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EFFECT OF PLOT SIZE ON ABOVE-GROUND CARBON STOCK ESTIMATES IN BERAU

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ABSTRACT

In designing data collection methods to estimate carbon stocks stored above and below the forest surface, plot size is a crucial factor that needs to be considered. This study aims to evaluate the effect of plot size differences on the results of above-ground carbon stock estimates at PT Wana Bakti Persada Utama, Berau Regency, East Kalimantan. This study is important because plot size is a fundamental component in forest inventory design that directly affects the accuracy, stability, and representativeness of carbon estimates. The selection of an inappropriate plot size can cause bias, either in the from of overestimation or underestimation of carbon stocks, thereby impacting the accuracy of data in supporting forest management planning and climate change mitigation. Data collection was carried out using a rectangular nested plot design with three sizes, namely (20×20 m), (20×50 m), and (20×100 m), for a total of 15 plots. All trees with a Diameter at Breast Height (DBH) ≥ 40 cm were measured and their above-ground biomass was calculated, then converted into carbon stocks. The results showed that the average carbon stock in small, medium, and large plots was 67.59 ± 22.21 tonsC/ha; 86.81 ± 37.51 tonsC/ha; and 89.67 ± 36.34 tonsC/ha, respectively. The t-test results show that there is no significant difference between plot sizes (α = 0.05), except between small and large plots. These findings confirm that plot size affects the accuracy of carbon stock estimates and needs to be carefully considered in the design of forest carbon inventories.

Keywords: *Carbon Stock; Global Warming; Plot Size; T-test*

INTRODUCTION

Forests are a natural resource that can be utilized in the form of both timber and non-timber forest products. Timber remains the main commodity in the forestry sector, so the highest source of income generated by forests comes from timber harvesting (Kadafin *et al*., 2024). With forests, we can utilize various natural resources, such as clean water, quality air, tourism services, biodiversity protection, and global climate regulation. All these benefits can be obtained as long as the sustainability of forests is maintained. Forests have vast potential and can provide various benefits if conservation is carried out properly. In other words, forest resources not only provide economic benefits through the commodities they produce, but also ecological benefits that support natural sustainability, as well as social and cultural benefits that strengthen community cultural life and education (Bolon *et al*., 2025). Deforestation in Indonesia contributes significantly to global greenhouse gas emissions. The conversion of forests into plantations and mining areas eliminates nature's ability to absorb carbon (Wahyuni and Suranto, 2021). Climate change due to global warming has caused the Earth's temperature to rise, leading to various disasters for humanity (Maulidin *et al*., 2023).

The ongoing climate change is currently a major issue caused by global warming. Global warming is caused by the increase in the levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) gases, which are referred to as greenhouse gases (Artiningrum and

Havianto, 2021). Climate change is indicated by broad, long-term patterns in temperature, precipitation, and other factors, such as pressure and humidity in the environment (Abbass *et al*. 2022; Heriyanto *et al*. 2023). It presents a complex, global, inter-governmental challenge, affecting the environmental, ecological, socio-economic, and socio-political systems (Baldos *et al*. 2023; Feliciano *et al*. 2022; Filho *et al*. 2021). As stated in the Enhanced Nationally Determined Contribution (ENDC) document, Indonesia aims to cut Green House Gas (GHG) emissions by 31.89% and by 43.20% with international support to prevent a global temperature increase of 2°C and to limit it to 1.5°C (UNFCCC, 2022).

On Earth, carbon is stored in the form of rocks, sediments, and in the oceans. Some carbon is also present in the atmosphere as carbon dioxide compounds, which play a significant role in causing global warming (NOAA, 2023). Naturally, carbon accumulates in the form of living and dead biomass. The decomposition of dead biomass ultimately contributes to its mixing with the soil, allowing carbon to be found in the materials that make up the soil. Living biomass can be found above and below the soil surface. Biomass on the soil surface can take the form of trunks, branches, twigs, and green leaves. Meanwhile, biomass beneath the soil consists of root systems that support the plants and vegetation above them. Dead biomass can include fallen trees that are still standing, fallen wood, and litter such as leaves and small twigs (Hamdani *et al*., 2024).

Carbon stocks in forests can be estimated using direct methods, estimation methods, or a combination of both (Thomas *et al*., 2020). Carbon stocks in forests are the total accumulation of all measured carbon pools, which include above-ground biomass, below-ground biomass, necromass, litter, and soil within the forest area (Murdiyarso *et al*., 2017). Although plot size is considered important, there is still a lack of research in Indonesian production forests that assesses the effect of different plot sizes on the accuracy of carbon stock estimates. Most carbon stock studies focus on estimation models, while the effect of plot size on estimation accuracy has rarely been examined, particularly in Indonesian production forests. Therefore, this study directly evaluates the impact of plot size differences on above-ground carbon stock estimates.

METHOD

Research Location

This study was conducted in the logging concession area of PT Wana Bakti Persada Utama (PT WBPU), located in Berau Regency, East Kalimantan. The research was conducted for approximately ten days with data collection in three different plot sizes. Fifteen research plots were established at this location as a basis for data collection for calculating above-ground carbon stocks (Figure 1).

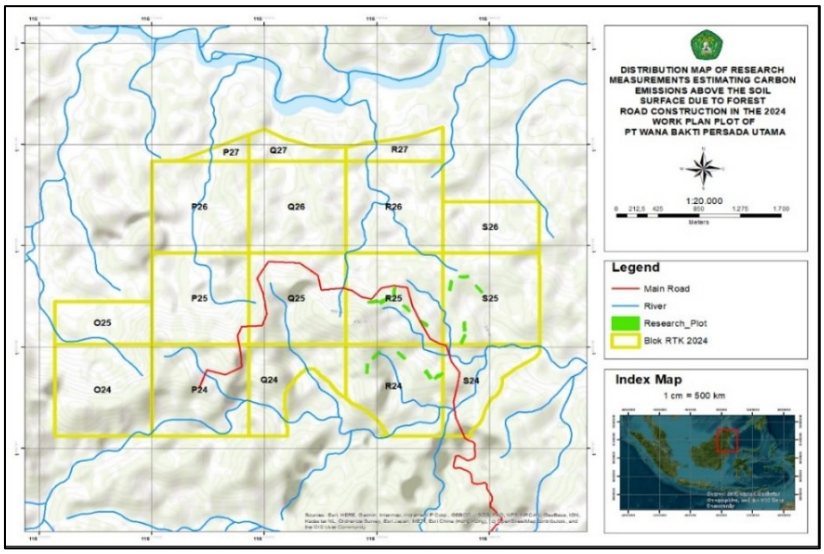

Figure 1. Location of Sample Plots

Data Collection

Data collection on trees was conducted by establishing sample plots with three rectangle sub plot adjacnent to each other, namely Small (20x20 m), Medium (20x50 m), and Large (20x100 m). The Medium Plot encompasses the Small Plot, and both plots are part of the Large Plot. This plot design is a modification of the method developed by Hairiah *et al*. (2011) for estimating forest biomass and carbon. The use of nested plots aims to improve measurement efficiency, capture stand structure variation at various scales, and improve the representativeness and accuracy of estimates. The plots were established by first designating the Large Plot as the main observation unit, then placing the Medium Plot and Small Plot sequentially within it, with plot boundaries determined using measuring tape and field markers.

Tools such as GPS receivers, measuring tapes, diameter tapes (phi-bands), compasses, and clinometers were used for navigation and plot construction. All trees with a Diameter at Breast Height (DBH) ≥ 40 cm were measured, and their species were identified.

Data Analysis

To test whether carbon stock estimates differ significantly among the three plot sizes Small, medium, and Large using a paired t-test at a significance level of α = 0.05. The difference is considered significant if the p-value is < 0.05. This analysis was conducted to assess the effect of plot size on above-ground carbon stock estimates. (Ghozali, 2021). The following is the t-test formula:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\frac{sd}{\sqrt{n}}}$$

Description:
$\bar{X}_1$ = represents the mean carbon stock estimated using the first model,
$\bar{X}_2$ = represents the mean carbon stock estimated using the second model,
Sd = is the standard deviation of the paired differences between observations; and
n = is the number of paired samples

Data Processing

The calculation of above-ground biomass follows the allometric equation developed by Basuki *et al*. (2009).

Table 1. Allometric Equation According

References	Allometric Equations	Remarks
Basuki et al. (2009)	AGB = exp{-1.232+2.178×ln(DBH)}	For *Dipterocarpus* tree species
Basuki et al. (2009)	AGB = exp{-2.193+2.371×ln(DBH)}	For *Shorea* tree species
Basuki et al. (2009)	AGB = exp{-1.498+2.234×ln(DBH)}	For commercial trees
Basuki et al. (2009)	AGB = exp{-1.201+2.196×ln(DBH)}	Mixed trees

The general form of the equation is:

$$AGB = \exp(a + b\ x\ In\ (DBH))$$

Description:
AGB = is aboveground biomass (kg)
Exp = denotes the exponential function
a and b = regression coefficients derived from the selected allometric model; and
DBH = is diameter at breast height (cm).

Once AGB was obtained, carbon stock per sample plot (C_s) was calculated by multiplying AGB by a carbon fraction value of 0.47, following the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006). Carbon stock per hectare (C_n) was calculated according to the Indonesian National Standard (SNI 7724:2019) using the following equation:

$$Cn = \frac{C}{1000}\ x\ \frac{10000}{l\ plot}$$

Description:
C_n = is carbon stock per hectare (ton C/ha)
C_s = is total carbon per sample plot (kg); and
l plot = is the plot area (m^2).

RESULTS and DISCUSSION

Aboveground Carbon Stock

The results show that the average carbon stock estimates for Small, Medium, and Large plots vary significantly, indicating differences in carbon storage capacity between plot sizes. This variation shows that plot size affects the amount of carbon stock produced, which is likely due to differences in stand density, tree diameter distribution, and stand structure in each plot. Small plots produced more variable values because they were influenced by the presence of large-diameter trees in a limited area. In contrast, medium and large plots provided more stable estimates that were more representative of the stand structure.

Table 2. Results of Carbon Stock Estimation (tonC/ha)

Plots	Carbon Estimation (tonC/ha)		
	Small	**Medium**	**Large**
1	60.04	75.12	55.00
2	117.45	107.44	85.01
3	97.58	146.22	131.09
4	12.07	14.40	44.60
5	110.98	71.94	136.67
6	44.37	45.06	59.72
7	66.36	77.98	99.03
8	42.39	47.00	47.00
9	129.38	257.95	238.96
10	43.68	41.37	41.37
11	11.91	14.52	45.48
12	43.64	46.67	58.09
13	119.56	182.27	184.10
14	25.94	42.51	42.19
15	88.48	131.71	76.69
Average	**67.59**	**86.81**	**89.67**
Standard Deviation	**40.11**	**67.74**	**59.10**
Standard Error	**10.36**	**17.49**	**15.26**
Confidence Level (95,0%)	**22.21**	**37.51**	**32.73**
Uncertanty	**32.86**	**43.21**	**36.50**

Source: Primary Data (2024)

The highest carbon stock was found in plot Small at 67.59 ± 22.21 tonC/ha, plot Medium at 86.81 ± 37.51 tonC/ha, and plot Large at 89.67 ± 36.50 tonC/ha. Data collected from three plots produced different estimates of carbon stocks. The results showed that the average carbon stock ranged from 67.59 to 89.67 tonC/ha, with the highest value found in large plots. This indicates that plot size affects the representativeness of carbon estimates, as larger plots are able to capture the distribution of large-diameter trees that contribute significantly to biomass. This value is higher than the carbon stock of 22.48 tonC/ha reported in the study by Kundariati *et al*. (2024), which was likely influenced by differences in stand structure, density, and ecological conditions of the location. In general, these results indicate that the forest stands studied have a fairly high carbon storage potential and play an important role in climate change mitigation.

Natural forest carbon stocks are dominated by Above-Ground Biomass (AGB), which has a very strong relationship with Diameter at Breast Height (DBH) and tree height. The study shows that an increase in DBH significantly increases the value of biomass and carbon stocks per hectare. Large-diameter trees contribute the largest proportion to total carbon stocks, while stands with a small diameter distribution produce lower carbon stocks (Tam *et al*., 2025). Based on the results of the study, it was found that forest carbon stock estimates have a significant relationship with stand structure parameters, stating that the regression model between vegetation index and carbon stock produced a correlation coefficient (r) of 0.663, indicating a fairly strong relationship (Fauzan *et al*., 2023)

Stated that the use of small plots measuring 10×10 m or 10×20 m can cause the carbon stock produced to differ from the actual average Omar *et al*. (2013). The most appropriate plot size for measuring biomass in natural forests ranges from 0.25 to 0.40 ha, as this size statistically reduces errors and provides more representative results of field conditions. Nanjaya *et al*. (2020) in a study on tropical forest ecosystems in Indonesia also showed that variations in biomass and basal area increased significantly in small plots and then decreased and stabilized after the plot size was increased beyond 0.25 ha.

Research conducted by Mauya *et al*. (2015) through analysis of varying plot sizes, ranging from 200 m² to 3000 m², found that changes in plot size have a direct effect on the accuracy and stability of biomass and carbon estimates. Smaller plot sizes tend to yield higher carbon stock estimates, but with large standard deviations, indicating instability in the data. These results indicate that estimates from small plots are greatly influenced by the presence of large trees in the vicinity. This is due to several factors, including boundary effects and positioning errors between data collected in the field and data obtained from remote sensing such as ALS (Airborne Laser Scanning).

This study reinforces the understanding that small plot sizes are highly susceptible to producing large carbon stock estimates, due to the presence of large trees in limited space, uneven spatial distribution, and increased risk of statistical error. As a solution, the study proposes the use of single plots with a size of ≥ 0.75 ha to obtain more accurate estimates of structural parameters. However, if the use of large plots is not feasible, several plots of 0.25 ha are considered the best option that combines field efficiency with estimation accuracy (Peck & Zenner 2021).

Stefanoni *et al*. (2018) This study examined three plot sizes (80 m², 400 m², and 1000 m²) and found that the accuracy of estimates increased continuously as plot size increased, as measured by both the coefficient of determination (R^2) and the reduction in Root Mean Square Error (RMSE). Small plots are more susceptible to local variations (such as the presence of large trees), which result in significant changes in carbon stock estimates, and can even produce higher estimates if they happen to be located in areas with many trees. This study shows that clusters of medium-sized plots (500–1000 m²) provide more efficient and accurate estimates than single small plots (Zhao *et al*, 2022).

Statistical Test Results

The independent t-test results for all pairwise comparisons among the three allometric models are presented in Tables 3–5. These tables summarize the differences in mean aboveground carbon stock estimates, including variance, coefficient of variation, t-values, and significance levels (p-values), allowing a clearer evaluation of statistical differences among plot sizes and applied models.

Table 3. Results T-Test Result of Small *VS Medium*

	Small	**Medium**
Mean	67.59	86.81
Variance	1608.49	4588.85
Observations	15.00	15.00
Coefficient Of Variation (CV)	0.59	0.78
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-1.90	
P(T<=t) one-tail	0.04	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.08	
t Critical two-tail	2.14	

Source: Primary Data (2024)

Table 4. Results T-Test Result Small *VS Large*

	Small	**Large**
Mean	67.59	89.67
Variance	1608.49	3492.52
Observations	15.00	15.00
Coefficient Of Variation (CV)	0.59	0.66
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-2.54	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.02	
t Critical two-tail	2.14	

Source: Primary Data (2024)

Table 5. Results T-Test Result of Medium VS Large

	Medium	**Large**
Mean	86.81	89.67
Variance	4588.85	3492.52
Observations	15.00	15.00
Coefficient Of Variation (CV)	0.78	0.66
Hypothesized Mean Difference	0.00	
df	14.00	
t Stat	-0.39	
P(T<=t) one-tail	0.35	
t Critical one-tail	1.76	
P(T<=t) two-tail	0.70	
t Critical two-tail	2.14	

Source: Primary Data (2024)

Based on the results of the t-test calculation from fifteen research plots conducted with a value of ($\alpha = 0.05$), it was found that the average carbon reserve calculation for small, medium, and large plots had a probability value greater than the specified significance level ($t > 0.05$). However, there was a difference between the small and large plots, which showed a value of ($t < 0.05$), meaning that there was a significant difference between the sizes of these plots.

These results indicate that the effect of plot size on carbon stock estimates is scale-dependent. Comparisons between small and medium plots did not reveal significant differences, suggesting that internal stand variation still dominates. However, significant differences

between small and large plots confirm that small plots are more susceptible to fluctuations due to the distribution of large-diameter trees. Conversely, the absence of significant differences between medium and large plots indicates that after reaching a certain size, increasing plot size no longer significantly improves the accuracy of estimates. This study confirms that small plots tend to produce less stable estimates, while medium to large plots are more representative in describing stand structure and are more suitable for forest carbon inventory.

Research conducted by Darcha *et al*. (2025) states that the significance of model parameters is tested using p-values to ensure that the relationship between variables does not occur by chance, but rather reflects a real effect on biomass estimates. This principle is similar to the use of the t-test in this study, where the p-value is used to determine whether the difference in average carbon stocks between plot sizes is statistically significant. Variations in stand structure and vegetation density affect carbon stock estimates, especially when the observation area increases so that spatial variation is better represented (Hartoyo *et al*., 2025).

A larger observation area produces a more stable carbon stock estimate because it is better able to capture stand heterogeneity (Hikmana *et al*., 2025). This supports the finding that there is a significant difference between Small and Large plots, but no longer a significant difference between Medium and Large plots. This means that once the threshold for variability representation is reached (at Medium size), adding more plot area no longer provides a significant improvement in the estimate.

Furthermore, a study by Mulyana *et al*. (2024) states that statistical significance ($p < 0.05$) indicates that a factor has a real effect on biomass estimates, rather than just random variation. The differences in biomass and carbon stocks between diameter classes show statistical significance ($p < 0.05$), reflecting real variations in vegetation structure (Bhutia *et al.*, 2025). The study confirms that diameter distribution and vegetation composition are the main factors affecting carbon accumulation.

CONCLUSION AND RECOMMENDATIONS

The results showed that plot size affected the total above-ground carbon stock, although the difference in carbon stock between small, medium, and large plots was not statistically significant at a 95% confidence level ($\alpha = 0.05$). The average carbon stocks obtained were 67.59 ± 22.21 tonC/ha, 86.81 ± 37.51 tonC/ha, and 83.78 ± 36.34 tonC/ha, respectively. Medium to large plots tend to produce more consistent and representative carbon stock estimates because they are able to better describe tree diameter diversity and spatial distribution of vegetation. Therefore, it is recommended to use larger plots or a combination of several medium-sized plots to obtain more accurate measurement results and reduce uncertainty in carbon stock calculations.

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