Journal of Natural Resources and Environmental Management
http://dx.doi.org/10.29244/jpsl.15.6.995

RESEARCH ARTICLE

OPEN ACCESS

Check for updates

Ecological Index and Aboveground Biomass Carbon Value on Burn Swamp Forests After Rehabilitation

Sujarwo Sujatmoko[a], Muhammad Rum[b], Farida Herry Susanty[c], Susy Andriani[d], Mohamad Sopan[b], Muhammad Abdul Qirom[e]

[a] Directorate of Utilization of Environmental Services of Conservation Areas, Ministry of Forestry, Bogor, 16122, Indonesia
[b] PT Suprabari Mapanindo Mineral, Gedung Pamapersada II Lt. 3, Jatinegara, Jakarta, 13930, Indonesia
[c] Center for Sustainable Forest Development, Ministry of Forestry, Bogor, 16118, Indonesia
[d] Kalimantan Forest Fire Control Center, Landasan Ulin Timur, Kalimantan Selatan, 70721, Indonesia
[e] Center for Ecology and Ethnobiology Research, National Research and Innovation Agency, Build.B.J. Habibie, Jakarta Pusat, 10340, Indonesia

Article History
Received
11 September 2025
Revised
27 September 2025
Accepted 16 October 2025

Keywords
carbon, ecological value, peat swamp forest, rehabilitation

ABSTRACT

Rehabilitation efforts were conducted in 2018 and 2020 to restore, maintain, and enhance forest and land functions following the 2015 fire on forest area with special purpose (KHDTK) Tumbang Nusa, Central Kalimantan. This study aims to determine the characteristics of stand structure, quantitative ecological values, aboveground biomass values, and preliminary projections of rehabilitation plant valuation in post-fire peat forest ecosystems. Study area was conducted in two rehabilitation blocks in 5 and 7 years old after rehabilitation. Vegetation analysis employed a nested sampling method, utilizing a plot size of 60 x 60 m, with Block I contain three plots (27 subplots) and Block II containing eight plots (72 subplots). Vegetation inventory and four carbon pool measurements were carried out on the understorey, seedlings, saplings, poles, and trees. The stand density value in Block I is 379 stems ha^{-1} with a basal area of 21.18 m^2 ha^{-1}, while in Block II it is 503 stems ha^{-1} and 11.27 m^2 ha^{-1}. The stands have good ecological value and stable vegetation, with a medium-scale species diversity level (H' = 1.53–2.80), a low-scale species dominance level (D = 0.10–0.42), commonly a high species richness value (R = 3.07–6.01), and medium to high species evenness values. The composition of rehabilitation plants are similar, but Block I has a higher proportional basal area of 3.72%. The projection of aboveground carbon biomass is 70.7 ton ha^{-1} and 77.7 ton ha^{-1}, respectively. As a preliminary study, the effectiveness of the rehabilitation valuation approach can be assessed by the productivity and quantitative ecology.

Introduction

The biodiversity and potential of Southeast Asia's lowland forests have faced significant threats from deforestation over the years [1,2]. Degradation by forest fires in both dryland and wetland forests has a significant impact, not only on reducing forest cover but also on biodiversity loss. In particular, biodiversity comprising rare and endangered species, as well as high levels of plant endemism, is found in many types of forest ecosystems [2,3]. Each forest formation will have a different plant community composition due to varying environmental characteristics. The peatland ecosystem supports high biodiversity and provides essential socio-economic services to the local community, including the provision of timber and non-timber forest products, as well as livelihoods [4,5]. The impact of fires in peat forests poses even greater risks to the broader environment, both to wildlife and human health.

Forest quality assessments are conducted primarily using quantitative approaches based on various environmental parameters. In peat forests, hydrological and nutrient gradients are key factors for ecosystem stability [2,6]. To understand the condition of a healthy ecosystem, a holistic and comprehensive assessment is necessary. In conservation, the forest quality index is used to assess ecosystem health. In swamp forest

Corresponding Author: Farida Herry Susanty fhsusanty@gmail.com Center for Sustainable Forest Development, Ministry of Forestry, Bogor, Indonesia.

ecosystems, the condition can be assessed by examining the forest, soil, and hydrology [7]. A quantitative approach is used to assess key components of forest condition, ensuring the sustainability of its resources [5]. These forest quality assessment studies serve as a tool for managers in making decisions regarding the need for action to protect resources through aquaculture projects, rehabilitation, or restoration activities.

In 2015, peat fires occurred in Central Kalimantan, particularly within the Tumbang Nusa Special Purpose Forest Area (*Kawasan Hutan Dengan Tujuan Khusus*/KHDTK), resulting in the destruction of vegetation, reduced accessibility, and changes in forest cover. The scorched region was anticipated to surpass 2,749 hectares (ha), constituting 54.87% of the KHDTK territory [8]. This area features a peat swamp ecosystem that plays a crucial role in regulating peat hydrology, biodiversity, and carbon stocks. With peat depths ranging from 2 to 5 meters (m), the KHDTK area holds significant carbon reserves that must be maintained, which supports Indonesia's achievement of the 2030 FOLU (Forestry and Other Land Use) Net Sink target [9]. The FOLU Net Sink programs highlight the crucial role of peat forest areas in this region, emphasizing the need for their well-maintained conservation. To restore, maintain, and improve forest and land functions, thereby increasing carrying capacity, productivity, and their role in maintaining life support systems, rehabilitation activities are carried out after fires.

Many studies have been conducted on the diversity of tropical communities in peat swamp forests. However, investigations into the young growth or seedling stage and environmental influences in these unique forests are still lacking. Given the vulnerability of peat forests after fire, silvicultural inputs are needed to accelerate recovery [1,10]. A comprehensive formulation or tool for assessing the success of rehabilitation is still not available. Generally, it is only based on the percentage of growth. Projections for assessing rehabilitation effectiveness can be conducted quantitatively by considering multiple aspects of the stand. This study aims to determine the characteristics of stand structure, quantitative ecological values, aboveground carbon biomass values, and preliminary projections for valuing rehabilitated plants in post-fire peat forest ecosystems, based on potential and biodiversity aspects, in the Tumbang Nusa KHDTK.

Materials and Methods

Research Site

This research was conducted in the rehabilitation area of KHDTK Tumbang Nusa from January to May 2025. Geographically, it is located at 02°18'52.93" to 02°24'34.35" S and 114°0'58.27" to 114°06'39.72" E, which presented in Figure 1. By government administration, it is located in the Tumbang Nusa and Tanjung Taruna Village areas, Jabiren Raya District, Pulang Pisau Regency, Central Kalimantan Province. Additionally, it is part of the Forest Area Management Unit (*Kesatuan Pengusahaan Hutan Produksi*/KPHP) in the Kahayan Ilir area [8]. The topographic conditions of the Tumbang Nusa KHDTK are relatively flat, with an altitude ranging from 0 to 5 m above sea level and an elevation of between 0% and 18%. The location represents a landscape within a peat swamp forest, particularly in the Peat Hydrology Unit (*Kawasan Hutan Gambut*/KHG) 4 sub-unit, which is part of the Kahayan River-Sebangau River KHG. KHG is a peat ecosystem comprising all peat and minerals formed between two rivers that serve as reservoirs and regulators of water management, carbon storage, and areas where biodiversity thrives [11]. The water level generally ranges from 20 to 30 cm from the beginning of the year until June, but tends to decrease in July and October.

Design Plots

Sampling plots were constructed to collect quantitative ecological data and assess carbon biomass values in the vegetation of the rehabilitation area. Plot construction was carried out in rehabilitation areas implemented by PT Suprabari Mapanindo Mineral in 2018 (covering 200 ha) and 2020 (covering 600 ha). Sample plots were determined using a stratified purposive sampling method, where the watershed rehabilitation area was classified by planting year and area size. Based on previous studies and Landsat image analysis, more than 90% of the rehabilitation area has peat depths of more than 100 cm [8]. Therefore, most of the research locations are in the same tidal category. Three plots were established in planting year 2018, 7 years after rehabilitation (Block I), and eight sample plots were established in planting year 2020, 5 years after rehabilitation (Block II). Purposive plot placement was carried out across the Blocks and peat depths to obtain data on various forest conditions. The distribution of sampling plots is presented in Figure 1. The plot design was constructed for vegetation analysis, measurement, and observation, measuring 60 × 60 m, and included a sub-sampling of 20 × 20 m. For carbon biomass measurement, in addition to the measurement data from the allometric vegetation sampling plot, data collection was also carried out using the destructive (direct) method. Understorey and litter sampling data were collected on three subplots in each sampling plot.

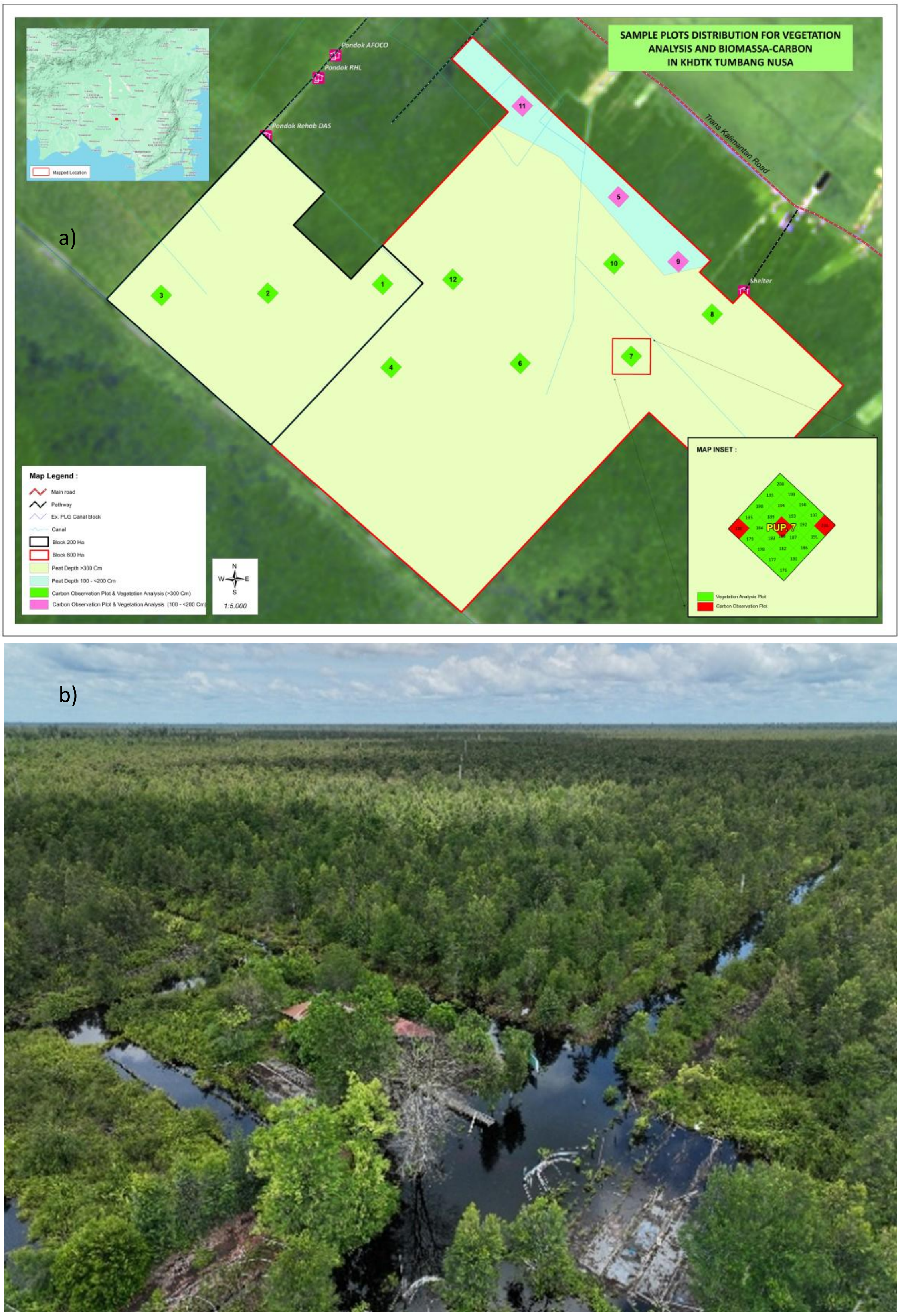


Figure 1. Study site in KHDTK Tumbang Nusa with a) Distribution of sampling plots for collecting vegetation ecology data and carbon measurement, and b) the condition of the rehabilitation area. This figure illustrated the allocation of plots measuring 60 × 60 m, containing subplots of 20 × 20 m. The allocation of the plots at the rehabilitation site in 2018 and 2020. Frequent fires and the presence of artificial waterways characterize the restoration area.

Method

Quantitative Ecological Vegetation

Quantitative ecological vegetation analysis data collection was carried out using multi-stage stand sampling inventory [8,9], including: (a) seedling, bush, shrub stage with category of height < 1.5 m on subplot sized 2 × 2 m; covering data: plot no, sub plot number, plant number, species, quantity; (b) sapling stage that has category of height > 1.5 m and diameter < 10 cm or circumference < 31.4 cm with subplot sized 5 × 5 m; covering data: plot number, sub plot number, plant number, species name, circumference (cm); (c) pole and tree stage that has category diameter ≥ 10 cm or circumference ≥ 31.4 cm with subplot sized 20 × 20 m, covering data: plot number, subplot number, tree number, species name, circumference (cm). An inventory for each growth stage is conducted by census within the plot. The data analysis carried out includes calculating the productivity parameters, such as density and dominancy basal area of the stand, thus biodiversity parameters, as: Shannon Diversity Index, Simpson Dominance Index, Margalef Species Richness Index, and Evenness Index [12,13], with the following formula:

$$Density\ (K) = \frac{Number\ of\ individuals\ of\ a\ species}{Total\ area\ of\ sample\ plots} \quad (1)$$

$$Dominancy\ (D) = \frac{Basal\ area\ of\ a\ species}{Total\ area\ of\ sample\ plots} \quad (2)$$

$$Shannon\ diversity\ index\ (H') = -\sum_{i=1}^{s}\left(Pi \times In(Pi)\right) \quad (3)$$

where: $\mathrm{Pi} = \frac{\mathrm{ni}}{\mathrm{N}}$ and $\mathrm{N} = \sum_{\mathrm{i}=1}^{\mathrm{s}} \mathrm{ni}$

$$Simpson's\ Dominance\ Index\ (D) = \sum(Pi)^2 \quad (4)$$

where: ni = number of individuals of the i-th species; N = number of individuals of all species.

$$Margalef\ Species\ Richness\ Index\ (R_{Mg}) = \frac{S-1}{Ln\ N} \quad (5)$$

where: N = total number of individuals of the species; S = number of species.

$$Evenness\ Index\ (E) = \frac{H'}{H'max} \quad (6)$$

where: H'max = Ln S; S = number of species.

Carbon Measurement and Accounting

Four carbon pool calculations were carried out, namely understorey [shrub, seedlings], polish, trees, and litter. The aboveground biomass extraction is adjusted to the vegetation category. Vegetation categories are divided into four classes: understorey and seedlings (diameter < 2cm), saplings (diameter between 2cm and < 10 cm), poles (diameter between 10 cm and < 20 cm), and trees with a diameter ≥ 20 cm [14]. The data measurement uses the same plot and data for the vegetation inventory. For litter and understorey carbon pool measurement presented on Figure 2. The calculations for aboveground biomass (AGB) carbon pools for poles and trees were performed using allometric equations, based on the species or species group for which the measurement data were available [15].

The calculation of carbon from vegetation biomass using the Biomass Conversion and Expansion Factor (BCEF) based on IPCC 2006 [16], following the formula:

$$Cv = Bov \times \%C - organic/BCEF \quad (7)$$

where: Cv = carbon content of vegetation biomass (kg); Bov = total vegetation biomass (kg/ton); %C organic/BCEF = percentage value of carbon content, calculated using the percentage value of carbon obtained from the laboratory analysis results.

For the understorey and litter carbon pools, measurements were conducted through laboratory analysis. The measurement of the carbon content in organic material samples is performed through carbonization. Carbonization is the process of converting research samples into ash using the pyrolysis method [17]. The carbonization process occurs optimally when the temperature ranges from 400 to 600 °C. Samples are oven-dried for 24 hours at 105 °C for dry weight data, then taken in quantities of ± 1 to 2 grams for the ash process. The sample ash process uses a furnace for 4 hours at a temperature of 600 °C. Calculation of total carbon stocks in the measurement plot using the following formula:

$$Cplot = Ctrees + Cpoles + Clitter + Cunderstorey \quad (8)$$

where: Cplot = total carbon content (ton ha^{-1}); Ctrees = total carbon content of trees stage per hectare (ton ha^{-1}); Cpoles = total carbon content of poles stage per hectare (ton ha^{-1}); Cunderstorey = total carbon content of understorey stage including shrub and seedling per hectare (ton ha^{-1}); Clitter = total carbon content of litter per hectare (ton ha^{-1}).

Figure 2. Sampling plot for data measurement of a) the litter carbon pool and b) the understorey carbon pool. The sampling area was 2 × 2 m for litter and understorey. The data collected was destructive, with harvesting litter and understorey, then weighing the sample using a scale with an accuracy of 0.1 g.

Analysis Multivariate

To compile a preliminary assessment of rehabilitation effectiveness, a technical assessment approach was used to assess the quality of stands formed after the activity [5]. The research was based on two parameters for stand potential and four parameters for biodiversity. An assessment of rehabilitation valuation was conducted by responding to the parameters of structure and biodiversity in peat forest stands using a multivariate analysis with a Principal Component Analysis (PCA) approach, by calculating the covariance matrix, correlation matrix, and thus analysis factor by Kaesar Meyer Olkin (KMO) value with Bartlett's test [18]. A multivariate data visualization method is used to display the relationship between objects and variables in two dimensions or to visualize the distribution of parameters, carried out using bi-plot analysis in Minitab.

Results and Discussion

Results

Stand Structure

The vegetation analysis results were conducted based on two conditions or activity blocks, representing different rehabilitation years. The rehabilitation areas have varying land cover conditions and fire severity levels. The area is dominated by heavy brush with a low severity level. The proportion of areas with light brush cover or high severity reached 481.4 ha, or 80.2%, in the area five years after rehabilitation, and 152.8 ha, or 76.4%, in the area five years after rehabilitation. The following are the structural values of the stands in KHDTK Tumbang Nusa, respectively, for the seedling, sapling, pole, and tree stages (Table 1). According to the stand structure in the peat swamp forest, the classification of pole and tree stage stands is grouped into one analysis. Based on the average values, the stand rehabilitated seven years ago (Block I) shows a higher potential for land cover, as indicated by a greater basal area, compared to the stand rehabilitated five years ago (Block II). While the density of saplings is similar in both blocks, the density of poles and trees is lower in the younger block (Block II). This indicates that the older stand is more dominated by larger-dimensional individuals with bigger diameters. The proportion of rehabilitation plants reveals that both areas have a similar density value of approximately 0.20%. However, the basal area value is significantly higher in the older block (3.72% of total stand) than in the younger one (0.09%). This confirms that the older rehabilitation area has more developed vegetation structure despite a similar number of plants.

Table 1. Stand structure based on value of stand density, basal area, and number of species in different-aged rehabilitation areas on a peat swamp forest. The tables showed various growth stages and differences in stem averages on Block I and Block II which presented the aged of rehabilitation area. In Block II as younger aged of rehabilitation is higher than Block I in terms of total density and basal area. The proportion of the rehabilitation plant is lower than that of natural regeneration.

Location (aged after rehabilitation)	Plot	Growth stage	Diameter		Stems	Basal area	Number of species	Average	
			min	max				Stems ha^{-1}	m^2 ha^{-1}
Block I (7 years)	1	Seedling	-	-	148	-	17	73,611	-
		Sapling	0.1	9.8	139	0.2	30	3,600	16.15
		Poles & Trees	10	65	133	2.13	21	379	5.03
	2	Seedling	-	-	279	-	16		
		Sapling	0.5	9.54	63	0.79	9		
		Poles & Trees	10.18	77.67	155	1.96	6		
	3	Seedling	-	-	368	-	18		
		Sapling	0.6	8.7	41	0.1	9		
		Poles & Trees	10.19	20.06	121	1.34	4		
		Total							21.18
		Rehabilitation plant						119 (0.20%)	0.79 (3.72%)
Block II (5 years)	1	Seedling	-	-	96	-	12	42,083	-
		Sapling	0.3	9.8	77	0.12	19	3,078	3.86
		Poles & Trees	9.55	48	147	2.77	32	503	7.41
	2	Seedling	-	-	178	-	15		
		Sapling	0.4	9.2	145	0.2	22		
		Poles & Trees	10.19	56.02	316	4.88	14		
	3	Seedling	-	-	125	-	17		
		Sapling	0.2	9.1	71	0.07	15		
		Poles & Trees	10.19	24.19	166	1.93	8		
	4	Seedling	-	-	180	-	8		
		Sapling	0.2	9.5	30	0.02	8		
		Poles & Trees	10	107	86	2.03	2		
	5	Seedling	-	-	190	-	14		
		Sapling	0.2	9.2	81	0.07	7		
		Poles & Trees	10.19	18.78	89	1.06	3		
	6	Seedling	-	-	208	-	12		
		Sapling	0.4	9.3	55	0.04	10		
		Poles & Trees	10.03	23.24	94	1.5	4		
	7	Seedling	-	-	131	-	11		
		Sapling	1.1	8.2	61	0.11	7		
		Poles & Trees	9.87	53	271	3.49	9		
	8	Seedling	-	-	104	-	14		
		Sapling	2.1	7.2	34	0.065	9		
		Poles & Trees	9.87	37	279	3.67	12		
		Total							11.27
		Rehabilitation plant						89 (0.19%)	0.01 (0.09%)

Comparison of density and basal area in each plot across two stand categories for each growth stage will be dynamic within the stand. The distribution pattern of stand density values formed at the sapling, pole, and tree levels will be similar in areas with different rehabilitation ages. Meanwhile, the distribution pattern of basal area values at these growth levels will tend to differ (Figure 3). Based on the average value, stands aged 7 years after rehabilitation have higher density at the seedling, pole, and tree stages than younger-aged areas. The sapling stage is similar in both blocks, with a range of 50 to 150 stems per block. Additionally, at the pole and tree stages, density variation ranges from 100 to 300 stems per hectare. Based on basal area values, the older rehabilitation-aged area is dominated by younger growth (sapling stage). This result is thought to be influenced by the initial condition of the stand due to varying fire intensities.

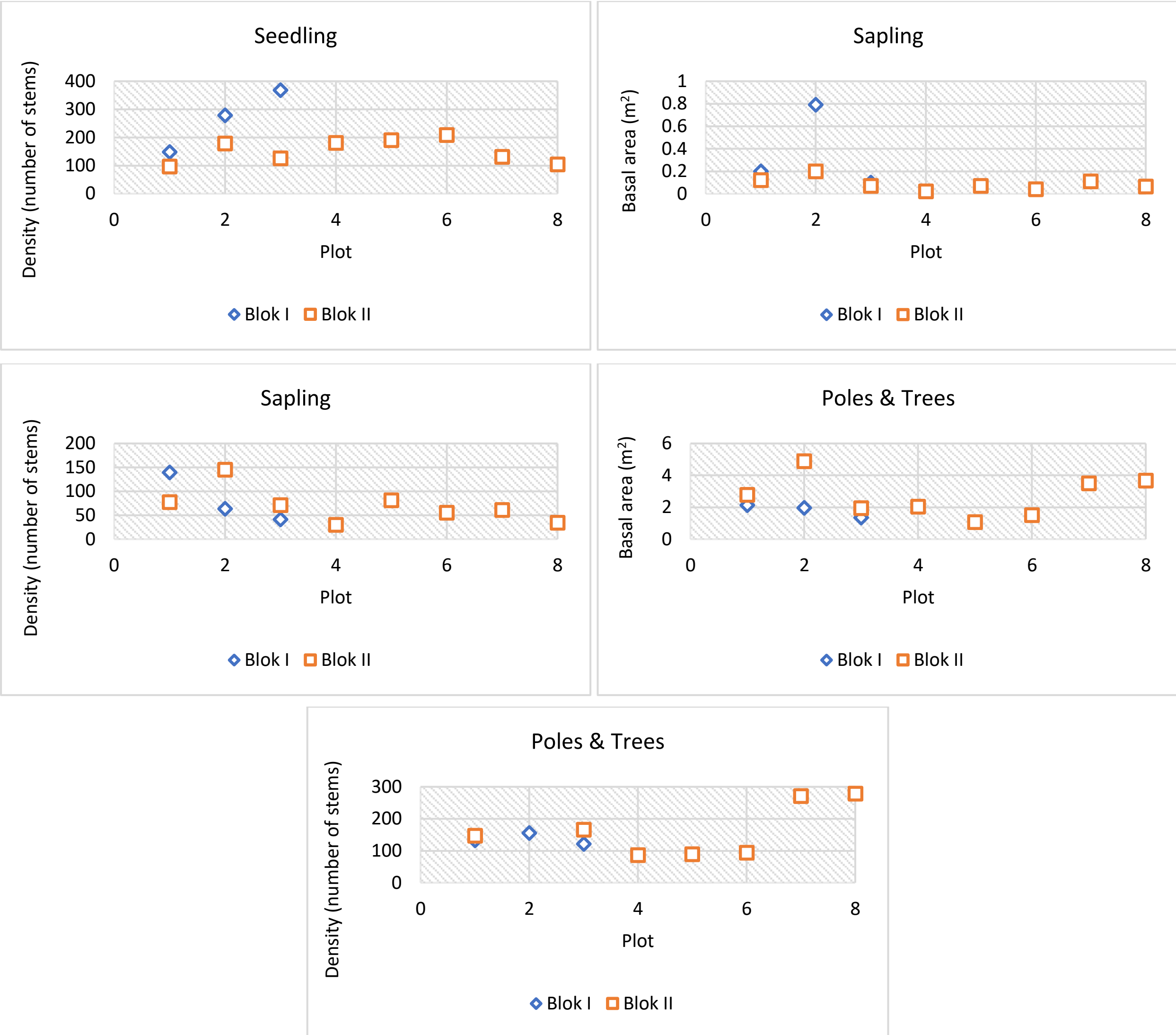


Figure 3. Distribution of stand density (number of stem) and basal area value (m^2) of the seedling, sapling, poles and tree stage stand on different ages 5 and 7 years after rehabilitation. The pattern of basal area and density is consistent. In low-density blocks and growth phases, the basal area is correspondingly low, and vice versa. The density at the seedling level in block I as older aged of rehabilitation area is significantly greater than that in block II.

Biodiversity Ecologically Quantitative

The index of diversity and richness of vegetation composition indicates the improvement of forest conditions after fire. Valuation of rehabilitated areas after 5 years and 7 years is shown based on the quantitative ecological value, respectively presented in the value of Shannon Diversity Index, Simpson Dominance Index, Margalef Species Richness Index, and Evenness Index presented in Figure 4. The assessment of the biodiversity aspect shows that at all growth levels in Blocks I and II by category classes [9,10]. It tends to have a diversity index value in the 'moderate' category (1 < H < 3) and tends to be high in young growth (sapling stage). The distribution of species dominance in the area is relatively even among the existing species, with a low dominance index value, especially at the young growth stage. While at the pole and tree stage, the stand structure has been observed to form with a dominance pattern in the moderate category. The species richness index value, as determined by the Margalef Index, generally has a high category value (R > 5.0) for all growth stages. The pattern of community structure and its stability, based on the species evenness index value, falls into a moderate category (E 0.3–0.6) for the poles and trees stage. Then, to the high-value category (E > 0.6) for younger growth stages (seedling and sapling) [8,9]. It indicates that the community is more resistant to environmental changes and more stable.

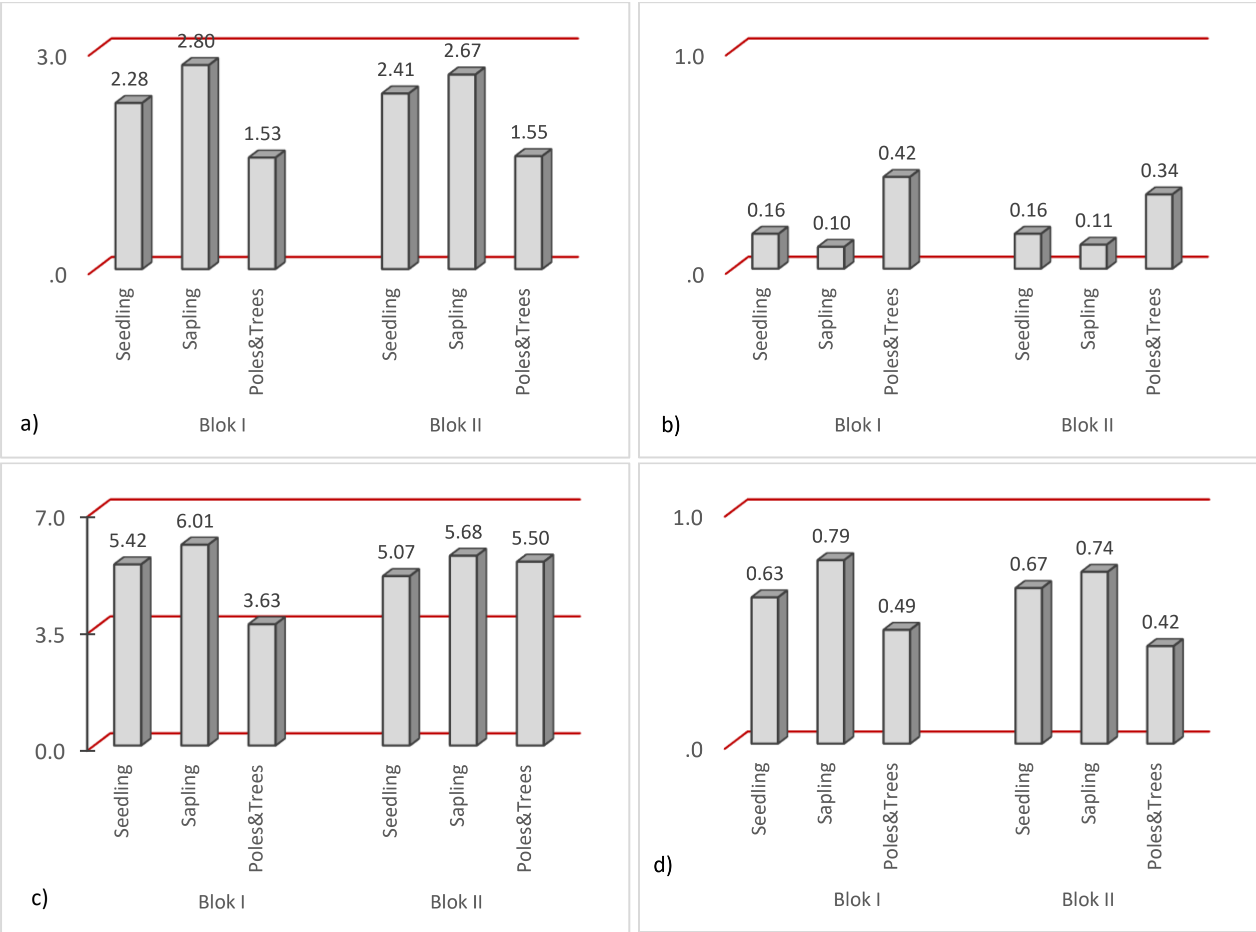


Figure 4. Biodiversity ecological index covering a) Shannon-Wiener Index (H'), b) Simpson Index, c) Margalef Index, and d) Evenness Index of the seedling, sapling, poles and tree stage stand on different-aged trees after rehabilitation. The growth stages of poles and trees consistently exhibited lower heterogeneity by Shannon-Wiener Index and evenness Index relative to other regeneration rates across all rehabilitation locations. Low dominance for all stage growth in the stand. It tends to remain consistent for the general regeneration rate by Margalef Index value, with the exception of trees and poles in block I.

Potential Carbon Value

Assessment of the improvement of the condition of the area after being rehabilitated based on the potential content of carbon biomass distributed in several carbon pools, especially above the surface of the peat swamp forest. This study encompasses carbon pools at all levels, including stands and litter. The results of the calculation of the potential carbon content in the rehabilitated area are presented in Table 2. The average total potential carbon on two study sites with different ages after rehabilitation has a similar value. However, 5 years after rehabilitation (in the younger age group), the yield had a wide range, with values of 36.2–135.8 ton ha^{-1}, compared to the older age group after rehabilitation (Block I), which had values of 57.2–92.3 ton ha^{-1}. This indicated that in older-aged areas after rehabilitation, the carbon potential showed no further fluctuation according to density and basal area values, resulting in a more stable stand.

Table 2. Carbon potential (ton ha^{-1}) in different-aged areas after rehabilitation in a peat swamp forest. Vegetation is the primary contributor to aboveground biomass. Litter carbon pools exceed understory carbon pools at all rehabilitation locations. Poles and trees are the primary contributors to aboveground biomass carbon reservoirs in vegetation, contingent upon their growth stage.

Location (aged after rehabilitation)	Carbon pools	Number of plots (ton ha^{-1})								Average (ton ha^{-1})
		1	2	3	4	5	6	7	8	
Block I (7 years)	Sapling	35.6	14.4	29.0						26.4
	Poles & Trees	42.9	40.9	23.3						35.7
	Litters	10.9	3.6	2.1						5.6
	Understorey	2.9	3.5	2.8						3.0
	Total	92.3	62.4	57.2						70.7
Block II (5 years)	Sapling	23.6	38.2	40.4	13.1	8.0	2.5	19.3	11.3	19.6
	Poles & Trees	56.1	92.2	34.8	17.6	26.6	59.9	62.2	63.3	51.6
	Litters	3.9	3.5	2.6	3.5	2.7	2.8	11.8		4.4
	Understorey	0.7	1.9	2.6	2.0	2.7	3.3	1.8		2.1
	Total	84.3	135.8	80.4	36.2	40	68.5	95.1	74.6	77.7

Projected Stand Valuation After Rehabilitation

The rehabilitation effectiveness assessment approach was conducted using multi-parameter stand valuation based on multivariate analysis. The results of the multivariate analysis on the response parameters of structure and biodiversity in peat forest stands are presented in Table 3 to 5, indicating a high similarity pattern for all parameters across the two different condition areas. In this research, the results were based on cumulative variance exceeding 80% and an eigenvalue greater than 1 [18,19], indicating that all parameters can be expressed by two principal components (as shown in the scree plot). The analysis factor, as indicated by the KMO value and Bartlett's test of PCA, was 0.5. The variables analysis indicated that the adequacy of the research data is not acceptable. This is possible because data from monitoring ages 5 and 7 years after rehabilitation were not yet strong enough to formulate a valuation. These results indicate the need for additional measurement data based on variations or ranges of forest conditions, additional parameters or longer measurement times to meet the specified validity standards.

Table 3. Analysis result of covariance matrix and correlation matrix on productivity and ecology parameters by principal component analysis. The values in the covariance matrix indicate that the direction and magnitude of the variability of the two variables which are productivity and ecology parameters are quite wide, while the values in the correlation matrix indicate that the closeness of the direction of the standard linear relationship between the variables is very high.

Covariance matrix			
	Block I	Block II	
Block I	300.39	164.49	
Block II	164.49	93.91	
Correlation matrix[a]			
Correlation		Block I	Block II
	Block I	1	0.98
	Block II	0.98	1

a. Determinant = 0.041

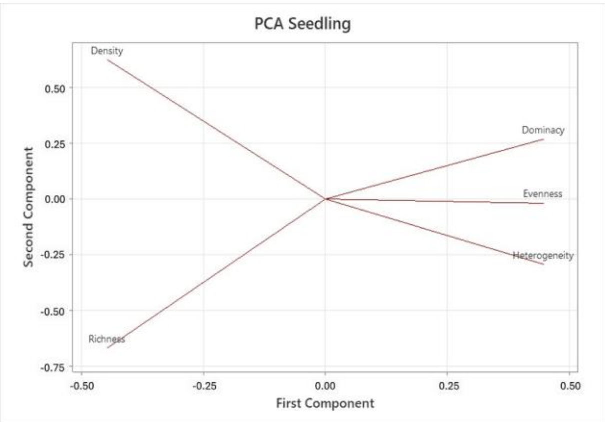
Table 4. KMO and Bartlett's test result of ecology parameters by principal component analysis. The Measure of Sampling Adequacy (MSA) value of 0.50 and the Bartlett's Test significance value (p-value) < 0.01 indicate that the variables compiled have minimum sufficient shared variance (correlation) to conduct principal component analysis. In an ecological context, this KMO value is not yet significant, so the measured ecological parameters may not be sufficiently interrelated to be grouped into fewer and more meaningful principal components.

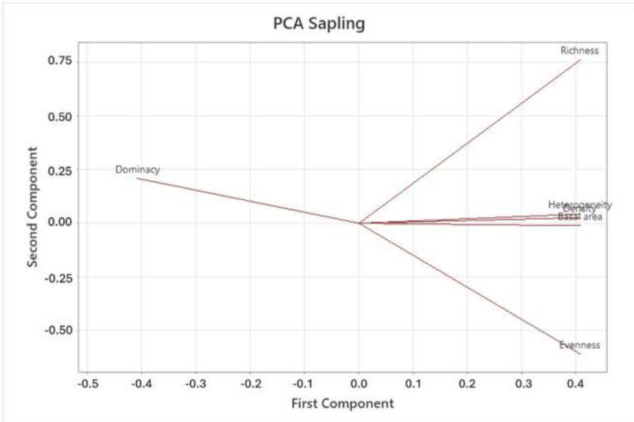
Kaiser-Meyer-Olkin measure of sampling adequacy.		0.50
Bartlett's test of sphericity	Approx. chi-square	49.58
	df	1
	Sig.	<.001

Table 5. Analysis result of total variance explained value of ecology parameters by principal component analysis. The percentage value of the total diversity (variation) for productivity and ecological parameters in the original data set that can be explained or captured by the principal components (PC) formed.

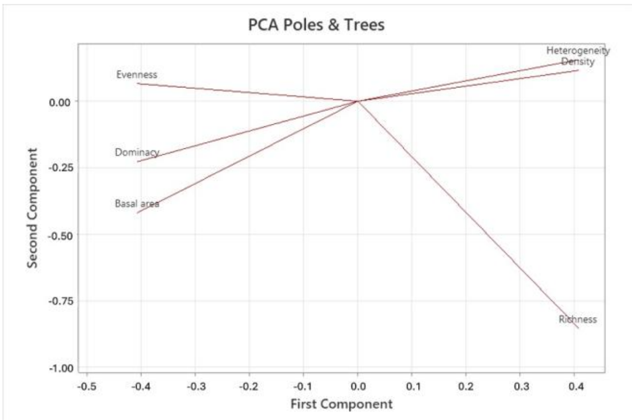
Component	Initial eigenvalues			Extraction sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	1.98	98.97	98.97	1.98	98.97	98.97
2	0.021	1.03	100			

Based on the results of PCA, the distribution trends of structure and ecologically relevant biodiversity parameters are built for each growth stage. With bi-plot analysis, the parameters tend to be divided into two clusters for all growth stages (Figure 5). The clusters consist of ecologically relevant parameters, including structure and biodiversity. For the seedling, pole, and tree stages, a similar pattern of clustering is observed. Based on the trend of parameters, distance, indicated dominance, evenness, and heterogeneity indices can be used to describe the seedling stage. For the sapling stage, parameters that can be described are density, basal area, and heterogeneity index. Meanwhile, the density and heterogeneity index can be described for poles and tree stages. This result shows that the biodiversity ecologically parameter plays a central role in valuing the young growth. For the next growth stage (for poles and trees), both parameters have important values.





(a) (b)



(c)

Figure 5. Cluster analysis result of structure and biodiversity ecological parameters for the rehabilitation area of a) seedling; b) sapling and c) poles and trees stage on the peat swamp forest. Matrix visualization of multivariate productivity and ecological component data for each growth stage of stand into a two-dimensional graph demonstrates the identification of similarities between objects, correlations between variables, and overall data distribution. The proximity between parameters, shown graphically and forming clusters, indicates similar characteristics based on the measured variables.

Discussion

The structure and potential of stands, as measured by density and basal area, differ between the two research Blocks. This shows that the impact of rehabilitation on the former fire area in the peat swamp forest is heading in a positive direction. Based on the comparison of the two rehabilitation ages, a pattern of forest improvement after the fire is shown. At an older rehabilitation age, there will be structural improvements, biodiversity stability, and a higher carbon content. The influence of the time of recovery of damaged forests is an important factor in the recovery function [20–22]. The time of recovery plays a crucial role in determining the success and sustainability of forest rehabilitation following disturbance or degradation. The recovery period represents the duration needed for ecological processes such as regeneration, nutrient cycling, and biomass accumulation to reestablish equilibrium within the forest ecosystem. The longer the time allowed for natural or assisted recovery, the greater the opportunity for structural complexity, species diversity, and ecological functionality to be restored. Restoring peat swamp forests after degradation is important because they are more vulnerable compared to dryland forests [22,23]. The vulnerability factors of peat swamp forests do not only include the condition of their flora and fauna.

Additionally, there is a possibility of a gap in the growth rate of forest stands. If this happens, there will be a gap or even a loss of regeneration of the typical constituent species. Forest fire factors result in a longer recovery time compared to other forms of forest degradation [24,25]. The species diversity in both planting blocks was limited, with fewer than 50 tree species present at all stages of regeneration. Fires resulted in a decline in species diversity and richness in peat swamp ecosystems. The low species diversity resulted from the frequency and severity of fires occurring in peatlands. Volkova's research showed a strong correlation between fire frequency and natural peatland recovery after fire. Peatland recovery time was extended in regions experiencing repeated fires relative to those affected by a single fire [21]. The condition of stand species diversity after fire will influence the development of species diversity levels. In this study, the unavailability of stand data immediately after logging limited the testing of fire age projections on diversity values. In cases of species loss or endangerment due to degradation, rehabilitation through replanting with selected species may be necessary to restore biodiversity. However, planting every species that once existed in the area is impractical. Forest restoration does not need to be limited to native species alone; incorporating well-selected and stable species can enhance the restoration process more effectively than relying solely on natural recovery [26].

Several approaches to assessing the effectiveness of activities, especially planting in the context of stand rehabilitation, include shifts in the stand structure curve, the value of vegetation cover in the area, and the stability of the ecosystem due to changes in species composition [6,10,27,28]. Through planting means filling the loss of density and increasing land cover. The assessment of the effectiveness of rehabilitation activities is determined by the function of time. Rehabilitation is a function of time, and its parameters require a thorough understanding of their characteristics when measuring and monitoring them. In this study, it's possible that periods of 5 and 7 years after rehabilitation may not significantly increase the carbon stored in forest areas. Similar studies in wetland areas suggest that carbon value projections will vary widely. So, to compile more reliable valuation parameters, it is necessary to conduct long-term observations [19]. According to this research, rehabilitation activity projections are considered quite effective in restoring or maintaining stand quality.

This is demonstrated by the quantitative ecological index in stands with moderate diversity values and high species richness. Rehabilitation supports improvements in vegetation diversity and biomass-carbon stocks, which play a crucial role in regulating peat hydrology and enhancing productivity. The carbon potential in the two blocks did not differ significantly, despite variations in rehabilitation ages. The potential for rehabilitation has not yet led to changes in the carbon stock of the peatland following combustion. The results show a significantly lower density of rehabilitated plants compared to natural regeneration in the rehabilitated areas. Rehabilitation locations are areas that have been burned with a range of fire frequencies. These differences directly influence the carbon potential of the remaining stands following the fire. Krisnawati's research demonstrated that the carbon potential of charred areas varied among those with different fire frequencies. The disparity between a single fire and two or three flames exceeded 100% [29].

To build a rehabilitation valuation model, multivariate analysis is widely used for multi-aspect analysis, enabling a deeper understanding of the complexity that exists in forest ecosystems [30]. The need to understand these multi-variables is to determine key parameters that play a role in describing the many variables that exist in nature. The characteristics of forest stands in terms of productivity and ecology are often assessed separately. However, they are actually a unity of forest performance forms, encompassing the factors that occur throughout the stand's growth [19,29,31]. The need for data from more diverse conditions, additional parameters, and long-term observations is a crucial follow-up suggestion to enhance the validity of the proposed approach. The monitoring of data helps to assess the potential parameters, which are important indicators for the health ecosystem [32]. The clusters formed from the bi-plot analysis reveal the distribution of parameters that are believed to explain the basic characteristics of the existing stands. This indicated productivity and ecologically important aspects for valuating the ecosystem peat forest after fire. A compilation of studies on restoration and rehabilitation reveals a growing recognition of the importance of forests in addressing the interconnected challenges of climate regulation, biodiversity protection, and sustainable development [33].

Peatlands, unique ecosystems, store approximately 30% of the world's soil carbon. Peatland fires can cause significant carbon loss [34–36]. Degradation also occurs in all types of peat areas, including both flooded and dry areas [37]. In this rehabilitation planting case, consideration of improving species diversity is important, not just the target of increasing stand density [38,39]. Therefore, it is essential to have an adaptive peat swamp forest management pattern that allows the forest to become healthy and function effectively within the hydrological system, thereby protecting its flora, fauna, and life environment.

Conclusions

Differences in rehabilitation age will affect stand structure, potential value, ecological biodiversity of species, and stand carbon storage. Peat swamp forest stands after 5 and 7 years of rehabilitation are capable of maintaining stable stand structure, particularly at the pole and tree levels. Post-fire stands that have been rehabilitated for 5 years or more will maintain a relatively high level of species diversity, richness, and evenness. The role of time in forest recovery through rehabilitation is a crucial factor in determining the stability of stand structure and the ecology of its constituent species. Evaluating the effectiveness of rehabilitation activities can be done using a multi-parameter approach based on productivity and quantitative stand ecology. As a preliminary valuation approach, this study has limitations. Therefore, for further study to obtain a formulation with sufficient validity to represent the ecological characteristics of peat forests, a wider variety of data and parameters, as well as long-term monitoring or measurement, are required.

Acknowledgments

The authors thank PT Suprabari Mapanindo Mineral for financial support for this research project.

AI Writing Statement

The authors did not use any artificial intelligence assisted technologies in the writing process.

Author Contributions

SS: Conceptualization, Methodology, Investigation, Writing - Review & Editing; **MR**: Conceptualization, Methodology, Investigation, Writing; **FHS**: Conceptualization, Methodology, Data Curation, Software, Writing - Review & Editing; **SA**: Methodology, Data Curation; **MS**: Methodology, Data Curation; **MAQ**: Writing - Review & Editing.

Conflict of Interest

There are no conflicts to declare.

References

1. Maimunah, S.; Capilla, B.; Armadiyanto; Harrison, M. Tree diversity and forest composition of a Bornean heath forest, Indonesia. *IOP Conference Series: Earth and Environmental Science* **2019**, *270*, 012028.
2. Nafiah, N.S.; Sukri, R.S.; Muhammad Y.S.M.; Ya'akub; Salwana, M.; Jaafar; Metali, F. Contrasting patterns of woody seedlings diversity, abundance and community composition in Bornean heath and peat swamp forests. *Mires and Peat.* **2022**, *28*, 1–18, doi:10.19189/MaP.2021.MEH.StA.2160.

3. Neo, L.; Wong, K.M.; Tan, H.T.W. A synopsis of the endemic plant genera of Borneo. *Nordic Journal of Botany* **2020**, *38*, 1–41.
4. Ramdzan, K.N.M.; Moss, P.T.; Jacobsen, G.; Sala, A.G.; Charman, D.; Harrison M.E.; Page, S.; Mishra, S.; Wardle D.A.; Jaya, A.; et al. Insights for restoration: Reconstructing the drivers of long-term local fire events and vegetation turnover of a tropical peatland in Central Kalimantan. *Palaeoecology* **2023**, *628*, 111772, doi:10.1016/j.palaeo.2023.111772.
5. Fahim, S.I.; Amin, S.; Saimun, R.; Rahman, W.; Ahammed, S.; Hossain, M.; Sultana, F.; Mukul, S.A.; Khan, M.A.S.A. Assessing the ecosystem health of Ratargul Freshwater Swamp Forest in Bangladesh using a modified forest quality index. *Ecological Indicators* **2025**, *178*, 113938, doi:10.1016/j.ecolind.
6. Dommain, R.; Dittrich, I.; Giesen, W.; Joosten, H.; Rais, D.S.; Silvius, M.; Wibisono, I.T.C. Ecosystem services, degradation and restoration of peat swamps in the South East Asian tropics. In *Peatland Restoration and Ecosystem Services*; Bonn, A., Allott, T., Evans, M., Joosten, H., Stoneman, R., Eds.; Cambridge University Press: Cambridge, UK, 2016.
7. Khan, A.; Karim, M.R.; Mohammed, M.; Kibria, M.G.; Sinha, K.; Sultana, F.; Mukul, S.A.; Arfin-Khan, M.A.S. Anthropogenic disturbance modifies tree functional traits in the only remnant swamp forest of Bangladesh. *Frontiers in Ecology and Evolution* **2023**, *11*, 1062764, doi:10.3389/fevo.2023.1062764.
8. Environmental and Forestry Instrument Standards Implementation Center of Banjarbaru. *Report on the Management of Special Purpose Forest Areas in Tumbang Nusa* 2024. Agency for Standardization of Environment and Forestry Instruments; Banjarbaru, ID, 2024;
9. Ministry of Environment and Forestry. *Operational plan Indonesia's FOLU Net Sink 2030.* Ministry of Environment and Forestry: Jakarta, ID, 2022;
10. Alhamd, L.; Sundari, S.; Brearley, F.Q.; Rahajoe, J.S. Effects of fire on tree species composition and carbon stocks of a peat swamp forest in Central Kalimantan, Indonesia. *Journal of Forest Research* **2025**, *30*, 42–48, doi:10.1080/13416979.2024.2389990.
11. Wibisono, I.T.C.; Dohong, A. *Panduan Teknis Revegetasi Lahan Gambut*; Badan Restorasi Gambut: Jakarta, ID, 2017;
12. Soerianegara, I.; Indrawan. *Ekologi Hutan Indonesia*; Faculty of Forestry, Bogor Agricultural University: Bogor, ID, 1988;
13. Mueller-Dombois, D.; Ellenberg, H. *Aims and Methods of Vegetation Ecology*; John Wiley & Sons: New York, USA, 1974;
14. National Standardization Agency of Indonesia. *Indonesian National Standard (SNI) 7724:2019 Measurement and Calculation of Carbon Stocks – Field Measurements for Land-Based Carbon Accounting*; National Standardization Agency: Jakarta, ID, 2019;
15. Manuri, M.; Brack, C.; Nugroho, N.P.; Hergoualc'h, K.; Novita, N.; Dotzauer, H.; Verchot, L.; Putra, C.A.S.; Widyasari, E. Tree biomass equations for tropical peat swamp forest ecosystems in Indonesia. *Forest Ecology and Management* **2014**, *334*, 241–253, doi:10.1016/j.foreco.2014.08.031.
16. Intergovernmental Panel on Climate Change. *2006 IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 4: Agriculture, Forestry and Other Land Use*. 2006;
17. Bansal, R.G.; Donnet, J.B.; Stoeckly, F. *Active Carbon*; Marcel Dekker: New York, USA, 1988;
18. Mattjik, A.; Sumertajaya, I.M. *Experiment Design with SAS and Minitab Applications*; IPB Press: Bogor, ID, 2000;
19. Susanty, F.H. Study of recovery rates of natural forest stands after logging in East Kalimantan. *IOP Conf. Series: Earth and Environmental Science* **2020**, *533*, 012015, doi:10.1088/1755-1315/533/1/012015.
20. Vetrita, Y.; Cochrane, M.A. Fire frequency and related land-use and land-cover changes in Indonesia's peatlands. *Remote Sens*. **2020**, *12*, 11–14.
21. Volkova, L.; Krisnawati, H.; Adinugroho, W.C.; Imanuddin, R.; Qirom, M.A.; Santosa, P.B.; Halwany, W.; Weston, C.J. Identifying and addressing knowledge gaps for improving greenhouse gas emissions estimates from tropical peat forest fires. *Sci. Total Environ*. **2021**, *763*, 142933.

22. Krisnawati, H.; Adinugroho, W.C.; Imanuddin, R.; Weston, C.J.; Volkova, L. Carbon balance of tropical peat forests at different fire history and implications for carbon emissions. *Sci. Total Environ*. **2021**, *779*, 146365.

23. Turetsky, M.R.; Benscoter, B.; Page, S.; Rein, G.; van der Werf, G.R.; Watts, A. Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci*. **2015**, *8*, 11–14.

24. Morison, M.; van Beest, C.; Macrae, M.; Nwaishi, F.; Petrone, R. Deeper burning in a boreal fen peatland 1-year post-wildfire accelerates recovery trajectory of carbon dioxide uptake. *Ecohydrology* **2021**, *14*, e2277, doi:10.1002/eco.2277.

25. United Nation. CO_2 Emissions from Peatlands Degradation. Available online: https://www.grida.no/resources/12529 (accessed on 25 October 2025).

26. Sattraburut, T.; Vongvassana, S.; Phutthai, T.; Thasod, Y. Palynological approaches to forest restoration in Southeast Asia: Challenges and opportunities for Thailand—A systematic review. *Trees, Forests and People* **2024**, *18*, 100714, doi:10.1016/j.tfp.2024.100714.

27. Volkova, L.; Krisnawati, H.; Qirom, M.A.; Adinugroho, W.C.; Imanuddin, R.; Hutapea, F.J.; McCharty, M.A.; Stefano, J.D.; Weston, C.J. Fire and tree species diversity in tropical peat swamp forests. *For. Ecol. Manag.* **2023**, *529*, 120704.

28. Volkova, L.; Adinugroho W.A.; Krisnawati, H.; Imanuddin, R.; Weston, C.J. Loss and Recovery of Carbon in Repeatedly Burned Degraded Peatlands of Kalimantan, Indonesia. *Fire* **2021**, *4*, 1–9, doi:10.3390/fire4040064.

29. Krisnawati, H.; Volkova, L.; Budiharto; Zamzani, F.; Adinugroho, W.C.; Qirom, M.A.; Weston, C.J. Building capacity for estimating fire emissions from tropical peatlands; a worked example from Indonesia. *Scientific Reports* **2023**, *13*, 14355, doi:10.1038/s41598-023-40894-z.

30. Timm, N.H. *Applied Multivariate Analysis*; Springer-Verlag: New York, USA, 2002;

31. Pretzsch, H. Density and growth of forest stand revisited. Effect of the temporal scale of observation, site quality and thinning. *For. Ecol. Manage.* **2020**, *460*, 117879, doi:10.1016/j.foreco.2020.117879.

32. Karurung, W.S.; Lee, K.; Lee, W. Assessment of forest fire vulnerability prediction in Indonesia: Seasonal variability analysis using machine learning techniques. *International Journal of Applied Earth Observation and Geoinformation* **2025**, *138*, 104435, doi: 10.1016/j.jag.2025.104435.

33. Buthelezi, M.N.M.; Lottering, R.T; Peerbhay, K.Y.; Mutanga, O. Exploring forest rehabilitation and restoration: A brief systematic review. *Trees, Forests and People* **2025**, *20*, 100898, doi:10.1016/j.tfp.2025.100898.

34. Krisnawati, H.; Adinugroho, W.C.; Imanuddin, R.; Suyoko, W.C.J.; Volkova, L. Carbon balance of tropical peat forests at different fire history and implications for carbon emissions. *Sci. Total Environ*. **2021**, *779*, 146365.

35. Qirom, M.; Yuwati, T.; Rachmanadi, D; Halwany, W. The variation of carbon content and bulk density on different time period post fire and peat depth. *IOP Conf. Ser*. **2021**, *886*, 012096.

36. Hergoualc'h, K.; van Lent, J.; Dezzeo, N.; Verchot, L.V.; van Groenigen, J.W.; Gonzales, M.L.; Grandez-Rios, J. Major carbon losses from degradation of *Mauritia flexuosa* peat swamp forests in western Amazonia. *Biogeochemistry* **2024**, *167*, 327–345, doi:10.1007/s10533-023-01057-4.

37. Swails, E.; Frolking, S.; Deng, J; Hergoualc'h, K. Degradation increases peat greenhouse gas emissions in undrained tropical peat swamp forests. *Biogeochemistry* **2024**, *167*, 59–74, doi:10.1007/s10533-023-01110-2.

38. Darusman, T.; Lestari, D.P.; Arriyadi, D. Management Practice and Restoration of the Peat Swamp Forest in Katingan-Mentaya, Indonesia. In *Tropical Peatland Eco-management*; Osaki, M., Tsuji, N., Foead, N., Rieley, J., Eds.; Springer: Singapore, 2021;

39. van Hoeflaken, J.; Demies, M.; van der Meer, P.J. Historical data guides restoration of degraded peat swamp forests in Southeast Asia. *IOP Conf. Ser.: Earth Environ. Sci.* **2021**, *914*, 012044, doi:10.1088/1755-1315/914/1/012044.