; however, the focus is more on rural areas leaving out the urban populations creating a gap between populations, which equally contribute to the challenges being addressed [15]. Most of the projects implemented so far have offered nonmonetary value to target communities [16]. Furthermore, limitations to implementation of carbon sequestration can be attributed to inadequate information to guide issues of property rights, protocol, and the sacrificed benefits concerning preceding lucrative land utilization options, which have not been fully explored for Africa [17].

The contribution of Pine plantations toward carbon sequestration are reported to be enormous; for instance, Spanish Pines alone were observed to accumulate about 249 Mg of carbon stock in 2010 [18]. Pine plantation's rapid growth, ability to out compete extra inherent classes, and ability to strive in a wide range of conditions and altitudes entail the unanimous recognition for the plantation's contribution toward mitigation of climate change and carbon sequestration efficiency [19]. Nevertheless, the degree of SOC accretion in Pine plantations under all management types follows species-specific characteristics. These influence other species to accumulate more than their counterparts [20]. In addition, stocking density of the stand contributes to determination of the amount of biomass and carbon to be accumulated by Pine stand [19, 20]. Findings of earlier studies provide an indication of monoculture plantations as having more carbon accumulation capacity than mixed plantations. In a study conducted by [21], monoculture exotic plantations were detected to hoard 127% more carbon than native mixed plantations. SOC is an equally important carbon sink as its carbon stock is estimated to be twice the amount of atmospheric carbon [22]. Furthermore, SOC is crucial for soil fertility, as it plays a significant role in maintaining soil's physical and chemical properties. However, it is concentrated in the supernal 20 cm of soil, making it vulnerable to depletion from human activities such as land-use changes, cultivation, grazing, and climate change impacts [23].

Previous studies report that the amount of SOC increase or decrease in the forest is dependent on regional scale factors including type of species, climate, location, soil type,

topography as well as forest management regimes [8, 12, 20]. These factors influence the forest's net primary productivity and other carbon storage dynamics, leading to varying carbon stocks over the ecosystems [19]. While types of forest harvesting methods are distinguished to have no noteworthy effects on SOC accretion, the sawlog method of harvesting is reported to have significant effects on SOC dynamics. The method results in an increase of SOC by up to 18%. The effect is more paramount into coniferous species like Pine. This follows increased and aided compaction of saw dust in the soil and soil compaction enhancements following the process [22]. Although insignificant, incorporation of slash in harvesting offers positive contribution toward SOC accretion increase [24]. Following morphological, physiological, chemical, and mechanical properties variations that are available between species, SOC accretion rates follow the type of species to some degree [23]. Physical, chemical, and structural differences impact the degradation of SOC rates. Species chemical composition will determine the degree of undergrowth establishment and availability.

In addition, the rate of invasion by lower plants also affects the increase in SOC accretion. Significant decreases in SOC occur due to land-use changes and forest harvesting, particularly when followed by intense broadcast burning [24]. The processes cause typical disturbances that manipulate forests to becoming sources of increased levels of CO_2 secretions. The changes trigger the rate of oxidation for both plants; soil and dead organic matter increases to surpass net primary productivity easing the degree of SOC accumulation [25]. Basically, initiated increase in soil respiration following the process increased the amount of CO_2 discharges for the forests ecosystem while reducing the amount of soil carbon stock [3]. Supporting the claims, studies reported lower SOC quantities accumulated in lands subjected to agriculture while managed forests plantations accumulated higher amounts of SOC. Intermittent land disturbances and plant removals left soil susceptible to factors that enhance soil carbon loss [26].

Therefore, understanding SOC accumulation in *Pinus* plantations is crucial for sustainable forest management and climate change mitigation [20]. In Malawi, *Pinus kesiya* and *Pinus oocarpa* are widely planted, yet their comparative influence on SOC dynamics remains poorly studied. Given the critical role of SOC in soil fertility, carbon sequestration, and ecosystem stability, identifying species-specific differences can inform better plantation management strategies [8]. This study addresses the research gap by evaluating SOC variations between these species at Viphya plantations, providing essential insights for optimizing carbon storage and enhancing forest sustainability in Malawi's changing environmental and land-use context. Consequently, the specific objectives of this study were (1) to estimate the SOC accumulation variations between *P. kesiya* and *P. oocarpa* at 16 years and (2) to determine the annual SOC sequestration variations between *P. kesiya* and *P. oocarpa* at Viphya plantations in Malawi. The study enhances the understanding of carbon accumulation dynamics in Pine tree plantations supporting precise variations in carbon accumulation across various age classes and enhanced management of carbon credit incentives.

2. Methods and Materials

2.1. Study Area. The present study was carried out at Viphya plantations (Figure 1), located in the Mzimba and Nkhata Bay districts in northern Malawi, at latitude 11° 50′ 0″ South and 33° 48′ 0″ East, with an elevation ranging from 1500 to 1800 m, situated approximately 71.6 km south of Mzuzu City and 284 km north of Lilongwe [27]. The plantation was created in the 1950s to meet timber needs. However, in 1964, its objectives for all plant species shifted to focus on paper and pulp production [28]. The area receives an average annual precipitation of 1200 mm, ranging between 750 mm and 1560 mm. Its mean temperature is about 19°C, with winter temperatures dropping to an average of 10°C, and reaching a high of 28°C in November. The undulating topography has slopes that vary from somewhat high (19.3° on the eastern escarpments) to flat. The estimate terrain elevation is 1729 m above the sea level [29]. Viphya plantation occupies 53,500 ha of land of which 15,000 ha of the forest is managed by the government, while 38,500 ha is managed under concession as follows: RAIPLY Malawi Limited 20,000 ha, AKL Timbers 6000 ha, Total Landcare 2500 ha, and Timber Millers Union managing 10,000 ha [30].

2.2. Data Collection and Analysis. The study required specific materials for soil sampling and forest inventory. Furthermore, navigation to sampled areas also required special appliances and chemicals. Navigation around the sample plots was done using the Global Positioning System (GPS). Using GPS for navigation around sample plots is not a standard soil sampling method, as traditional protocols often rely on fixed transects or grid layouts marked physically on the ground [30]. However, it was appropriate for this study because it allowed accurate and efficient location of plots across the large and potentially inaccessible terrain of Viphya plantations [17]. GPS ensured consistency in plot positioning, minimized location errors, and supported repeatability in future sampling efforts, making it a practical and reliable tool for field navigation in this context [16]. Once the plots were identified with the GPS, a measuring tape was used to establish the plot size. Samples of soil were collected using the Intergovernmental Panel on Climate Change (IPCC) requirements and standards [31, 32]. In brief, samples of soil were collected at a depth of 30 cm. An auger was used for excavation of the samples of soil. Scientifically, it is recommended to collect soil samples at a 30 cm depth because this layer contains most organic matter, microbial activity, and root interactions, significantly influencing nutrient cycling and carbon storage [31]. It also represents the primary zone of soil formation and land-use impact, making it crucial for assessing soil health, fertility, and ecosystem dynamics [32]. With the aid of a 2-mm sieve, the samples of soil were filtered to remove roots, stones, and other unwanted particles. A total of forty composite samples of soil were gathered, thus twenty composite soil samples per site. Twenty composite samples per site are scientifically appropriate as they enhance representativeness, reduce variability, and improve result

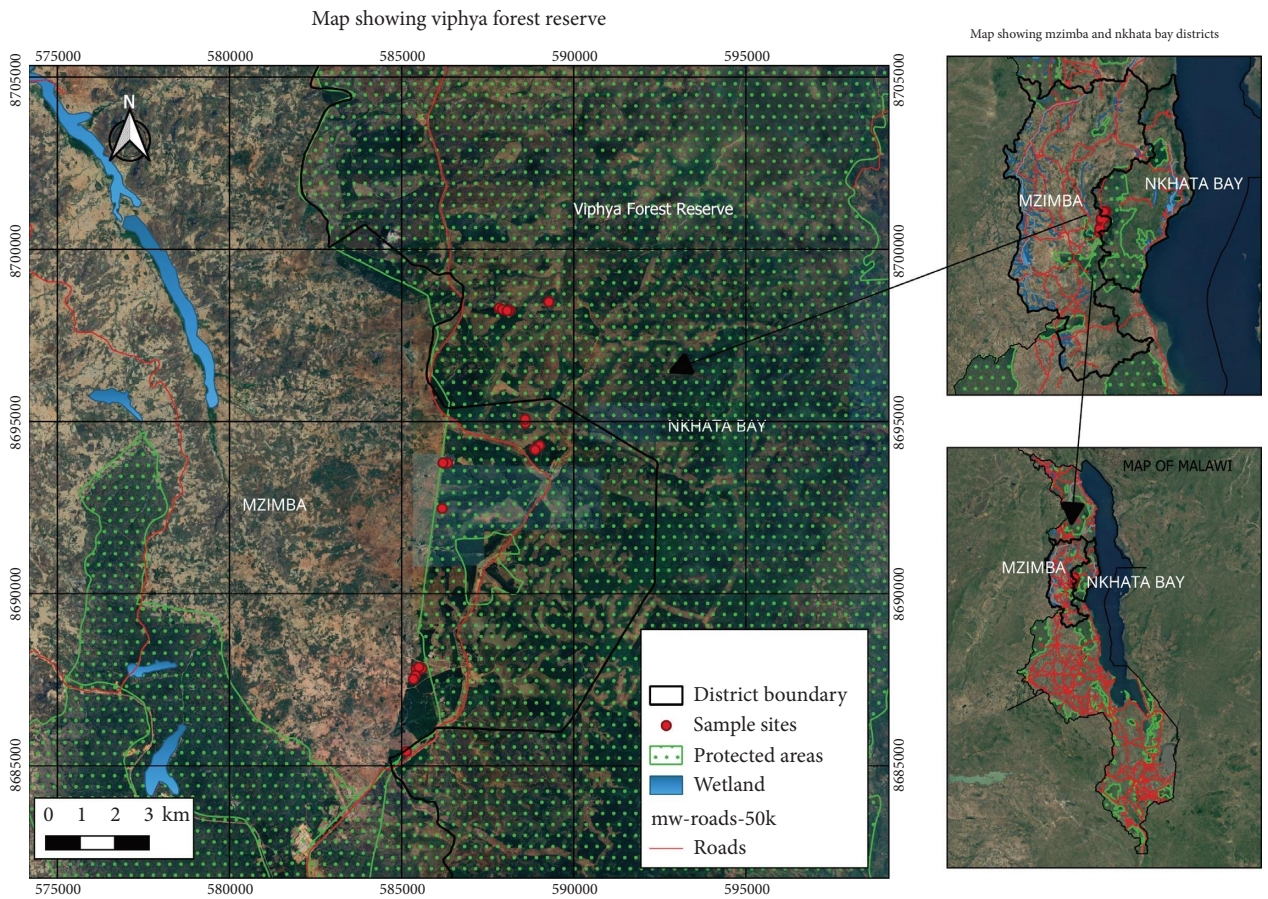


Figure 1: Location of the study area: Malawi.

reliability [33]. By combining multiple subsamples, composite sampling ensures a more accurate assessment of soil properties, minimizing localized anomalies. This approach is particularly useful in heterogeneous environments like forest plantations, where soil characteristics can vary due to factors such as tree species, microclimate, and management practices, thereby improving data precision and reliability [34]. Samples of soil were air-dried for 14 days to remove moisture before the laboratory analysis [33, 34]. Air-drying is not a standard method in all soil studies because it can alter certain soil properties, such as microbial activity or the form of some nutrients [33]. Standard protocols may recommend oven-drying at controlled temperatures for consistency [34]. However, air-drying was appropriate for this study because the primary objective was to analyze SOC, which is not significantly affected by air-drying. It also avoided the risk of carbon loss through heating and was more practical under field conditions with limited access to drying ovens, ensuring preservation of the samples' integrity for SOC analysis [33]. To minimize contamination, several sampling bags were combined, and a plastic pail was used to guarantee the bags remained stable during navigation [35].

SOC was analyzed using the Walkley–Black method which follows a dichromate-titrimetric procedure involving absorption of samples with an acidified dichromate [36]. The method was chosen for its universal applicability, ease of use, and cost-effectiveness compared with dry combustion, particularly when using automated analyzers. So, soil bulk density (SBD) was determined using the following equation [37].

$$\text{SBD} = \frac{\text{WS}}{\text{VS}}, \tag{1}$$

where SBD = soil bulk density (g/cm^3), WS = sample of soil weight (g), and VS = volume soil core (cm^3). The total organic carbon was quantified using the following equation [37]:

$$\text{Organic carbon (\%)} = \frac{(V_B - V_S) \times M \times f}{W} \times 100, \tag{2}$$

where V_B is the titrant volume in blank (mL), V_S is the titrant volume in sample (mL), M is the molar concentration of ammonium ferrous sulfate, f represents 1.3, the correction factor, and W is the air-dry sample mass (mg) [38]. Then, SOC (Mg C ha^{-1}) was determined using the following equation [37].

$$\text{SOC} = \text{SBD} \times \text{OCS} \times \text{SHT} \times 100, \tag{3}$$

where SOC is the soil organic carbon (Mg C ha^{-1}), SBD is soil bulk density (gcm^{-3}), OCS is the soil organic content (%), and SHT is the soil horizon thickness (cm).

The emission factor (tCO_2e/ha/yr) was quantified by multiplying the SOC with a factor of 3.67 then dividing by age of the plantations [39].

Data were gathered from the *P. kesiya* and *P. oocarpa* plantations in October 2023, when the trees were 16 years old. Data obtained were subjected to Kolmogorov–Smirnov D and normal probability plot tests in GenStat 18. This was done to check the normality of the data. When the criterion was met, the data were subjected to Student's *t*-test in GenStat 18 to match the SOC involving the two *Pinus* plantation species, and the p value of equal or less than 5% was considered statistically significant. In addition, carbon stock estimates often come with uncertainties due to factors such as sampling, measurement, and estimation errors [39]. Quantifying these uncertainties is essential for understanding the accuracy of carbon stock estimates. Consequently, the Monte Carlo method, thoroughly detailed by other researchers [40], was utilized to quantify the uncertainty at 95% confidence interval. The Monte Carlo method was chosen for its flexibility, ease of implementation, and ability to handle complex, nonlinear models. Unlike other techniques, it requires minimal assumptions about input distributions and scales well with computational resources, making it ideal for accurately quantifying uncertainty in diverse and high-dimensional systems [40].

3. Results and Discussion

3.1. Soil Carbon for P. kesiya and P. oocarpa of the Age of 16 Years. A summary of the accumulated SOC for *P. kesiya* and *P. oocarpa* for 16 years is presented in Figure 2. The outcomes indicate that there were no significant ($p > 0.05$) differences on SOC accrual between *P. kesiya* and *P. oocarpa* plantations. However, *P. kesiya* plantation accumulated more SOC (32.37 ± 2.75 tC/ha) than *P. oocarpa* plantation (28.85 ± 1.22 tC/ha).

SOC accretion for Pine species decreases with increasing stand density [41]. In the recent outcomes, *P. oocarpa* having a higher stand density (results not presented), is observed to accumulate less soil carbon compared with *P. kesiya* whose density was less. Similarly, a strong negative correlation was found between SOC and biomass density [42]. In addition, differences in morphological or physical and chemical characteristics of diverse species would contribute to SOC accumulation variations between *P. kesiya* and *P. oocarpa* in the Viphya plantations [43]. The presentation of earlier research shows statistically significant differences between species regarding length, volume, surface area, fine root tip density, number of root tips, and fine root diameter [44]. However, in the current outcome, there were no statistically significant differences between the species regarding specific root length and root tissue density. However, the value parameters for *P. kesiya* were higher than those of *P. oocarpa*. Furthermore, *P. kesiya* forest floor was characterized by an abundance of lower plants lacking in the *P. oocarpa* plantations. This may possibly be one of the factors causing the larger SOC accumulation in *P. kesiya*. This suggests that there is an optimistic relationship between SOC accretion and species richness [41]. This suggestion is theoretical, not experimentally tested, and assumes that greater species richness enhances ecosystem functions, potentially promoting higher SOC accretion [40]. Therefore, further studies are recommended to quantify this statement.

The lack of significant difference in SOC accumulation between *P. kesiya* and *P. oocarpa* plantations in Malawi may be due to their similar growth forms, litter quality, and root structures, leading to comparable organic matter inputs and decomposition rates [36]. Both species may also experience similar environmental and management conditions [32]. This result implies that species selection between the two has limited impact on SOC levels, allowing forest managers to prioritize other factors such as growth rate, wood quality, or resilience. It also highlights the importance of broader management practices, such as residue retention and minimal soil disturbance, in enhancing SOC [39].

3.2. Annual Soil Carbon Sequestration for P. kesiya and P. oocarpa Plantations for 16 Years. The results for the annual SOC sequestration for *P. kesiya* and *P. oocarpa* for an interval of 16 years are given in Table 1. The outcome indicates that there were no significant ($p > 0.05$) differences on the annual SOC sequestration between *P. kesiya* and *P. oocarpa* plantations. Consequently, *P. kesiya* plantation had higher annual SOC sequestration (7.41 ± 1.12 tCO_2e/ha/yr) compared to *P. oocarpa* annual SOC sequestration (6.62 ± 0.46 tCO_2e/ha/yr). This implies a significant annual increase of SOC sequestration of 6.3% for both *P. kesiya* and *P. oocarpa* plantations.

These differences could be because of changes in growth rate, biomass accumulation, and other ecological factors involving the two varieties [41]. Understanding this discharge is prominent for evaluating the role of each species in carbon cycling and developing forest management strategies that can optimize carbon sequestration and minimize emissions [44].

The variation underscores species-specific traits that influence biomass and SOC dynamics, such as growth rates, density, and root system characteristics [42]. However, comparing the total carbon accumulation across stands is essential to classify the species with the uppermost carbon storage potential, which can guide the selection of the most appropriate species for initiatives aimed at reducing atmospheric carbon dioxide levels and mitigating climate change. Variations in SOC accretion between species align with findings from earlier studies, which attribute these differences to stand density, and the morphological, physical, and chemical properties of the soil [43]. According to Ahmad [37], discrepancies in SOC accumulation are noted, as it does not always increase with stand age, and estimates of tree biomass and SOC accretion are greater than those in literature [30, 37, 43]. These deviations arise from differences in forest managing procedures, environment, ecological factors, and the stand history [41].

Furthermore, SOC data can quantify carbon stored in soils, enabling landowners to earn carbon credits by demonstrating enhanced sequestration through sustainable land management [32]. Verified increases in SOC can be

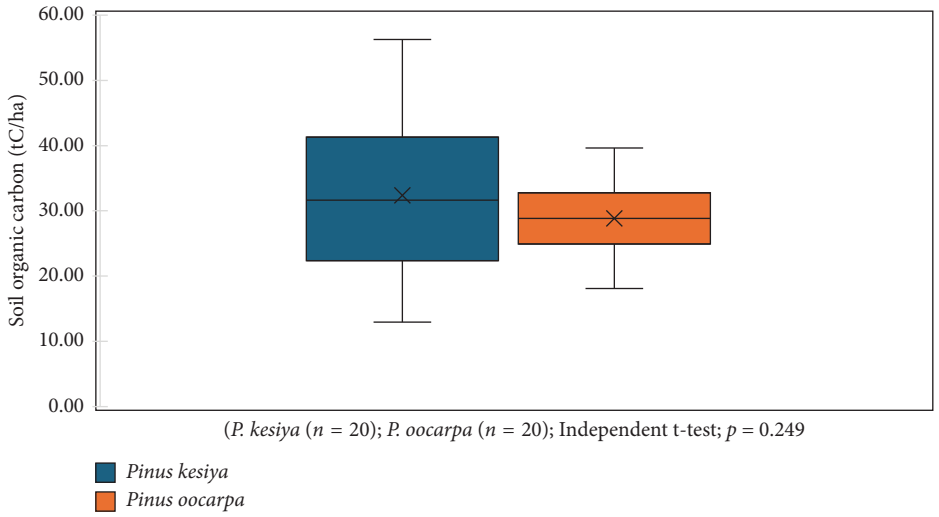


Figure 2: Boxplot for soil organic carbon for *Pinus kesiya* and *Pinus oocarpa* at Viphya plantations at the age of 16 years.

Table 1: Annual soil carbon sequestration for *Pinus kesiya* and *Pinus oocarpa* at Viphya plantations at the age of 16 years.

Type of *Pinus* species plantation	Annual soil carbon sequestration (tCO_2e/ha/yr)	Uncertainty (%)
Pinus kesiya	7.41 ± 1.12^a	1.87
Pinus oocarpa	6.62 ± 0.46^a	0.86
Mean	7.01 ± 0.58	1.10

Note: Means within the column that share the same superscript letter are not significantly different ($p > 0.05$).

monetized under carbon offset programs [41]. This incentivizes reforestation, reduced tillage, and residue retention practices, promoting both climate mitigation and improved soil health [30]. Therefore, accurate SOC monitoring is essential for participation in voluntary or compliance-based carbon markets [42].

3.3. Uncertainty Analysis. Estimating forest carbon stock involves inherent uncertainties, which are important to quantify and minimize to improve the accuracy and reliability of carbon assessments [45]. Errors in these estimates can stem from factors such as the distribution of sample plots and field measurements [45–47]. Table 1 displays the uncertainty estimates for SOC and annual carbon sequestration in the current study. The outcomes indicate that the uncertainties were low (< 2.0%) and fell within the IPCC's recommended range (< 15.0%) [46]. This suggests that there is potential for carbon trading in Malawi using *P. kesiya* or *P. oocarpa* plantations.

Potential biases in the present study may include site heterogeneity, sampling depth inconsistencies, and human error during field and laboratory procedures [46]. To minimize these, sampling plots were randomly selected within uniform site conditions, and standardized depths and protocols were strictly followed. Replication within each plantation helped reduce spatial variability, while calibrated equipment and quality-controlled laboratory analyses ensured measurement accuracy [45]. These strategies enhanced the reliability of comparisons and ensured that observed differences, or lack thereof, were due to species effects rather than methodological inconsistencies [42].

The study's low uncertainty enhances confidence in carbon stock estimates, strengthening Malawi's prospects for carbon trading. Accurate and reliable data attracts investors and facilitates the country's participation in international carbon markets. This credibility ensures fair valuation of carbon credits, promoting sustainable forest management [45]. In addition, the findings support policy development by providing scientific evidence for setting carbon sequestration baselines, improving monitoring frameworks, and guiding plantation management strategies [44]. Policymakers can use these insights to establish transparent carbon pricing mechanisms, incentivize afforestation, and integrate carbon trading into national climate mitigation and economic development strategies [46].

It should be noted that this study focused on SOC and its dynamics in *P. kesiya* and *P. oocarpa* plantations, but it did not include all potential carbon pools, such as aboveground biomass, litter, and root carbon. These pools are significant components of total carbon storage and could provide a more comprehensive understanding of carbon sequestration in forest ecosystems [44]. Future research could expand upon our findings by incorporating these additional carbon pools, enabling a more holistic assessment of the carbon storage potential in *Pinus* plantations. Such studies would improve carbon accounting and strengthen forest management strategies for climate change mitigation.

4. Conclusion

The study has revealed that there were no significant differences in SOC accretion and annual emissions factors between *P. kesiya* and *P. oocarpa* plantations at the age of 16 years at Viphya plantations in Malawi. However, *P. kesiya* plantations showed higher SOC accretion and annual soil carbon sequestration compared with *P. oocarpa*. This trend

suggests a potential difference that may be biologically or environmentally relevant, even if not statistically confirmed. Further research with longer observation periods could help clarify these differences and their broader implications. Given the findings and the fact that uncertainties were within the IPCC's recommended range, there is a clear potential for carbon trading using either *P. kesiya* or *P. oocarpa* plantations. These results can be pivotal in shaping policy recommendations for Malawi's forestry sector. Policymakers can use this information to prioritize *P. kesiya* for carbon sequestration initiatives, potentially enhancing Malawi's involvement in carbon markets. The findings also provide valuable insights for developing carbon credit programs, supporting sustainable land management practices, and guiding reforestation efforts. In turn, these policy actions can contribute to national climate change mitigation strategies, promote economic growth through carbon trading, and strengthen forest management practices.

Data Availability Statement

The data used to support the findings of this study are available in the Supporting Information file submitted alongside this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding

No funding was received for this research.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. *(Supporting Information)*

The SOC accumulation in Pines plantation demonstrates a significant carbon stock assessment. This enhances Malawi's carbon trading mechanisms and informs evidence-based implementation of REDD + strategies.

References

[1] E. Missanjo, G. Kamanga-Thole, and A. Ndema, "Biomass and Carbon Stock Estimation for Miombo Woodland in Selected Part of Chongoni Forest Reserve, Dedza, Malawi," *International Journal of Forestry and Horticulture* 1, no. 1 (2015): 12–17.

[2] A. D. Agbelade and J. C. Onyekwelu, "Tree Species Diversity, Volume Yield, Biomass and Carbon Sequestration in Urban Forests in Two Nigerian Cities," *Urban Ecosystems* 23, no. 5 (2020): 957–970, https://doi.org/10.1007/s11252-020-00994-4.

[3] C. Q. Dahik, P. Crespo, B. Stimm, et al., "Impacts of Pine Plantations on Carbon Stocks of Páramo Sites in Southern Ecuador," *Carbon Balance and Management* 16 (2021): 5, https://doi.org/10.1186/s13021-021-00168-5.

[4] L. A. Fitts, M. B. Russell, G. M. Domke, and J. K. Knight, "Modeling Land Use Change and Forest Carbon Stock Changes in Temperate Forests in the United States," *Carbon Balance and Management* 16, no. 1 (2021): 20, https://doi.org/10.1186/s13021-021-00183-6.

[5] L. Atwoli, A. H. Baqui, T. Benfield, et al., "Call for Emergency Action to Limit Global Temperature Increases, Restore Biodiversity and Protect Health," *International Journal of Older People Nursing* 16, no. 5 (2021): e12422, https://doi.org/10.1111/opn.12422.

[6] I. E. Olorunfemi, A. A. Olufayo, J. T. Fasinmirin, and A. A. Komolafe, "Dynamics of Land Use Land Cover and Its Impact on Carbon Stocks in Sub-Saharan Africa: An Overview," *Environment, Development and Sustainability* 24, no. 1 (2022): 40–76, https://doi.org/10.1007/s10668-021-01484-z.

[7] K. Murugesan, P. Balasubramani, P. R. Murugan, and S. Sankaranarayanan, "Color-Based SAR Image Segmentation Using HSV+FKM Clustering for Estimating the Deforestation Rate of LBA-ECO LC-14 Modeled Deforestation Scenarios, Amazon Basin: 2002–2050," *Arabian Journal of Geosciences* 14, no. 9 (2021): 777, https://doi.org/10.1007/s12517-021-07069-4.

[8] D. L. Skole, J. H. Samek, C. Mbow, et al., "Direct Measurement of Forest Degradation Rates in Malawi: Toward a National Forest Monitoring System to Support REDD+," *Forests* 12, no. 4 (2021): https://doi.org/10.3390/f12040426.

[9] J. H. A. Krug, "How Can Forest Management Increase Biomass Accumulation and CO2 Sequestration? A Case Study on Beech Forests in Hesse, Germany," *Carbon Balance and Management* 14, no. 1 (2019): 17, https://doi.org/10.1186/s13021-019-0132-x.

[10] I. N. S. Djenontin and L. C. Zulu, "The Quest for Context-Relevant Governance of Agro-Forest Landscape Restoration in Central Malawi: Insights From Local Processes," *Forest Policy and Economics* 131 (2021): 102555, https://doi.org/10.1016/j.forpol.2021.102555.

[11] J. A. Andersson and S. D'Souza, "From Adoption Claims to Understanding Farmers and Contexts: A Literature Review of Conservation Agriculture (CA) Adoption Among Smallholder Farmers in Southern Africa," *Agriculture, Ecosystems and Environment* 187 (2014): 116–132, https://doi.org/10.1016/j.agee.2013.08.008.

[12] I. N. S. Djenontin, L. C. Zulu, and R. B. Richardson, "Smallholder Farmers and Forest Landscape Restoration in Sub-Saharan Africa: Evidence From Central Malawi," *Land Use Policy* 122 (2022): 106345, https://doi.org/10.1016/j.landusepol.2022.106345.

[13] K. John, D. S. A. Silayo, and A. Vatn, "The Cost of Managing Forest Carbon Under REDD+ Initiatives: A Case of Kolo Hills Forests in Kondoa District, Dodoma, Tanzania," *International Journal of Financial Research* 2014 (2014): e920964, https://doi.org/10.1155/2014/920964.

[14] X. Liu, T. Yang, Q. Wang, F. Huang, and L. Li, "Dynamics of Soil Carbon and Nitrogen Stocks After Afforestation in Arid and Semi-Arid Regions: A Meta-Analysis," *Science and Total Environment* 618 (2018): 1658–1664, https://doi.org/10.1016/j.scitotenv.2017.10.009.

[15] Z. Gong, Y. Tang, W. Xu, and Z. Mou, "Rapid Sequestration of Ecosystem Carbon in 30-Year Reforestation With Mixed Species in Dry Hot Valley of the Jinsha River," *International Journal of Environmental Research and Public Health* 16, no. 11 (2024): 1937, https://doi.org/10.3390/ijerph16111937.

[16] J. Lee, M. Ingalls, J. D. Erickson, and E. Wollenberg, "Bridging Organizations in Agricultural Carbon Markets and Poverty Alleviation: An Analysis of Pro-Poor Carbon Market Projects

in East Africa," *Global Environmental Change* 39 (2016): 98–107, https://doi.org/10.1016/j.gloenvcha.2016.04.015.

[17] G. M. Mosquera, F. Marín, M. Stern, et al., "Progress in Understanding the Hydrology of High-Elevation Andean Grasslands Under Changing Land Use," *Science and Total Environment* 804 (2022): 150112, https://doi.org/10.1016/j.scitotenv.2021.150112.

[18] M. T. L. Bonner, S. Schmidt, and L. P. Shoo, "A Meta-Analytical Global Comparison of Aboveground Biomass Accumulation Between Tropical Secondary Forests and Monoculture Plantations," *Forest Ecology and Management* 291 (2013): 73–86, https://doi.org/10.1016/j.foreco.2012.11.024.

[19] D. Domingo, M. T. Lamelas, A. L. Montealegre, A. García-Martín, and J. de la Riva, "Estimation of Total Biomass in Aleppo Pine Forest Stands Applying Parametric and Nonparametric Methods to Low-Density Airborne Laser Scanning Data," *Forests* 9 (2018): 158.

[20] L. He, J. M. Chen, Y. Pan, R. Birdsey, and J. Kattge, "Relationships Between Net Primary Productivity and Forest Stand Age in U.S. Forests," *Global Biogeochemical Cycles* 26, no. 3 (2012): https://doi.org/10.1029/2010GB003942.

[21] J. J. Bukoski, S. C. Cook-Patton, C. Melikov, et al., "Rates and Drivers of Aboveground Carbon Accumulation in Global Monoculture Plantation Forests," *Nature Communications* 13, no. 1 (2022): 4206, https://doi.org/10.1038/s41467-022-31380-7.

[22] L. Duncanson, W. Huang, K. Johnson, A. Swatantran, R. E. McRoberts, and R. Dubayah, "Implications of Allometric Model Selection for County-Level Biomass Mapping," *Carbon Balance and Management* 12 (2017): 18.

[23] M. Del Río Gaztelurrutia, J. A. Oviedo, H. Pretzsch, M. Löf, and R. Ruiz-Peinado, "A Review of Thinning Effects on Scots Pine Stands: From Growth and Yield to New Challenges Under Global Change," *Forestry Systems* 26 (2017): 9.

[24] C. C. Dymond, S. Beukema, C. R. Nitschke, K. D. Coates, and R. M. Scheller, "Carbon Sequestration in Managed Temperate Coniferous Forests Under Climate Change," *Biogeosciences* 13 (2016): 1933.

[25] P. Smith, J. I. House, M. Bustamante, J. Sobocká, R. Harper, and G. Pan, "Global Change Pressures on Soils From Land Use and Management," *Global Change Biology* 22, no. 3 (2016): 1008–1028.

[26] X. Sun, G. Wang, Q. Ma, et al., "Organic Mulching Promotes Soil Organic Carbon Accumulation to Deep Soil Layer in an Urban Plantation Forest," *Forest Ecosystems* 8, no. 1 (2021): 2, https://doi.org/10.1186/s40663-020-00278-5.

[27] M. L. Chitawo, *Systems Approach in Developing a Model for Sustainable Production of Bioenergy in Malawi* (Stellenbosch University, 2018).

[28] R. Kafakoma and B. Mataya, *Timber Value Chain Analysis for the Viphya Plantations* (Lilongwe, 2009).

[29] E. Ngulube, M. Brink, and P. Chirwa, "Productivity and Cost Analysis of Semi-Mechanised and Mechanised Systems on the Viphya Forest Plantations in Malawi," *Southern Forests: A Journal of Forest Science* 76 (2014): 195–200.

[30] Department of Forestry, *Annual Report 2022. Lilongwe* (Malawi, 2023).

[31] R. M. Navarro-Cerrillo, F. J. Ruiz-Gómez, J. J. Camarero, et al., "Long-Term Carbon Sequestration in Pine Forests Under Different Silvicultural and Climatic Regimes in Spain," *Forests* 13, no. 3 (2022): https://doi.org/10.3390/f13030450.

[32] S. Li, J. Su, W. Liu, et al., "Changes in Biomass Carbon and Soil Organic Carbon Stocks Following the Conversion From a Secondary Coniferous Forest to a Pine Plantation," *PLoS One* 10, no. 9 (2015): e0135946, https://doi.org/10.1371/journal.pone.0135946.

[33] N. Cools and B. De Vos, "Chapter 15-Forest Soil: Characterization, Sampling, Physical, and Chemical Analyses," in *Developments in Environmental Science*, ed. M. Ferretti and R. Fischer (2013), 267–300, https://doi.org/10.1016/B978-0-08-098222-9.00015-7.

[34] L. Guo, M. Linderman, T. Shi, Y. Chen, L. Duan, and H. Zhang, "Exploring the Sensitivity of Sampling Density in Digital Mapping of Soil Organic Carbon and Its Application in Soil Sampling," *Remote Sensing* 10, no. 6 (2018): https://doi.org/10.3390/rs10060888.

[35] A. A. Mustapha, N. Abdu, E. Y. Oyinlola, and A. A. Nuhu, "Evaluating Different Methods of Organic Carbon Estimation on Nigerian Savannah Soils," *Journal of Soil Science and Plant Nutrition* 23, no. 1 (2023): 790–800, https://doi.org/10.1007/s42729-022-01082-6.

[36] T. A. Gessesse and A. Khamzina, "How Reliable Is the Walkley-Black Method for Analyzing Carbon-Poor, Semi-Arid Soils in Ethiopia?" *Journal of Arid Environments* 153 (2018): 98–101, https://doi.org/10.1016/j.jaridenv.2018.01.008.

[37] D. Ahmad, "Carbon Stocks of Different Land Uses in the Kumrat Valley, Hindu Kush Region of Pakistan," *Journal of Forestry Research* (2014): https://doi.org/10.1007/s11676-014-0008-6.

[38] FAO, *Standard Operating Procedure for Soil Organic Carbon: Walkley-Black Method Titration and Colorimetric Method* (2020).

[39] E. Missanjo and H. Kadzuwa, "Activity Data and Emission Factor for Forestry and Other Land Use Change Subsector to Enhance Carbon Market Policy and Action in Malawi," *Journal of Environmental Protection* 15 (2024): 401–414, https://doi.org/10.4236/jep.2024.154023.

[40] S. Kim, C. Kim, S. H. Han, S. T. Lee, and Y. Son, "A Multi-Site Approach Toward Assessing the Effect of Thinning on Soil Carbon Contents Across Temperate Pine, Oak, and Larch Forests," *Forest Ecology and Management* 424 (2018): 62–70.

[41] X. Liu, S. Trogisch, J.-S. He, et al., "Tree Species Richness Increases Ecosystem Carbon Storage in Subtropical Forests," *Proceedings of the Royal Society B: Biological Sciences* 285, no. 1885 (2018): 20181240, https://doi.org/10.1098/rspb.2018.1240.

[42] H. Pandey, P. Pandey, S. Pokhrel, and R. Mandal, "Relationship Between Soil Properties and Forests Carbon: Case of Three Community Forests From Far Western Nepal," *Banko Janakari* 29 (2019): 43–52, https://doi.org/10.3126/banko.v29i1.25154.

[43] R. Lal, W. Negassa, and K. Lorenz, "Carbon Sequestration in Soil," *Current Opinion in Environmental Sustainability* 15 (2015): 79–86.

[44] A. M. Jagodzinski, J. Ziółkowski, A. Warnkowska, and H. Prais, "Tree Age Effects on Fine Root Biomass and Morphology over Chronosequences of Fagus Sylvatica, Quercus Robur and Alnus Glutinosa Stands," *PLoS One* 11, no. 2 (2016): e0148668, https://doi.org/10.1371/journal.pone.0148668.

[45] L. L. Bremer, K. A. Farley, O. A. Chadwick, and C. P. Harden, "Changes in Carbon Storage With Land Management

Promoted by Payment for Ecosystem Services," *Environmental Conservation* 43, no. 4 (2016): 397–406.

[46] M. A. Navarrete-Poyatos, R. M. Navarro-Cerrillo, M. A. Lara-Gómez, J. Duque-Lazo, M. A. Varo, and G. P. Rodriguez, "Assessment of the Carbon Stock in Pine Plantations in Southern Spain Through ALS Data and K-Nearest Neighbour Algorithm Based Models," *Geosciences* 9 (2019): 442, https://doi.org/10.3390/geosciences9100442.

[47] Y. Xiang, L. Yuan, X. Luo, et al., "Mixed Plantations Enhance More Soil Organic Carbon Stocks Than Monocultures Across China: Implication for Optimizing Afforestation/Reforestation Strategies," *Science of The Total Environment* 821 (2022): 153449, https://doi.org/10.1016/j.scitotenv.2022.153449.