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Tree diversity and carbon sequestration assessment using multiple methods in a dry evergreen forest restoration site, Nakhon Ratchasima, Thailand

WARIS KAEWBANLAO, PASUTA SUNTHORNHAO♥, PICHIT LUMYAI
Laboratory of Forest Indigenous Knowledge Management, Department of Forest Management, Faculty of Forestry, Kasetsart University. 50 Ngamwongwan Rd, Chatuchak, Bangkok 10900, Thailand. Tel.: +662-942-8372, Fax.: +662-942-8108, ♥email: fforpts@ku.ac.th

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Abstract. *Kaewbanlao W, Sunthornhao P, Lumyai P. 2025. Tree diversity and carbon sequestration assessment using multiple methods in a dry evergreen forest restoration site, Nakhon Ratchasima, Thailand. Biodiversitas 26: 3886-3902.* This study assessed the forest structure, tree diversity, and carbon sequestration in a Dry Evergreen Forest (DEF) restoration area (Forest Plantation Target 49: FPT 49) in Nakhon Ratchasima Province, Thailand. The site contained 4,538 individual trees across 96 species, with a high tree density (1,512 stems ha^{-1}), basal area (130.84 m² ha^{-1}), and diversity (Simpson's index: 0.90; Shannon-Wiener index: 3.02). *Microcos tomentosa, Nephelium hypoleucum,* and *Dialium cochinchinense* were the dominant species, with Fabaceae being the most species-rich family. Biomass and carbon sequestration were estimated using three methods. Wood volume-based estimation method used the Wood specific Density (WD) and Biomass Expansion Factors (BEFs) and resulted in the highest estimates (152.36 Mg ha^{-1} of biomass; 71.61 Mg C ha^{-1}; 262.59 Mg CO_2 ha^{-1}), likely due to the inclusion of Biomass Expansion Factors (BEFs) and species-specific wood density. Method I yielded intermediate estimates, while Method II produced the lowest. Statistical analysis revealed that the DBH size class had the strongest effect on carbon sequestration (ε^2: 0.14), followed by its interaction with the method used (ε^2: 0.17), with significant differences observed across DBH classes and methods. Bland-Altman and boxplot analyses showed a strong agreement between the allometric method and the direct carbon method, but highlighted variability and potential overestimation by Method III, especially for trees with large DBH. Although carbon content estimates were lower than those found in old-growth forests, the results indicated substantial recovery in tree diversity and carbon stock 28 years post restoration. The study emphasizes the importance of method selection in estimating carbon sequestration and recommends integrating structural and ecological factors to enhance the accuracy of forest carbon accounting.

Keywords: Carbon sequestration, dry evergreen forest, forest restoration, FPT 49 Nakhon Ratchasima, species diversity

INTRODUCTION

Anthropogenic climate change has led to a global rise in greenhouse gas emissions, resulting in long-term shifts in temperature and rainfall patterns that negatively impact ecosystems worldwide (Jamil et al. 2024; Sandal 2024). Deforestation, in particular, contributes significantly to carbon dioxide (CO_2) emissions and net carbon loss, thereby accelerating global warming (Csillik et al. 2024; Singh et al. 2024). Forests play a crucial role in mitigating climate change by absorbing carbon. They absorb atmospheric CO_2 through photosynthesis and store it in biomass and soil (Meeussen et al. 2021; Mustamu et al. 2024). Globally, forests can store nearly twice the amount of carbon they emit (Harris and Gibbs 2021). thereby supporting both climate regulation and biodiversity conservation (Appanah et al. 2016; Zhao et al. 2022). Forests cover about 31% of the Earth's surface (FAO and UNEP 2020), with tropical forests in Southeast Asia accounting for nearly 15% (Stibig et al. 2014). However, tropical forests are especially vulnerable to climate change and human activity. They often experience shifts in species composition, growth dynamics, and biodiversity due to ongoing degradation and deforestation (Lewis et al. 2015; Chen et al. 2024; Guo et al. 2024a; Fayaz et al. 2025). It is estimated that the forest area in Southeast Asia has declined by 5.2 million hectares, resulting in a corresponding loss of 790 teragrams of aboveground carbon (Estoque et al. 2019).

Thailand has experienced multiple decades of forest degradation, especially between 1961 and 1998, driven by agricultural expansion and population growth. Despite a logging ban in 1989, deforestation continued until around 2000. Today, Thailand ranks 9th on the Climate Risk Index, reflecting the severity of forest loss and its impact on future climate vulnerability (Eckstein et al. 2021). In response, the Permanent Reforestation Project in Golden Jubilee of the King (PRPGJK), inaugurated in 1994, aims to restore over 800,000 hectares of degraded forest across Thailand (The Rajapruek Institute Foundation n.d., unpublished data). A key site is the Forest Plantation Target 49 (FPT 49) in Nakhon Ratchasima Province, which is a recovering dry evergreen forest that has undergone restoration for 28 years. Despite progress, it remains under pressure from environmental and human disturbances. Local studies have explored the forest structure and reported the carbon sequestration rates (Diloksumpun et al. 2005; Phumphuang et al. 2018, et al. 2024; Chandaeng et al. 2020; Marod et al. 2024). An accurate estimation of carbon is essential for tracking forest recovery and supporting mechanisms such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation) and Thailand Voluntary Emission Reduction (T-VER) program, which promote voluntary greenhouse gas reductions through carbon credit systems (Thammanu et al. 2021; Uttaruk et al. 2024).

Most frequently used methods include allometric equations using Diameter at Breast Height (DBH) and tree height (Hussin 2022; Doraisami et al. 2024), to estimate biomass across forest types Dry Evergreen Forest (DEF), Hill Evergreen Forest (HEF), Mixed Deciduous Forest (MDF), Dry Dipterocarp Forest (DDF), Tropical Rain Forest (TRF), Pine Forest (*Pinus merkusii*), and bamboo (Ogawa et al. 1965; Suwannapinunt 1983; Tsutsumi et al. 1983; Kajornsrichon 1988; Kutintara et al. 1995). Wood density is also used in biomass estimation, with methods tailored to tropical (Chave et al. 2005) and mangroves forests (Komiyama et al. 2008), and the tree volume based on tree form, biomass expansion factors, and species-specific wood density (Viriyabuncha et al. 2014), which also varies in carbon fractions, with 0.47 for aboveground, 0.27 for belowground, and 0.48 for mangroves (IPCC 2006). Additionally, allometric models and remote sensing technologies have been employed to estimate biomass. For example, a new equation for estimating carbon in seasonal dry secondary forests in northern Thailand was reported to improve carbon estimation (Pothong et al. 2022). Direct carbon estimation methods have also been developed for MDF, DDF, and DEF (Duangsathaporn et al. 2023). Although various carbon estimation methods have been applied to different forest types in Thailand, it is still unclear whether these methods yield significantly different results. Understanding these differences is important for carbon credit tracking systems and ecosystem service valuation programs, such as REDD+ and T-VER.

In the case of FPT 49, information on tree species diversity and carbon sequestration potential is still limited, particularly regarding whether different biomass estimation methods yield significantly different carbon stock estimates across DBH size classes. Therefore, it is of great interest to study the yield, tree composition and diversity, through carbon sequestration capacity using different methods. Therefore, this study evaluated the forest structure, species diversity, and carbon stocks in the restored dry evergreen forest (FPT 49), using three biomass estimation methods. By comparing estimates across DBH classes, method-based variation was determined, given the potential to overestimate carbon in large trees.

MATERIALS AND METHODS

Study area

The study area is part of Permanent Reforestation Project in Golden Jubilee of the King (PRPGJK), specifically “Forest Plantation Target 49” (FPT 49), which was established to commemorate the 50th anniversary of His Majesty’s accession to the throne under the management of PTT Public Company Limited. The study area is the largest under the PRPGJK, with a focus on the restoration of DEF. It is located in the Lam Nang Kaew Sub-district, Pak Thong Chai District, Nakhon Ratchasima Province (14°55'N, 101°86'E) (Figure 1), at an elevation of 240-807 meters above sea level, within a sandstone mountain range-oriented northwest-southwest.

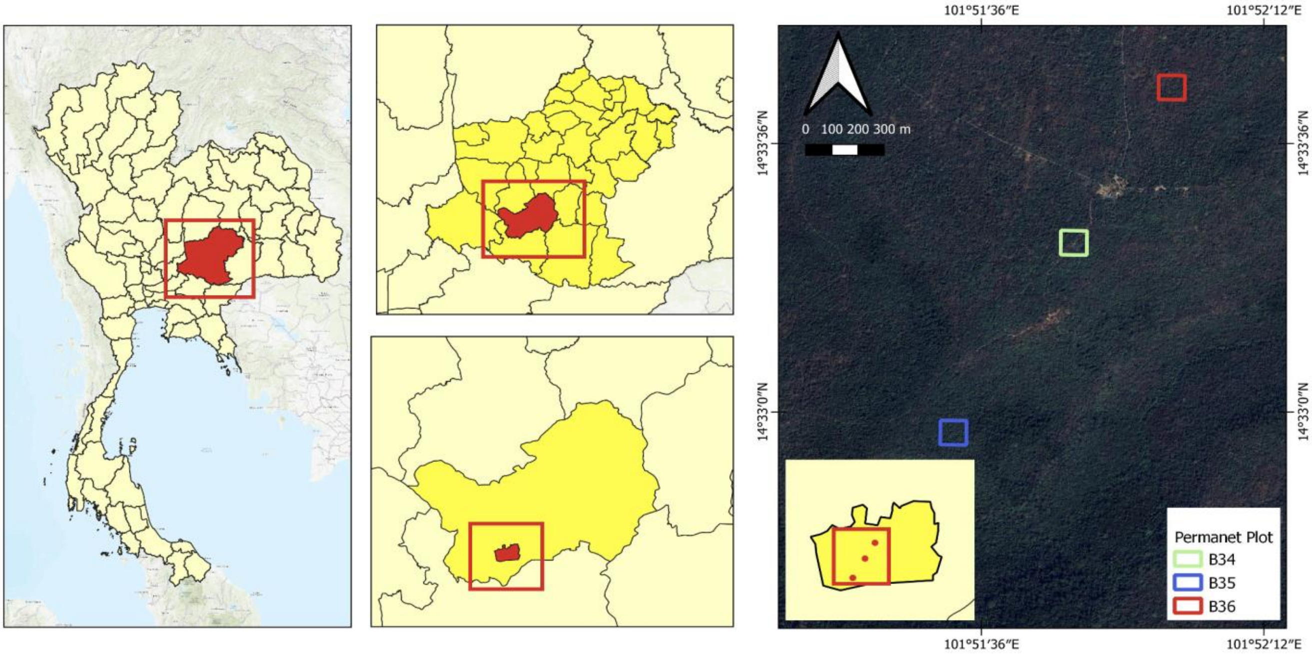

Figure 1. Location of the study area and established 1-hectare permanent plots in the dry evergreen forest in FPT 49, Nakhon Ratchasima, Thailand

The study site did not have an on-site meteorological station; therefore, climatic data were obtained from the nearest meteorological station located approximately 10 km away from DEF at the Wang Nam Khiao Research and Student Practice Station (WFRS). The average annual rainfall is 1,100 mm year^{-1}, with an average temperature of around 26.2°C. The highest temperatures of 29.2°C were measured in April, while the minimum temperatures of around 21.9°C were measured in December (Marod et al. 2024). Established in 1995 with the support of local communities, government agencies, Royal Forest Department (RFD) and Department of National Parks, Wildlife and Plant Conservation (DNP), the project initially covered an area of 348.8 hectares and was expanded to 682.88 hectares by the year 1997 (PTT Reforestation and Ecosystem Institute 2017, unpublished data).

The PRPGJK focused on using native tree species, with active participation from local communities in the reforestation efforts. As the forest recovered, it became a vital source of food and an additional source of income for nearby residents. The increased biodiversity attracted wildlife, including rare animals such as the silver pheasant (*Lophura nycthemera*), forest foxes, and more than 40 bird species. In addition to its role in biodiversity conservation, waterbodies in the FPT 49 also serve as an important water source that flows into Lam Pradon and eventually into Lam Phra Phloeng Reservoir. This forest area was recognized for its ecological importance in 1996, winning first prize in forest conservation and second prize in reforestation in the permanent forest planting competition of the RFD. Its success has instilled pride in the local community, leading to the establishment of the first volunteer forest ranger unit in Nakhon Ratchasima Province in 1997, which received the royal decoration of the Royal Flag (PTT Reforestation and Ecosystem Institute n.d., unpublished data). Currently, the administrative status of FPT 49 has been changed to the Khao Phu Luang No-Hunting Area and is now part of the natural forest area surrounding the Sakaerat Environmental Research Station.

Data analysis

Forest structure and plant species diversity

In 2023, three permanent sample plots of size 100×100 m² (1 ha) (labeled B34, B35 and B36 in Figure 1), were established in the study area. Each sample plot was subdivided into 10×10 m² subplots, resulting in a total of 300 subplots (Figure 1). Individual trees with a Diameter at Breast Height (DBH) greater than 4.5 cm or at 1.30 m above ground level were sampled (Murali et al. 2023). and identified based on Smitinand (2014).

The Importance Value Index (IVI) for tree species is calculated as the sum of relative density, relative frequency, and relative dominance (Curtis and McIntosh 1950), providing a comprehensive measure of a species' ecological significance within a community. Species diversity is commonly assessed using indices such as Simpson's Index of Diversity (Simpson 1949) and the Shannon-Wiener Index (Magurran 1988), which help in quantifying species richness and evenness. Simpson’s Index estimates the probability that two randomly selected individuals belong to the same species, while the Shannon-Wiener Index quantifies species diversity by accounting for both the abundance and distribution. In addition, the Sørensen index was used to calculate species similarity among the permanent plots (Biering-Sørensen 1984), taking species co-occurrence into account to assess spatial variation in tree species composition.

Biomass and carbon sequestration

The estimation was made using three distinct methodological approaches, with each based on established equations and guidelines. These approaches include: (I) an allometric biomass equation, (II) a direct carbon content equation, and (III) a wood volume-based method incorporating Wood specific Density (WD) and Biomass Expansion Factors (BEFs) (Table 1).

Table 1. The summary detial of three methods to assess biomass and carbon sequestration

Method	Aboveground biomass (AGB)	Input Variables	Belowground biomass (BGB)	Carbon conversion factor	Carbon dioxide (CO_2) sequestration	Remark
I (Allometric biomass equation)	$W_s = 0.0509(DBH^2H)^{0.919}$ $W_b = 0.00893(DBH^2H)^{0.977}$ $W_l = 0.0140(DBH^2H)^{0.669}$ $W_T = Ws+Wb+Wl$	DBH (cm) Height (m)	0.27 (IPCC 2006)	0.47 (IPCC 2006)	44/12 ratio atom weight of CO_2/carbon (IPCC 2006)	Tsutsumi et al. (1983) W_s: Weight of stem biomass (kg), W_b: Weight of branch biomass (kg), W_l: Weight of leaves biomass (kg)
II (Direct carbon content equations)	$C_{DEF} = 0.0185DBH^{2.1371}H^{0.6804}$	DBH (cm) Height (m)	-	-	44/12 ratio atom weight of CO_2/carbon (IPCC 2006)	Duangsathaporn et al. (2023) C_{DEF}: Carbon content (kg)
III (Biomass Expansion Factors (BEFs))	AGB = V x WD	Tree volume (m^3) Wood specific Density (WD)	0.27 (IPCC 2006)	0.47 (IPCC 2006)	44/12 ratio atom weight of CO_2/carbon (IPCC 2006)	Viriyabuncha et al. (2014) Volume Equations Based on Tree Form, Biomass Expansion Factors (BEFs), and Wood specific Density (WD) as Table S1

Statistical analysis

Statistical analyses were conducted using R software version 4.3.3., then several statistical methods were chosen to quantify the differences in carbon sequestration estimates among sample groups classified by DBH into three equal widths: small (4.50-20.99 cm), medium (21.00-37.49 cm), and large (37.50-54.09 cm). Given the non-normal nature of data distribution (as indicated by the Kolmogorov-Smirnov test, $p<0.05$) and unequal variances (as indicated by the Levene's test, $p<0.05$), the Kruskal-Wallis test was used to compare the sequestration values across DBH classes and calculation methods. For significant differences, Wilcoxon rank-sum test with Bonferroni-adjusted p-values was conducted for pairwise comparisons to ensure statistical rigor. To quantify the effect magnitude, effect size (ε^2) was calculated to determine the proportion of variance explained by each factor at a confidence of 95%. Additionally, Bland-Altman analysis was performed to detect any systematic biases between the calculation methods.

RESULTS AND DISCUSSION

Composition and diversity of tree

The study of tree composition in FPT 49 found 4,538 individual trees, classified under 96 species, 74 genera, and 42 families. The stand density was determined at 1,512 stems per hectare and the cumulative basal area was 130.84 m² per hectare. Dominant tree species with the highest Importance Value Index (IVI) (Table 3) was *Microcos tomentosa* (41.72%), which also had the highest stem density at 279 stems per hectare, fllowed by *Nephelium hypoleucum* (40.91%), with 242 stems per hectare, *Dialium cochinchinense* (30.42%), *Suregada multiflora* (29.08%), and *Xylia xylocarpa* (16.26%).

Other species, such as *Stereospermum neuranthum*, *Melodorum fruticosum*, *Syzygium cumini*, *Memecylon scutellatum*, and *Pterocarpus macrocarpus*, also played important roles in shaping the forest structure, with IVI values ranging from 7.49% to 13.93%. Species with moderate contributions (IVI of 3-6%) included *Albizia lebbeck*, *Trema orientalis*, *Millettia leucantha*, etc. The "Other species" category, comprising 76 species, accounted for 52.68% of IVI, highlighting the site's high species richness and structural complexity. At a family level, Fabaceae was the most species-rich family with 17 species, followed by Euphorbiaceae (10 species), Malvaceae (8 species), and Melastomataceae (6 species). Both Lauraceae and Moraceae were represented by five species each. Fabaceae species are commonly abundant in DEF due to their ecological traits and functional roles in forest dynamics. Many are pioneer species, meaning they are always first species to colonize disturbed or degraded areas, which is typical in forest restoration contexts. Additionally, Fabaceae species exhibit drought tolerance, with adaptations such as deep root systems and compound leaves that reduce water loss. Their ecological versatility, including a wide range of growth forms (trees, shrubs, climbers, and herbs), enables them to occupy diverse niches. Furthermore, seed traits such as hard-coated seeds capable of dormancy support long-term persistence and regeneration. In Thailand, Fabaceae are also widely used in reforestation and carbon sequestration projects, contributing to their high representation in restoration plots (Delgado-Salinas et al. 1999). Diversity metrics further supported these observations: the Simpson's diversity index (D: 0.90) and the Shannon-Wiener index (H′: 3.02) both indicated a highly diverse and an ecologically stable tree community. Table 2 shows the pairwise Sørensen similarity index (IS) of the tree species composition in the three permanent plots (B34, B35 and B36). The highest similarity was found between plots B34 and B35 (IS: 0.60), followed by B35 and B36 (IS: 0.52), while B34 and B36 were the least similar (IS: 0.48). The corresponding dissimilarity index (1-IS) reflects the proportion of unique tree species in each pair. Overall similarity of the three plots combined was moderate (IS: 0.41), indicating a mix of shared and unique species within the restoration area. Although many species were common among the plots, each plot also contained distinct species that contributed to the area's biodiversity. This diversity is visually represented in Figure 2 through a Venn diagram, with 18 species unique to B34, 24 to B35, and 10 to B36, along with 15 species shared between B34 and B35, 6 between B35 and B36, 1 between B34 and B36, and 22 species shared among all three plots, illustrating the complexity of species assemblages in the FPT 49.

The results showed that key tree species from the Fabaceae family, such as *D. cochinchinense*, *X. xylocarpa*, *P. macrocarpus*, *A. lebbeck*, and *M. leucantha*, are commonly found in DEF, drought-tolerant, and well adapted to semi-arid conditions. Moreover, *A. lebbeck* also contributes to nitrogen-fixing symbiotic relationship with Rhizobium bacteria in root nodules. This capability supports early forest recovery, improving nutrient-poor soils, and fostering growth of other plant species, particularly in degraded or semi-arid regions. Its presence is crucial for ecosystem restoration, as it enhances nutrient cycling and promotes biodiversity in recovering forests (Amorim et al. 2016; Mahananda et al. 2021; Rojas-Sandoval et al. 2022). This observation is consistent with the findings of Marod et al. (2024) , who showed that similar soil characteristics affected the distribution of *D. cochinchinense* as a pioneer species. It also indicates a diverse composition of forest species in late and potentially late successional stages, often found in nutrient-rich, well-drained soils that can promote slow growth and high biomass accumulation (Table 4) (Hu et al. 2024). In contrast, *M. tomentosa*, included among the tropical pioneer species, was found to be the most dominant species, demonstrating strong adaptability to disturbed environments and contributing to soil stabilization and the development of early forest structure (Lee et al. 2020).

Significant contribution of the "other tree species" group, comprising 76 species and accounting for 52.68% of IVI, further emphasizes the structural complexity and ecological richness. In contrast, a comparison with the nearby Sakaerat Biosphere Reserve, which is ecologically similar to the WFRS site, exhibited a higher Shannon-

Wiener index, despite having a lower tree density and basal area. This suggests that both native and pioneer tree species have recovered successfully in DEF ecosystems. Such recovery may be attributed to management practices that promote regeneration and support the growth of diverse species, reinforcing the critical role of environmental factors such as soil properties and topography. Such factors have been reported to influence species distribution within DEF ecosystems (Phumphuang et al. 2018, et al. 2024; Feng et al. 2021). The results of this study underscore the combined influence of environmental conditions and restoration practices on forest recovery and biodiversity conservation across different sites (Sarkissian and Kutia 2024). The DEF examined in this study had a higher number of species and tree density than previously reported in secondary and natural DEFs in central Thailand, which recorded 11 and 37 species, and densities of 293 and 523 stems per hectare, respectively (Kamsanor et al. 2022). This high diversity reflects the effectiveness of restoration management strategy (Kumar et al. 2022), particularly the selection of diverse native species for planting during the initial stages, which positively contributed to the overall recovery of the ecosystem, including nutrient cycling and carbon sequestration (Loehle et al. 2024).

The average DBH was 11.01±5.28 cm, with the distribution exhibiting an inverted J-shape (Figure 3), characterized by a higher density of small-diameter trees that gradually decreased with increasing diameter. This pattern is commonly observed in natural forests, particularly those with irregular management or multi-aged structures. In such forests, tree growth and mortality processes occur at a balanced rate, indicating ongoing recovery and development (Biaou et al. 2023; Li et al. 2024). This distribution aligns with findings from Zhao et al. (2015) and Koppad et al. (2024) and is consistent with trends observed across various forest types, including urban and natural forests (Morgenroth et al. 2020; Rijal and Sharma 2024). Tree height distribution followed a bell-shaped curve (Figure 3), indicating a distinct vertical stratification typical of multi-species and uneven-aged forests. Climate conditions, soil characteristics, and topography can significantly influence tree height, leading to variations in distribution of shape, including increased skewness. Water availability, particularly the balance between precipitation and evapotranspiration, plays a crucial role in tropical forests (Adrah et al. 2022), while temperature fluctuations also affect height distribution (Gorgens et al. 2020). Elevation and soil depth influence tree height by affecting water retention and growth potential, whereas wind exposure and canopy openness can limit height, especially in older stands (Tange and Ge 2020). Site-specific environmental variability can further influence the observed differences in height within the same species, even among trees of the same age (Freitas et al. 2019).

Biomass and carbon sequestration

Aboveground Biomass (AGB) and belowground Biomass (BGB) were estimated using three methods (Table 4), indicating notable differences in total biomass values. Method III yielded the highest total biomass at 152.36 Mg ha^{-1}, followed by Method I at 119.57 Mg ha^{-1}, while Method II produced the lowest estimate at 88.94 Mg ha^{-1}. The high values obtained using Method III were primarily influenced by the inclusion of BEFs and WD, which substantially increased the BGB to 46.62 Mg ha^{-1}, a value which is nearly double of that obtained by Method I despite only a slight increase in AGB. These discrepancies emphasize the importance of method selection when estimating forest biomass and carbon sequestration. The corresponding carbon stock and CO_2 sequestration estimates using Method I were 56.20 Mg C ha^{-1} and 206.09 Mg CO_2 ha^{-1}, with the lowest values obtained using Method II at 41.80 Mg C ha^{-1} and 153.30 Mg CO_2 ha^{-1}, whereas the use of Method III resulted in the highest values at 71.61 Mg C ha^{-1} and 262.59 Mg CO_2 ha^{-1}, reflecting varying methodological assumptions. At the species level (Table 5), *D. cochinchinensis* and *N. hypoleuca* were consistently identified as major contributors to the total biomass and carbon stock across all methods, underscoring their structural dominance in the study area. Method III again produced the highest species-level values, with *N. hypoleuca* contributing 28.32 Mg ha^{-1} and 12.12 Mg ha^{-1} to the AGB and BGB, accounting for 19.01 Mg C ha^{-1} (26.54%) and 69.70 Mg CO_2 ha^{-1}.

Table 2. Pairwise Sørensen dissimilarity and dissimilarity index of tree species composition among the three permanent plots, B34, B35 and B36, in FPT 49, Nakhon Ratchasima, Thailand

Permanent plot	Similarity index (IS)	Dissimilarity index
B34 vs B35	0.60	0.39
B34 vs B36	0.48	0.51
B35 vs B36	0.52	0.47
B34 vs B35 vsB36	0.40	0.59

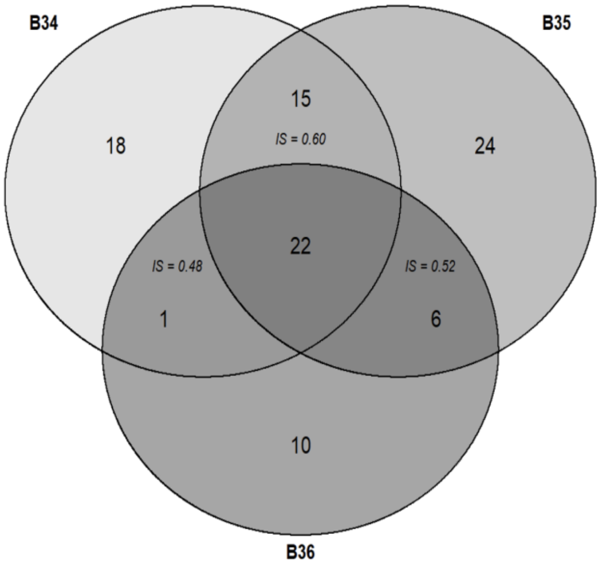

Figure 2. Venn diagram of the Sørensen similarity and tree species composition among the three permanent plots (B34, B35 and B36) in FPT 49, Nakhon Ratchasima, Thailand

Table 3. List of the top 20 dominant tree species in FPT 49, Nakhon Ratchasima, Thailand

Species	**Family**	**Density (stem ha-1)**	**F (%)**	**BA (m^2 ha^{-1})**	**IVI (%)**	**Growth forms**
Microcos tomentosa Smith	Malvaceae	279	32.66	61.01	41.72	T
Nephelium hypoleucum Kurz	Sapindaceae	242	31.33	68.74	40.91	T
Dialium cochinchinense Pierre	Fabaceae	144	32.33	52.14	30.42	T
Suregada multiflora (A.Juss.) Baill.	Euphorbiaceae	167	29.00	43.92	29.08	S/ST
Xylia xylocarpa var. kerrii	Fabaceae	68	26.00	22.05	16.26	T
Stereospermum neuranthum Kurz	Bignoniaceae	83	15.66	18.49	13.93	T
Melodorum fruticosum Lour.	Annonaceae	49	20.66	11.55	11.05	S
Syzygium cumini (L.) Skeels	Myrtaceae	45	13.33	9.44	8.52	T
Memecylon scutellatum (Lour.) Hook.	Melastomataceae	28	18.66	5.73	7.71	S/ST
Pterocarpus macrocarpus Kurz	Fabaceae	35	12.66	8.61	7.49	T
Albizia lebbeck (L.) Benth.	Fabaceae	23	14.00	6.23	6.40	T
Trema orientalis (L.) Blume	Cannabaceae	18	8.66	4.17	4.32	ST
Millettia leucantha Kurz	Fabaceae	18	9.33	3.60	4.19	T
Artocarpus lakoocha Roxb.	Moraceae	17	7.00	5.48	4.02	T
Pterospermum acerifolium Willd.	Malvaceae	15	8.33	4.04	3.98	T
Randia wittii (Craib.) Bremek.	Rubiaceae	14	8.00	3.27	3.66	S
Litsea glutinosa (Lour.) C.B.Rob.	Lauraceae	15	5.66	4.94	3.58	T
Mallotus philippensis (Lam.) Müll.Arg.	Euphorbiaceae	18	5.33	3.50	3.46	S/T
Fernandoa adenophylla (Wall.ex G.Don) Steenis.	Bignoniaceae	16	5.00	4.2	3.35	T
Wrightia tomentosa (Roxb.) Roem. & Schult.	Apocynaceae	12	6.66	3.05	3.18	ST
Other species (76)		206	310.33	344.26	52.68	
Total		1,512	425.33	392.52	300	

Note: T: Tree, ST: Shrubby Tree, S: Shrub, and S/T: Shrub or Tree

Table 4. Biomass, carbon stock and CO_2 sequestration estimates using different methods in FPT 49, Nakhon Ratchasima, Thailand

Methods	**AGB (Mg ha^{-1})**	**BGB (Mg ha^{-1})**	**Total Biomass (Mg ha^{-1})**	**Carbon stock (Mg C ha^{-1})**	**CO_2 sequestration (Mg CO_2 ha^{-1})**
I	94.79	24.78	119.57	56.20	206.09
II	70.04	18.90	88.94	41.80	153.30
III	105.74	46.62	152.36	71.61	262.59

Note: Mg ha^{-1} is Megagram per hectare, Mg C ha^{-1} is Megagram carbon per hectare, and Mg CO_2 ha^{-1} is Megagram carbon dioxide per hectare

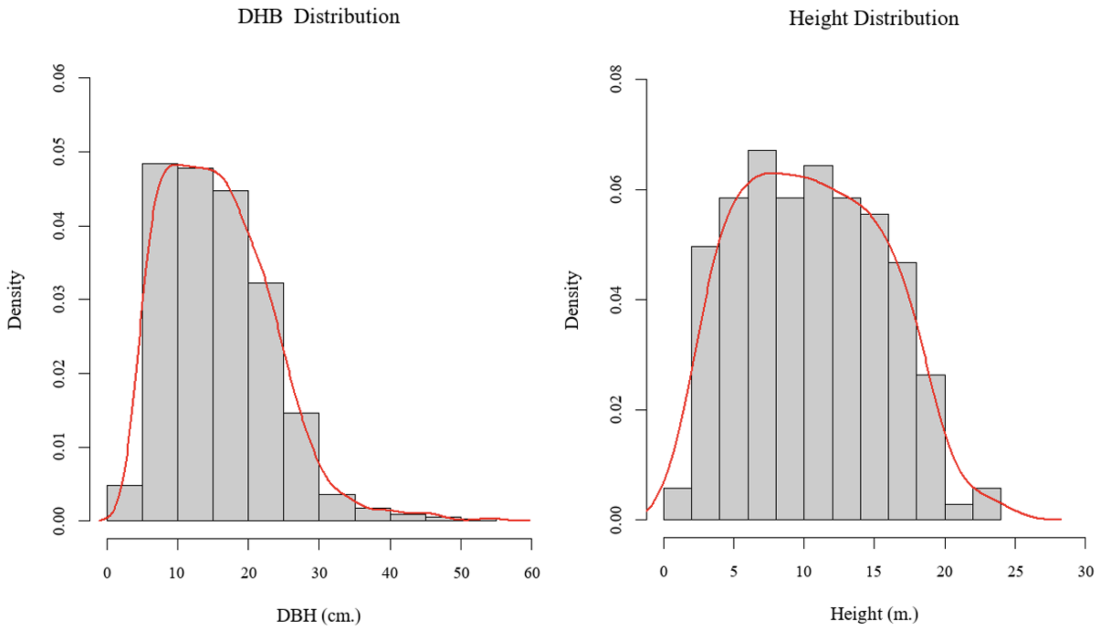

Figure 3. The distribution of DBH and tree height sampled in FPT 49, Nakhon Ratchasima, Thailand

Table 5. Top five species in terms of Aboveground Biomass (AGB), Belowground Biomass (BGB), carbon stock, and CO$_2$ sequestration categorized by the three methods in FPT 49, Nakhon Ratchasima, Thailand

Methods	Species	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	Carbon stock (Mg C ha^{-1})	CO$_2$ sequestration (Mg CO$_2$ ha^{-1})	%
I	*Dialium cochinchinense* Pierre	19.17	4.93	11.33	41.54	20.16
	Nephelium hypoleucum Kurz	18.32	4.93	10.93	40.08	19.45
	Microcos tomentosa Smith	10.29	2.66	6.09	22.34	10.84
	Suregada multiflora (A.Juss.) Baill.	9.472	2.52	5.63	20.67	10.02
	Xylia xylocarpa var. kerrii	5.97	1.43	3.48	12.77	6.19
	Others species (92)	31.54	8.30	18.72	68.66	33.34
	Total	94.79	24.78	56.20	206.09	100.00
II	*Dialium cochinchinense* Pierre	14.64	3.95	8.74	32.06	20.91
	Nephelium hypoleucum Kurz	13.56	3.66	8.09	29.69	19.36
	Microcos tomentosa Smith	7.23	1.95	4.31	15.83	10.32
	Suregada multiflora (A.Juss.) Baill.	6.81	1.84	4.06	14.91	9.73
	Xylia xylocarpa var. kerrii	4.53	1.22	2.70	9.931	6.47
	Others species (92)	23.24	6.27	13.87	50.87	33.21
	Total	70.04	18.90	41.80	153.30	100.00
III	*Nephelium hypoleucum* Kurz	28.32	12.12	19.01	69.70	26.54
	Dialium cochinchinense Pierre	25.17	10.20	16.62	60.97	23.21
	Suregada multiflora (A.Juss.) Baill.	8.14	3.88	5.65	20.72	7.89
	Xylia xylocarpa var. kerrii	7.95	3.42	5.34	19.60	7.46
	Microcos tomentosa Smith	5.99	3.13	4.289	15.72	5.98
	Others species (92)	30.15	13.86	20.68	75.85	28.92
	Total	105.74	46.62	71.61	262.59	100.00

Note: % is the ratio of tree CO$_2$ sequestration i / total tree CO$_2$ sequestration using each method

Similarly, *D. cochinchinensis* contributed 16.62 Mg C ha^{-1} (23.21%) and 60.97 Mg CO$_2$ ha^{-1} when using the same method. In contrast, using Method I, 11.33 Mg C ha^{-1} (20.16%) and 41.54 Mg CO$_2$ ha^{-1} were estimated for *D. cochinchinensis*, and 10.93 Mg C ha^{-1} (19.45%) and 40.08 Mg CO$_2$ ha^{-1} for *N. hypoleuca*. On the other hand, Method II provided estimates of 8.74 Mg C ha^{-1} (20.91%) and 32.06 Mg CO$_2$ ha^{-1} for *D. cochinchinensis*, and 8.09 Mg C ha^{-1} (19.36%) and 29.69 Mg CO$_2$ ha^{-1} for *N. hypoleuca*. Other species such as *M. tomentosa*, *S. multiflora*, and *X. xylocarpa* also contributed significantly to the total biomass and carbon. All the three methods indicated that *D. cochinchinense* and *N. hypoleucum* had high carbon storage, which reflects the characteristics of species that are likely to be climax species, such as slow growth, shade tolerance and high wood density, all important factors in long-term carbon sequestration. In contrast, pioneer species (*M. tomentosa*) contributed to early carbon sequestration and low wood density, which is clearly seen in the estimates from Method III. The coexistence of species with different functional traits, including pioneer and climax species, increases ecosystem resilience, biodiversity and carbon dynamics. This diversity supports both short-term carbon sequestration and long-term carbon sequestration (Chai et al. 2016), as late-successional species typically store higher biomass over extended timeframes, thus further supporting the ecological value and carbon sequestration potential of the DEF ecosystem in FPT 49 (Poorter et al. 2015).

Biomass estimates obtained in this study were generally lower than those reported for nearby areas such as the WFRS site, where Method II yielded 111.92 Mg ha^{-1} (Chandaeng et al. 2020), with similar patterns observed in tropical rainforests of India (98.87 Mg ha^{-1}) (Sahu et al. 2016), montane evergreen forests in village forests (75.3±17.1 Mg ha^{-1} of AGB and 19.9±4.3 Mg ha^{-1} of BGB) (Mir et al. 2021), and dry evergreen montane forests in Tanzania (Mwakalukwa et al. 2023). In contrast, the biomass values from all three methods in this study were higher than those reported for DEF in central Thailand (68.01 Mg ha^{-1} for natural DEF and 27.67 Mg ha^{-1} for secondary DEF) (Kamsanor et al. 2022). Other DEF sites in northern and eastern Thailand reported estimates of 81.37 Mg ha^{-1} (Thongnun et al. 2022), and 63.81 Mg ha^{-1} (Sieosathanakul et al. 2023), while that recorded in a recreational forest in northeastern Thailand was 57.78±29.37 Mg ha^{-1} (Chawa et al. 2025). However, all three methods yielded biomass estimates that were lower than tropical DEF in India, with reported valus of 423.33 Mg ha^{-1} AGB and 110.07 Mg ha^{-1} BGB (Dar et al. 2023), Another study in similar forests reported 121.33±27.68 Mg ha^{-1} of AGB and 5.24±0.14 Mg ha^{-1} of BGB (Udayakumar and Izayas 2025). While Method III may overestimate biomass under certain conditions, its ability to capture species-level contributions would help guide forest management strategies, restoration, and climate action through identifying high-biomass storing species as important carbon sinks.

Carbon stock estimates were found to be lower than those for mature forests, with the values obtained from all three methods being consistent with biomass patterns. For instance, stock estimates for dry evergreen and mixed deciduous forests in western Thailand were reported as 203.83±82.74 Mg C ha^{-1} (Chanlabut and Nahok 2022), while those for tropical rainforests and deciduous forests in India ranged from 125.94 to 243.57 Mg C ha^{-1} (Babu et al. 2021). Method III resulted in higher carbon estimates than those reported for the Sepanjang Village Community Forest in Indonesia (66.75 Mg C ha^{-1}) (Setyasih et al. 2025). Conversely, carbon stock values in this study were higher than that estimated for Kaeng Krachan National Park (67.65±40.64 Mg C ha^{-1}) (Phetchaburi National Park Research And Development Center 2019) and a restored DEF in eastern Thailand (Sieosathanakul et al. 2023), and recreational forests (27.15±13.80 Mg C ha^{-1} and 99.58±50.62 Mg CO_2 ha^{-1}) (Chawa et al. 2025). Values for DEF in Tanzania were reported as 16.04±7.7 to 32.98±15.7 Mg C ha^{-1} for trees and shrubs (Mwaluseke et al. 2023). However, the carbon stock values obtained by the three methods exhibited a similar variability to carbon-dominated forests in Vietnam, which ranged from 24.07 to 98.42 Mg C ha^{-1} (Hop et al. 2023), and locally managed forests in Indonesia, with values reported from 27.22 to 99.15 Mg C ha^{-1} (Tohirin et al. 2021). Additionally, the carbon stock in FPT 49 were lower than that of undisturbed forests because of recovery from degradation for 28 years ago. As a secondary forest undergoing natural regeneration, it may require additional time to reach carbon levels comparable to mature forests. Currently, FPT 49 continues to face anthropogenic pressures such as plant harvesting, mushroom collection, and ecotourism, which may hinder its recovery (Wang et al. 2023). Variability in carbon stocks may also be influenced by ecological disturbances like wildfires and storms (Vallet et al. 2023), as well as human activities such as land-use change and resource extraction (Liu et al. 2023). Additionally, regional differences in soil nutrients and climate, along with canopy structure, can affect the photosynthetic efficiency and long-term carbon accumulation (Chen et al. 2024; Wang et al. 2024).

Statistical outputs

The Kruskal-Wallis test (Table 6) confirms that all three factors i.e., DBH size class, carbon assessment method, and their interaction, had statistically significant effects on carbon sequestration ($p<0.001$). Among these, DBH size class had the greatest individual influence (ε^2: 0.14), followed by the interaction between method type and DBH size (ε^2: 0.17), while the effect of assessment method alone was smaller (ε^2: 0.03). The use of different methods across DBH classes also showed notable variations (Table 7), with carbon sequestration values differing significantly across all DBH size class pairs. Moderate effect sizes were observed between medium vs. small trees (r: 0.36) and large vs. medium trees (r: 0.31), reinforcing the ecological principle of carbon sequestration increasing with tree size.

For the estimation methods, although all pairwise comparisons showed statistically significant differences (Method I vs. II: r: 0.16; Method II vs. III: r: 0.21; Method I vs. III: r: 0.05), the overall effect sizes were small, indicating relatively minor discrepancies when methods are considered collectively, however, stratifying the analysis by DBH class revealed distinct patterns. For small trees, Method II consistently produced the lowest carbon stock, while Methods I and III yielded slightly higher values. The greatest difference was observed for the medium DBH class, where Methods II and III showed statistically significant differences (r: 0.63).

Box plots in Figure 4 exhibit distinct variation in carbon sequestration estimates across DBH classes and methods, highlighting differences in reliability and consistency of each approach. In the small DBH class, all three methods exhibited relatively narrow distributions. Estimates using Method I had a compact interquartile range (IQR) of approximately 0.015 to 0.035 Mg CO_2 ha^{-1}, with a median around 0.027, while that using Method II had an even narrower IQR (~0.012 to 0.025) and a slightly lower median (~0.020). Method III, although centered at a higher median (~0.036), had a slightly wider spread, extending up to ~0.06 in its upper whisker, indicating slightly higher variability. In the medium DBH class, differences became more evident: Method I had a symmetric distribution (IQR ~0.17 to 0.35, median ~0.268), Method II was more specific method (IQR ~0.12 to 0.25, median ~0.182), while Method III yielded both the highest median estimate (~0.403) and widest IQR (~0.27 to 0.58), with longer whiskers and potential outliers, indicating greater variability and skewness. In the large DBH class, dispersion was the most substantial: Method I had an IQR between ~0.7 to 1.3 Mg CO_2 ha^{-1} with a median near 1.003, Method II resulted in the narrowest spread of estimates (~0.55 to 0.95) and the lowest median (~0.744), whereas Method III again had the broadest distribution (IQR ~1.0 to 1.8) and highest median (~1.345), with long upper whiskers and visible outliers, suggesting a tendency for overestimation. These findings indicate that while Methods I and II yielded stable and closely aligned estimates, especially for trees in small and medium DBH classes, Method III tended to produce higher and more variable estimates, particularly in larger trees.

Table 6. Kruskal-Wallis test for the effects of DBH size class, method, and their interaction on carbon sequestration

Factor	**Chi-square**	**Degrees of freedom (df)**	***p*-value**	**Effect size (ε^2)**
Method	463.85	2	<0.001 **	0.03
DBH Size Class	1933.5	2	<0.001 **	0.14
Interaction (Method×DBH Size)	2411.7	8	<0.001 **	0.17

Note: Kruskal-Wallis test was used to assess the differences due to non-parametric data. Effect sizes were reported using epsilon squared (ε^2), $p<0.05$ was considered statistically significant and marked with **

Table 7. Wilcoxon pairwise comparisons of carbon sequestration across DBH size classes and methods

No.	Comparison	*p*-value	Adjusted *p*-value	Effect size (r)	Magnitude
- DBH Size Classes					
1	Large-Medium	< 0.0001	< 0.0001 **	0.31	Moderate
2	Large-Small	< 0.0001	< 0.0001 **	0.07	Low
3	Medium-Small	< 0.0001	< 0.0001 **	0.36	Moderate
- Methods					
1	Method I-Method II	< 0.0001	< 0.0001 **	0.16	Low
2	Method II-Method III	< 0.0001	< 0.0001 **	0.21	Low
3	Method I-Method III	< 0.0001	< 0.0001 **	0.05	Low
- Methods and DBH Size Classes					
Small DBH					
1	Method I-Method II	< 0.0001	< 0.0001 **	0.18	Low
2	Method II-Method III	< 0.0001	< 0.0001 **	0.23	Low
3	Method I-Method III	< 0.0001	< 0.0001 **	0.06	Low
Medium DBH					
1	Method I-Method II	< 0.0001	< 0.0001 **	0.37	Moderate
2	Method II-Method III	< 0.0001	< 0.0001 **	0.63	High
3	Method I-Method III	< 0.0001	< 0.0001 **	0.47	Moderate
Large DBH					
1	Method I-Method II	0.3400	1.0000	0.23	Low
2	Method II-Method III	0.0620	0.1880	0.44	Moderate
3	Method I-Method III	0.1130	0.3390	0.38	Moderate

Note: Wilcoxon rank-sum tests were conducted with Bonferroni-adjusted *p*-values to correct for multiple comparisons. Effect sizes were reported using rank-biserial correlation (r), and interpreted as Low (r: 0.1-0.3), Moderate (0.3-0.5), or High, and (r>0.5), $p<0.05$ was considered statistically significant and marked with **

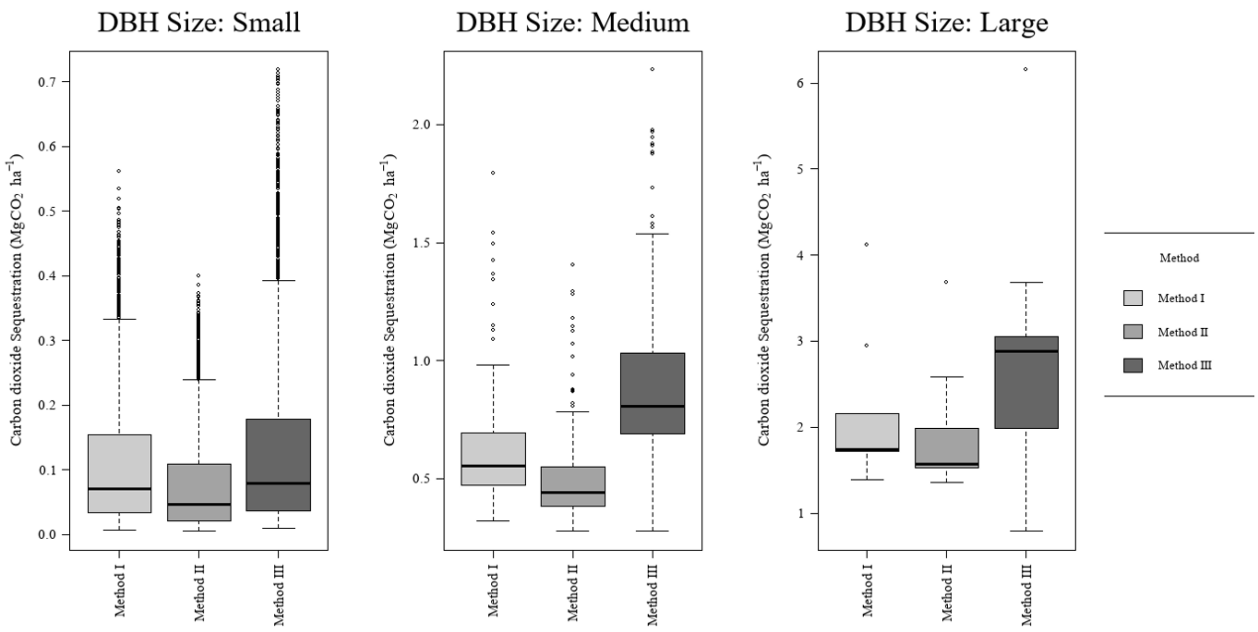

Figure 4. Distribution of carbon dioxide sequestration (Mg CO$_2$ ha^{-1}) across DBH size classes and methods

The Bland-Altman plots (Figure 5) support the findings observed in the box plots (Figure 4), with both visualizations clearly indicating significant differences among the three carbon sequestration estimating methods. The Bland-Altman analysis compares the differences between each pair of methods against their average values and provides key indicators such as mean bias and Limits of Agreement (LoA). For Method I and Method II (Figure 5.A), the mean bias was only 0.035, with a relatively narrow LoA ranging from -0.031 to 0.101, with most of data points densely clustered around the mean, particularly for trees with small DBH, indicating strong agreement and high accuracy between these two methods. In contrast, the comparison between Method I and Method III (Figure 5.B) shows a slightly higher standard deviation of 0.037 and noticeably wider LoA (-0.244 to 0.17), reflecting greater variability, especially among medium and large DBH trees.

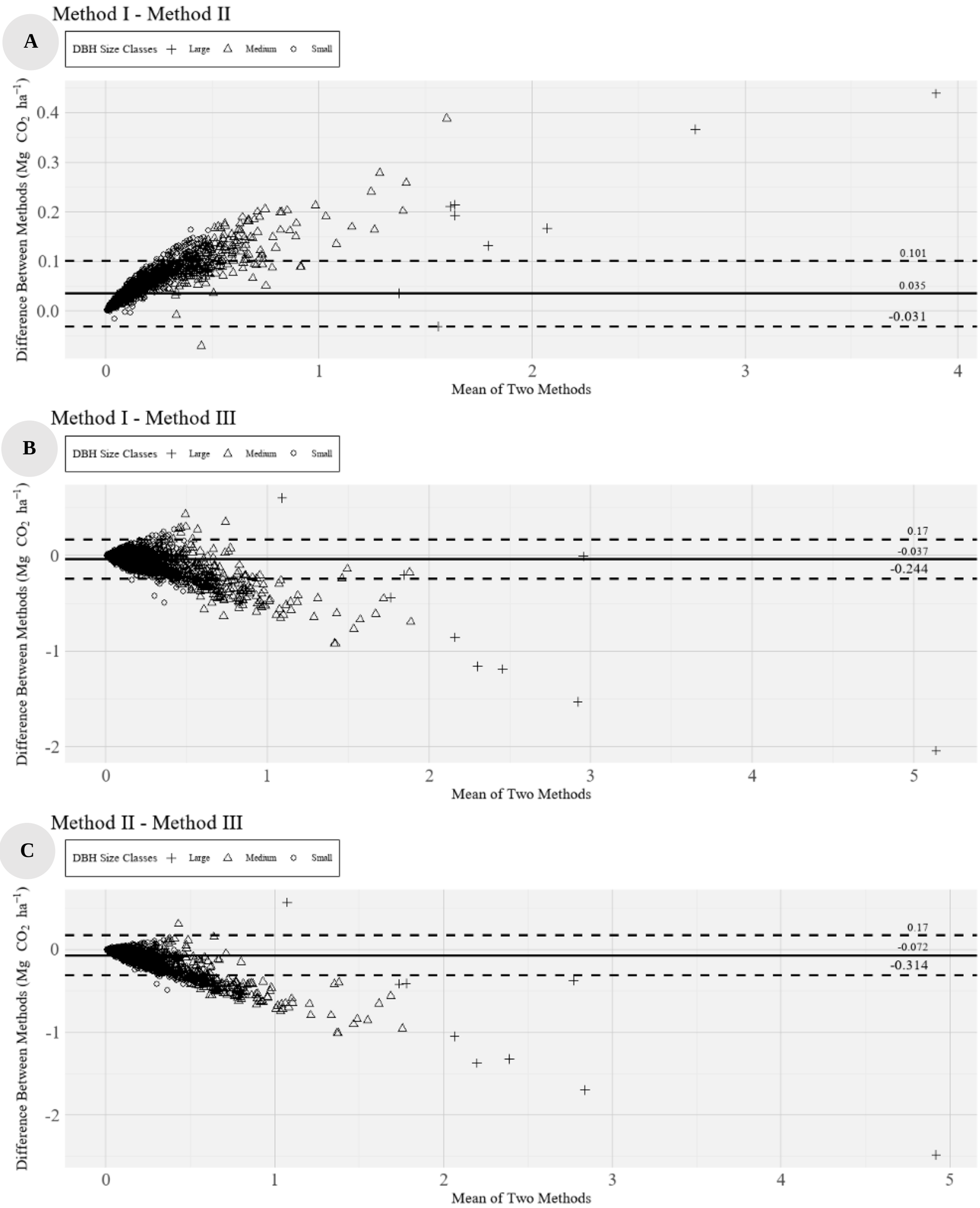

Figure 5. Bland-Altman plots comparing carbon sequestration estimates using the three methods

Comparison between Method II and Method III (Figure 5.C) reveals the highest standard deviation (0.072) and the widest LoA (-0.314 to 0.17), indicating substantial inconsistency. This discrepancy was most evident in trees with large DBH, where Method III tends tended to produce significantly higher value of carbon sequestration among the three methods. For small DBH trees, the differences were minimal and tightly clustered near zero, demonstrating a high consistency across methods. Medium DBH trees exhibited increased variability, with some points falling outside the LoA, particularly in comparisons involving Method III, suggesting reduced reliability. Large DBH trees exhibited the greatest dispersion, with many points deviating significantly from the mean and LoA, reflecting notable disagreement, especially with Method III. Therefore, the plots emphasize that method performance varies with DBH size, and accurate carbon sequestration estimation may require method-specific adjustments or tailored equations for medium and large trees.

The observed differences in this study highlight the critical role of DBH in determining the carbon sequestration potential of forest ecosystems. Trees with larger DBH had a significantly higher carbon sequestration, a trend consistent with previous research (Gray 2015; Lutz et al. 2018; Villanova et al. 2018; Mildrexler et al. 2020; Oktan and Atar 2023; Lee et al. 2024). The positive relationship between DBH and carbon sequestration was reaffirmed by Singh and Pandey (2024) and Ma et al. (2025), who identified DBH as a key biophysical variable influencing carbon stocks in trees. However, the discrepancies observed between estimation methods, particularly in the medium sized trees, reflect the uncertainties associated with the underlying assumptions of each model. These include factors such as BEFs and volumetric measurement techniques, which tend to vary with tree size or age (Pasalodos-Tato et al. 2017; Mamonov et al. 2022).

When examined in detail, the three methods used for estimating carbon sequestration show clear method driven differences: Method I employed destructive sampling approach, which has a high accuracy. This method involves weighing various parts of actual trees (both fresh and dry) from 60 samples and constructing equations using least squares regression. Method II used a non-destructive sampling technique, collecting wood cores from 150 randomly selected trees. These trees were stratified by DBH size class (small, medium, large) and species Importance Value Index (IVI) for DEF across wood density groups. Samples were taken at 1.3 meters above ground using an increment borer, then dried and analyzed for carbon stock. Method III used a form class volume table approach, calculating stem volume from 10 cm above ground to the first branch, combined with species-specific wood density and BEFs for branches, leaves, and stems. Each method presents distinct advantages and limitations:

The strengths of Method I lie in its ability to provide true biomass values through direct measurement, through direct measurement of both fresh and dry weight data for all tree components. This approach allows for detailed assessments of nutrient cycling, forest structure, and regeneration. However, its limitations include a relatively small sample size (60 trees), which may not capture the full range of species or size class variability. Furthermore, the data reported in earlier studies may not accurately reflect the current forest conditions or species composition.

The strengths of Method II include the selection of tree species based on ecological dominance, as determined by the Importance Value Index (IVI), which ensures ecological relevance within the study area. Carbon fractions are determined specifically for each species, improving the accuracy of carbon stock estimates. Additionally, a relatively large sample size (150 trees) provides statistical rigor. However, this method also has some limitations that is carbon content is estimated using a small core sample taken at a single height (1.3 m), which may not represent carbon variability across the entire tree. The study was conducted in natural forests dominated by trees with relatively large DBH values, which may reduce the model's predictive accuracy for smaller trees. Although the method spans a wide DBH range, its validated accuracy is limited to trees with DBH between 9.7 and 147.0 cm. Thus, estimates for trees with sizes below this range may be less reliable. Moreover, the approach may underestimate or overestimate the total carbon stock due to unaccounted variation in carbon allocation among different tree components such as branches, leaves, and roots.

The strengths of Method III lie in its integration of species-specific wood density values, which can improve the accuracy of biomass and carbon stock estimates in tropical forest ecosystems. This method has been adapted to reflect regional forest characteristics and is widely applied within Thailand's REDD+ framework. It is particularly efficient for large-scale forest inventories and supports national-level carbon accounting efforts. Standardization of stem volume estimation is achieved through the use of form class volume tables, improving methodological consistency. However, several limitations are worth noting. The method may overestimate biomass due to generalized assumptions in volume calculations. Its accuracy diminishes when applied to smaller trees and younger forest stands. Additionally, the results are sensitive to variability in branch expansion factors, which can differ by age class and environmental conditions. Accurate application of this method requires precise identification of species and access to reliable wood density data. Furthermore, the estimation is restricted to merchantable trunk volume, excluding significant biomass components such as branches, foliage, and roots. The methodology also involves relatively complex procedures, which may present challenges for practical implementation in some conditions.

These methodological differences likely contribute to the variation in carbon sequestration estimates. Method III, which relies heavily on DBH, species-specific wood density, and BEFs, tends to yield higher carbon sequestration values. This aligns with findings that denser wood stores more carbon (Tables 4, 5, and 6) and facilitates greater carbon sequestration (Moreira et al. 2019). However, the assumptions about WD and BEFs can vary with forest age and environmental conditions, potentially leading to inaccuracies (Teegalapalli et al. 2019; Guo et al. 2024b). Changes in branch and leaf biomass across age classes suggest shifts in biomass allocation as trees mature (Oluwajuwon et al. 2024), which may impact the sample trees used in method development. The environmental factors and management practices can also significantly influence BEF estimates. Additionally, differences in tree density and site climate may contribute to variability in results (Krejza et al. 2017). Furthermore, although volume is a morphological measure, the wood volume obtained typically represents only the merchantable portion of the tree, rather than its total volume. Consequently, the integration of different estimation techniques may introduce additional uncertainty into the results. The high variability observed in Method III also reflects a broader issue: the lack of standardized definitions of biomass composition in models (El Mderssa et al. 2019; Vorster et al. 2020; Picard et al. 2025). This often leads to inconsistencies in the interpretation of general models that do not account for species-specific wood density or tree architecture, potentially resulting in significant biases. In contrast, Methods I and II share common variables, such as DBH and height, which are obtained through direct measurement. Although they use entirely different sample sets, Method II incorporates elements of Method I in its development process. It has also been observed that the sampling approach used in Method I yielded highly accurate tree estimates (Rohmatiah 2017; Ung et al. 2017). Meanwhile, the sampling technique used in Method II is also widely accepted, particularly in dendrochronological studies. The sample sizes and DBH ranges used in each method also differ, which affects carbon sequestration and biomass estimation. The DBH class significantly influences carbon sequestration and biomass estimates (Daryaei and Sohrabi 2016; Zhang et al. 2019), and the relationship among DBH, biomass, and carbon sequestration varies across DBH classes (Zhou et al. 2025).

The uncertainty in biomass estimation using generalized allometric models is a major concern, especially in the absence of species-specific equations. These models often rely on assumptions about tree density and biomass allocation, which can vary across species and environments, leading to potentially variable estimates of carbon stocks (Wayson et al. 2015), with the statistical differences observed being consistent with concerns raised by Neumann et al. (2016) regarding carbon estimating methods in Europe which they highlighted inconsistencies in carbon sequestration estimation systems and emphasized the importance of method selection, such as using species-specific Allometric Biomass Functions (ABFs) or general BEFs. Using generalized conversion rates may systematically overestimate the values for young trees and underestimate the same for mature ones, which may also contribute to variability. In addition, large trees and endemic species are often underrepresented in the datasets used to develop these models, which limits their broad application (Frank et al. 2019). Taken together, the statistical results, box plot distributions, and Bland-Altman analyses underscore the complexity of carbon sequestration estimation across different DBH classes and methodological approaches. While the DBH remains the most reliable predictor of carbon sequestration, the magnitude and direction of estimates vary depending on the method used, particularly for medium- and large-sized trees. The discrepancies, especially between Methods II and III, appear to stem from differing assumptions about wood density, biomass allocation, and expansion factors. Method III, although efficient for large-scale inventories, tended to yield higher and more variable carbon sequestration estimates, likely due to generalized volume assumptions and its reliance on merchantable stem volume. In contrast, Methods I and II produced more consistent results for small and medium DBH classes, owing to their use of direct measurements and stratified sampling. These findings emphasize that method selection must align with forest structural characteristics, and model limitations should be explicitly considered in any rigorous carbon accounting framework. The choice of method should also account for factors such as study area, tree species, research objectives, and the availability of reliable datasets to ensure both appropriateness and maximum efficiency. However, when considering mechanisms for climate change mitigation, Methods I and III are certified for REDD+, while Methods I and II are approved for T-VER carbon trading in Thailand. Carefully, when DBH exceeds approximately 90 cm, Method II tended to yield higher estimates than Method I. Further consideration should therefore be given to the certification standards and contextual suitability of each method.

In conclusion, the restored DEF of the FPT 49 plot exhibited a high species richness and ecological complexity, with 4,538 individuals from 96 species across 42 families. Simpson’s index of 0.90 and Shannon-Wiener index of 3.02 indicated strong ecological stability and successful recovery. Dominant species, such as *M. tomentosa*, *N. hypoleucum*, and *D. cochinchinense*, played key roles in shaping tree diversity and contributing to carbon sequestration. Stand structure displayed an inverted J-shaped DBH distribution and a bell-shaped height distribution, characteristic of naturally regenerating forests with multi-aged and multi-layered dynamics. Biomass and carbon sequestration estimates varied across three methods: Method III yielded the highest values (71.61 Mg C ha^{-1} and 262.59 Mg CO$_2$ ha^{-1}), next to Method I (56.20 Mg C ha^{-1} and 206.09 CO$_2$ ha^{-1}) and Method II (41.80 Mg C ha^{-1} and 153.30 CO$_2$ ha^{-1}), reflecting differences in assumptions such as BEFs, sampling techniques, and wood density data. Method III, while useful for large-scale inventories and REDD+ reporting, tended to overestimate biomass for large DBH trees, as confirmed by box plots and Bland-Altman analysis, which revealed a wide variability and tendency to overestimate. Statistical results confirmed that DBH size class (ε^2: 0.14) and its interaction with method (ε^2: 0.17) had the greatest influence on carbon stock estimation, while differences among methods alone were minor (ε^2: 0.03). Wilcoxon tests further supported the observation that carbon sequestration increases significantly with DBH, with Method III diverging most strongly for medium DBH trees (r: 0.63), while estimates among methods converged for large DBH trees. Method I (destructive sampling) and Method II (core sampling) yielded more consistent results across DBH classes, thanks to direct measurements and species stratification. A comparative study with the tropical forests in Thailand and globally indicated that FPT 49 had moderate to high biomass and carbon sequestration, reflecting 28 years of effective restoration. However, carbon stocks remained below those of undisturbed forests, likely due to ongoing anthropogenic pressures and site-specific environmental factors. These findings underscore the crucial need for method-specific adjustments, careful model selection based on forest structure, and consideration of DBH class when evaluating the carbon sequestration potential. For policy relevance, all three methods have been certified under REDD+ or Thailand’s T-VER schemes; however, their suitability varies depending on the specific forest and application. Ultimately, DBH remains the most important biophysical predictor of carbon storage, and integrating structural, ecological, and methodological factors is essential for improving the accuracy of forest carbon accounting.

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Table S1. Tree volume equations based on tree shape, Wood specific Density (WD) (Na Nakorn 1995), and Biomass Expansion Factor (BEF) (Sabhasri and Wood 1967)

Group	**Equation**	**Species (Wood specific density: WD)**	**Biomass Expansion Factor (BEF)**	
			Branch / Stem	**Leaf / Stem**
1	$\ln V = 2.372083+2.443847 \ln (DBH/100)$ R^2: 0.94, sample size: 188	*Anisoptera costata* Korth. (0.49), *Cotylelobium lanceolatum* Craib (0.74), *Cotylelobium lanceolatum* Craib. (0.74), *Dipterocarpus obtusifolius* Teijsm.ex Miq. (0.73), *Dipterocarpus tuberculatns* Roxb. (0.70), *Hopea odorata* Roxb. (0.64), *Parashorea stellata.* Kurz. (0.45), *Pinus latteri* Mason (0.60), *Shorea assamica* Dyer subsp. globifera (Ridl.) Y.K.Yang & J.K.Wu (0.42), *Shorea henryana* Pierre. (0.59), *Shorea obtusa* Wall. ex Blume (0.85), *Shorea roxburghii* G. Don. (0.69), *Shorea siamensis* Miq. (0.81), Trees from the genus *Dipterocarpus* spp., and *Vatica diospyroides* Symington (0.69)	0.28	0.07
2	$\ln V = 2.134494+2.363034 \ln (DBH/100)$ R^2: 0.91, sample size: 135	*Albizia procera* (Roxb.) Benth. (0.60), *Dalbergia assamica* Benth. (0.59), *Dalbergia cana* Graham ex Kurz. (0.59), *Dalbergia candenatensis* (Dennst.) Prain (0.59*), *Dalbergia cochinchinensis* Pierre. (0.84), *Dalbergia cultrata Graham* ex Benth (0.89), *Dalbergia foliacea* Wall. ex Benth. (0.59*), *Dalbergia nigrescens* Kurz. (0.59*), *Dalbergia oliveri* Gamble & Prain. (0.93), *Dalbergia ovata* Graham ex Benth. var. glomeriflora (Kurz) Thoth. (0.59*), *Diospyros areolata* King & Gamble (0.57), *Diospyros mollis* Griff. (1.0), *Diospyros pilosanthera* Blanco. (0.59*), *Millettia leucantha* Kurz var. buteoides (Gagnep.) P.K.Lôc. (0.97), *Millettia leucantha* Kurz var. leucantha (0.97), *Stereospermum cylindricum* Pierre ex Dop. (0.62), *Stereospermum neuranthum* Kurz (0.65), and Xylia xylocarpa (Roxb.) W.Theob. var. kerrii (Craib & Hutch.) I.C.Nielsen (0.82)	0.36	0.13
3	$\ln V = 1.880578+2.053321 \ln (DBH/100)$ R^2: 0.89, sample size: 186	*Aglaia cucullata* (Roxb.) Pellegr. (0.54), *Aglaia edulis* (Roxb.) Wall. (0.59), *Ailanthus fauveliana* Pierre ex Laness. (0.39), *Azadirachta indica* A.Juss. (0.59), *Cananga latifolia* (Hook.f. & Thomson) Finet & Gagnep. (0.44), *Chukrasia tabularis* A.Juss. (0.73), *Cratoxylum* spp. (0.65), *Dillenia* spp. (0.64), *Garcinia cowa* Roxb. Ex Choisy (0.75), *Garcinia speciosa* Wall. (0.67), *Garuga pinnata* Roxb. (0.59*), *Irvingia malayana* Oliv. ex A.W.Benn. (0.85), *Lagerstroemia loudonii* Teijsm. & Binn. (0.59*), *Lagerstroemia ovalifolia* Teijsm. & Binn. (0.59*), *Lagerstroemia speciosa (L.) Pers.* (0.53), *Mammea siamensis* (Miq.) T.Anderson. (0.59*), *Melia azedarach* L. (0.39), Mesua ferrea L. (0.91), *Nephelium hypoleucum Kurz* (0.79), *Pterospermum acerifolium* Willd. (0.47), *Sandoricum koetjape* (Burm. f.) Merr. (0.43), *Schleichera oleosa* (Lour.) Merr. (0.59*), *Swietenia macrophylla* King. (0.59*), *Terminalia bellirica* (Gaertn.) Roxb. (0.61), *Terminalia catappa* L. (0.52), *Terminalia chebula* Retz. (0.72), *Terminalia elliptica* Willd. (0.85), *Terminalia glaucifolia* Craib (0.59*), *Terminalia ivorensis* A. Chev. (0.59*), *Terminalia nigrovenulosa* Pierre (0.59*), *Toona ciliata* M. Roem. (0.44), *Xylocarpus granatum* J.Koenig (0.59*), and *Xylocarpus rumphii* (Kostel.) Mabb. (0.59*)	0.31	0.10
4	$\ln V = 1.789563+2.025666 \ln (DBH/100)$ R^2: 0.90, sample size: 36	*Afzelia xylocarpa* (Kurz) Craib. (0.69), *Albizia lebbeck* (L.) Benth. (0.67), *Albizia odoratissima* (L.f.) Benth. (0.76), *Cassia fistula* L. (0.71), *Intsia palembanica* Miq. (0.65), *Peltophorum pterocarpum* (DC.) Backer ex K. Heyne. (0.56), *Senna siamea* (Lam.) Irwin & Barneby. (0.33), Species in the genus *Senna* spp. (0.58), *Tamarindus indica* L. (0.59), *Vachellia tomentosa* (Rottler) Maslin, Seigler & Ebinger (0.59)	0.43	0.16

5	ln V = 2.037096+2.299618 ln (DBH/100) R^2: 0.94, sample size: 99	Trees from the genus *Pterocarpus* spp. (0.75), and *Bischofia javanica* Blume. (0.75)	0.07	0.06
6	ln V = 2.119907+2.296511 ln (DBH/100) R^2: 0.94, sample size: 186	*Tectona grandis* Linn.f. (0.53), *Vitex canescens* Kurz. (0.59*), *Vitex pinnata* L. (0.73), *Vitex scabra* Wall.ex. Schauer. (0.59*), *Vitex gamosepala* Griff. (0.59*), *Vitex glabrata* R. Br. (0.59*), *Vitex peduncularis* Wall. ex-Schauer. (0.96), *Vitex pinnata* L. (0.59*), *Vitex quinata* (Lour.) F.N.Williams (0.53)	0.29	0.04
7	ln V = 2.250111+2.414209 ln (DBH/100) R^2: 0.93, sample size: 138	*Alchornea rugosa* Lour. (0.59), *Alstonia Scholaris* (L.) R. Br. (0.33), *Antidesma puncticulatum Miq.* (0.59), *Artocarpus lanceifolius* Roxb. (0.59*), *Baccaurea ramiflora* Lour. (0.59*), *Beilschmiedia roxburghiana* Nees (0.59*), *Bombax anceps* Pierre var. anceps (0.59*), *Cassia garrettiana* Craib (0.59*), *Cleidion javanicum* Blume. (0.50), *Cordia cochinchinensis* Pierre (0.54), *Dehaasia candolleana* Kosterm. (0.59*), *Dialium cochinchinense* Pierre (0.89), *Diospyros longipilosa* Phengklai (0.59*), *Dolichandrone spathacea* (L.f.) K.Schum. (0.59*), *Erythrina subumbrans* (Hassk.) Merr. (0.24), *Gmelina arborea* Roxb. (0.43), *Grewia eriocarpa* Juss. (0.59*), *Grewia paniculata* Roxb. (0.40), *Haldina cordifolia* (Roxb.) Ridsdale. (0.57), *Hydnocarpus anthelminthicus* Pierre ex Laness. (0.59*), *Lannea coromandelica* (Houtt.) Merr. (0.59*), *Leptonychia* spp. (0.79), *Lepisanthes rubiginosa* (Roxb.) Leenh. (0.59*), *Litsea glutinosa* (Lour.) C.B.Robinson (0.59*), *Mallotus philippinensis* Muell. Arg (0.59*), *Mangifera caloneura* Kurz. (0.66), *Markhamia stipulata* (Wall.) Seem. (0.59*), *Melodorum fruticosum* Lour. (0.59*), *Memecylon garcinioides* Blume. (0.59*), *Microcos tomentosa* Smith (0.40), *Murraya paniculata* (L.) Jack) (0.59*), *Pterocymbium tinctorium* (Blanco) Merr. (0.49), *Rothmannia wittii* (Craib.) Bremek. (0.59*), Species in the genus *Castanopsis* spp., *Lithocarpus* spp., *Quercus* spp., and *Trigonobalanus* spp. (0.59*), *Croton* spp. (0.59*), *Sterculia* spp. (0.59*), *Streblus asper* Lour. (0.59*), *Streblus taxoides* (Heynes) Kurz (0.59*), *Suregada multiflora* (A.Juss.) Baill. (0.59*), *Syzygium cumini* (L.) Skeels (0.70), *Syzygium ripicola* (Craib) Merr. & L.M.Perry (0.53), and *Wrightia arborea* (Dennst.) Mabb. (0.51)	0.31	0.11

Note: V represents the volume of trunk from the stump (cut at ground level) to the first usable branch (m^3), DBH is the diameter at breast height (cm), and * indicates average specific wood density, which can be used in cases where specific data are not available for the species.

The wood specific gravity was converted to basic wood density following the approach of Reyes et al. (1992) through the following equations:

Wood specific density = 0.0134 + 0.8 X [1]

Where X: Density of wood with moisture content of 12% (Mg /m^3)