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Assessing Forest Carbon Accumulation Potential Across Different Treatments using Field Inventory Data

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Abstract. Deforestation and forest degradation lead to an increase in the level of carbon in the atmosphere and disrupted the global carbon cycle. The tropical forest has received a lot of interest since it contributes around 60% of the total global forest carbon. By enhancing carbon sink, tropical forests have a great potential in mitigating climate change. Assessing aboveground biomass (AGB) and carbon stock through field inventories is crucial for this purpose as it provides the most accurate result. The research was conducted at Danum Valley Conservation Area and INFAPRO in Sabah, Malaysia. An earlier study over 35 years ago at this site suggests that restored forests accrue AGB at twice the rate of regenerating forests, though the cause of this difference between treatments is unclear. Thus, this study will focus on three principal study sites which are restored, naturally regenerating and old-growth forests to determine the forest's potential to sequester and store carbon in the forest ecosystem. These three sites were chosen because it is a well-established plot from the earlier inventory over the last seven years. The field measuring method is a non-destructive methodology. Tree parameters such as diameter at breast height (DBH), tree height and tree species diversity were collected for calculating AGB using a species-specific allometric equation. Results showed a positive correlation between tree species, diameter at breast height, and biomass/carbon stock across three different forest treatments. The active restoration increases up to 151% carbon stock whilst the old-growth forest increased by 34% and natural regeneration increased by 73%, which active restoration can be the best solution for forest treatment. The outcome of this study will increase the ability of forest authorities and the Malaysian government to effective monitoring of carbon stock for establishing reliable standard guidelines in measuring deforestation and forest degradation toward achieving sustainable forest management.

Keywords: Aboveground biomass, carbon stock, forest treatments, carbon dynamics, allometric

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1. Introduction

Forests span almost one-third of the Earth's land area and are home to most of its terrestrial species. Despite attempts to prevent deforestation and repair damaged lands, the forest area continues to diminish. Forests are critical for climate change mitigation, whereby they store 662 billion tonnes of carbon, which accounts of more than half of the world's carbon storage in soils and vegetation [12]. Trees can reduce atmospheric carbon dioxide concentrations despite the devastation caused by climate change, limiting global warming and climate change.

Mapping and monitoring of aboveground carbon dynamics (ACD) have become more common [1,2], and it now offers the opportunity to accelerate efforts to conserve forests in the context of climate change mitigation by identifying areas of high biomass, old growth canopies, and areas deemed ecologically viable for recovery [3,4]. In this study, the forest AGB was quantified along with an analysis of the accumulation on forest AGB across three different forest treatments at Danum Valley Conservation Area (DVCA) and Innoprise-FACE Rainforest Rehabilitation Project (INFAPRO). In addition, this study compares the analysis of AGB with the 2015 AGB calculated in the same study plot.

2. Method and Study Area

2.1 Study area

The study was conducted at DVCA, an undisturbed old-growth forest, and selectively logged forest at INFAPRO, Sabah. The DVCA is located around 80 kilometers from Lahad Datu town and classed as a Class 1 (Protection) Forest Reserve under the Sabah Forestry Enactment 1968. The DVCA encompasses 438 km^2 of old-growth lowland dipterocarp and lower montane rainforest (200-1000 m above sea level), contiguous with a logging concession of 10,000 km^2 in East Sabah, Malaysian Borneo. The average daily temperature ranges from 22.5°C to 30.9°C, and the average annual rainfall is 2700 mm spread out over 220 days [5,6].

A region of selectively logged forest inside the Ulu Segama forest reserve (USFR) next to the DVCA was harvested in yearly coupes (defined logging zones) between 1981 and 1993 [7], around 29-41 years prior to the census used as the foundation for this article. INFAPRO is a tree nursery project base responsible for replanting portions of forest that have been logged in the past. It is in the USFR, which buffers the world-renowned DVCA. The INFAPRO was founded in July 1992 by the Yayasan Sabah Group and Forest Absorbing Carbon Dioxide Emissions (FACE), formerly the Netherlands Foundation. The logging coupes were generally 27 km^2 in size [7] and were harvested using either tractor (for intermediate terrain) or high-lead logging techniques (for steep slopes). Figure 1 depicts the plots and research area map.

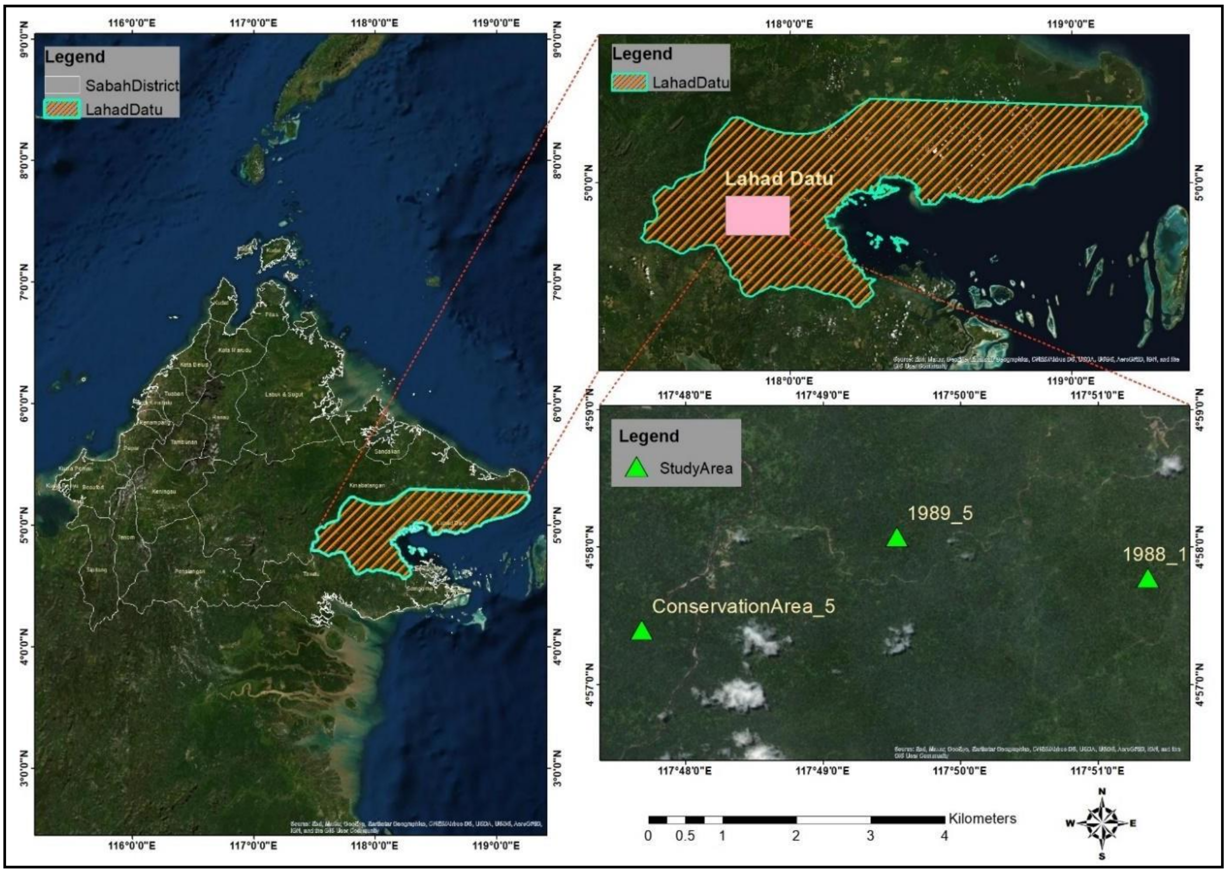

Figure 1. The plots and research area map

2.2. Field data collection

Fieldwork was carried out in April 2022 in the DVCA and INFAPRO. As part of the Forest Sustainability Indicators (INDFORSUS) and Forest Global Earth Observation Network (ForestGEO) project network, these areas consist of well-established 46 circular forest plots (radius = 12.61 m, area = 500 m^2) censused across seven selected logging coupes (34 plots) and unlogged forests (12 plots) in 2015. Three plots have been chosen based on the 46 plots, which correspond to the desired characteristics of primary forest, natural forest generation, and active restoration. The plots are named as Conservation Area 5, 1988_1, and 1989_5. The selected plots are categorized in Table 1 according to their characteristics. Each visited plot area was tagged as shown in Figure 2 as a sign that the plot has been measured. In addition, the square method is used for sampling.

Table 1. Plots name classification based on type of forest.

Type of Forests	Plots Name
Old-growth Forest	ConservativeArea_5
Active Restored	1988_1
Natural Regeneration	1989_5

Figure 2. The plot marking

2.3. Sampling method

Previous study discovered that rectangular samples of 20×50m and 10×50m, had the highest accuracy, the lowest inventory error, and the closest density (tree/ha) in a comparison of genuine quantity (perfect inventory) [8]. These sampling strategies are appropriate for studying tree density. In this study, the rectangle approach was employed to perform the field sampling. The sample plot comprises of five subplots of 20×20m (Figure 3). In total, 30 square plots were censused across two selective logging coupes (20 plots) and unlogged forests (10 plots) with a total area of 12,000 m^2.

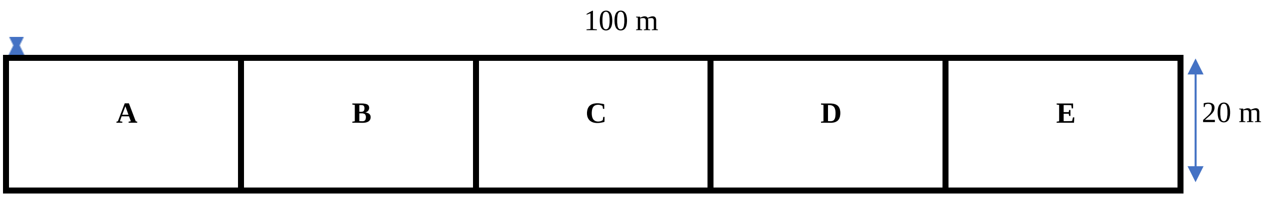

Figure 3. Rectangular method used to do sampling.

2.4. Measuring tree parameters

In each sampling plot, all live stems of ≥15 cm DBH were measured its diameter, tree height, crown area and crown density (Figure 4a-d). The DBH is measured at approximately of 1.3 m above the ground surface. All measurements were recorded in the designated form.

Figure 4. (a) Recording information of the study plots (b) Measuring the DBH of a tree (c) Measuring tree height and crown density. (d) Identifying tree species at the site

2.5. Biomass calculation

The allometric equation is the most frequently used to determine forest biomass. To estimate forest biomass and carbon stocks of forests, allometric equations are constructed and applied to forest inventory data [9]. The allometric equation for biomass estimation is created by determining the correlation between several physical tree parameters such as diameter at breast height, tree trunk height, total tree height, crown diameter, tree type, and so on. The equation that was published in 2014 was used to estimate aboveground carbon biomass as the most appropriate pantropic model because it establishes a relationship between DBH, height, and wood density [10]. Furthermore, this model performs well across forest types and bioclimatic conditions of the pantropical region where it is based on an extensive data set, where there are approximately 4004 trees with diameter greater than 5 cm from 58 sites worldwide [11]:

$$\text{ABG} = 0.673 * (p\text{D}^2\text{h})^{0.976} \quad (1)$$

Where p = density of tree (g cm^{-3}), D^2 = square root of DBH (cm) and h = height of the tree (m).

3. Results and discussions

The three forest treatments consist of 46 trees in old-growth forest, 100 trees in natural regeneration, and 93 trees under active restoration. Overall, the composition of these 239 comprises of 17 genera and 34 families, with 83 trees belong to the Dipterocarpaceae (Table 2). Comparing the current census with the data recorded in the same plots in 2015, the 2015 census enumerated 335 trees, of which 124 trees were encountered in the old-growth forest, 87 trees in the natural regeneration plot, and 124 trees in the active conservation plot. The maximum DHB recorded as in Table 3. In Table 4 shows the rate of the tree growth and it is increase 2 times compared to the height in 2015 by average. As for the mortality rate per forest treatment are 13.2%, -1% and 3% for old-growth forest, active restored and natural regeneration as shows in Table 5 for the 7 years.

Table 2. List of family names of the total trees involved in census 2022.

Family Names	Tree numbers
Dipterocarpaceae	83
Annonanceae	19
Meliaceae	15
Euphorbiaceae	13
Lauraceae and Malvaceae	11 for each family name
Rhizophoraceae	10
Lythraceae	8
Polygalaceae	6
Fagaceae, Myrtaceae and Rubiaceae	5 for each family name
Sapindaceae and Tetramelaceae	4 for each family name
Ebenaceae, Lamiaceae, Magnoliaceae and Rutaceae and Sapotaceae	3 for each family name
Cornaceae, Dilleniaceae, Myristicaceae, Oleaceae, Symplocacea and Thymelaeaceae	2 for each family name
Anacardiaceae, Fabaceae, Irvingiaceae, Lecythidacea, Leguminosae, Myrsinaceae, Myrtaceae, Phyllanthaceae, and Verbenaceae	1 for each family name

Table 3. Rate tree growth based on forest type.

Forest type	Max value DBH recorded (cm)
Old-growth Forest	115
Active Restored	66
Natural Regeneration	105

Table 4. Rate of tree growth based on forest type.

Forest Type	Tree Height 2015 (m)	Average	Tree Height 2022 (m)	Average	Rate of growth
Old-growth Forest	2.6 – 16.7	5.9	8.5 – 42.9	21.5	2.6
Active Restored	1.2 – 15.8	5.2	5.9 – 35.2	18.3	2.6
Natural Regeneration	1.9 – 13.2	5.8	8.2 - 95	21.8	2.8

Table 5. Mortality rate based on forest type.

Forest type	No. of trees 2015	No. of trees 2022	Mortality rate
Old-growth Forest	124	46	13.2
Active Restored	87	93	-1.0
Natural Regeneration	124	100	3.0

3.1 Effect of DBH towards the biomass

Correlation coefficients measure the strength of the relationship between two variables. A correlation between variables indicates that as one variable changes in value, the other variable tends to change in a specific direction. Understanding that relationship is helpful because it can use one variable's value to predict the other variable's value.

Allometric relationships were examined for the underlying biomass estimation to see the correlation between the biomass and the DBH range, as shown in Figure 5. The results of biomass equations, it is independently fitted as it is suitable for the pantropical forest. Variables used in this equation are D, *p*, and H [10]. According to the results that have been done, the old-growth forest area has an R^2 value of 0.816 in year 2015 and 0.803 in year 2022. Meanwhile, the other graphs shows that R^2 = 0.836 and R^2 = 0.843 for the actively restored area whilst R^2 = 0.791 and R^2 = 0.905 for the natural regeneration area in 2015 and 2022, respectively. Regarding to the relationship, the data are in line with the correlation that has been published from the previous study. With this strong relationship, it accurately represents the best scenario to describe the entire data set.

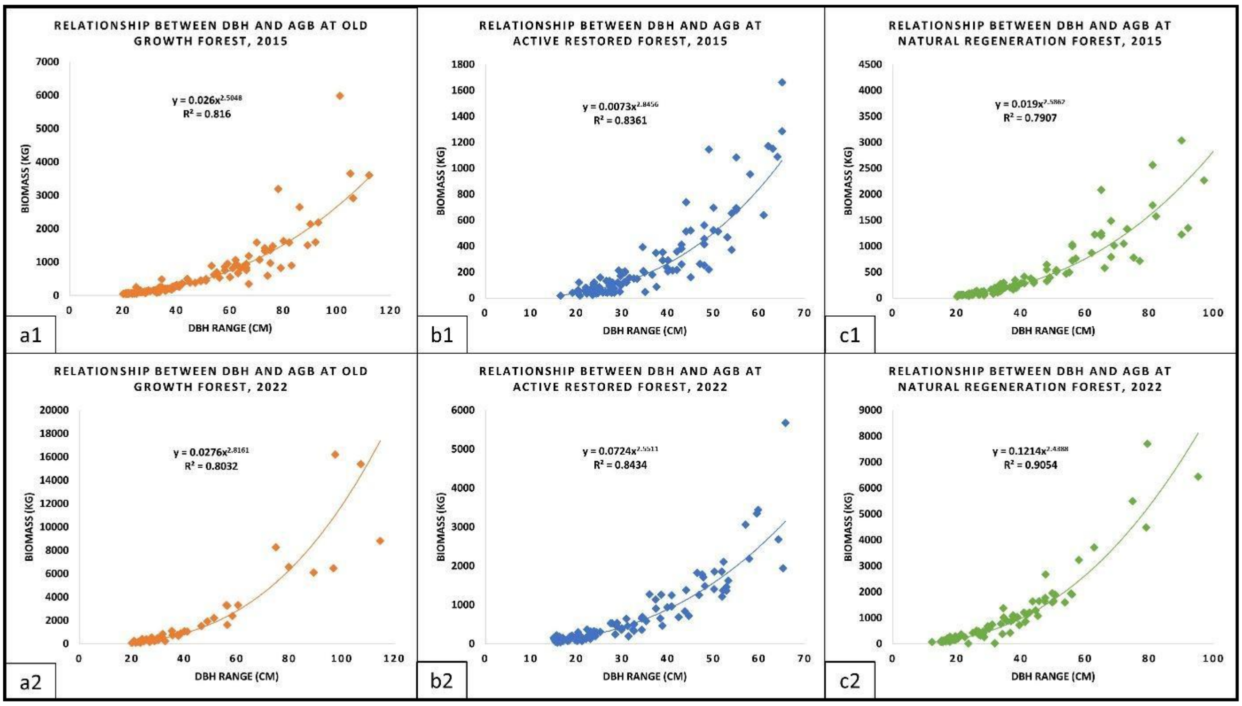

Figure 5. The relationship between DBH and AGB at (a1) old-growth forest 2015, (a2) old-growth forest 2022, (b1) active restored 2015, (b2) active restored 2022, (c1) natural regeneration 2015 and (c2) natural regeneration 2022.

3.2 Accumulation forest AGB across different treatment

Based on three different forest treatments, the carbon stock as biomass (kg) is increasing, as shown in Figure 6. Abrupt carbon stock increases due to the positive correlation between DBH and biomass. Increasing the DBH value will lead to a higher value of biomass. This can be seen through the carbon stock increased from 35278.59 to 47432.61 kg for the old-growth forest, 13575.30 to 34061.18 kg for active restored, and 23151.24 to 40116.00 kg for the naturally regenerated forest. The trend is increasing over time. As the trend increases, it shows that actively restored sequester more carbon than the other two treatments. It increases by 151% more carbon stock from the year 2015 whilst the old-growth forest increased by 34% and natural regeneration increased by 73% (Figure 7).

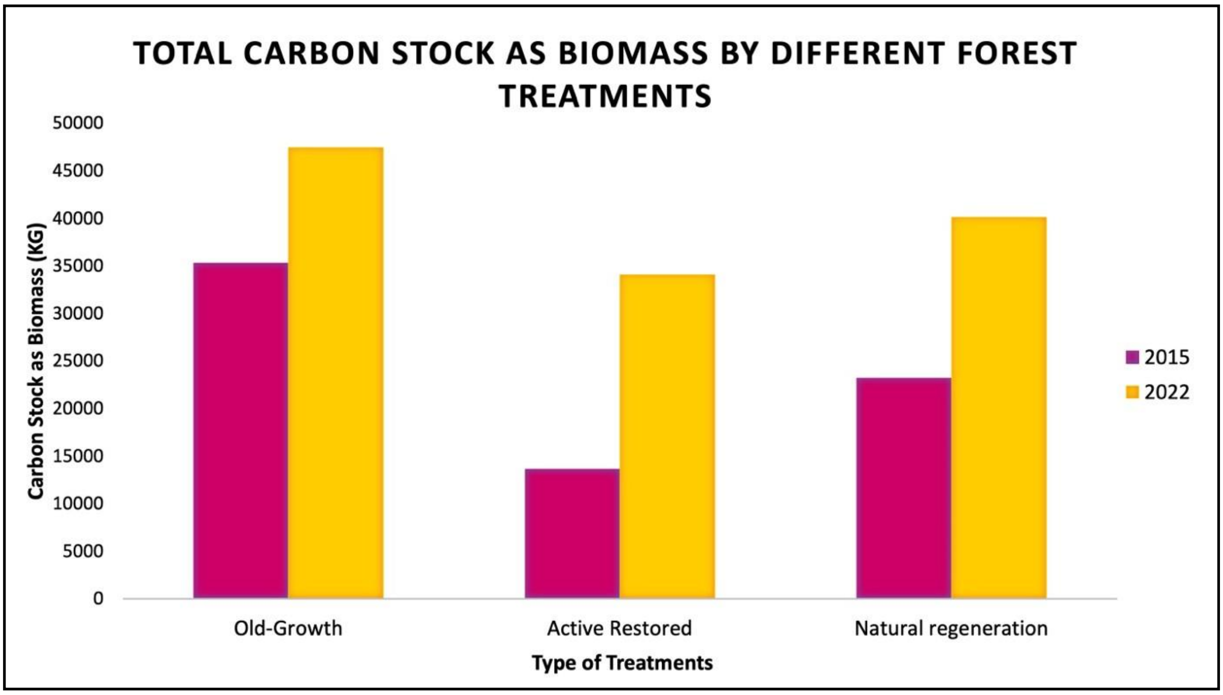

Figure 6. Total carbon stock as biomass (kg) by different forest treatments where the colour is the indicator of the different year.

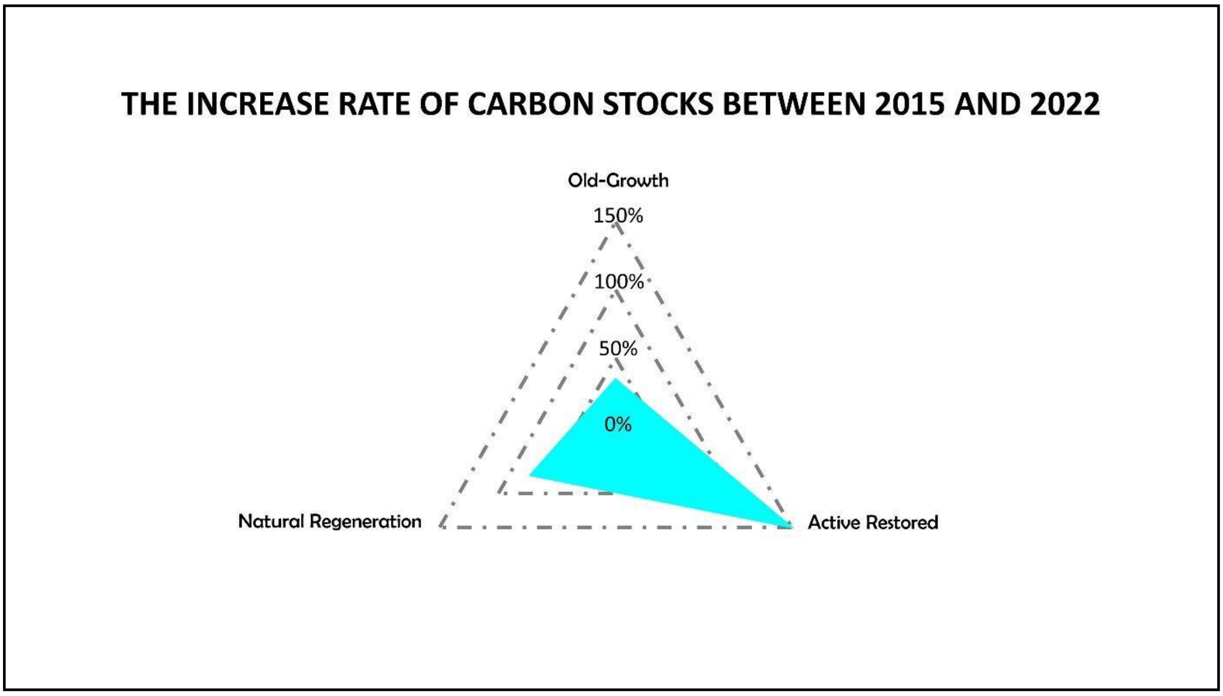

Figure 7. The increase rate of carbon stocks between 2015 to 2022 for different treatment methods.

4. Conclusion

The result of this study indicates an apparent different carbon stock increase towards the different treatments of a forest. It is due to the factor of forest growth during 2015-2022. The AGB can be calculated accurately using an allometric equation fitting the pantropical forest. The overall correlation between the DBH and the biomass shows a high relationship of ≥0.79 to ≤0.91 for the old-growth forest, active restored, and natural regeneration, respectively. It also shows that active restoration increases up to 151% carbon stock, which can be the best solution for forest treatment. The outcome of this study will increase the ability of forest authorities and the Malaysian government to adequately monitor carbon stock for establishing reliable standard guidelines in measuring deforestation and forest degradation toward achieving sustainable forest management.

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