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Phytosociology and carbon sequestration potential of tropical forest landscape: A case from Northwest Chittagong, Bangladesh

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Abstract. *Chowdhury MIH, Rakib MH. 2024. Phytosociology and carbon sequestration potential of tropical forest landscape: A case from Northwest Chittagong, Bangladesh. Asian J For 8: 126-135.* This study evaluates the carbon sequestration potential of tree species within Sheikh Russel Aviary and Eco-Park, Bangladesh, emphasizing its contribution to carbon storage and biodiversity. Conducted in 2023, 781 individual trees from 27 families of 35 species were assessed across 18 plots (26×26 meters each) using a Randomized Block Design (RBD) to account for altitudinal variation (top, middle, bottom zones, total of 54 samples from 18 plots). Carbon sequestration was measured through allometric equations, while soil Organic Carbon (OC) was determined using the Loss on Ignition (LOI) method. Phytosociological parameters, such as species composition and height class, were analyzed to assess carbon storage. Results indicated that 44.3% of trees fell within the significant height class (12.1-17 m) for carbon sequestration, with *Acacia auriculiformis*, *Tectona grandis*, and *Gmelina arborea* sequestering 18.95, 13.18, and 3.67 tons/ha of carbon, respectively. The average biomass was 102.774 tons/ha, and carbon sequestration averaged 51.387 tons/ha. Soil organic carbon averaged 1.46%, with soil moisture content at 18.73%, indicating favorable growing conditions. Statistical analyses, including ANOVA, confirmed significant differences in carbon sequestration across altitudinal zones. Comparison with similar studies demonstrated that the park's carbon storage capacity is comparable to other hilly forests in Bangladesh. This research highlights the park's role in climate mitigation and suggests adaptive management for enhancing carbon storage and biodiversity. Future studies should include understory vegetation and refined allometric models for a more comprehensive evaluation of its ecological potential.

Keywords: *Acacia auriculiformis,* allometric model, carbon sequestration, Eco-Park, importance value index

INTRODUCTION

Carbon sequestration is a vital ecosystem service that mitigates climate change by capturing and storing atmospheric carbon dioxide in vegetation, soils, and oceans. Forest ecosystems, particularly in tropical regions, play a crucial role in carbon storage, contributing significantly to global efforts to reduce greenhouse gas emissions (Talukdar et al. 2020). Bangladesh, a country rich in biodiversity, faces significant challenges in forest conservation. Besides its importance for biodiversity, forests in Bangladesh are also essential in term of carbon sequestration to mitigate climate change. The country's forests are a critical component of global carbon cycles, storing an estimated 251.8 million Mg of carbon, with nearly half of this stored in the mangrove forests alone. Along with hill forests, they provide high potential for carbon conservation through REDD+ (Reducing Emissions from Deforestation and Forest Degradation) (Simon et al. 2018). However, deforestation and forest degradation due to overpopulation, shifting cultivation, and agricultural expansion pose serious threats to these ecosystems (Wabnitz et al. 2018).

In tropical developing countries like Bangladesh, REDD+ is becoming an increasingly important mechanism for conserving forests and protecting biodiversity, as in the case of the Sheikh Russel Aviary and Eco-Park which is situated in Rangunia Upazila, Chittagong, Bangladesh. This conservation area is an example of remarkable site that integrates ecological conservation with public recreation. Spanning 210 hectares, this park was established in 2001 to honor Sheikh Russel, the youngest son of Bangabandhu Sheikh Mujibur Rahman. Inaugurated by Prime Minister Sheikh Hasina, the park has since become a popular destination for tourists, especially nature and bird enthusiasts (Zhou 2018). Managed by the Chittagong South Forest Division, its unique features (Schnell et al. 2014), including hill forests, artificial plantations, and a ropeway cable car, attract visitors year-round, making it an ideal spot for ecotourism. The park's strategic location, close to the Chittagong-Kaptai Highway, Karnafuly Paper Mill, and Kaptai hydroelectric project (Simiele et al. 2022), enhances its accessibility and significance.

The objectives of the Sheikh Russel Aviary and Eco-Park establishment are multifaceted. The park aims to conserve biodiversity, promote natural beauty, and create ecotourism opportunities for public recreation. Additionally, it seeks to establish an educational and research center to enhance knowledge about forest resources and wildlife. Public awareness campaigns within the park focus on the importance of conserving natural forest resources and wildlife, further emphasizing its role in environmental education. the park is dedicated to biodiversity conservation, offering a sanctuary for various bird species, including those that are endangered. The park also serves as a rehabilitation center for injured birds, providing them with proper care and treatment (Zukswert et al. 2023).

Phytosociology, the study of plant communities and their relationships, offers valuable insights into the ecological structure and carbon storage potential of forests. By analyzing species composition, abundance, and spatial distribution, phytosociological assessments help identify key species contributing to carbon sequestration (Mukul et al. 2014). Understanding the capacity of different tree species and forest stands to sequester carbon is essential for informing conservation and sustainable land management practices. Baseline estimates of carbon in forest ecosystems are crucial for the success of these projects. For instance, the hill forests in Bangladesh have a carbon density of 115.56 Mg/ha, while mangrove forests and Sal forests have carbon densities of 98.9 Mg/ha and 153.9 Mg/ha, respectively (Uddin et al. 2020; Teets et al. 2023). These figures highlight the significant role that Bangladesh's forests play in global carbon sequestration efforts. In the context of Sheikh Russel Aviary and Eco-Park, phytosociology provides a detailed understanding of the park's capacity to act as a carbon sink, emphasizing the importance of local biodiversity for climate change mitigation.

The Sheikh Russel Aviary and Eco-Park, with its diverse ecosystems, offers a unique opportunity to study the interplay between biodiversity conservation and carbon sequestration. The park's efforts to protect endangered bird species and rehabilitate injured birds contribute to the overall health of the ecosystem (Rolkier 2021), which in turn enhances its capacity for carbon storage (Rahman et al. 2022). Moreover, the park's focus on public education and awareness is crucial for fostering a deeper understanding of the importance of forest conservation in the fight against climate change. It is not only just a recreational site but also a vital ecological reserve that plays a significant role in biodiversity conservation, carbon sequestration (Talukdar et al. 2020), and environmental education. Research conducted in this park can provide valuable insights into the effectiveness of conservation strategies in Bangladesh, contributing to global efforts to mitigate climate change and preserve natural resources for future generations.

The aim of this study is to assess the phytosociological status and carbon sequestration potentials in Sheikh Russel Aviary and Eco-Park. Specifically, the research seeks to examine the diversity of tree species within the park, quantify the total carbon sequestration by these species, and explore the relationship between carbon sequestration potential and tree species diversity. Additionally, the study will measure soil moisture content and soil organic carbon to discover how tree species diversity and altitudinal variation influence carbon storage and soil properties (Rakib et al. 2024). By analyzing tree species distribution and biomass across different altitudes, the research aims to identify which species contribute the most to carbon sequestration (Ouimette et al. 2019). The hypothesis is that higher tree species diversity will positively correlate with greater carbon sequestration potential, and altitude will significantly impact both soil moisture content and organic carbon levels (NOAA 2019). The study also aims to identify the five species with the highest Importance Value Index (IVI) to determine their critical role in carbon capture. These insights will contribute to understanding how biodiversity enhances carbon sequestration and will provide valuable data for improving sustainable forest management practices.

MATERIALS AND METHODS

Study area and period

Sheikh Russel Aviary and Eco-Park is located in Nischintapur Mouza, Kudala Beat, under the Rangunia Range of the Chittagong South Forest Division, Bangladesh (Figure 1). The park spans 210 hectares, positioned between 22°18'–22°37' N and 91°58'-92°08' E (Rahman et al. 2022). Approximately 35 km east of Chittagong City, Aviary Park is easily accessible via the Chittagong-Kaptai Highway, near Chandraghona, the Karnafuly paper mill, and the Kaptai hydroelectric project. The park’s hilly terrain, ranging from 50 to 350 meters in altitude (Mukul et al. 2014), offers a valuable landscape for studying carbon sequestration, Soil Moisture Content (SMC), and Organic Carbon (OC) across elevation zones, where altitude influences vegetation and soil properties (Moeys 2018). Climate conditions are subtropical, with annual precipitation of approximately 3000 mm and an average temperature of 26°C.

Research design

The study followed a Randomized Block Design (RBD), which was adopted to ensure the randomness and representativeness of the data collected. This design helps minimize environmental and soil variability across different parts of the study area, improving the reliability of the results (Mamun et al. 2022). The study area was divided into nine blocks based on altitude, which was further categorized into three plots within each block. These plots were labeled as Top, Middle, and Bottom zones to reflect the altitude at which they were located on the hills (Hossain et al. 2020; Uddin et al. 2020; Islam et al. 2022). This division allowed for an in-depth analysis of the effects of altitude on SMC, OC, and carbon sequestration potential (CSP). The quadratic sampling method was used to determine plot sizes, which were fixed at 26 meters by 26 meters for uniformity and to facilitate comparable data collection across all plots. This method is commonly used in ecological studies to assess the density and distribution of trees and soil properties within a specified area (Mamun et al. 2022) within each plot, detailed measurements of SMC and OC were recorded, enabling the analysis of carbon storage potential at different altitudes (Metzger et al. 2021). The data gathered from the different soil layers (Top and Bottom) within each block provide insights into the potential for sustainable forest management in similar hilly regions of Bangladesh (Figure 1).

Vegetation data collection

Soil data collection

In this study, a total of 18 plots were selected from nine blocks across the study area, ensuring a representative sample from different altitudinal zones (Mason et al. 2022a). Soil samples were collected from each plot at two depths: 0-15 cm and 15-35 cm. For each plot, soil samples were collected from two layers: surface soil (0-15 cm) and subsoil (15-35 cm). The rationale for selecting these depth intervals stems from their critical role in nutrient cycling and carbon storage. Surface soils generally contain higher concentrations of organic matter due to the accumulation of plant litter, while subsoil layers play a key role in long-term carbon sequestration. This sampling design aimed to assess variations in soil Organic Carbon (OC) and other soil properties (Zhang et al. 2014; Thong et al. 2020), such as Soil Moisture Content (SMC), across both the top to bottom portions of the hills. Collecting soil from these depths allows for a comprehensive understanding of the vertical distribution of OC and how it is influenced by environmental factors such as elevation, slope, and vegetation cover. The depth differentiation is essential for understanding how OC and SMC change with soil depth (Mason et al. 2022b), a factor that can significantly influence soil fertility, carbon storage capacity, and overall ecosystem functioning.

After collection, soil samples were prepared for analysis. The organic carbon content of the soil was determined using the Loss on Ignition (LOI) methodology via dry it at oven (112°C) till it reaches at constant weight after that burned it at furnace at 65°C for two and half hours the each 5 gram of dry soil sample and measures the log of ignition through equation mention in data analysis section properly (Shivanna 2022), a well-established technique for estimating OC in soil samples (Mamun et al. 2022). The LOI method involves heating soil samples to high temperatures to burn off organic matter, which can then be quantified by measuring the weight loss of the soil sample (Siarudin et al. 2021). This method is particularly useful in studies of soil carbon dynamics as it provides a reliable estimate of OC, especially in forest soils where organic matter content can vary significantly with depth and topography.

The determination of OC in this study followed a series of carefully controlled laboratory procedures (Shiferaw et al. 2022). First, the soil samples were placed in washed silica crucibles, which were pre-dried in an oven at 105°C for 20 minutes to remove any residual moisture. After drying, the soil samples were finely ground to ensure homogeneity, a crucial step for accurate OC measurements (Sharma et al. 2021). A 5-grams sample of the ground soil was weighed and placed in a silica crucible, which was then transferred to an electric furnace. The furnace was heated to 850°C, a temperature high enough to burn off the organic matter in the soil. The samples were kept in the furnace for three hours to ensure complete combustion of organic materials. After the combustion process, the crucibles were removed from the furnace and placed in a desiccator to cool. Cooling the samples in a desiccator is important as it prevents moisture from the air from being absorbed by the soil samples, which could alter the weight measurements. Once cooled, the crucibles were reweighed using an electric balance (Sharma et al. 2021), and the percentage Loss on Ignition (LOI) was calculated based on the weight difference before and after combustion. LOI represents the amount of organic matter that was burned off during the heating process and is a proxy for OC. The LOI values were then used to estimate the percentage of OC in each soil sample, which was expressed relative to the weight of the oven-dry soil.

Analysis of vegetation biomass and carbons

Tree Above-Ground Biomass (TAGB) was calculated using the formula provided by Mahmood et al. (2020). This formula estimates AGB based on tree diameter at breast height (D), tree height (H), and wood density (W). The formula is expressed as:

$$AGB = -6.6937 + 0.809 \times \ln (D^2 \times H \times W)$$

Where: Ln represents the natural logarithm. The diameter (D) is squared and multiplied by height (H) and wood density (W) to estimate the biomass in logarithmic terms. The constants (-6.6937 and 0.809) are derived from empirical data and calibrated the model to better fit the biomass data (Mahmood et al. 2020).

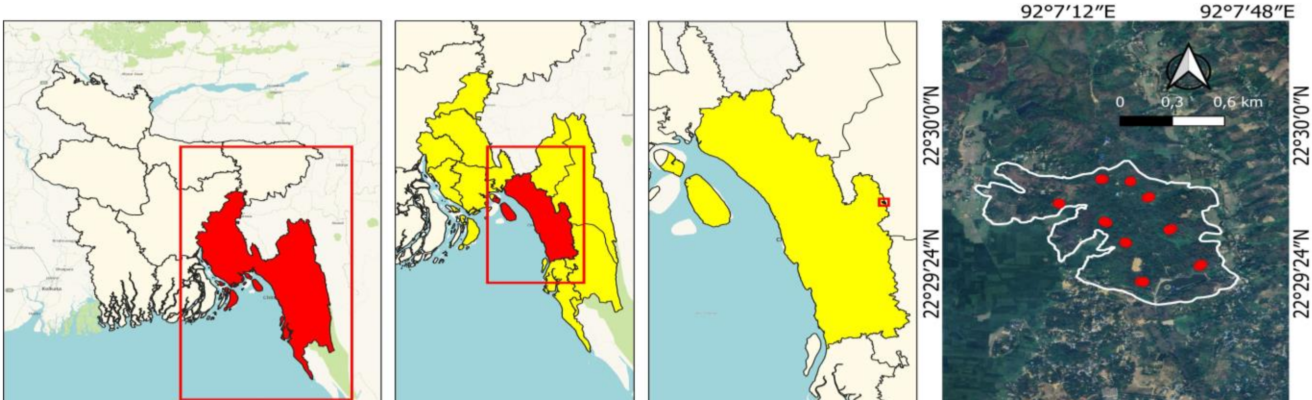


Figure 1. Map of study area showing sampling blocks in Sheikh Russel Aviary and Eco-Park, Bangladesh

Below-Ground Tree Biomass (BGTB) was estimated by applying a root-to-shoot ratio of 0.26 to the TAGB. This ratio, based on studies by Islam et al. (2016) and Hale et al. (2019), reflects the typical proportion of biomass found in the roots compared to the above-ground parts of the tree (Sharmake et al. 2023):

$$BGB = AGB \times 0.26$$

To find the Total Tree Biomass (TTB), both The Above-Ground Biomass (TAGB) and Below-Ground Biomass (BGTB) are summed:

$$TTB = AGB + BGB$$

Carbon Sequestration Potential (CSP) was calculated as 50% of the Total Tree Biomass (TTB). This estimation reflects the portion of biomass that is converted to carbon and stored in the environment (Pearson et al. 2005; Islam et al. 2016):

$$CSP = TTB \times 50\%$$

Analysis of soil organic carbon

Soil Organic Carbon (OC) content was calculated with the formula (Seid 2022):

$$OC = 0.476 \times (\%LOI\text{-}108)$$

The subtraction of 108 from %LOI (percentage loss on ignition) adjusts for the residual inorganic matter, and the factor 0.476 converts the loss into an estimate of organic carbon content.

Statistical analysis

All collected data were analyzed using ANOVA (Analysis of Variance) to identify significant differences in soil Organic Carbon (OC) and Soil Moisture Content (SMC) between the top and bottom soil layers and among plots at different altitudes. Pairwise comparisons were conducted using the Tukey HSD test to detect specific differences between blocks (Mamun et al. 2022). Correlation analysis was performed to examine the relationship between OC and SMC. Results were visualized using ggplot2 in R, and ggboxplot was used to represent the distribution of SMC and OC across the study area, including pairwise comparisons between soil layers (Lovett et al. 2018).

RESULTS AND DISCUSSION

Phytosociological status

Acacia auriculiformis, Gmelina arborea, and *Tectona grandis* were three dominant species with the highest Importance Value Index (IVI), Relative Density (RD), Relative Dominance (RDo), and Relative Frequency (RF) (Table 1). Among the species, *A. auriculiformis* exhibited the highest IVI, exceeding 60%, which indicates its significant role in the forest's structure and composition. Both *G. arborea* and *T. grandis* had lower IVI values, suggesting they play a less prominent role in the forest. In terms of RD, *A. auriculiformis* and *T. grandis* showed comparable percentages, with both exhibiting high relative densities, whereas *G. arborea* had a notably lower RD. On the other hand, *T. grandis* displayed the highest RF among the species, indicating that it is more widely distributed throughout the sampled forest plots. The patterns of these forest parameters reveal that while *A. auriculiformis* dominates in terms of importance and density, *T. grandis* is more consistently distributed across the area.

In addition to its role in carbon sequestration, the diversity of tree species and families within the park supports a wide range of ecological processes and services. These include habitat provision for various wildlife species, soil stabilization, water regulation, and nutrient cycling. The presence of species from different families also indicates a resilient ecosystem capable of withstanding environmental changes and disturbances (Talukdar et al. 2020; Yousefiard et al. 2024). However, the study also points to the need for ongoing monitoring and management to maintain and enhance the ecological health of the park. This includes efforts to protect and promote the growth of young trees, manage invasive species (Sahoo et al. 2019), and ensure sustainable tourism practices. The high IVI values of certain species suggest that they are particularly well-suited to the local conditions and may be prioritized in future afforestation and conservation efforts (Siddique et al. 2024). Overall, the study provides a comprehensive overview of the tree species composition and structure within Sheikh Russel Aviary and Eco-Park, highlighting its significant role in carbon sequestration and biodiversity conservation.

Soil moisture content and soil organic carbon across varying depths

The comparison of Soil Moisture Content (SMC) between the top and bottom soil layers showed no significant differences, as indicated by the ANOVA test ($p=0.54$) (Figure 2.A). The mean SMC values were relatively similar between the two layers, with the top layer showing a mean value of approximately 17%, while the bottom layer demonstrated a slightly higher median value, although the difference was not statistically significant. The variability in moisture content, as observed through the scatter plot, was somewhat greater in the bottom layer, with some outliers indicating higher moisture retention at deeper soil levels (Kreiselmeier et al. 2020). This suggests that moisture distribution across soil depths is relatively uniform, with no clear stratification between the top and bottom layers.

The soil Organic Carbon (OC) was also assessed for both the top and bottom layers (Figure 2.B). The results showed no significant difference between the layers ($p =0.44$). However, the bottom layer exhibited higher variability in OC content compared to the top layer (Singh et al. 2018), as indicated by a broader interquartile range and several higher data points in the scatter plot. The median OC content in the top layer was approximately 1.5%, whereas the bottom layer's median was slightly higher, at around 2%. Although the difference was not statistically significant, the broader spread of OC values in the bottom layer suggests greater heterogeneity in organic matter accumulation at deeper soil depths.

Tree biomass and carbon estimation

The *A. auriculiformis* exhibited the highest total biomass, with an Above-Ground Biomass (AGB) of 29.49 t/ha (Table 2) and a Below-Ground Biomass (BGB) of 7.51 t/ha. This resulted in a Total Tree Biomass (TTB) of 34.89 t/ha, which was the highest among the species studied. The *T. grandis* ranked second, with a AGB of 11.05 t/ha and a BGB of 7.17 t/ha, contributing to a TTB of 25.23 t/ha. The *G. arborea* followed with a AGB of 9.41 t/ha and a BGB of 2 t/ha, leading to a TTB of 9.37 t/ha. These three species are the major contributors to the overall biomass in the study area (Table 2).

Species such as *Artocarpus heterophyllus* and *Terminalia arjuna* exhibited lower biomass levels, with TTB values of 4.38 t/ha and 3.50 t/ha, respectively as sample results showed (Chowdhury and Das 2024) where field study conducted in 2019 at Sheikh Russel Aviary and Eco-Park. The remaining species, including *Artocarpus chama*, *Syzygium cumini*, *Terminalia bellerica*, *Grewia nervosa*, and *Protium serratum*, had relatively smaller contributions to the total biomass, ranging between 1.98 t/ha and 3.23 t/ha.

Carbon sequestration potential (CSP)

The carbon sequestration potential (CSP) reflects the ability of these tree species to capture and store carbon. The *A. auriculiformis* demonstrated the highest CSP at 18.95 t/ha, aligning with its highest biomass values (Table 2). Similarly, *T. grandis* had a CSP of 13.18 t/ha (Karmakar et al. 2019), and *G. arborea* had 3.67 t/ha which is low from (Rudgers et al. 2022; Chowdhury and Das 2024). These three species stand out for their superior ability to sequester carbon (Talukdar et al. 2020), making them vital contributors to mitigating climate change impacts within the forest ecosystem. Lower CSP values were observed for *A. heterophyllus* (2.19 t/ha), *T. arjuna* (1.75 t/ha), and *A. chama* (1.62 t/ha). The remaining species had even lower CSP values, ranging from 0.99 t/ha (*P. serratum*) to 1.35 t/ha (*S. cumini*), reflecting their smaller role in carbon sequestration due to lower biomass accumulation. In summary the data suggests that tree species such as *A. auriculiformis*, *T. grandis*, and *G. arborea* not only dominate in terms of biomass but also hold significant potential for carbon sequestration (Islam et al. 2016, 2020). These findings highlight the importance of preserving and promoting such species in forest management and conservation efforts for maximizing carbon capture in the ecosystem (Hale et al. 2019).

Table 1. Relative frequency (RF), relative density (RD), relative dominance (RDo), and Importance Value Index (IVI) of trees

Species name	Family Name	RD (%)	RF (%)	RDo (%)	IVI
Acacia auriculiformis A. Cunn.	Mimosaceae	21.25	8.79	32.09	62.14
Tectona grandis L.f.	Verbenaceae	17.67	9.21	17.14	44.01
Gmelina arborea Roxb.	Verbenaceae	11.27	8.37	10.90	30.54
Artocarpus heterophyllus Lam.	Moraceae	7.04	2.93	5.57	15.54
Terminalia arjuna (Roxb.ex DC.)	Combretaceae	4.74	2.93	3.72	11.39
Artocarpus chama Buch.-Ham.	Moraceae	3.33	5.02	2.84	11.19
Syzygium cumini (L.) Skeels	Myrtaceae	3.46	5.02	1.81	10.29
Terminalia bellerica (Gaertn.)	Combretaceae	2.94	3.35	2.81	9.10
Grewia nervosa (Lour.) Panigr.	Tiliaceae	2.56	3.77	2.70	9.03
Protium serratum (Wall. Ex Coelbr.) Engl.	Burseraceae	2.30	2.93	1.71	6.95

Table 2. Total biomass and carbon sequestration potential of top 9 tree species based on relative density

Species	Biomass (kg)	AGB (t/ha)	BGB (t/ha)	TTB (t/ha)	CSP (t/ha)
Acacia auriculiformis A. Cunn.	167	29.49	7.51	34.89	18.95
Tectona grandis L.f.	139	11.05	7.17	25.23	13.18
Gmelina arborea Roxb.	90	9.41	2.00	9.37	3.67
Artocarpus heterophyllus Lam.	55	3.48	0.90	4.38	2.19
Terminalia arjuna (Roxb.ex DC.)	37	2.78	0.72	3.50	1.75
Artocarpus chama Buch.-Ham.	23	2.57	0.67	3.23	1.62
Syzygium cumini (L.) Skeels	26	2.15	0.56	2.71	1.35
Terminalia bellerica (Gaertn.)	13	1.85	0.48	2.34	1.17
Grewia nervosa (Lour.) Panigr.	20	1.78	0.46	2.24	1.12
Protium serratum (Wall. Ex Coelbr.) Engl.	18	1.57	0.41	1.98	0.99

Note: The table presents data on Biomass (kg), Above-Ground Biomass (AGB) in tons per hectare (t/ha), Below-Ground Biomass (BGB) in tons per hectare (t/ha), Total Tree Biomass (TTB) in tons per hectare (t/ha), and Carbon Sequestration Potential (CSP) in tons per hectare (t/ha)

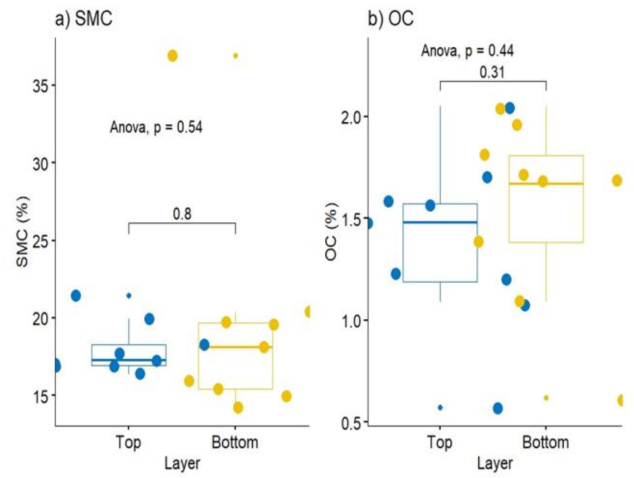


Figure 2. A. Soil moisture content across different layers of the hill in Sheikh Russel Aviary and Ecopark, Bangladesh; B. Organic carbon across different layers of the hill in Sheikh Russel Aviary and Ecopark, Bangladesh. For Soil Moisture Content (SMC) and Organic Carbon (OC), "top" refers to the soil layer at a depth of 0-15 cm, and "bottom" refers to the soil layer at a depth of 15-35 cm.

Soil carbon potential, soil moisture, and soil organic carbon across blocks

This study assessed the Carbon Sequestration Potential (CSP), Soil Moisture Content (SMC), and soil Organic Carbon (OC) across different blocks, with data collected at two distinct soil depths: Top (0-15 cm) and Bottom (15-35 cm). CSP, expressed in tons per hectare (t/ha), represents the soil's capacity to capture and store carbon dioxide (CO_2), which is essential for mitigating climate change by reducing atmospheric CO_2 concentrations (IPCC et al. 2019). Higher CSP values are crucial for long-term carbon storage, playing a key role in regulating global temperatures and supporting environmental sustainability (Islam et al. 2016).

The study found significant variations in CSP across different blocks, which were differentiated into three zones: top, middle and bottom (Harris and Gibbs 2021). At the top layer, Block 3 had the highest CSP (2.68 t/ha), a 141.4% higher compared to Block 5 (Table 3), which recorded the lowest value (1.09 t/ha). The middle layer showed the greatest variability (Hasan et al. 2021), with Block 2 having the highest CSP (4.55 t/ha), marking a 342% increase over Block 4 (Figure 3), which had the lowest CSP (1.03 t/ha). In the bottom layer, CSP was highest in Block 1 (2.74 t/ha), closely followed by Block 3 (2.82 t/ha), while Block 8 had the lowest value (1.43 t/ha), a difference of 94% between the highest and lowest blocks (Islam et al. 2022).

Soil Moisture Content (SMC) exhibited significant differences between different soil layers through different blocks. In the top layer, Block 2 recorded the highest SMC (21.45%), which was 30.8% greater than the lowest value in Block 1 (16.39%). The Bottom layer had the most pronounced variation (Henry et al .2021), with Block 6 showing the highest SMC (36.92%), more than double that of Block 8 (14.19%), a difference of 160%. Block 2 had the lowest Bottom-layer SMC (14.97%), 59.5% lower than Block 6, indicating substantial moisture retention differences across the study area.

Soil Organic Carbon (OC) levels also varied notably across soil layers and blocks. In the Top layer, Block 5 exhibited the highest OC (2.05%), which was 79.8% higher than Block 1 (0.57%). For the Bottom layer, Block 7 had the highest OC (2.05%), while Block 4 recorded the lowest OC (0.62%), resulting in a 230% difference. These variations in OC reflect differences in soil fertility and organic matter content across the blocks, influencing plant growth and carbon sequestration. The results revealed considerable variability in CSP, SMC, and OC across the study area. CSP values ranged from 1.03 to 4.55 t/ha, highlighting the differences in carbon storage capacity across different blocks (Hossain and Moniruzzaman 2021). Block 2 stood out with the highest CSP in the Middle layer (4.55 t/ha), indicating its superior ability to sequester carbon compared to other blocks, while Block 4 had the lowest CSP values overall. SMC also varied substantially between the Top and Bottom layers (Table 3), with Block 6 recording the highest Bottom-layer SMC (36.92%), suggesting better moisture retention in deeper soil layers, which could support more robust root systems and improve nutrient cycling. OC levels varied significantly as well (Hossain et al. 2015, 2020), with Block 5 exhibiting the highest Top-layer OC (2.05%) and Block 4 showing the lowest Bottom-layer OC (0.62%), indicating differences in soil organic matter content and fertility.

In summary, the findings from this study show that CSP, SMC, and OC exhibit high spatial and vertical variability across blocks and soil depths. Block 2 displayed the highest CSP in the Middle layer, Block 6 demonstrated significantly higher moisture content in the Bottom layer (Hossain et al. 2020), and Block 5 had elevated organic carbon in both Top and Bottom layers. This variability highlights the need for site-specific management strategies to optimize carbon sequestration, moisture retention, and overall soil health. Recognizing these spatial and vertical differences in soil properties is critical for developing effective forest management and conservation practices that maximize carbon capture and improve soil conditions across different regions.

Discussion

The study at Sheikh Russel Aviary and Eco-Park offers a comprehensive assessment of carbon sequestration potential, revealing the critical contributions of certain tree species to the park’s ecological balance and carbon storage capacity. The *A. auriculiformis*, *T. grandis*, and other key species are highlighted for their substantial carbon sequestration rates, ranging from 17.95 to 1.35 t/ha (Zukswert et al. 2023). These findings underscore the significant role that targeted species selection plays in enhancing the carbon sink capacity of reforestation and afforestation projects, particularly in tropical regions like Bangladesh. The selection of *A. auriculiformis* and *T. grandis* as focal species in this study is particularly noteworthy given their well-documented growth rates and resilience in a variety of environmental conditions. The *A. auriculiformis*, for instance (Zhang et al. 2023), is recognized for its rapid growth and adaptability to poor soil conditions, making it a suitable candidate for areas in need of quick green cover and carbon sequestration. Also, the Mimosaceae has an excellent nitrogen-fixing ability which contributes to soil enrichment (Ahirwal et al. 2021a,b; Akhtar et al. 2022), indirectly supporting the growth of other plant species and enhancing overall forest productivity (French et al. 2023b). The *T. grandis*, commonly known as teak, is another fast-growing species that is valued not only for its timber but also for its significant carbon storage potential (Urcuqui-Bustamante et al. 2023). Its deep-rooting system helps stabilize soil (Aziz and Paul 2015; Aryal et al. 2020), reducing erosion, and maintaining soil moisture levels (Tables 2 and 3), which are critical for sustaining forest ecosystems in the long term. The presence of species like *G. arborea* and *A. heterophyllus*, which contribute to both carbon storage and biodiversity, adds an additional layer of ecological value to the park (French et al. 2023a). The *G. arborea*, for example (BFD 2017, 2020a), is known for its fast growth and ability to thrive in a variety of soil types, making it an excellent choice for reforestation projects aimed at both carbon sequestration and habitat restoration (Barna et al. 2011). Its wood is also used for various purposes, contributing to the local economy (Teets et al. 2023). The *A. heterophyllus*, or jackfruit (Table 1, Figure 2), not only sequesters carbon but also supports local food security by providing a nutritious fruit that is a staple in the region. The dual benefits of these species highlight the importance of integrating multifunctional trees into reforestation efforts to achieve both environmental and socio-economic goals (Mason et al. 2022a). The *T. arjuna*, another species highlighted in the study, plays a unique role in the ecosystem (Figure 3) due to its medicinal properties and its ability to support a diverse range of wildlife. Traditionally used in Ayurvedic medicine (Mason et al. 2022b), *T. arjuna* is valued for its therapeutic properties, which include the treatment of heart conditions. Its presence in the park not only contributes to carbon sequestration but also supports the conservation of traditional knowledge and practices (Fuss et al. 2019). Additionally, its role in providing habitat for various bird and insect species enhances the park's biodiversity (Jacob et al. 2024), making it a vital component of the ecosystem. The study also provides critical insights into the soil characteristics within the park (Banik et al. 2018; BFD 2020), which are essential for understanding the broader dynamics of carbon storage and ecosystem health (Bricker 2013). The soil Organic Carbon (OC) content (Mason et al. 2022b), averaging 1.46%, indicates a relatively healthy soil profile that is capable of supporting robust plant growth (Figures 3.A-B). OC is a key indicator of soil fertility and plays (Figure 2) a vital role in the global carbon cycle (Zhou et al. 2018) by acting as both a source and a sink for atmospheric carbon dioxide. The relatively high soil moisture content, averaging 18.73% (Gogoi and Sahoo 2018; Gogoi et al. 2021; Ghale et al. 2022), further supports the growth of the park's vegetation, contributing to a dense canopy that enhances the park's overall carbon sequestration potential (Ouimette et al. 2019).

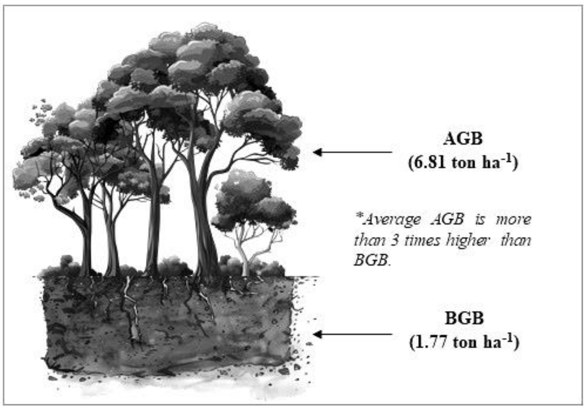
However, the study acknowledges several limitations that could impact the accuracy and comprehensiveness of its findings. The exclusion of understory vegetation and soil carbon measurements, for instance, represents a significant gap in the assessment of the park's total carbon sequestration potential. Understory vegetation, while often overlooked, plays a crucial role in the carbon cycle by contributing to biomass and supporting nutrient cycling within the forest ecosystem (Chowdhury et al. 2023, 2024). Similarly, soil carbon is a critical component of the carbon cycle (Figure 3.B) that, if not fully accounted for, can lead to an underestimation of the ecosystem's true carbon storage capacity. Future studies should aim to include these factors to provide a more complete picture of the park's role in carbon sequestration (Fuss et al. 2019).

Table 3. Carbon sequestration potential, soil moisture content (%), and soil organic carbon (%) status from selected blocks of the study area

	CSP(t/ha)			**SMC (%)**		**OC (%)**	
	Top	**Middle**	**Bottom**	**Top**	**Bottom**	**Top**	**Bottom**
Block 1	1.11	1.17	2.74	16.39	19.57	0.57	1.67
Block 2	1.72	4.55	2.47	21.45	14.97	1.57	1.81
Block 3	2.68	1.51	2.82	16.94	18.12	1.71	1.71
Block 4	2.33	1.03	1.51	16.83	15.45	1.24	0.62
Block 5	1.09	1.60	1.54	17.08	20.37	2.05	1.95
Block 6	1.49	1.05	1.77	17.71	36.92	1.57	1.67
Block 7	1.61	1.89	1.94	19.97	19.71	1.48	2.05
Block 8	2.24	1.37	1.43	18.27	14.19	1.09	1.09
Block 9	1.99	2.06	2.70	17.28	15.98	1.19	1.38

Note: In the context of Carbon Sequestration Potential (CSP), the terms "top," "middle," and "bottom" refer to different zones of the hill. For Soil Moisture Content (SMC) and Organic Carbon (OC), "top" refers to the soil layer at a depth of 0-15 cm, while "bottom" refers to the soil layer at a depth of 15-35 cm

A



B

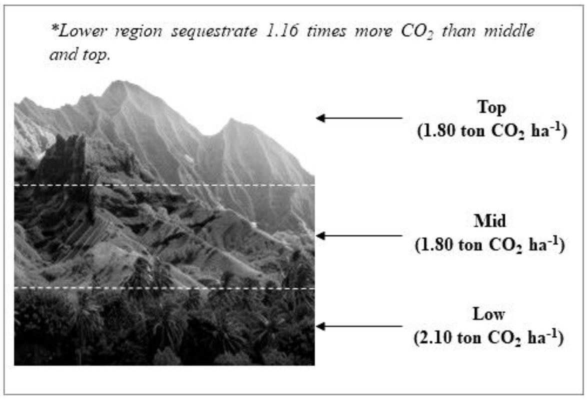


Figure 3. The figure illustrates: A. The average biomass of ten tree, and B. The carbon sequestration potential of hill at top, middle and bottoma of Sheikh Russel Aviary and Ecopark, Bangladesh

Moreover, the study's reliance on allometric equations for estimating carbon sequestration introduces potential uncertainties. While these equations are widely used in ecological research, they are often based on generalized models that may not fully capture the growth patterns and biomass accumulation of specific species (Lovett et al. 2018). This highlights the need for more field-based measurements to validate and refine the estimates provided by allometric models (Chowdhury et al. 2023). Additionally, the focus on carbon sequestration, while important, should be balanced with the consideration of other ecosystem services provided by the park. Biodiversity conservation, water regulation (Costello et al. 2016; Das et al. 2023), and soil protection are equally critical components of ecosystem health that should be integrated into park management and conservation strategies (Nath et al. 2019; Rakib et al. 2024). While the study offers valuable insights into the carbon sequestration potential of key tree species within Sheikh Russel Aviary and Eco-Park, it also emphasizes the need for a more holistic approach to understanding and managing the park's ecological contributions. Integrating a broader range of species (French et al. 2023b), accounting for understory vegetation and soil carbon, and considering the full spectrum of ecosystem services will be crucial for developing sustainable management practices. These practices should aim to balance the dual goals of carbon sequestration and biodiversity conservation, ensuring the long-term health and resilience of the park's ecosystem in the face of ongoing environmental challenges.

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