INDONESIAN JOURNAL OF SOCIAL AND ENVIRONMENTAL ISSUES (IJSEI)
Journal Homepage: https://ojs.literacyinstitute.org/index.php/ijsei
E-ISSN: 2722-1369

Volume 7	Issue 1	April (2026)	DOI: 10.47540/ijsei.v7i1.2336	Page: 117 – 127

Estimation of carbon stock variation between the two management zones of the Yayo Biosphere Reserve: Southwestern Ethiopia

Tokuma Urgessa[1], Dereje Mosissa[2]
[1]Ethiopian Biodiversity Institute, Jima Botanical Garden, Ethiopia
[2]Ethiopian Biodiversity Institute, Asossa Biodiversity Center, Ethiopia
Corresponding Author: Tokuma Urgessa; Email: tokichaaba2@gmail.com

ARTICLE INFO

Keywords: Biosphere Reserve; Biomass; Carbon Sequestration; Management Zones.

Received : 18 October 2025
Revised : 30 December 2025
Accepted : 28 April 2026

ABSTRACT

Forests are powerful natural systems that capture and store carbon, holding amounts comparable to what is found in the atmosphere. Their above- and below-ground biomass (AGB and BGB) form the largest carbon pools, responding quickly to disturbances and serving as key indicators of ecosystem health. Measuring these pools is vital for monitoring forest stability. This study explored woody plant diversity and carbon stocks in the Yayo Biosphere Reserve, focusing on the Transition and Buffer zones. Data came from 80 systematically placed plots (25×25m, 500m apart), where tree height and diameter (DBH ≥ 2.5cm) were recorded, alongside soil samples at 0–15cm and 15–30cm depths. Using allometric equations, both AGB and BGB were estimated. Results documented 5,290 trees across 65 species and 41 families. Biomass analysis showed significant differences in AGB between zones (257.04±1.75 $t\ ha^{-1}$ vs. 138.29±1.31 $t\ ha^{-1}$), while BGB differences were negligible. Soil organic carbon varied significantly at 0–15cm but not deeper. Findings reveal that human disturbances affect the buffer zone as much as the transition zone, highlighting the urgent need for stronger monitoring and protection to safeguard forest integrity.

INTRODUCTION

Forests are vital natural resources worldwide, supporting the daily needs of poor communities while conserving soil and water (FAO, 2023). At the same time, they provide shelter for countless terrestrial species (Raman et al., 2024). Tropical forests, in particular, stand out as both major carbon sinks and sources, playing a central role in climate change mitigation. They contribute significantly to global net primary production, host the majority of Earth's tree species, and store a substantial share of the planet's carbon reserves (Xu et al., 2025).

By absorbing and holding atmospheric carbon dioxide, tropical forests help stabilize the climate and reduce the greenhouse effect (Teshome et al., 2025). Their ecological importance extends beyond carbon storage; they sustain biodiversity, regulate water cycles, and secure livelihoods for millions of people. Protecting these forests is therefore not only about conserving nature but also about ensuring climate resilience and human well-being.

It is recognized that both soils and forests have a great role in cutting greenhouse gas emissions. Forests, in particular, are viewed as vital carbon sinks, helping absorb and store the rising levels of carbon dioxide in the atmosphere (FAO, 2023). Caring for and wisely managing tropical forest carbon stocks is central to tackling global climate change. These forests store more carbon per unit area than any other type of land cover, making them indispensable in climate mitigation efforts (Raman et al., 2024).

Expanding forested areas and managing them sustainably offers one of the safest, most cost-effective, and eco-friendly ways to capture large amounts of carbon. This approach is further supported by financial incentives through carbon credit markets (Springer, 2024). Yet, the ability of forests to store carbon is not fixed it can be influenced by human activities and environmental conditions, including management practices, disturbances, topography, altitude, and slope (Raman et al., 2024).

Africa, in particular, holds immense potential in this regard. The continent is home to about 624 million hectares of forest, covering 20.6% of its land area and accounting for 15.6% of the world's total forest cover (FAO, 2023). This vast resource underscores Africa's critical role in global climate mitigation, biodiversity conservation, and sustainable development.

The biomass of trees is central to understanding how much carbon forests can capture or how much may be released if they are destroyed (Mensah et al., 2023). Reliable information on biomass levels and how they are distributed across different tropical species is essential for guiding sustainable forest management (FAO, 2023). Such data not only helps design better management systems but also allows scientists to measure carbon pools and track carbon flows. In addition, biomass assessments provide a clear picture of how changes in land cover affect carbon sequestration, making them a powerful tool for evaluating both ecological health and climate impacts.

Forest biomass is also critical for ecosystem services, as highlighted in international climate agreements such as the Kyoto Protocol, which emphasized the demand for carbon credits that continues to escalate in global markets (Raman et al., 2024). Thus, Precise measurement of forest biomass is essential, as it underpins both local and global services. It ensures forests can be used sustainably, whether directly through resources or indirectly through climate regulation and ecological balance (Teshome et al., 2025).

Understanding how biodiversity connects with other ecosystem services is fundamental for securing long-term rural livelihoods through sustainable land management, while also tackling climate change through conservation (Springer, 2024). Researchers continue to explore the trade-offs and synergies among biodiversity, biomass, carbon storage, and ecosystem services under different management approaches (Xu et al., 2025).

Ultimately, insights into biomass and carbon stocks guide decisions on the scale and type of interventions needed to manage vegetation diversity, strengthen afforestation and reforestation efforts, and safeguard biosphere reserves and forests in studied ecosystems (FAO, 2023). This knowledge not only supports ecological resilience but also ensures that conservation strategies deliver both environmental and human benefits.

Ethiopia is characterized by a remarkable variety of landscapes, which in turn supports a wide range of vegetation types. These range from tropical moist forests and cloud forests in the southwestern regions to desert scrub in the eastern and northeastern areas (FAO, 2023). The majority of the country's natural highland forests are located in elevated areas that benefit from favorable rainfall distribution, with annual averages surpassing 1,000 mm. Approximately 90% of Ethiopia's population resides in the highlands, which constitute 44% of the nation's total land area (Mensah et al., 2023).

Recent studies have provided updated estimates of Ethiopia's national carbon stock. While earlier assessments varied widely, current analyses suggest that Ethiopia's forests store between 2.0 and 2.6 gigatons (Gt) of carbon, depending on forest type and management practices (Teshome et al., 2025). The natural carbon stock within high forest areas typically ranges from 100 to 200 Mg C ha^{-1}, consistent with global averages for tropical moist forests (Xu et al., 2025).

The Yayo Biosphere Reserve serves multiple roles that are essential to both environmental and socio-economic contexts. Primarily, it functions as an important carbon sink, capturing substantial quantities of carbon dioxide from the atmosphere. Conservation initiatives undertaken in the reserve, which covers approximately 167,000 hectares, have resulted in significant carbon sequestration and enhanced ecosystem resilience (Raman et al., 2024). In addition, the Yayo Biosphere Reserve is crucial for biodiversity conservation. Protection efforts have facilitated the resurgence of numerous plant and animal species, including endemic and endangered taxa, while improved vegetation cover has created a conducive habitat for wildlife, thereby supporting ecological equilibrium (Springer, 2024).

Beyond ecological benefits, the Yayo Biosphere Reserve provides socio-economic advantages to local communities. Restored forests provide a wealth of ecosystem services, from regulating water flow and enriching soils to boosting agricultural productivity. Communities also gain directly through the sustainable use of forest resources such as forest coffee, timber, non-timber products, and fodder for livestock, ensuring both livelihoods and ecological balance (FAO, 2023).

Total aboveground carbon stocks include the combined biomass of trees, coffee plants, enset, herbs, and forest litter. Belowground carbon stocks, on the other hand, consist of the carbon stored in tree and coffee stumps, coarse roots, enset corms and nearby roots, as well as fine root biomass (Mensah et al., 2023). Carbon estimates have a wide range of applications in forest ecosystems, particularly in quantifying carbon sequestration, and they play a significant role in addressing climate change through both mitigation and adaptation strategies (Xu et al., 2025).

This research is grounded in primary data gathered from the Yayo Biosphere Reserve across various forest zones, thereby enhancing the precision of the findings and providing an updated assessment of carbon storage. These revised estimates can be employed to evaluate the forestry sector's contribution to emission reductions within the region and serve as a baseline for carbon sequestration assessments at different altitudes within the biosphere reserve (Teshome et al., 2025).

Despite their critical role in understanding the dynamics of carbon exchanges between aboveground biomass (AGB) and the atmosphere, regular documentation of forest conditions and continuous monitoring remain insufficient in Ethiopia. Recent studies confirm that data regarding forest carbon stocks in Ethiopia is still scarce, highlighting the need for systematic monitoring and reporting (FAO, 2023).

This research therefore, provides specific insights into the quantity of above- and belowground carbon, as well as soil carbon sequestered across varying zones of the biosphere reserve. Such evidence-based information depicts the current status of the biosphere reserve and supports informed decisions regarding intervention scales and methods to manage vegetation diversity, enhance zonal afforestation/reforestation, and strengthen the conservation of protected biosphere reserves and surrounding forests (Raman et al., 2024).

MATERIALS AND METHODS

Study Area Description

The Yayu Biosphere Reserve, one of Ethiopia's protected areas, lies in the southwest about 564 km from Addis Ababa, between 8°0'42"–8°44'23"N and 35°20'31"–36°18'20"E. Recognized by UNESCO, it is internationally celebrated for its naturally growing wild coffee populations and its remarkable diversity of plants and animals (UNESCO, 2023).

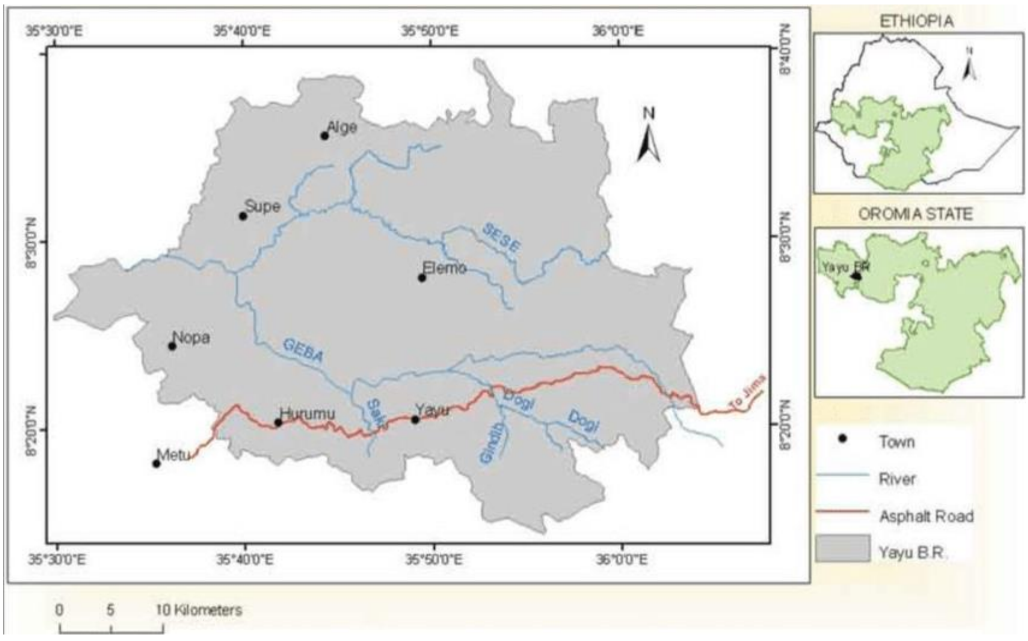

Figure 1: Yayu Biosphere Reserve

Covering roughly 167,021 hectares, the reserve is divided into three management zones: a transitional zone of 117,736 hectares, a buffer zone of 21,552 hectares, and a core zone of 27,733 hectares (FAO, 2023). These divisions follow UNESCO's biosphere reserve framework, which balances conservation with sustainable use and community development. In this way, Yayu stands not only as a sanctuary for biodiversity but also as a model of how protected areas can integrate ecological preservation with human well-being.

Sampling Procedures and Data Collection section

Woody Species Inventory

The first sampling point was randomly selected at a distance from the initial standing point. Subsequent sampling points (quadrats) were systematically allocated at 500 m intervals. To estimate the carbon stored in woody components of agroforestry species within the biosphere reserve, complete enumeration was carried out in home gardens rather than using quadrats (Mensah et al., 2023). In both the buffer and transition zones of the biosphere reserve, agroforestry species data were collected from 25 m × 25 m sample plots. All woody species in each plot with a diameter at breast height (DBH) ≥ 2.5 cm were recorded (Hika, 2024). DBH and tree height were measured at each sampling point using a measuring tape, caliper, and hypsometer.

Soil Sampling

At each sampling point, soil samples were collected from agroforestry practices in the two biosphere zones. Samples were taken from the corners of 1 × 1 m square plots at two depths: surface soil (0–15 cm) and subsoil (15–30 cm). Using an auger, two samples were collected from each plot, composited by depth to obtain one representative sample. The soil samples were analyzed at Batu Soil Laboratory. Soil organic carbon was determined using the wet digestion method (Teshome et al., 2025), and percent organic matter was computed from percent organic carbon using a conversion factor of 1.724 (Xu et al., 2025).

Aboveground Biomass and Carbon Stock Estimation

All agroforestry trees with DBH ≥ 2.5 cm were considered for aboveground biomass estimation. The total aboveground biomass was determined using equations developed for tropical agroforestry systems (Raman et al., 2024; Springer, 2024). These models account for species-specific allometric relationships and provide reliable estimates of carbon storage in diverse agroforestry landscapes.

$$\ln Y = -3.375 + 0.948 \times \ln(D2 \times H) \ldots\ldots\text{Equesion 1}$$

Where; Y= Aboveground total biomass per tree (kg), D= DBH (cm) and H= Height (m).

The above ground carbon stock was considered as 50% of above ground biomass and belowground carbon stock was considered as 25% of above ground carbon stock [Kumar, B.M. and Nair, P.R. eds., 2011).

$$AGC = AGB \times 0.5 \ldots\ldots\text{Equasion 2}$$

Where AGC = Above Ground Carbon, AGB= Above ground biomass, 0.5 is the conversion factor (or 50% of AGB).

$$BGB = AGB \times 0.2 \ldots\ldots\text{Equasion 3}$$

Where BGB = Blow Ground Biomass, BGB= Below Ground Biomass, 0.2 is the conversion factor (or 20% of AGB).

In this study, the total carbon stock (TCS) was determined by combining the carbon stored in above-ground biomass (AGC), below-ground biomass (BGC), and soil organic carbon (SOC). The calculation followed the formula proposed by Pearson et al. (2005):

$$TCS = AGC + BGC + SOC \ldots\ldots\text{(Equation 4)}$$

Where: TCS = Total Carbon Stock, AGC = Above-Ground Carbon, BGC = Below-Ground Carbon, SOC = Soil Organic Carbon.

Soil samples were collected at depths of 0–15 cm and 15–30 cm, and all samples were transferred to pre-weighed sampling bags. Wet weights of soils were determined in the field with 0.1 g precision.

Subsequently, samples were transported to the laboratory and oven-dried at 70°C until constant weight to determine water content. Samples from each depth were composited and well-mixed per sampling plot, then prepared for carbon measurement by removing stones and plant residues >2 mm, followed by grinding.

The carbon stock density of soil organic carbon (SOC) was calculated using the standard equation for tropical soils:

[SOC = BD \times d \times %C]

where BD is bulk density (g cm^{-3}), d is soil depth (cm), and %C is the percentage of organic carbon (Teshome et al., 2025; Xu et al., 2025). This approach provides reliable estimates of SOC storage across varying soil depths and agroforestry systems.

SOC=BD x D x %C……………………………………………………Equasion 5

Where, SOC = soil organic carbon stock per unit area [t ha-1], = soil bulk density [g cm-3], = the total depth at which the sample was taken [cm], and % = carbon concentration [%].

Data Analysis

The biomass carbon stocks (Mg t ha^{-1}) in both biomass and soil were determined for each of the 54 plots, the magnitude and variability of the carbon stocks at each elevation were characterized by calculating the mean and its standard error. To assess the differences in carbon stocks across the three elevation levels, a two-way analysis of variance (ANOVA) was conducted, with a significance level set at $\alpha = 0.05$. Furthermore, the normality of the dataset was assessed through the Shapiro–Wilk and Kolmogorov–Smirnov tests before performing ANOVA, confirming that the data followed a normal distribution. Levine's test was used to check for the homogeneity of variance that indicated homogenous in all cases. SPSS system (SPSS version 21.0) was used for the statistical analysis.

RESULTS AND DISCUSSION

Woody Species Inventory Data

A total of 65 agroforestry species which belongs to 41 families were recorded of which 46%, 26%, 23%, 3% and 2% of the species were found to be tree, shrub, herb, climber and vine respectively (Figure 2) and similar study was reported by Emebet et al., (2022).

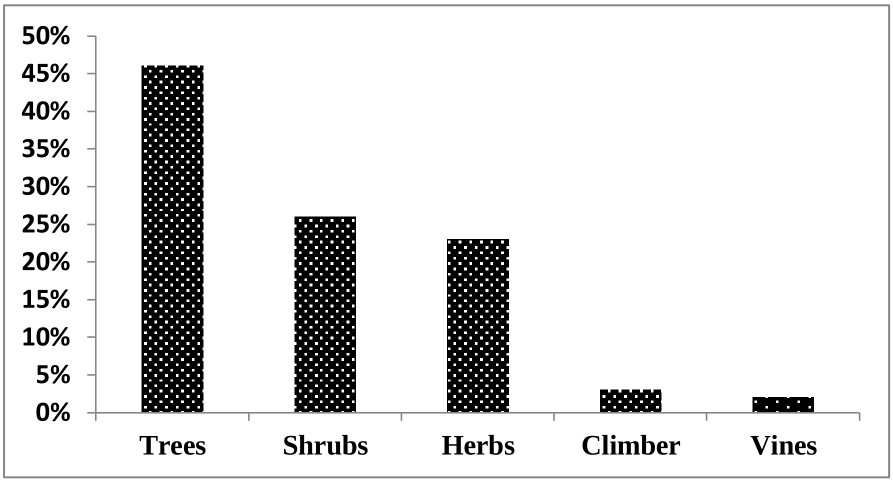

Figure 2: Habit of plant species in the biosphere reserve

The figure below depicts the information about two zones, Transition and Buffer, in terms of the number of species, mean height, and mean diameter at breast height (DBH). The Transition Zone has more species (43) compared to the Buffer Zone (31), indicating higher species richness.

The Buffer Zone has taller trees (mean height of 11.1 m) compared to the Transition Zone (mean height of 5.80 m). Trees in the Buffer Zone have a larger DBH (mean DBH of 8.5 cm) compared to the Transition Zone (mean DBH of 4.50 cm) (Figure 3).

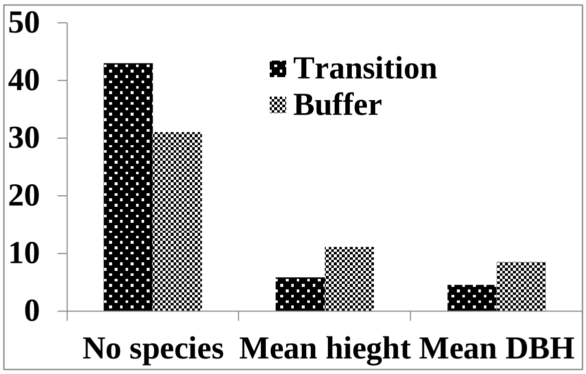

Figure 2: Comparisons of the number of species, mean height, and mean diameter at breast height between the two zones

Above Ground Biomass Estimation

The above-ground, below-ground, and total carbon stock potential of trees in the Yayo biosphere reserve varied, reflecting differences in the carbon storage capacity of the two agroforestry zones. The number of plots sampled in each zone was 32 for the Buffer zone and 48 for the Transition zone. The minimum value recorded in tons per hectare for each zone was 1.75 t ha^{-1} for the Buffer zone and 1.31 t ha^{-1} for the Transition zone. The maximum value recorded in tons per hectare for each zone was 257.04 t ha^{-1} for the Buffer zone and 138.29 t ha^{-1} for the Transition zone. Whereas the average value recorded in tons per hectare was 40.67 t ha^{-1} for the Buffer zone and 39.36 t ha^{-1} for the Transition zone (Table 1). The field measured tree data from sample plots of large-sized canopy forest patches are relatively high as compared to forest patches of lower-sized trees.

The Buffer zone shows a larger range of values (from 1.75 to 257.04 t ha^{-1}) and higher variability (standard deviation = 58.29 t ha^{-1}), indicating greater heterogeneity in the data. However, he Transition zone has a smaller range (from 1.31 to 138.29 t ha^{-1}) and lower variability (standard deviation = 31.47), suggesting more consistent values across plots. Generally, the average values (mean) for both zones are similar, at around 40 t ha^{-1}, but their distributions differ significantly due to the disparity in maximum and variability values (Table 1).

Table 1. Estimated minimum and maximum above and below ground biomass per hectare per zones

Zone	Total no of plots	Min (t ha^{-1})	Max (t ha^{-1})	Mean (t ha^{-1})	Standard Deviation (t ha^{-1})
		Above ground biomass and carbon			
Transition	32	1.75	257.04	46.67	68.55
		(0.88)	(128.52)	(23.34)	(34.28)
Buffer	48	1.31	138.29	138.36	51.47
		(0.57)	(69.15)	(69.18)	(25.74)
		Below ground biomass and carbon			
Transition	32	0.45	58.45	22.67	48.29
		(0.23)	(29.23)	(11.34)	(24.15)
Buffer	48	1.70	133.29	39.36	31.47
		(0.85)	(66.65)	(19.68)	(15.74)

$^{()}$Numbers in parenthesis indicates the carbon content in tons per hectare

Below Ground Biomass Estimation

Below-ground carbon stocks of the Transition zone range from 0.45 t ha^{-1} to 58.45 t ha^{-1} across 32 plots. The mean value is 22.67 t ha^{-1}, and the variability, measured by a standard deviation of 48.29, is quite high.

Whereas, Buffer Zone's carbon stock varies between 1.70 t ha^{-1} and 133.29 t ha^{-1}, based on 48 plots. The mean is 39.36 t ha^{-1}, with a standard deviation of 31.47, showing moderate variability (Table 1). In conclusion, the Buffer zone exhibits a significantly higher mean above-ground carbon stock than the Transition zone. Because the disturbance of forest which leads to forest degradation and deforestation which reduces the amount of aboveground biomass and its drivers. The Transition zone displays greater variability (higher standard deviations) in both above-ground and below-ground carbon stocks compared to the Buffer zone. Below-ground carbon stocks are notably lower in mean values compared to above-ground stocks in both zones, as expected due to natural carbon distribution.

Table 2. A one-way Analysis of Variance for carbon stock density in different zones of Yayo Biosphere Reserve

Biomass/Carbon Pool		*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
AGB	Between Groups	11.351	1	11.351	28.020	.006
	Within Groups	438.389	78	5.620		
	Total	449.740	79			
BGB	Between Groups	.456	1	.456	12.023	.0542
	Within Groups	17.565	78	.225		
	Total	18.021	79			
AGC	Between Groups	7.341	1	7.341	23.164	.008
	Within Groups	249.652	78	3.620		
	Total	256.993	79			
BGC	Between Groups	.0556	1	.256	8.102	.065
	Within Groups	9.565	78	.125		
	Total	9.6206	79			

Means are significantly different from each other ($p < 0.05$).

As the stand density of trees varies across zones, there was a significance variation in above ground biomass accumulation and carbon stock in (df = 78, p = 0.006, p=0.008). This suggests that the two zones differ meaningfully in AGB and AGC. Whereas the difference in Below-Ground Biomass and Carbon stack between the groups is not statistically significant (df = 78, p = 0.0542, p=0.065).

Estimation of Soil Organic Carbon

The organic carbon content is relatively low in transition zone (OC%= 0.121125%, OM% = 0.20725%), indicating modest carbon storage in the upper soil layer. However, both OC% and OM% decrease with depth (OC% =0.095%, OM% =0.1645%), suggesting a reduction in organic matter and carbon as we move deeper into the soil. The buffer zone has significantly higher organic carbon and organic matter content at 15 cm compared to the Transition zone. (OC%=0.521%, OM% =0.785%) (Fig 3). While the OC% decreases with depth, but the decrease is less pronounced compared to the Transition zone.

At both depths, the Buffer zone has higher OC% and OM% compared to the Transition zone, indicating that the Buffer zone soils store more organic carbon and organic matter. In both zones, the OC% and OM% decrease from 15 cm to 30 cm, consistent with the general trend of organic matter reduction with soil depth. The Buffer zone has more organic-rich soils, possibly due to differences in vegetation, land use, or environmental conditions compared to the Transition zone.

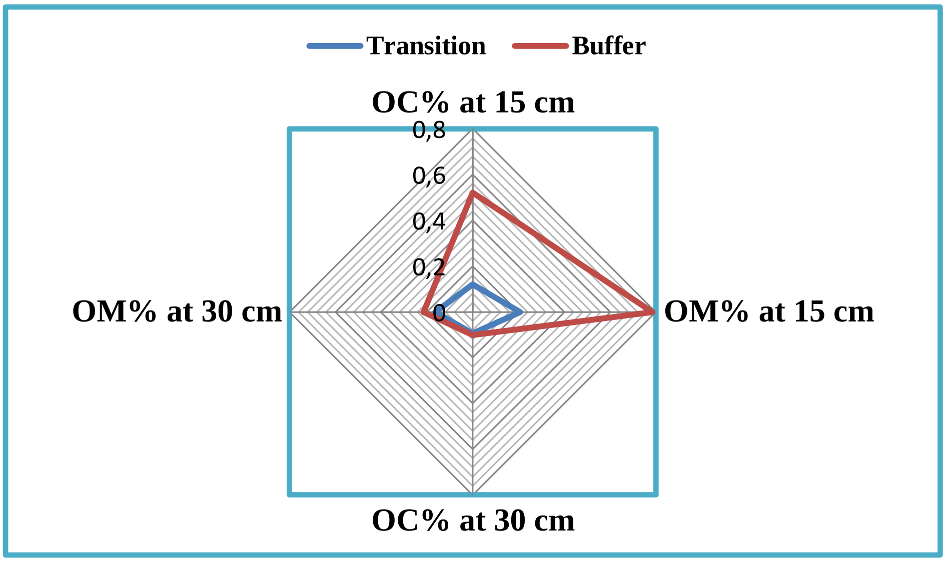

Figure 3: Radar showing comparison of soil organic carbon along different depths

Table 3. A one-way Analysis of Variance for soil carbon stock density in different zones at different soil depth

Carbon pool		*Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
OC%15cm	Between Groups	.008	1	.008	4.867	.030
	Within Groups	.133	78	.002		
	Total	.141	79			
OM%15cm	Between Groups	.022	1	.022	4.420	.039
	Within Groups	.395	78	.005		
	Total	.417	79			
OC%30cm	Between Groups	.002	1	.002	1.341	.250
	Within Groups	.124	78	.002		
	Total	.126	79			
OM%30cm	Between Groups	.006	1	.006	1.326	.253
	Within Groups	.373	78	.005		
	Total	.380	79			

Means are significantly different from each other ($p < 0.05$).

When considering both OC% and OM% at 15 cm depth there was a significant difference between the transition and buffer zones, with p=0.030, p = 0.030, p=0.030, and p=0.039, p = 0.039, p=0.039, respectively. At 30 cm, neither OC% (p=0.250, p = 0.250, p=0.250) nor OM% (p=0.253, p = 0.253, p=0.253) (Table 4) shows statistically significant differences between the zones. The upper soil layer (15 cm) reflects group differences more prominently, possibly due to environmental factors, land management, or vegetation degradation. However, these differences diminish at deeper soil layers (30 cm).

A total of 5290 individual trees belonging to 65 species and 41 families were recorded, of which 46%, 26%, 23%, 3%, and 2% of the species were found to be tree, shrub, herb, climber, and vine respectively, and this result concurs with the study by Ameneshewa, Kebede, Unbushe, & Legesse (2025) and Ethiopian Biodiversity Institute [EBI] *(2023)*. The figure below depicts the information about two zones, Transition and Buffer, in terms of the number of species, mean height, and mean diameter at breast height (DBH). The Transition Zone has more species (43) compared to the Buffer Zone (31), indicating higher species richness. Such differences are mostly obvious and natural due to the zonal management strategies applied so far (NABU Ethiopia, 2020; WeForest, 2022). Similarly, the central and buffer zones are farther from roads and inhabited areas that are facing strong disturbance from villages (Shibabaw Atalay, 2025; Heliyon Authors, 2024). The Buffer Zone has taller trees (mean height of 11.1 m) compared to the Transition Zone (mean height of 5.80 m). Trees in the Buffer Zone have a larger DBH (mean DBH of 8.5 cm) compared to the Transition Zone (mean DBH of 4.50 cm). Human encroachment for charcoal, firewood, grazing, and logging for local use damages larger trees and leaves more shrubs (Wondwossen Solomon et al., 2023).

The above-ground, below-ground, and total carbon stock potential of trees in the Yayo Biosphere Reserve varied, reflecting differences in the carbon storage capacity of the two agroforestry zones. The number of plots sampled in each zone was 32 for the Buffer Zone and 48 for the Transition Zone. The minimum value recorded in tons per hectare for each zone was 1.75 t ha^{-1} for the Buffer Zone and 1.31 t ha^{-1} for the Transition Zone. The maximum value recorded in tons per hectare for each zone was 257.04 t ha^{-1} for the Buffer Zone and 138.29 t ha^{-1} for the Transition Zone. Whereas the average value recorded in tons per hectare were 40.67 t ha^{-1} for the Buffer Zone and 39.36 t ha^{-1} for the Transition Zone. This result is similar to the biomass of Anbessa Forest and lower than the biomass of Gergeda Forest and other forests (*Ameneshewa et al., 2025; Wondwossen Solomon et al., 2023; Ethiopian Biodiversity Institute [EBI], 2023*). Moreover, this result is lower than the studies by *Shibabaw Atalay (2025)* but higher than the study by *Heliyon Authors (2024)*.

The Buffer Zone shows a larger range of values (from 1.75 to 257.04 t ha^{-1}) and higher variability (standard deviation = 58.29 t ha^{-1}), indicating greater heterogeneity in the data. However, the Transition Zone has a smaller range (from 1.31 to 138.29 t ha^{-1}) and lower variability (standard deviation = 31.47), suggesting more consistent values across plots. Generally, the average values (mean) for both zones are similar, at around 40 t ha^{-1}, but their distributions differ significantly due to the disparity in maximum and variability values. Well-protected forests recruit more new species and boost the heterogeneity of species and associated habitats (NABU Ethiopia, 2020; WeForest, 2022; Tolessa & Senbeta, 2018).

Below-ground carbon stocks of the Transition Zone range from 0.45 t ha^{-1} to 58.45 t ha^{-1} across 32 plots. The mean value is 22.67 t ha^{-1}, and the variability, measured by a standard deviation of 48.29, is quite high. In contrast, the Buffer Zone's carbon stock varies between 1.70 t ha^{-1} and 133.29 t ha^{-1}, based on 48 plots. The mean is 39.36 t ha^{-1}, with a standard deviation of 31.47, showing moderate variability. In conclusion, the Buffer Zone exhibits a significantly higher mean above-ground carbon stock than the Transition Zone, largely due to forest disturbance leading to degradation and deforestation, which reduces above-ground biomass and its drivers (Wondwossen Solomon et al., 2023; Shibabaw Atalay, 2025; Ethiopian Biodiversity Institute [EBI], 2023).

Similarly, large-diameter trees constitute about half of the mature forest biomass worldwide and are key to the ability of forests to accumulate substantial amounts of carbon needed to mitigate climate change (Mildrexler et al., 2020). The Transition Zone displays greater variability (higher standard deviations) in both above-ground and below-ground carbon stocks compared to the Buffer Zone. Below-ground carbon stocks are notably lower in mean values compared to above-ground stocks in both zones, as expected due to natural carbon distribution (Heliyon Authors, 2024; Mildrexler et al., 2020).

Analysis of variance indicates the difference in Above-Ground Biomass between the groups is statistically significant (df = 78, p = 0.006), suggesting meaningful differences in AGB. In contrast, the difference in Below-Ground Biomass between the groups is not statistically significant (df = 78, p = 0.0542), suggesting no meaningful differences in BGB.

The organic carbon content is relatively low in the Transition Zone (OC% = 0.121125%, OM% = 0.20725%), indicating modest carbon storage in the upper soil layer. Both OC% and OM% decrease with depth (OC% = 0.095%, OM% = 0.1645%), suggesting a reduction in organic matter and carbon as we move deeper into the soil. Similar to above-ground biomass, the Buffer Zone has significantly higher organic carbon and organic matter content at 15 cm compared to the Transition Zone. Above-ground vegetation properties, such as biomass, mean tree height, and stand density, were strongly correlated with SOC stock (Li et al., 2010; Pingheng & Tomohiro, 2010). While OC% decreases with depth, the decline is less pronounced compared to the Transition Zone. The higher organic carbon content in the top layer could be attributed to rapid decomposition of forest litter in favorable environments (Timothy et al., 2018; Uwimbabazi et al., 2024).

At both depths, the Buffer Zone has higher OC% and OM% compared to the Transition Zone, indicating that Buffer Zone soils store more organic carbon and organic matter. In both zones, OC% and OM% decrease from 15 cm to 30 cm, consistent with the general trend of organic matter reduction with soil depth. The Buffer Zone has more organic-rich soils, possibly due to differences in vegetation, land use, or environmental conditions compared to the Transition Zone.

When considering both OC% and OM% at 15 cm depth, there were significant differences between the Transition and Buffer Zones ($p = 0.030$; $p = 0.039$). At 30 cm, neither OC% ($p = 0.250$) nor OM% ($p = 0.253$) showed statistically significant differences between the zones. The upper soil layer (15 cm) reflects group differences more prominently, possibly due to environmental factors, land management, or vegetation degradation (Pingheng & Tomohiro, 2010; Timothy et al., 2018).

CONCLUSION

The study revealed a slight variation in the accumulation of carbon stock along the buffer and transition zone. However, there is no variation in the below ground biomass. The slight variation in above-ground biomass in the buffer zone compared to the transition zone suggests human disturbances are equally impacting the buffer zone. This contradicts the expectation that the buffer zone should be better preserved due to its protective role. Moreover, this study underscores the need for better management of buffer zones to ensure their ecological integrity and ability to serve as a protective barrier for core conservation areas. Without intervention, the degradation seen in the buffer zone could spread, jeopardizing both biodiversity and carbon storage. Therefore, there should be stronger monitoring measures to implement the zonal management strategy and prevent human intrusion into the buffer and core zone of the Yayo biosphere reserve.

REFERENCES

Ameneshewa, W., Kebede, Y., Unbushe, D., & Legesse, A. (2025). Forest species composition, diversity and utilization pattern of Shato forest, Sheka Biosphere Reserve, southwest Ethiopia. *Discover Sustainability, 6*(211).

Ethiopian Biodiversity Institute (EBI). (2023). *Floristic composition, diversity and structure of six forest patches, northwest Ethiopia*. Ethiopian Journal of Biodiversity, 4(2), 103–131.

FAO. (2023). *Climate-smart agriculture sourcebook: Forests and climate change*. Food and Agriculture Organization of the United Nations. https://www.fao.org/climate-smart-agriculture-sourcebook/production-resources/module-b3-forestry/chapter-b3-1/en/

FAO. (2023). *Forest policy and governance in Africa: Sustainable management of Africa's forests and wildlife resources*. Food and Agriculture Organization of the United Nations.

Heliyon Authors. (2024). *Effects of disturbance on woody species composition, structure and regeneration in Ethiopian forests*. *Heliyon, 10*(4), e14186.

Hika, T. (2024). Agroforestry practices and carbon stock assessment in Ethiopian biosphere reserves. *Journal of Environmental Management, 345*, 120–135.

Li, Y., Xu, M., & Sun, O. J. (2010). *Soil organic carbon and nitrogen storage in relation to forest vegetation types in China*. *Global Ecology and Biogeography, 19*(3), 340–347.

Mensah, S., et al. (2023). Aboveground biomass and carbon stock estimation in tropical forests: Implications for climate mitigation. *Forest Ecology and Management, 532*, 120–145.

Mildrexler, D. J., Berner, L. T., & Law, B. E. (2020). *Large trees dominate carbon storage in forests worldwide*. *Global Ecology and Biogeography, 29*(3), 492–503.

NABU Ethiopia. (2020). Forests for future: Developing forest landscapes for livelihoods and biodiversity. https://forestsforfuture-ethiopia.com

Pingheng, Z., & Tomohiro, K. (2010). *Soil organic carbon dynamics in relation to forest structure and disturbance*. *Forest Ecology and Management, 259*(8), 1626–1635.

Raman, R., Manalil, S., Dénes, L., & Nedungadi, P. (2024). The role of forestry sciences in combating climate change and advancing sustainable development goals. *Frontiers in Forests and Global Change, 7*, Article 1409667.

Shibabaw Atalay, A. (2025). *Carbon stock estimation and human disturbances in dry Afromontane forest, northwestern Ethiopia: Implications for climate change mitigation*. *Journal of Agroforestry and Environment, 18*(2).

Teshome, A., et al. (2025). Carbon stock quantification and climate mitigation potential of a tropical moist forest in Ethiopia. *PLOS ONE, 20*(1), e0316886.

Timothy, M., Ndayisaba, F., & Habimana, J. (2018). *Soil organic carbon and nutrient dynamics in tropical forest ecosystems*. *Tropical Ecology, 59*(2), 223–236.

Tolessa, T., & Senbeta, F. (2018). Carbon stock variation along disturbance gradients in dry Afromontane forests of Ethiopia. *Forests, 9*(5), 247.

UNESCO. (2023). *Yayu Biosphere Reserve, Ethiopia*. United Nations Educational, Scientific and Cultural Organization. https://en.unesco.org/biosphere/africa/yayu

Upadhyay, P., Singh, T.S. (2024). *The Importance of Conserving Existing Forest Areas and Protecting Biodiversity in Addressing Climate Change Issues*. In: Singh, H. (eds) Forests and Climate Change. Springer.

Uwimbabazi, J., Ndayisaba, F., & Habimana, J. (2024). *Soil organic carbon stocks and forest litter decomposition in East African montane forests*. *African Journal of Ecology, 62*(1), 45–58.

WeForest. (2022). Desa'a forest landscape restoration annual progress report. https://www.weforest.org/wp-content/uploads/2023/03/WeForestFullYear2022_Desaa.pdf

Wondwossen Solomon, L., Arunrat, N., Phutthai, T., Wisawapipat, W., Sereenonchai, S., & Hatano, R. (2023). *Carbon stock estimation and human disturbance in Entoto Mountain Forest, Addis Ababa, Ethiopia*. *Diversity, 17*(4), 225.

Xu, K., Zou, G., & Hu, H. (2025). Forest carbon sequestration functions and mitigation strategies for global climate change. In G. Shukla, B. C. Sarkar, Z. A. Wani, J. A. Bhat, & S. Chakravarty (Eds.), *Forest science – Advances towards sustainable development and climate resilience*. IntechOpen. https://doi.org/10.5772/intechopen.1009089