

## Aboveground Carbon Stock Estimation in Different Forest Density Classes of the Nosar Protected Forest, Central Aceh Regency

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### ABSTRACT

Forests play an essential role in maintaining ecosystem balance through their ability to absorb and store carbon. Through the process of photosynthesis, forests absorb carbon dioxide (CO<sub>2</sub>) from the atmosphere and store it in the form of vegetation biomass. The forest's capacity to store carbon is strongly influenced by vegetation density. The denser an area is, the greater its biomass and carbon storage potential. This study aims to estimate the average carbon stock based on vegetation density levels in the Nosar Protected Forest, Bintang Subdistrict, Central Aceh Regency, using the Normalized Difference Vegetation Index (NDVI) method. Data were obtained from Sentinel-2 MSI Level-2A satellite imagery analysis and validated through field measurements using 15 observation plots with three vegetation density classes: moderate, dense, and very dense. Aboveground biomass was estimated using the allometric equation from SNI 7724:2011, assuming that carbon content is 0.47 of the total biomass. The results show that the highest average carbon stock was found in areas with very dense vegetation (33.82 ton ha<sup>-1</sup>), followed by dense areas (18.24 ton ha<sup>-1</sup>), and moderate areas (12.68 ton ha<sup>-1</sup>). The overall average carbon stock was 24.03 ton ha<sup>-1</sup>, with a total carbon stock of 22,037.02 tons C in the study area

**Keywords:** Carbon Stock Estimation; Aboveground Biomass; NDVI; Field Validation; Protected Forest; Sentinel-2 MSI; Vegetation Density; Allometric Equation; Forest Carbon Accounting; Climate Change Mitigation.

### 1. Introduction

Forests play a crucial role in maintaining ecological balance, serving both as a source of natural resources and as a carbon sink. Through photosynthesis, forests absorb carbon dioxide (CO<sub>2</sub>) from the atmosphere, thus playing an important role in regulating the global carbon cycle and mitigating climate change [1]. However, the increasing emission of greenhouse gases caused by human activities has made the estimation of forest carbon stocks essential to understanding forests' capacity for carbon sequestration and their contribution to climate change mitigation efforts. Population growth in Aceh Province has significantly driven land-use expansion, particularly for agriculture, plantations, and settlements. This condition has exerted considerable pressure on forest areas, leading to a continuous decline in forest cover. According to [2], from 1997 to 2023, Aceh Province lost approximately 664,379 hectares of forest converted into plantations and non-productive lands. Such massive land-use change not only reduces areas with high vegetation density but also decreases forests' ability to store carbon.

The Nosar Protected Forest in Central Aceh Regency is one of the protected forest areas covering 809.81 hectares, located in Bintang Subdistrict, Central Aceh. This area faces threats of land-use conversion due to its strategic location near residential areas. Nosar Protected Forest has a high diversity of vegetation types, consisting mainly of mixed forests and natural pine forests. Variations in forest types lead to differences in vegetation density, which directly affect the amount of carbon stock stored [3].

The Normalized Difference Vegetation Index (NDVI) is a type of vegetation index used to measure vegetation density and assess plant health [4]. This indicator is influenced by ground cover, vegetation type, and density

levels. NDVI provides an efficient way to monitor spatial variations in vegetation density and estimate carbon stocks based on satellite-detected vegetation coverage. The carbon stock estimated through NDVI analysis is then validated using conventional measurements based on allometric equations. This research is important to determine the forest ecosystem's quality and capacity to absorb carbon emissions and to support climate change mitigation efforts. Through carbon inventory, the forest's contribution to providing environmental services as a carbon reservoir can be better understood.

### 1.1. Study Objectives

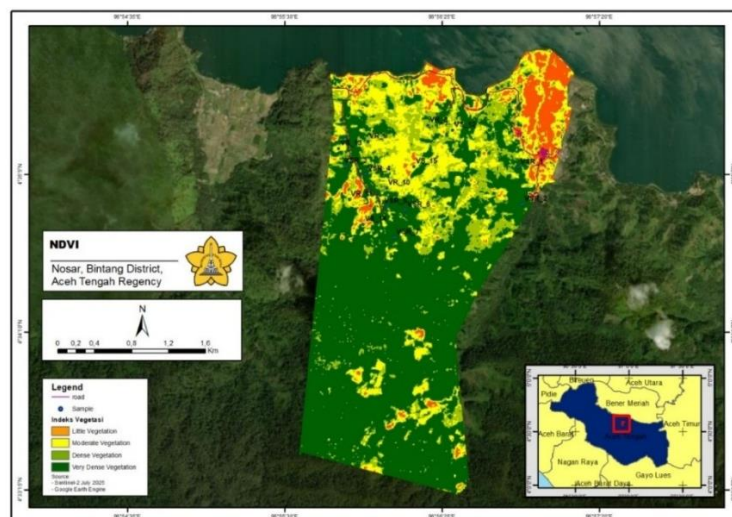
The objectives of this study were:

1. To estimate aboveground biomass across vegetation density classes in the Nosar Protected Forest using NDVI.
2. To analyze differences in carbon stocks across vegetation density classes.
3. To assess the contribution of dominant tree species to total carbon storage.
4. To quantify total carbon stocks at the landscape scale of the Nosar Protected Forest.
5. To support sustainable forest management policies through aboveground carbon stock assessment in the Nosar Protected Forest.

## 2. Materials and Methods

### 2.1. Site description

Biomass and carbon stock data were collected in the Nosar Protected Forest area, located in Bintang Subdistrict, Central Aceh Regency (Figure 1). This study was conducted from August 2025 to September 2025.



**Figure 1.** Research Location and Vegetation Density Appearance of Nosar Protected Forest

### 2.2. Tools and Materials

The tools used in this study were: Sentinel-2 imagery, PlantNet software, NDVI, tally sheets, GPS (Global Positioning System), Microsoft Excel, compass, phi band, clinometer, camera, stationery, measuring tape, and plot rope. The objects used in this study were seedlings, saplings, poles, and trees.

### 2.3. Stand Sampling Technique

The field data collected included plot coordinates, tree species, and tree diameter. Data collection was carried out through direct field surveys to determine the plot locations and record their coordinates using a Global Positioning System (GPS). Measurements were conducted at three growth stages with different plot sizes: 20 × 20 m for the tree stage (diameter > 20 cm), 10 × 10 m for the pole stage (diameter 10–20 cm), and 5 × 5 m for the sapling stage (diameter < 10 cm and height > 1.5 m) [5].

A sampling intensity of 1% is widely applied in forest carbon stock assessments and has been demonstrated to provide reliable biomass estimates in heterogeneous tropical forests [6]. The number of sample plots was calculated by multiplying the sampling intensity percentage by the total forest area, then dividing it by the area of each observation plot. Based on the calculation results, a total of 15 observation plots were obtained. These plots were classified according to vegetation density levels: moderate (4 plots), dense (4 plots), and very dense (7 plots)

### 2.4. Biomass

Tree biomass can be calculated using the allometric equation established in SNI 7724:2011 on the Measurement and Calculation of Forest Carbon Stock [SNI] [7].

$$AGB = 0.0912 \times DBH^{2.2}$$

Description:

AGB = Aboveground biomass (kg)

DBH = Tree diameter (cm)

$$C = AGB \times 0.47$$

Description:

C = Carbon content of litter organic matter (kg);

AGB = Total biomass/organic matter (kg);

0.47 = Percentage of carbon content [8].

### 2.5. Normalized Difference Vegetation Index

The NDVI value is obtained through a mathematical combination of the Near-Infrared (NIR) and Red bands reflected by vegetation. This study was conducted in the Nosar Protected Forest, located in Bintang Subdistrict, Central Aceh Regency, using Sentinel-2 Level 2A imagery processed in Google Earth Engine. The data were acquired in July 2025 and further processed (layouting) in ArcGIS 10.8 [9].

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Description:

NDVI = the Normalized Difference Vegetation Index (dimensionless);

NIR = the near-infrared reflectance band;

Red = the red reflectance band.

The measurement of carbon stock in this study was conducted only in areas with moderate, dense, and very dense vegetation classes. This is because in areas with low vegetation density, no vegetation with stand growth stages such as saplings, poles, or mature trees was found that could be used for biomass estimation. The low-density class was generally dominated by shrubs, grasses, and other types of understory vegetation [19].

**Table 1.** NDVI Value Classification

No.	NDVI Value Range	Description
1	-0.32 – 0.45	Low density
2	0.45 – 0.70	Moderate density
3	0.70 – 0.80	Dense
4	0.80 – 0.95	Very dense

### 3. Results and Discussion

#### 3.1. Species Composition

The stand structure and species composition at the study site were analyzed based on the number of individual trees of each species at three growth stages, including trees, poles, and saplings. Overall, the observation results of the stand characteristics are presented in Table 2.

**Table 2.** The composition in the Nosar Protected Forest, Central Aceh District

No.	Types Name	Family	Latin Name	Phases			
				Sapling	Pole	Tree	Amount
1	Pungkeh	Ulmaceae	<i>Ulmus lancefolius</i>	7	1	0	8
2	Kruing	Dipterocarpaceae	<i>Dipterocarpus retusus</i>	2	1	0	3
3	Damar	Dipterocarpaceae	<i>Hopea dryobalanoides</i>	9	9	5	23
4	Gala-Gala Rube	Moraceae	<i>Ficus racemosa</i>	1	0	0	1
5	Tarap	Moraceae	<i>Artocarpus odoratissimus</i>	0	1	4	5
6	Seumantok	Dipterocarpaceae	<i>Shorea sp.</i>	2	0	0	2
7	Beringin	Moraceae	<i>Ficus benjamina</i>	2	2	0	4
8	Jati Putih	Lamiaceae	<i>Tectona grandis</i>	6	3	3	12
9	Balik Angin	Moraceae	<i>Ficus sp.</i>	7	8	3	18
10	Pagar Anak	Fagaceae	<i>Quercus sp.</i>	1	0	1	2
11	Rambutan	Sapindaceae	<i>Nephelium lappaceum L.</i>	1	0	0	1
12	Macang	Anacardiaceae	<i>Mangifera foetida</i>	4	0	1	5
13	Durian	Malvaceae	<i>Durio zibethinus</i>	7	3	3	13
14	Karsen	Muntingiaceae	<i>Muntingia calabura</i>	0	3	1	4
15	Sukun	Moraceae	<i>Artocarpus altilis</i>	0	0	2	2
16	Pinus	Pinaceae	<i>Pinus merkusii</i>	43	6	4	53
17	Gesing	Fagaceae	<i>Lithocarpus sp.</i>	1	0	0	1
18	Kemiri	Euphorbiaceae	<i>Aleurites moluccana</i>	2	2	2	6
<b>Total</b>				<b>95</b>	<b>39</b>	<b>29</b>	<b>163</b>

Based on Table 2, a total of 18 plant species belonging to 11 families with 163 individual trees across all growth stages were recorded. The stand structure in the Nosar Protected Forest, Bintang Subdistrict, Central Aceh Regency, showed that the forest vegetation was dominated by the tree stage with 95 individuals, followed by the pole stage with 39 individuals, and the sapling stage with 29 individuals. This indicates that the forest condition in the study area still exhibits good vegetation growth, with the dominance of trees at the mature stage suggesting that the forest structure has developed toward a mature stand.

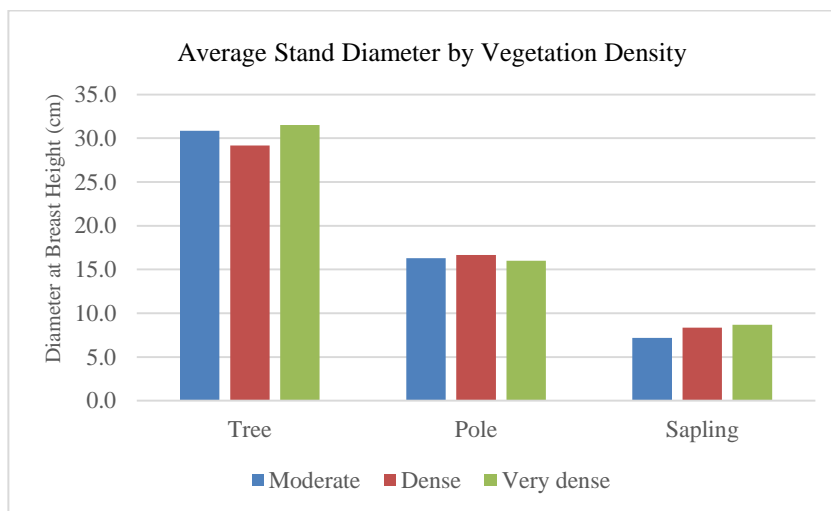
The most abundant species found was *Pinus merkusii* from the Pinaceae family, with a total of 53 individuals. *Pinus merkusii* is a common species in the mountainous areas of Central Aceh, including the Bintang Subdistrict, which lies at an elevation of approximately 1,225 meters above sea level [10]. The Aceh population of *Pinus merkusii* represents the largest of the three Sumatran pine varieties and grows naturally at elevations above 1,000 meters above sea level [11]. The local community around the Nosar Protected Forest utilizes pine trees for resin extraction, which has significant economic value. Meanwhile, several species, such as *Ficus racemosa*, *Nephelium lappaceum* L., and *Lithocarpus* sp. were found with only one individual each.



**Figure 2.** Condition of the area with moderate vegetation density (a), dense vegetation density (b), and very dense vegetation density (c)

The analysis results showed that in areas with moderate and dense land cover, the dominant vegetation species was *Pinus merkusii*, with the highest number of individuals, 14 in the moderate cover area and 25 in the dense cover area. In the very dense cover area, the dominant species was *Hopea dryobalanoides* (Damar) with a total of 19 individuals. Based on field measurements, the average tree diameter in the moderate cover area was 30.8 cm, while in the dense cover area it was 29.2 cm. Tree diameter plays an important role in determining the amount of stored biomass and carbon, as larger diameters correspond to greater wood volume and higher carbon storage capacity within plant tissues [12].

This species belongs to the Dipterocarpaceae family, which generally dominates lowland tropical rainforests in Southeast Asia. The presence of species from the Dipterocarpaceae family indicates that the Nosar Protected Forest has high potential as a carbon storage area. Species from this family can grow with large diameters and heights and possess high biomass, enabling them to store substantial amounts of carbon [13].



**Figure 3.** Average Diameter of Forest Stands Based on Vegetation Density

### 3.2. Biomass Estimation

The largest carbon storage in forest stands is found in the aboveground portion in the form of tree biomass. The stored carbon stock represents the amount of carbon absorbed by plants and retained in the form of biomass [14]. The estimated aboveground biomass for each stand type is presented in Table 3.

**Table 3.** Recapitulation of Biomass Based on Vegetation Density

Vegetation Strata	Biomass ton ha <sup>-1</sup>			Total
	Very Dense	Dense	Moderate density	
Pancang	77.78	22.42	16.81	117.01
Tiang	114.87	22.91	21.52	159.29
Pohon	311.04	109.90	69.58	490.52
<b>Total</b>	<b>503.69</b>	<b>155.22</b>	<b>107.90</b>	<b>766.82</b>
Number of Plots	7	4	4	15
<b>Average</b>	<b>71.96</b>	<b>38.81</b>	<b>26.98</b>	<b>51.12</b>

The analysis of biomass based on vegetation density levels showed differences among the vegetation density types. The highest total biomass was found in the very dense vegetation area, amounting to 503.69 ton ha<sup>-1</sup>, followed by the dense area with 155.22 ton ha<sup>-1</sup>, and the moderate area with 107.90 ton ha<sup>-1</sup>. This indicates that the higher the vegetation density, the greater the amount of biomass stored in the area.

At the tree stratum level, the highest biomass was also found in the very dense area, reaching 311.04 ton ha<sup>-1</sup>, while in the dense area it was 109.90 ton ha<sup>-1</sup>, and in the moderate area 69.58 ton ha<sup>-1</sup>. The dominant tree biomass value in the very dense area shows that the vegetation composition in this area is dominated by large-diameter and high-density tree species such as *Pinus merkusii* and species from the Dipterocarpaceae family. Diameter is the most influential variable in determining biomass content. This finding is consistent with the study by Mardhotillah et al. [15], which stated that there is a strong relationship between biomass and tree diameter, where biomass increases proportionally with an increase in tree diameter.

### 3.3. Carbon stocks

The carbon content within a given pool represents the carbon stock calculated based on biomass. The calculation of carbon stock in the Nosar Protected Forest area was carried out using the formula from SNI 7724:2011, assuming that the carbon concentration in organic matter or biomass is 47%. Therefore, the estimated amount of stored carbon was obtained by multiplying the biomass value by a factor of 0.47. The summary of carbon stock per species is presented in Table 4.

**Table 4.** Recapitulation of Carbon Stocks on Vegetation Density

Vegetation Strata	Carbon stocks (ton ha <sup>-1</sup> )			Total
	Very Dense	Dense	Moderate	
Sapling	36.56	10.54	7.90	54.99
Pole	53.99	10.77	10.11	74.87
Tree	146.19	51.65	32.70	230.54
<b>Total</b>	<b>236.73</b>	<b>72.96</b>	<b>50.72</b>	<b>360.40</b>
Number of Plots	7	4	4	15
<b>Average</b>	<b>33.82</b>	<b>18.24</b>	<b>12.68</b>	<b>24.03</b>

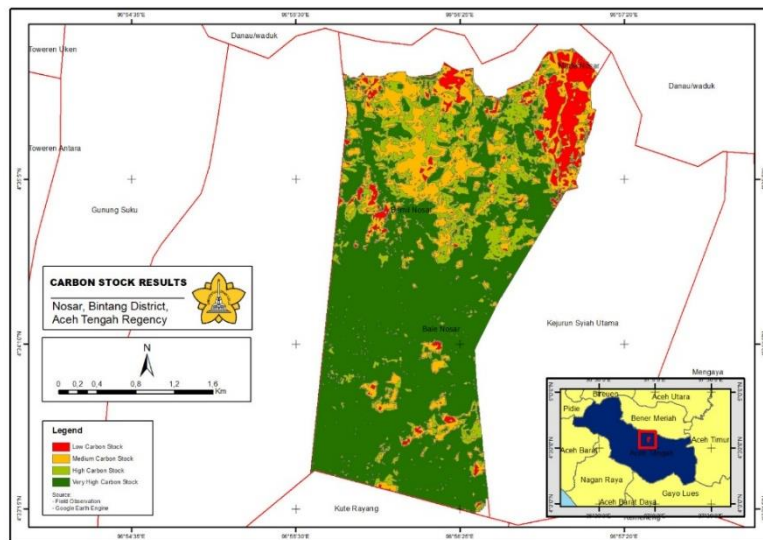
The analysis of carbon stock based on vegetation density levels showed that the very dense vegetation area had the highest carbon stock, amounting to 236.73 ton ha<sup>-1</sup>, followed by the dense area with 72.96 ton ha<sup>-1</sup>, and the moderate area with 50.72 ton ha<sup>-1</sup>. The average carbon stock across all plots was 24.03 ton ha<sup>-1</sup>.

Among vegetation strata, the tree stratum contributed the largest portion of total carbon stock, reaching 146.19 ton ha<sup>-1</sup> in the very dense vegetation area, while the pole and sapling strata contributed 53.99 ton ha<sup>-1</sup> and 36.56 ton ha<sup>-1</sup>, respectively. The dominance of large-diameter tree species, particularly those from the Dipterocarpaceae family, substantially contributes to higher biomass and carbon stocks in very dense vegetation areas. However, the use of NDVI-based approaches may lead to saturation effects in very dense canopies, potentially underestimating biomass in closed forests. Therefore, the integration of NDVI with field-based measurements, as applied in this study, is essential to improve estimation accuracy. The relatively low carbon stock value in areas with low vegetation density was due to the dominance of small-diameter trees and the presence of open spaces between stands. Biomass and carbon stocks in forest ecosystems are strongly influenced by factors such as tree diameter and vegetation density [17].

The calculation of carbon stock using the NDVI method by Mosa et al. [18] in the utilization zone of Mount Halimun Salak National Park (GHSNP) showed that the average carbon stock in the area reached 61.64 ton ha<sup>-1</sup>, with the highest value found in the high vegetation density class at 66.56 ton ha<sup>-1</sup>. This average value is lower than that obtained in the Nosar Protected Forest. The difference is mainly due to the use of different allometric equations, where Mosa et al. applied an allometric model that considered wood density.

Based on the summary in Table 5, the total carbon stock in the study area reached 22,037.02 tons C, distributed across three vegetation density levels. The very dense vegetation area contributed the highest carbon stock,

amounting to 17,562.86 tons C with an area of 519.32 ha, while the dense and moderate vegetation areas stored 2,595.03 tons C and 1,879.13 tons C, respectively. These results indicate that vegetation density level significantly influences the amount of carbon stock. The denser and larger the forest area, the greater the potential for carbon storage within the ecosystem.



**Figure 4.** Carbon Stock Distribution Map

**Table 5.** Total Carbon Stock in the Nosar Protected Forest Area

Vegetation Density	Area (ha)	Carbon Stock (tonC)	Percentage (%)
Very Dense	519.32	17.562.86	79.7
Dense	142.28	2.595.03	11.8
Moderate	148.21	1.879.13	8.5
<b>Total</b>	<b>809.81</b>	<b>22.037.02</b>	<b>100</b>

#### 4. Conclusion

The results of the study show that the level of vegetation density has a significant effect on the amount of carbon stock in the Nosar Protected Forest area. Areas with very dense vegetation have an average carbon stock of 33.82 ton ha<sup>-1</sup>, followed by dense areas with 18.24 ton ha<sup>-1</sup>, and moderate areas with 12.68 ton ha<sup>-1</sup>. The overall average carbon stock is 24.03 ton ha<sup>-1</sup>, with the largest contribution coming from very dense vegetation, accounting for 79.7% of the total carbon stock. This indicates that variations in stand diameter and vegetation density significantly influence the estimated carbon stock results. The findings highlight the critical role of very dense forest stands in maintaining carbon storage capacity and supporting climate change mitigation efforts. The distribution of carbon stocks provides valuable information for forest conservation planning and REDD+ implementation. Protecting areas with high vegetation density should be prioritized to maintain ecosystem services and enhance long-term carbon sequestration potential. The following future studies be investigated:

- 1) Incorporating wood density-based allometric equations to improve biomass estimation accuracy.
- 2) Applying multi-temporal methods analyze carbon stock dynamics over time.

- 3) Expanding carbon assessment to include belowground biomass and soil carbon pools.
- 4) Developing species-specific biomass models for dominant forest species.
- 5) Conducting long-term monitoring to support climate mitigation and REDD+ programs.

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#### **Competing Interests Statement**

The authors have declared that no competing financial, professional or personal interests exist.

#### **Consent for publication**

All the authors contributed to the manuscript and consented to the publication of this research work.

#### **Availability of data and material**

Supplementary information is available from the authors upon reasonable request.

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