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Estimation of Litter Carbon Stock in the Nosar Protected Forest, Bintang District, Central Aceh Regency

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ABSTRACT

Protected forests play a crucial role in climate change mitigation through their capacity to store carbon. Litter, as one of the essential components of forest ecosystems, contributes significantly to the total carbon stock. This study aims to estimate the amount of litter biomass and carbon content in the Nosar Protected Forest, Bintang District, Central Aceh Regency. Litter sampling was conducted in August 2025 using the destructive sampling method within designated measurement plots. The collected samples were then analyzed in the laboratory to obtain dry weight and ash content for calculating biomass and carbon concentration. The results showed that the total litter carbon stock in the Nosar Protected Forest reached 1,144,312.95 kg, with the largest contribution originating from areas with very dense vegetation, amounting to 855,895.90 kg or 74.8% of the total carbon stock in the area. Vegetation density was found to influence the amount of litter and carbon storage capacity, where higher vegetation density resulted in greater carbon reserves.

Keywords: Biomass Estimation; Litter Carbon Stock; Organic Carbon Content; Vegetation Density; Protected Forest; Forest Floor; Climate Change Mitigation; Carbon Sequestration; Tropical Forest; REDD+.

1. Introduction

The increasing concentration of greenhouse gases (GHGs) in the atmosphere has become an urgent global environmental issue, largely driven by human activities, particularly the use of fossil fuel–based energy. In Indonesia, the energy sector is the largest contributor to emissions, accounting for 56% of total national emissions in 2020 [1]. In this context, forests serve as invaluable providers of ecosystem services, especially in climate change mitigation efforts. Forests act as the "lungs of the Earth," absorbing carbon dioxide (CO_2) from the atmosphere through the process of photosynthesis [2].

The absorbed carbon is then stored in various forest biomass components, including stems, leaves, roots, litter, and soil. Litter, a layer of decomposing vegetation on the forest floor, not only plays an important role in nutrient cycling but is also a key component of carbon storage [3]. Litter functions as a medium- to long-term carbon reservoir, reinforcing the role of forests as natural carbon sinks and storage systems.

The Nosar Protected Forest in Central Aceh Regency, Aceh Province, has significant potential for carbon storage to support climate change mitigation. However, this area faces threats of land-use change that may release stored carbon into the atmosphere. Unfortunately, data on carbon storage potential in this forest, particularly from the litter component, remain very limited or even unavailable. Such data are essential to demonstrate the role of the Nosar Protected Forest in climate change mitigation and to serve as a basis for policy-making.

Therefore, this study aims to quantify the litter biomass and carbon stock in the Nosar Protected Forest. The results are expected to provide fundamental scientific data that can be used as a reference for future research in the

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Central Aceh region. Information on litter carbon stock is crucial to support planning and implementation of the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program in Indonesia.

1.1. Study Objectives

The objectives of this study were:

1. To estimate the litter biomass in the Nosar Protected Forest.

2. To quantify litter carbon stock across different vegetation density classes.

3. To analyze the relationship between vegetation density and litter carbon storage.

4. To assess the contribution of litter to total forest carbon stock.

5. To provide baseline data for climate change mitigation and REDD+ implementation.

2. Materials and Methods

2.1. Location and Time

The study site was conducted at the Nosar Protected Forest, Bintang District, Central Aceh Regency (Figure 1). Geographically, the research area was situated at coordinates 4°34.873' N and 96°56.205' E, with an elevation ranging from 1,390 to 1,570 meters above sea level. The topography of the area was predominantly characterized by moderately steep slopes. This study was conducted from July to August 2025.

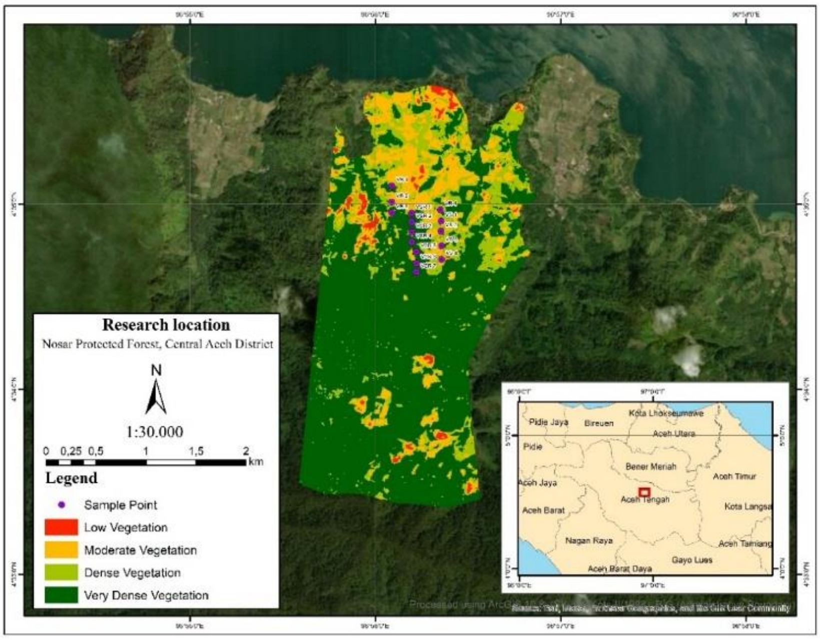

Figure 1. Research Location

2.2. Methods

2.2.1. Data Collection

Litter sampling was carried out by establishing measurement plots within the study area. All litter components (fallen leaves, twigs, flowers, and fruits) found inside the plots were collected. The collected samples were then transported to the laboratory for further analysis. Litter biomass was calculated using the destructive sampling method, in which the samples were oven-dried at a controlled temperature until reaching a constant weight (dry weight). A total of 15 litter samples were collected from 2 × 2 m plots, categorized based on vegetation density classes.

2.2.2. Environmental Characteristics Measurement

Environmental characteristics were measured in each observation plot representing different levels of vegetation density. The ecological parameters measured included elevation, air temperature, air humidity, soil moisture, and soil pH. Elevation was measured using a Global Positioning System (GPS) and expressed in meters above sea level (m asl). Air temperature and air humidity were measured using a digital thermo-hygrometer placed approximately ±1.5 m above the ground surface in each plot. Soil moisture was measured using a soil moisture meter at a depth of 0–20 cm, representing the soil layer where litter accumulation commonly occurs. Soil pH was measured using a soil pH meter by inserting the electrode into the soil at the same depth (0–20 cm).

2.2.3. Biomass Calculation

The calculation of organic matter content in the litter followed the formula issued by the National Standardization Agency (Badan Standardisasi Nasional) [4].

Bo = Bks x Bbt/Bbs

Description:

Bo = Organic matter weight (kg);

Bks = Dry weight of the sample (kg);

Bbt = Total fresh weight (kg);

Bbs = Fresh weight of the subsample (kg).

2.2.4. Carbon Stock Calculation

Forest carbon stock refers to the amount of carbon stored within vegetation, which can be quantified through biomass estimation [5]. The calculation of carbon derived from dead organic matter in litter was carried out using the following formula [6]:

Cs = Bo x % C organic

Description:

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

Bo = Total biomass/organic matter (kg);

%C organic = Percentage of carbon content, valued at 0.47

3. Results and Discussion

3.1. Characteristics of the Study Site

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Environmental characteristics at each vegetation density level represent essential baseline information for understanding the biophysical conditions of the study site. Factors such as elevation, air temperature, relative humidity, soil moisture, and soil pH can influence ecological processes within forest ecosystems [7]. The environmental characteristics of the Nosar Protected Forest based on vegetation density levels are presented in Table 1.

Table 1. Environmental Characteristics at Different Vegetation Density Levels

Density	Plot	Elevation (m asl)	Air Temperature (°C)	Air Humidity (%)	Soil Moisture (%)	Soil pH
Very Dense	1	1,510	25.6	67.0	75	6.0
	2	1,451	25.2	68.0	72	6.5
	3	1,488	24.7	70.0	78	6.1
	4	1,525	25.5	66.8	72	6.4
	5	1,561	22.0	75.0	75	7.0
	6	1,628	24.2	70.2	75	6.7
	7	1,645	25.0	66.3	65	6.8
Dense	1	1,435	26.5	62.8	67	6.3
	2	1,435	25.8	67.0	65	6.1
	3	1,396	26.2	64.2	67	6.2
	4	1,517	26.6	63.2	72	6.2
Moderate	1	1,517	28.3	55.0	68	7.0
	2	1,593	27.2	60.0	65	6.8
	3	1,657	27.6	58.8	70	6.4
	4	1,727	27.8	57.5	68	6.5

Based on Table 1, the Nosar Protected Forest exhibits variations in environmental conditions influenced by differences in elevation, which range from 1,510 to 1,727 meters above sea level. These elevation differences directly affect air temperature, recorded between 22.0 and 28.3 °C, and relative humidity, which ranges from 55% to 75%. Plots categorized as "very dense" show higher air and soil moisture compared with the "moderate" density category, indicating that denser vegetation cover is more capable of intercepting solar radiation and reducing water loss through evaporation. Elevation and vegetation structure serve as primary regulators of microclimate conditions, including local temperature and humidity [7].

Soil moisture in the Nosar Protected Forest ranges from 65% to 78%, with the highest levels observed in the "very dense" plots, indicating better water retention due to canopy protection and lower evaporation intensity. Meanwhile, soil pH values range from 6.0 to 7.0, categorized as slightly acidic to neutral conditions generally optimal for microbial activity and nutrient availability for plants. Neutral pH conditions also indicate fertile soil, as most nutrients remain in forms readily absorbed by vegetation [8].

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(a) (b) (c)

Figure 2. Vegetation conditions in the Nosar Protected Forest area (a), litter sampling process (b), and litter drying process (c)

3.2. Biomass

Litter is an important component of mixed forest ecosystems because it plays a role in maintaining soil fertility, supporting decomposition processes, and sustaining nutrient availability for vegetation. The continuous production and decomposition of litter contribute to increasing soil organic matter [9]. Litter biomass calculations in the Nosar Protected Forest, based on vegetation density levels, are presented in Table 2.

Table 2. Litter Biomass by Vegetation Density Class in the Nosar Protected Forest

Density	**Number of plots**	**Bbt (kg)**		**Bbs (kg)**		**Bks (kg)**		**Biomass (kg ha^{-1})**	
		Total	$\bar{x}$	**Total**	$\bar{x}$	**Total**	**Total**	**Total**	$\bar{x}$
Very Dense	7	6.03	0.86	2.10	0.30	1.80	0.26	12,848.6	1,835.5
Dense	4	2.77	0.69	1.20	0.30	1.08	0.27	6,227.8	1,556.9
Moderate	4	1.87	0.47	1.20	0.30	1.08	0.27	4,216.3	1,054.1

Notes: Bbt (total fresh weight), Bks (dry weight of the sample), Bbs (fresh weight of the sample), $\bar{x}$ (average).

Based on Table 2, the average litter biomass in the very dense vegetation category is 1,835.5 kg ha^{-1}, in the dense category is 1,556.9 kg ha^{-1}, and in the moderate category is 1,054.1 kg ha^{-1}. Differences in average biomass values across density levels are influenced by the varying quantities of litter found within each plot. The higher the vegetation density in an area, the more litter is produced, resulting in greater litter biomass.

This finding aligns with [9], who stated that biomass potential is strongly influenced by the amount of biomass generated by forest stands within a given area. Stands with high density produce denser canopies, more branches, and more leaves, thereby increasing litter production.

The amount of litter obtained at each vegetation density level is also affected by stand conditions, including the canopy size of the constituent vegetation. In areas with very dense vegetation, canopy cover is thicker and the spacing between trees is narrower compared with areas of dense and moderate vegetation. These conditions result in greater quantities of litter falling onto the forest floor in very dense plots. This observation is consistent with [10], who noted that differences in litter production are influenced by environmental conditions, forest quality, stand composition, and variations in canopy cover across different topographic settings.

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3.3. Carbon Stock

Litter accumulated on the forest floor becomes a carbon source that contributes to the increase in soil organic matter content and influences carbon stability and storage. The decomposition process of litter also regulates the rate of the carbon cycle, thereby affecting the overall carbon balance within forest ecosystems [11]. Litter biomass calculations in the Nosar Protected Forest based on vegetation density levels are presented in Table 3.

Table 3. Carbon Stock Based on Stand Density in the Nosar Protected Forest

Density	Area (ha)	Number of Plots	C (kg ha^{-1})		Total Carbon Stock in the Nosar Protected Forest (kg)
			Total	Mean	
Very Dense	466.30	7	12,848.6	1,835.52	855,895.90
Dense	116.84	4	6,227.8	1,556.95	181,911.36
Moderate	101.04	4	4,216.3	1,054.09	106,505.68
Total	**684.18**	**15**	**23,292.77**	**1,482.18**	**1,144,312.95**

Based on Table 3, the total carbon stock in the Nosar Protected Forest reaches 1,144,312.95 kg, with variations across the different vegetation density classes. In the very dense category, which represents the highest carbon stock, the carbon value reaches 1,835.52 kg ha^{-1}, yielding a total of 855,895.90 kg, or approximately 74.8% of the total carbon stock in the area. In the dense category, carbon stock per hectare is recorded at 1,556.95 kg ha^{-1}, resulting in a total of 181,911.36 kg, contributing around 15.9% of the overall carbon stock. Meanwhile, in the moderate category, carbon stock reaches 1,054.09 kg ha^{-1}, with a total of 106,505.68 kg, or about 9.3% of the total carbon stock in the Nosar Protected Forest.

The variation in carbon stock demonstrates that differences in vegetation density levels directly influence the forest floor's ability to store carbon. This finding is consistent with [12], who stated that the presence and availability of carbon reserves in a forest are affected by the density of the overlying stand; thus, the denser the vegetation, the greater the amount of carbon that can be stored.

Higher tree density can enhance soil carbon storage through increased inputs of litter and roots, as well as reduced soil respiration rates, resulting in soil carbon stocks in dense forests that may be up to 40% higher than those in forests with low stand density [12]. For example, a study conducted in the Negeri Soya forest in Ambon City reported that the carbon stock of a very dense primary forest reached 1,020.9 kg ha^{-1}, whereas the more open secondary forest stored only 415 kg ha^{-1} [13]. This indicates that the denser and more structurally complex a forest stand is, the greater its capacity to store carbon.

4. Conclusion

This study demonstrates that litter contributes significantly to the total carbon stock in the Nosar Protected Forest. The total litter carbon stock obtained was 1,144,312.95 kg, with varying distributions across different vegetation density levels. The very dense category contributed the largest amount, at 855,895.90 kg, followed by the dense category with 181,911.36 kg, and the moderate category with 106,505.68 kg. These differences indicate that the higher the vegetation density, the greater the amount of litter produced and the higher the carbon storage capacity. The following future research directions are suggested:

1) Future studies should examine the seasonal variation of litter production and carbon stock to better understand temporal dynamics in the Nosar Protected Forest.

2) Further research is recommended to analyze the decomposition rate of litter and its influence on long-term carbon sequestration.

3) Comparative studies across different forest types or protected areas are needed to evaluate whether similar patterns of litter carbon storage occur in other ecosystems.

4) Future research should incorporate soil carbon measurements to assess the relationship between litter input and soil organic carbon accumulation.

5) Investigations into the species composition and dominant vegetation are suggested to determine their specific contributions to litter quantity and carbon content.

6) The impact of anthropogenic disturbances and forest management practices on litter production and carbon storage should be explored to support sustainable forest conservation strategies.

Declarations

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Competing Interests Statement

The authors state that there are no competing interests associated with this research.

Consent for publication

The authors declare their approval for this study to be published.

Authors' contributions

All authors contributed equally to the literature review, data analysis, and manuscript preparation.

Availability of data and material

Additional supporting information can be obtained from the authors upon request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

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