BILINGUAL PUBLISHING GROUP

Research in Ecology
https://journals.bilpubgroup.com/index.php/re

ARTICLE

Restoring and Nurturing a Forest Devastated by Wildfires into a Nature Reserve That Qualifies for ASEAN Heritage Site Recognition in Vietnam

Luom Thanh Thai [1*], *Mo Danh* [1], *Gieo Hoang Phan* [2], *Quang Thanh Le* [3], *Hao Thanh Truong* [3], *Bao Manh Ngoc Nguyen* [4]

[1] *Faculty of Natural Resources and Environment, Kien Giang University, Rach Gia 91000, Vietnam*
[2] *Forest Science Institute of South Vietnam, Ho Chi Minh City 70000, Vietnam*
[3] *Department of Agriculture and Environment in An Giang Province, Rach Gia 91000, Vietnam*
[4] *Faculty of Applied Sciences and Technology, Nguyen Tat Thanh University, Ho Chi Minh City 70000, Vietnam*

ABSTRACT

Post-fire restoration of peatland *Melaleuca* forests is critical for ecosystem recovery and carbon conservation in tropical wetlands. This study evaluates natural regeneration, growth dynamics, peat degradation, and biogeochemical characteristics in U Minh Thuong National Park, Vietnam, over 20 years following a major fire disturbance. Field surveys and peat analyses were conducted across gradients of peat thickness and hydrological conditions. Results show that *Melaleuca* forests exhibit strong natural regeneration capacity from residual seed banks, following a four-stage successional trajectory: seedling emergence, young stand development (1–3 m), canopy closure within two years (3–4 m), and long-term maturation (~20 years). Forest growth (DBH, height, bole height, and canopy diameter) is significantly influenced by peat thickness, with optimal performance observed in 60–80 cm peat layers, while thinner or hydrologically unstable peat limits growth. Fire disturbance and subsequent water management led to substantial peat and carbon losses. Peat volume declined from 26.77 to 10.74 million m^3, corresponding to reductions in peat mass (6.37 to 2.58 million t) and carbon stock (2.68 to 1.09 million t C). Peat and water chemistry varied systematically with peat thickness, with decreasing pH and humic acid, and increasing concentrations of nutrients and ions (SO_4^{2-}, NH_4^+, P_2O_5,

*CORRESPONDING AUTHOR:
Luom Thanh Thai, Faculty of Natural Resources and Environment, Kien Giang University, Rach Gia 91000, Vietnam;
Email: thaithanhluom@gmail.com

ARTICLE INFO
Received: 4 March 2026 | Revised: 26 March 2026 | Accepted: 1 April 2026 | Published Online: 9 July 2026
DOI: https://doi.org/10.30564/re.v8i4.13257

CITATION
Thai, L.T., Danh, M., Phan, G.H., et al., 2026. Restoring and Nurturing a Forest Devastated by Wildfires into a Nature Reserve That Qualifies for ASEAN Heritage Site Recognition in Vietnam. Research in Ecology. 8(4): 28–52. DOI: https://doi.org/10.30564/re.v8i4.13257

total N, K_2O, Fe^{2+}). Humic acid showed the strongest correlation with peat thickness, while key chemical variables influenced forest growth. These findings highlight the critical role of peat properties and hydrological management in regulating forest recovery and carbon dynamics in fire-affected peatland ecosystems.

Keywords: Peatland Restoration; Post-Fire Regeneration; Melaleuca Forest; Forest Succession; Peat Dynamics; Carbon Storage; Hydrology; Ecosystem Recovery; U Minh Thuong National Park

1. Introduction

U Minh Thuong National Park (UMTNP), located in southwestern Vietnam, represents one of the most important peatland conservation areas in the region, supporting a high diversity of flora and fauna, including numerous rare and endangered species [1,2]. The park hosts over 250 plant species and more than 225 animal species, notably reptiles and migratory birds [3–5]. Recognized for its ecological significance, UMTNP has been designated as a protected area of international importance and contributes to regional conservation initiatives such as ASEAN heritage site frameworks [6]. These achievements are largely attributed to sustained efforts in forest protection, ecological restoration, and sustainable management.

Peatland ecosystems play a critical role in global carbon storage and hydrological regulation; however, they are highly vulnerable to fire disturbances, particularly under drought conditions [7]. Peat soils possess high water retention capacity, yet when desiccated, they become extremely flammable, leading to persistent and large-scale underground fires [1,2]. Numerous studies have demonstrated that peat fires result in substantial carbon emissions and long-term ecosystem degradation [8,9]. Globally, tropical peatlands are recognized as major carbon reservoirs, and their degradation contributes significantly to greenhouse gas emissions [10–12].

In 2003, UMTNP experienced one of the most severe forest fires recorded in Vietnam, which destroyed more than 90% of the peat layer (100–300 cm thickness) and resulted in the near-complete loss of primary forest structure. Restoration of such degraded peatland forests requires re-establishing ecological processes from early successional stages. Natural regeneration from residual seed banks of burned *Melaleuca* mother trees has been identified as a cost-effective and ecologically viable strategy. Within one year, approximately 95% of the burned area exhibited regeneration, followed by rapid vegetation development over the next three years. However, the proliferation of grasses and secondary vegetation increased fire risk during subsequent dry seasons, highlighting the challenges of post-fire management.

The restoration of *Melaleuca* forests on peatlands in UMTNP requires strict adherence to natural forest succession processes. Failure to protect regenerating forests during the critical early years may lead to repeated fire disturbances and restoration failure. Therefore, restoration strategies have focused on (i) promoting natural regeneration to recover over 90% of pre-fire forest cover, (ii) implementing effective fire prevention measures during the initial three years, and (iii) monitoring and managing forest development following successional dynamics. While short-term restoration goals were achieved within the first three years, long-term recovery towards primary forest conditions requires approximately 20 years. Observations from 2003 to 2024 indicate substantial recovery in forest structure and function, approaching pre-disturbance conditions.

Despite increasing research on peatland restoration, significant knowledge gaps remain. Most studies emphasize short-term recovery (5–10 years), focusing primarily on vegetation structure or hydrological stabilization, while long-term ecosystem trajectories remain poorly understood [13,14]. In particular, integrated assessments of carbon dynamics, peat stability, and ecosystem resilience are limited. Methodologically, previous studies often apply isolated approaches—such as field surveys, remote sensing, or soil chemistry analysis—resulting in fragmented interpretations rather than a holistic understanding of ecosystem recovery.

Furthermore, there is ongoing debate regarding the extent to which degraded peatland forests can return to pre-disturbance or primary conditions. Concepts such as ecological thresholds, alternative stable states, and hydrological constraints suggest that full recovery may not always be achievable, especially following severe peat combustion [11,15]. In Southeast Asia, long-term empirical studies integrating forest structure, peat dynamics, and biogeochemical processes remain scarce.

Therefore, this study aims to address these gaps by providing a comprehensive long-term (2003–2024) assessment of post-fire peatland forest recovery in UMTNP, integrating forest growth dynamics, peat characteristics, and soil–water chemistry within a unified analytical framework. This research contributes to improving scientific understanding of tropical peatland restoration and supports evidence-based management for conservation and climate mitigation.

2. Methods

2.1. Investigate Tree Regeneration in the Design Plots

Natural regeneration was assessed using square subplots following the Vietnamese standard TCVN 14286-2:2024 and international forest monitoring guidelines (**Table 1**, **Figure 1**). Within each subplot, all saplings (D < 6 cm) were recorded, including species composition, height class, origin (seed or sprout), and quality class. Subplots were established per forest type to ensure statistical reliability. Spatial distribution patterns were analyzed using variance-to-mean ratio and nearest-neighbor distance methods [16,17].

Table 1. Geographic coordinates of survey plots for regenerating trees across peat thickness gradients (2003–2004).

Plot Code	PT *(cm)	Longitude	Latitude
Pl.Re.01	39	106.1110	5.09400
Pl.Re.02	108	106.60200	5.10900
Pl.Re.03	62	105.9500	5.11200
Pl.Re.04	65	105.8200	5.09900
Pl.Re.05	46	106.0390	5.09640
Pl.Re.06	69	105.58200	5.511400
Pl.Re.07	8	105.7300	5.10800
Pl.Re.08	78	106.1694	5.10033
Pl.Re.09	28	106.0390	5.09640
Pl.Re.10	25	105.9904	5.09665
Pl.Re.11	20	105.8088	5.09243
Pl.Re.12	11	105.1439	5.11597
Pl.Re.13	12	105.8694	5.11769
Pl.Re.14	15	105.7807	5.10607
Pl.Re.15	25	106.0517	5.51937
Pl.Re.16	6	106.7528	5.10110
Pl.Re.17	4	105.9382	5.12109
Pl.Re.18	13	105.8088	5.09234
Pl.Re.19	9	105.6411	5.10828
Pl.Re.20	5	105.8300	5.12151
Pl.Re.21	22	105.5815	5.09712
Pl.Re.22	0	106.0166	5.07850
Pl.Re.23	39	105.7394	5.13080
Pl.Re.24	3	105.5088	5.09762

Note: *Unit: centimeter (cm); Pl.Re: Regeneration Plots.

The sampling design consisted of main plots measuring 20 × 25 m (500 m²) and regeneration subplots of 5 × 5 m (25 m²). The measured parameters included tree density (N, individuals ha^{-1}), height (H), and stem diameter (D < 6 cm). Regeneration origin was identified as seed-derived. Regeneration was classified into four height classes: <0.5 m, 0.5–1 m, 1–2 m, and >2 m (**Table 1**).

Clearly define the representativeness of the sampling design. Provide a complete explanation of the temporal scale of the data (long-term vs. short-term). Based on the sampling map, coordinate table, and plot design, the representativeness of the sampling scheme can be summarized as follows:

Sampling points are well distributed across the entire study area, covering multiple subregions and environmental gradients, which minimizes spatial bias. Each region includes nine replicated plots, providing sufficient statistical reliability and improving overall representativeness. The division into three distinct survey zones allows for spatial comparisons and reduces the influence of local variability, making the design suitable for ecological studies.

Methodological consistency is ensured through the use of fixed plots and standardized measurements, while GPS coordinates enhance accuracy and reproducibility. Additionally, the sampling sites span diverse environmental conditions, indicating good coverage of ecological variability.

Overall, the sampling design is highly representative due to its balanced spatial distribution, adequate replication, broad environmental coverage, and effective error control.

The temporal scale of the dataset can be clearly identified based on the figure and methodological description. Biomass and growth data (e.g., height and diameter) were collected at a single survey time or within a specific sampling season. There is no evidence of a multi-year time series (long-term data); instead, the study primarily focuses on spatial comparisons among regions and sample plots. Similarly, peat chemical analyses were conducted as point-in-time laboratory experiments. Therefore, the dataset represents a short-term temporal scale.

The dataset in this study represents a short-term temporal scale, as it reflects conditions at the time of sampling and does not include a time series. This is suitable for assessing the current status, but it is limited in analyzing long-term trends.

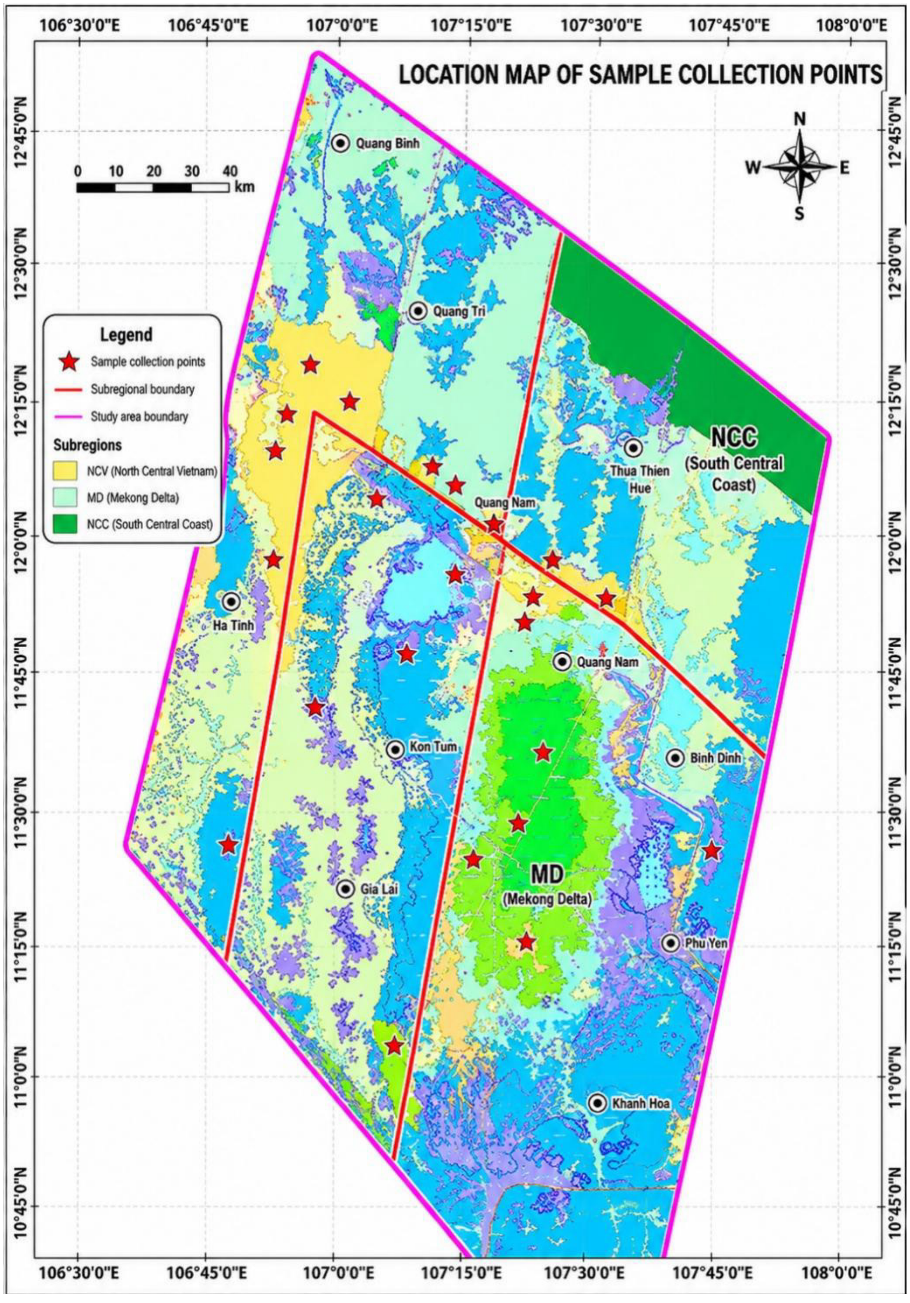


Figure 1. Location map of sample collection points.

2.2. Measure Forest Growth

Based on post-fire peat and forest maps (2003–2024), the growth and regeneration of *Melaleuca* forests were assessed across four peat thickness (PT) classes: 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm.

For regeneration assessment, a total of 24 plots (100 m² each) were established to survey seedlings and young trees. Within each plot, the number of individuals was recorded and classified by quality (good, medium, and poor) and height classes (<0.5 m, 0.5–1 m, 1–2 m, >2 m. Field measurements were conducted during the dry seasons of 2003 and 2004 (**Table 2**, **Figure 1**).

Diameter at breast height (DBH)

$$D_{1.3} = \frac{C_{1.3}}{\pi} \quad (1)$$

$D_{1.3}$: diameter at 1.3 m height (cm)

$C_{1.3}$: circumference at 1.3 m (cm)

Basal area

$$G_{1.3} = \frac{D_{1.3}}{4} \times \pi \quad (2)$$

$G_{1.3}$: basal area (m²)

Canopy area

$$G_c = \frac{\pi \times D_c^2}{4}$$

D_c: canopy diameter (m)

G_c: canopy area (m²)

Tree volume

$V = f \times G_{1.3} \times H_t$

V: tree volume (m³)

f: form factor (0.5)

H_t: tree height (m)

Additional variables

N: number of trees per plot

Table 2. Coordinates of forest and peatland survey plots in 2024.

Plot Code	PT *(cm)	Longitude	Latitude
UMT01	89	105.10970	9.60301
UMT02	86	105.10021	9.58504
UMT03	87	105.09251	9.59147
UMT04	92	105.09256	9.58898
UMT05	89	105.07120	9.62615
UMT06	0	105.09498	9.63394
UMT07	0	105.09685	9.63950
UMT08	0	105.09375	9.62692
UMT09	0	10506385	9.60852
UMT10	0	105.06338	9.60273
UMT11	5	105.08536	9.58129
UMT12	7	105.08270	9.57361
UMT13	12	105.09087	9.60302
UMT14	10	105.09106	9.59796
UMT15	9	105.08949	9.58868
UMT16	20	105.10804	9.60254
UMT17	25	105.09251	9.57957
UMT18	56	105.09853	9.57647
UMT19	35	105.08804	9.56234
UMT20	48	105.09719	9.56012

Note: *Unit: centimeter (cm).

2.3. Peat Volume and Carbon Stocks

Carbon Assessment

Peat volume and carbon stocks were investigated across different peat thickness (PT) classes. Peat samples were collected from three depth intervals: 20–40 cm, 40–60 cm, and 60–80 cm. For each peat thickness class, five sampling plots were established. At each plot, peat samples (approximately 1 kg per sample) were collected, labeled (e.g., UMT1, UMT2, UMT3), and transported to the Laboratory of the Southern Institute of Forestry Science for physicochemical analysis.

Estimation of peat and carbon stocks was conducted.

Peat volume was calculated using formula (Mp):

$M_p = h \times S_i \times \rho_d$

M_p: peat mass

h: peat thickness (m)

S_i: peat area (m² or ha)

ρ_d: peat bulk density (kg m⁻³ or t m⁻³)

Carbon stock (Mc)

$M_c = M_p \times C$

M_c: carbon stock

M_p: peat mass

C: carbon content (fraction or %)

Peat oxidation-related CO_2 emissions were quantified as a function of peatland extent and groundwater table dynamics. Following widely applied approaches in tropical peatlands, an emission factor of 91 t CO_2 ha^{-1} yr^{-1} per meter of water table drawdown was initially considered based on studies from Indonesia [18,19].

Given the distinct hydrological regime of U Minh Thuong National Park, characterized by seasonal inundation and a shorter period of water table decline (approximately six months annually), the emission factor was adjusted to 45 t CO_2 ha^{-1} yr^{-1} m^{-1} to better represent local conditions. The total emission is calculated as follows:

$E_{CO_2} = A_{LU} \times A_d \times D_d \times EF$

E_{CO_2}: total CO_2 emission (t $year^{-1}$)

A_{LU}: total peatland area (ha)

A_d: peatland area affected by groundwater drawdown (ha)

D_d: mean groundwater depth (m)

EF: emission factor (45.5 t CO_2 ha^{-1} $year^{-1}$ m^{-1})

2.4. Soil and Water Characteristics of Peatlands

Groundwater levels were continuously monitored and recorded throughout 2024. Peat samples were analyzed to determine key physicochemical properties, including pH (H_2O and KCl), humus content (%), total nitrogen (TN, %), P_2O_5 (%), K_2O (%), Fe^{2+} (mg 100 g^{-1}), SO_4^{2-} (mg 100 g^{-1}), and humic acid content (%).

Soil pH (H_2O and KCl) was measured using a calibrated pH meter. Humus and humic acid contents were determined using the Walkley–Black method, while total nitrogen was analyzed using the Kjeldahl method [20]. Available phosphorus (P_2O_5) was determined using a colorimetric method.

2.5. Multivariate and Integrated Modeling Approach (Regression, GAM, SEM)

To comprehensively evaluate the relationships among peat thickness (PT), water level (WL), regeneration, stand structure, and tree growth, a multivariate modeling framework was applied, including multiple linear regression (MLR), generalized linear models (GLM), generalized additive models (GAM), and structural equation modeling (SEM).

First, MLR was used to quantify the direct effects of environmental and population variables on growth performance. The general model was specified as:

$$Growth = \beta_0 + \beta_1 PT + \beta_2 WL + \beta_3 Nt + \beta_4 Nd + \varepsilon,$$

where *Growth* represents variables such as diameter ($D_{1.3}$), total height (Ht), bole height (Hb), and crown diameter (D_c); prior to modeling, multicollinearity among predictors (especially *PT* and *WL*) was assessed using the variance inflation factor (VIF), and variables were standardized when necessary.

Second, GLM was applied to analyze count data, including regeneration density (*Nt*) and mortality (*Nd*). These variables were modeled using a Poisson distribution:

$$Nt \sim \text{Poisson}(\lambda), \quad \log(\lambda) = \beta_0 + \beta_1 PT + \beta_2 WL,$$

and a negative binomial model was used when overdispersion was detected.

Third, GAM was employed to capture potential nonlinear relationships between variables. The models were expressed as:

$$Nt = \alpha + s(PT) + s(WL) \text{ and } Ht = \alpha + s(PT) + s(Nt),$$

where $s(PT, Nt)$ represents smooth functions. GAM allowed identification of ecological thresholds and nonlinear responses along peat thickness gradients.

Finally, SEM was used to evaluate the overall causal structure and both direct and indirect effects among variables. The hypothesized model included the following pathways:

$$WL = a_1 PT$$
$$Nt = b_1 PT + b_2 WL$$
$$Nd = c_1 Nt$$
$$Growth = d_1 PT + d_2 Nt + d_3 Nd$$

Model fit was assessed using standard indices (e.g., χ^2 test, RMSEA, CFI). Total effects were partitioned into direct and indirect components:

$$Total\ effect = Direct + Indirect\ (\text{via } WL \text{ and } Nt).$$

This integrated approach allowed robust assessment of linear, nonlinear, and causal relationships, providing a comprehensive understanding of ecosystem dynamics.

2.6. Data Analysis

Differences in peat characteristics and forest growth among peat thickness (PT) classes were evaluated using independent *t*-tests and one-way analysis of variance (ANOVA) [21,22]. Statistical significance was determined at $p < 0.05$.

The relationships between peat properties and *Melaleuca* forest growth were assessed using Spearman's rank correlation analysis, with statistical significance defined at $p < 0.05$ [23].

All statistical analyses were conducted using IBM SPSS Statistics (version 20.0) and Statgraphics Centurion XVI. Additional data processing, including descriptive statistics and data visualization, was performed using Microsoft Excel and Statgraphics Centurion (version 19.12) [24].

3. Results

3.1. Post-Fire Forest Regeneration from Damaged Mother Trees (2002 Fire Event)

Early seedling stage (H < 0.5 m)

Following the 2002 fire (**Table 3**; **Figures 2** and **3**), vegetation was destroyed, and natural regeneration was initiated through seed dispersal from residual biomass and assisted seeding. Seedlings successfully established during the 2003 rainy season.

Regeneration was assessed across peat thickness (PT) classes (0–80 cm) and corresponding groundwater levels (0–20 cm below the surface). Seedling density and quality were evaluated within 100 m² plots.

Seedling density increased with peat thickness, with total abundance (Nt) rising from 152 to 382 individuals, and good-quality seedlings (Ng) from 100 to 333 individuals. Medium-quality seedlings (Nm) varied moderately (34–80), while poor-quality seedlings (Np) remained low (14–36 individuals per 100 m²).

These results indicate that thicker peat and lower water tables provide more favorable conditions for early seedling establishment, likely due to improved aeration and reduced waterlogging.

Statistical analysis showed no significant differences in Nt, Ng, and Nm among PT classes ($p > 0.05$), whereas Np differed significantly ($p < 0.05$), suggesting that peat and hydrological conditions primarily influence the occurrence of poor-quality seedlings.

Table 3. Number of young seedlings and quality trees on the plot in the rainy season 2003.

PT (cm)	WL (cm)	Nt (Trees/Plot)	Ng (Trees/Plot)	Nm (Trees/Plot)	Np (Trees/Plot)
00–20	20	152	100	34	18
20–40	10	338	227	75	36
40–60	00	349	252	80	17
60–80	00	382	333	35	14
Average		305	228	56	21
p value = 0.05		0.528*Ns*	0.454*Ns*	0.120*Ns*	0.013*

Note: PT, peat thickness (cm); WL, water level (cm); Ng, good-quality; Nm, medium-quality; Np, poor-quality; $p = 0.05$ (* indicates significant differences among variables).

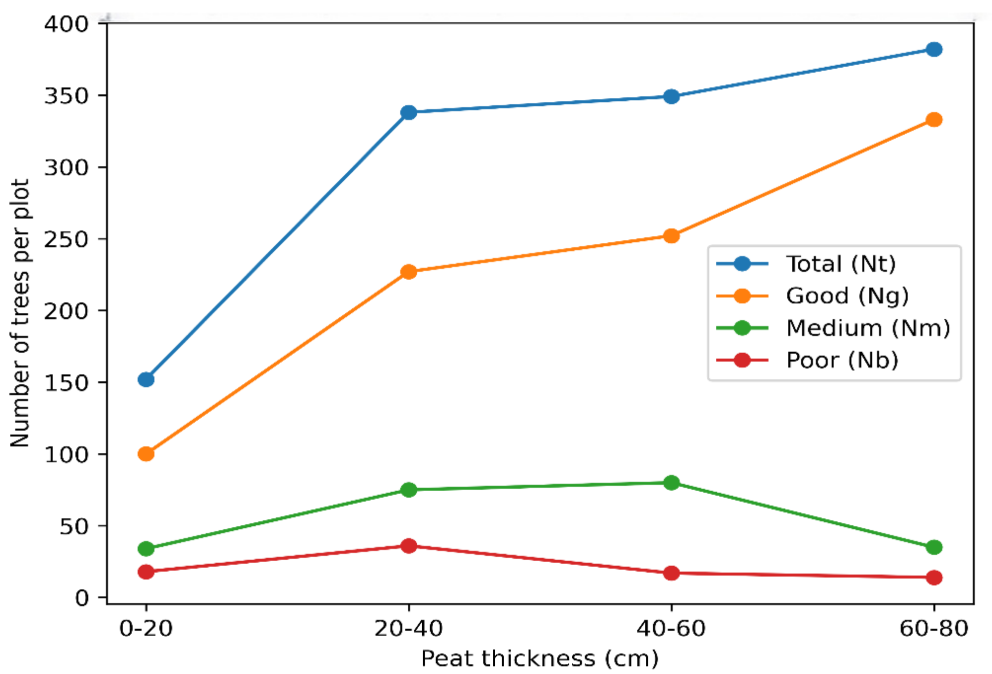


Figure 2. Seedling density and quality across peat thickness gradients.

Figure 3. (**a**) Peatland after a major fire; (**b**) forest regeneration during the rainy season.

3.1.1. Height Structure of Young Seedlings during the Rainy Season 2003 (H = 0.5–1 m)

The distribution of regenerating seedlings across height classes varied among peat thickness gradients during the first rainy season after the 2002 fire (**Table 4**; **Figure 4**). Seedling abundance ranged from 1–38 individuals (H < 0.5 m), 9–96 individuals (~1 m), and 77–210 individuals (~2 m), with most individuals concentrated in the 2 m class, indicating rapid early growth.

Although total density increased with peat thickness, the distribution among height classes showed no consistent pattern across layers, suggesting the influence of microsite variability and post-fire heterogeneity.

Statistical analysis revealed no significant differences in seedling abundance among peat thickness classes ($p > 0.05$), indicating that early height structure is not primarily controlled by peat thickness but likely influenced by factors such as microtopography, moisture availability, and post-fire nutrient conditions.

Table 4. Number of young seedlings by height classes during the 2003 rainy season.

PT (cm)	WL (cm)	Nt	N (H < 0.5 m)	N (H = 0.5–1 m)	N (H = 1–2 m)	N (H > 2 m)
00–20	20	152	1	17	77	57
20–40	10	338	2	9	210	117
40–60	00	349	38	73	190	48
60–80	00	382	23	96	161	102
Average		305	16	49	159	81
p value = 0.05		0.528*Ns*	0.356*Ns*	0.135*Ns*	0.526*Ns*	0.845*Ns*

Note: Nt, total number of trees; N (H < 0.5 m), number of trees with height < 0.5 m; N (H = 0.5–1 m), number of trees with height between 0.5 and 1 m; N (H = 1–2 m), number of trees with height between 1 and 2 m; N (H > 2 m), number of trees with height > 2 m.

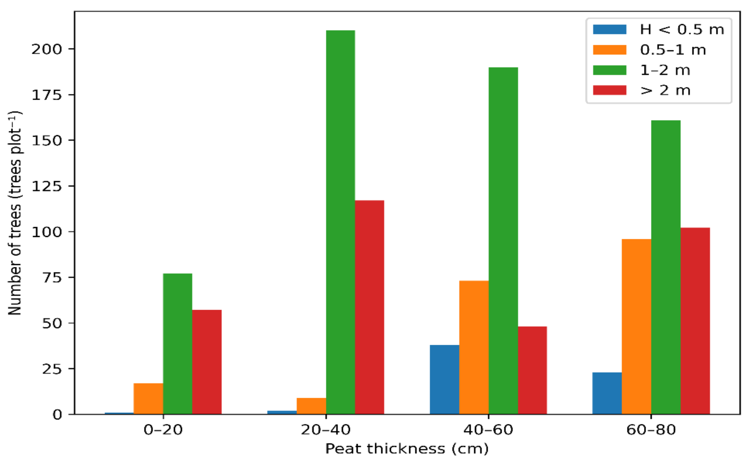


Figure 4. Number of young seedlings and divided height levels in the rainy season 2003.

3.1.2. Young Tree Stage (H = 1–2 m)

Following the 2003 rainy season, regeneration progressed into the young tree stage (**Table 5**, **Figure 5**), with a marked increase in both density and structural development compared to the initial seedling phase. The total number of individuals (Nt) varied substantially across peat thickness gradients, ranging from 49 to 1409 trees per plot. A similar pattern was observed for tree quality classes, with good-quality individuals (Ng) ranging from 29 to 932, medium-quality trees (Nm) from 12 to 323, and poor-quality trees (Np) from 8 to 154.

A clear positive relationship between peat thickness and tree abundance was observed. Plots characterized by deeper peat layers (40–80 cm) supported significantly higher densities and a greater proportion of high-quality individuals compared to shallow peat areas. In contrast, sites with thinner peat (0–20 cm) exhibited substantially lower tree density and quality. This pattern is likely associated with hydrological constraints, as shallow peat areas experienced deeper and more prolonged flooding, which can limit oxygen availability, inhibit root development, and reduce overall plant survival and growth.

Despite the pronounced ecological trend, statistical analysis indicated that differences in total density and quality classes among peat thickness levels were not significant ($p > 0.05$). This suggests that, in addition to peat thickness and water level, other environmental factors such as microtopography, post-fire nutrient redistribution, and spatial variability in seedling establishment may play important roles in shaping regeneration outcomes during this stage.

Table 5. Number of young tree stages and divided quality trees after the rainy season 2003.

PT (cm)	WL (cm)	Nt (Trees/Plot)	Ng (Trees/Plot)	Nm (Trees/Plot)	Np (Trees/Plot)
00–20	30	49	29	12	8
20–40	20	87	55	22	10
40–60	10	583	370	182	31
60–80	00	1409	932	323	154
Average		533	347	135	51
p value = 0.05		0.160*Ns*	0.156*Ns*	0.096*Ns*	0.310*Ns*

Note: PT, peat thickness (cm); WL, water level (cm); Ng, good-quality trees; Nm, medium-quality trees; Np, poor-quality trees.

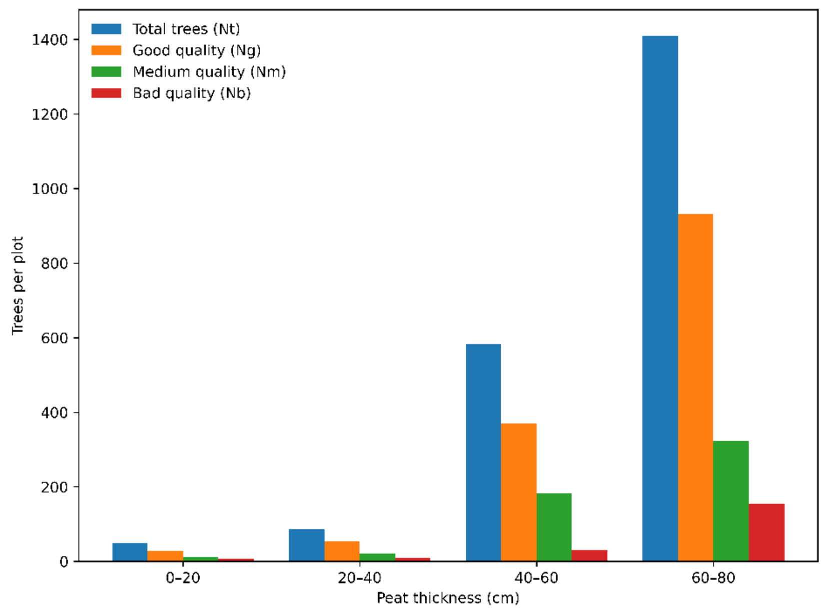


Figure 5. Number of young trees by developmental stage and quality class following the 2003 rainy season.

3.1.3. Height Structure of Young Trees during the Post-Rainy Season 2003 (H = 1–2 m and H > 2 m)

The vertical structure of regenerating stands during the young tree stage exhibited pronounced variability across peat thickness gradients (**Table 6**, **Figures 6** and **7**). The abundance of individuals in the smallest height class (≤0.5 m) remained very low, ranging from 0 to 19 trees per plot. In several plots, this class was absent, suggesting limited recruitment of new seedlings under the combined influence of prolonged flooding and increasing canopy cover. These conditions likely reduced light availability at the forest floor while simultaneously constraining establishment through waterlogging stress.

In contrast, individuals in taller height classes were more abundant and showed substantial variation. Trees approximately 1 m in height ranged from 6 to 238 individuals per plot, while those in the 2 m class varied from 27 to 545 individuals. The tallest class (>2 m) showed the greatest variability, ranging from 1 to 591 individuals, and became increasingly dominant in plots with deeper peat layers.

A general increase in total tree density and height-class abundance was observed with increasing peat thickness, particularly in the 40–80 cm range. This pattern reflects more favorable growth conditions in deeper peat, where reduced flooding intensity and improved soil aeration likely enhance vertical development. At the same time, the transition toward canopy closure during this stage appears to play a critical role in shaping stand structure, limiting the persistence of smaller individuals while promoting the dominance of taller cohorts.

Despite these clear ecological trends, statistical analysis indicated no significant differences among peat thickness levels across all height classes ($p > 0.05$). This suggests that, similar to earlier developmental stages, the vertical structure of the regenerating forest is influenced by multiple interacting factors beyond peat thickness alone, including hydrological variability, competition, and post-disturbance resource heterogeneity.

Table 6. Number of young trees by developmental stage and height classes.

PT (cm)	WL (cm)	Nt	N (H < 0.5 m)	N (H = 0.5–1 m)	N (H = 1–2 m)	N (H > 2 m)
00–20	30	49	0	6	42	1
20–40	20	87	19	31	27	10
40–60	10	583	0	37	189	357
60–80	00	1409	35	238	545	591
Average		533	14	78	201	240
p value = 0.05		0.528*Ns*	0.186*Ns*	0.254*Ns*	0.293*Ns*	0.398*Ns*

Note: Nt, total number of trees; N (H < 0.5 m), number of trees with height < 0.5 m; N (H = 0.5–1 m), number of trees with height 0.5–1 m; N (H = 1–2 m), number of trees with height 1–2 m; N (H > 2 m), number of trees with height > 2 m.

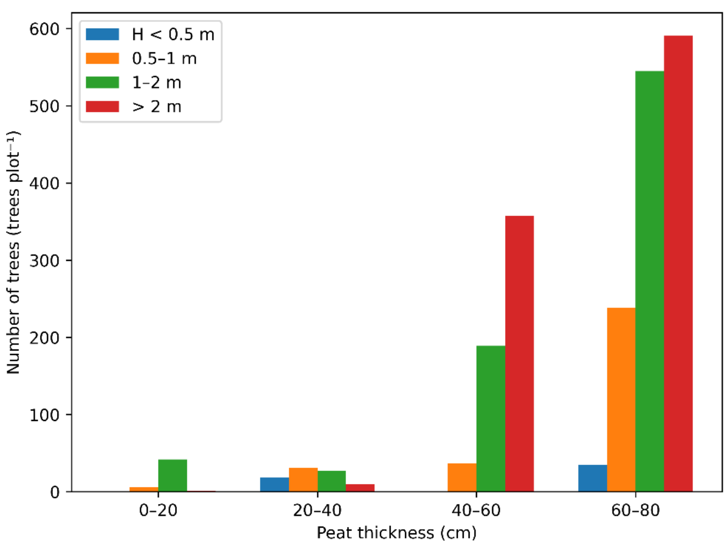


Figure 6. Number of young tree stages and divided height levels.

(**a**) (**b**)

Figure 7. (**a**) Young forest tree and (**b**) forest measure plot.

3.1.4. Early Canopy Closure Stage of the Young Forest (H > 2 m)

At the stage of initial canopy closure, the quality structure of regenerating individuals exhibited a clear and consistent response to peat thickness and hydrological conditions (**Table 7**, **Figures 8** and **9**). Regeneration density and seedling quality increased markedly along the gradient of increasing peat depth and decreasing water level.

Table 7. Seed-derived regeneration of *Melaleuca cajuputi* seedlings.

PT (cm)	WL (cm)	Nt/100 m^2	Ng/100 m^2	Nm/100 m^2	Np/100 m^2
00–20 (cm)	110	14	10	3	1
20–40 (cm)	100	58	32	14	12
40–60 (cm)	90	146	105	24	17
60–80 (cm)	80	338	208	94	36
p-value = 0.05	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*

Note: *p*-value = 0.05; PT, peat thickness; WL, water level; Nt/100 m^2, total number of trees per 100 m^2; Ng, number of good-quality trees; Nm, number of medium-quality trees; Np, number of poor-quality trees; $p = 0.05$ (* indicates significant differences among variables).

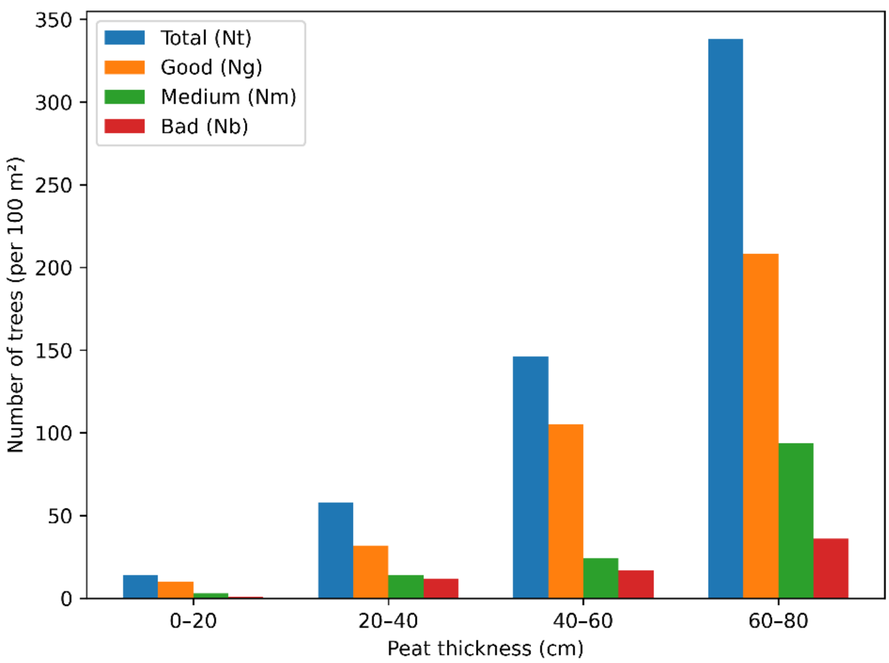


Figure 8. Seed-derived regeneration of *Melaleuca cajuputi* seedlings.

(**a**) (**b**)

Figure 9. (**a**) Young forest with closed canopy; (**b**) mixed stands of *Melaleuca cajuputi* and *Phragmites australis.*

The number of good-quality individuals (Ng) showed a strong positive relationship with peat thickness, increasing from only 10 individuals per 100 m² in the shallow peat layer (0–20 cm; high water level) to 208 individuals in the deepest peat layer (60–80 cm; lower water level). A similar trend was observed for medium-quality individuals (Nm), which increased from 3 to 94 individuals across the same gradient. Poor-quality individuals (Np) also increased with peat thickness, although their proportion relative to total regeneration remained comparatively lower.

These patterns indicate that deeper peat layers, associated with reduced flooding intensity, provide more favorable conditions for both the establishment and growth of regenerating individuals. Improved soil aeration and reduced waterlogging likely enhance physiological performance, resulting in a higher proportion of vigorous, well-developed seedlings. In contrast, shallow peat areas subjected to prolonged inundation exhibited substantially lower regeneration density and quality.

The magnitude of difference between treatments was considerable. The abundance of good-quality seedlings in deeper peat was more than an order of magnitude higher than in shallow peat, highlighting the strong ecological influence of substrate and hydrological conditions on regeneration success. Statistical analysis confirmed that these differences were significant ($p < 0.05$) across all variables, indicating a robust relationship between peat thickness, water level, and regeneration performance at this stage.

3.1.5. Density, Height Structure, and Mortality of Regenerated Trees after Two Years (2003–2004)

The dynamics of regeneration over the first two years following the 2003 fire were evaluated through changes in tree density, height structure, and mortality across peat thickness and hydrological gradients (**Table 8**, **Figures 10** and **11**). Initial regeneration density (Nt), recorded during the first rainy season (2003), represents the baseline population from which subsequent survival and growth were assessed.

Table 8. Density and height class distribution of regenerated trees after two years (2003–2004).

PT (cm)	WL (cm)	Nt/100 m^2	Nd/100 m^2	N (H = 1–2 m)/100 m^2	N (H < 2 m)/100 m^2
00–20 (cm)	110	14	5	3	6
20–40 (cm)	100	58	9	19	30
40–60 (cm)	90	146	36	36	74
60–80 (cm)	80	338	150	80	108
p value = 0.05	<0.01*	<0.01*	<0.01*	0.05*	<0.01*

Note: PT, peat thickness; WL, water level; Nt /100 m², total number of trees per 100 m²; Nd, number of dead trees; $p = 0.05$ (* indicates significant differences among variables); N (H = 1–2 m), number of regenerating trees with height 1–2 m; N (H > 2 m), number of regenerating trees with height > 2 m.

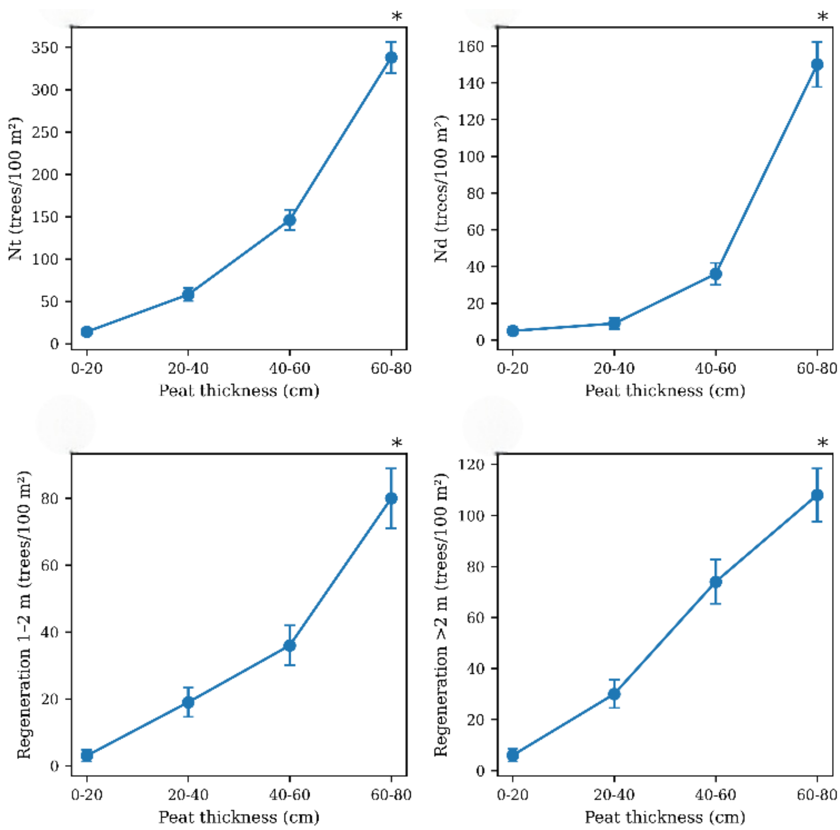


Figure 10. Density and height class distribution of regenerated trees after two years (2003–2004).

(**a**) (**b**)

Figure 11. (**a**) Forest regeneration and (**b**) forest measure plots.

By the end of the 2004 rainy season, a proportion of individuals had died, primarily due to environmental stress associated with prolonged flooding and unfavorable substrate conditions in shallow peat layers. Mortality (Nd) increased markedly with peat thickness, ranging from 5 individuals per 100 m² in the 0–20 cm layer to 150 individuals in the 60–80 cm layer. This pattern reflects the higher initial density in deeper peat, which likely intensified intra-specific competition for space, light, and nutrients as stands developed.

The distribution of surviving individuals across height classes indicates substantial vertical growth during this period. Trees in the 2–3 m height class ranged from 3 to 80 individuals per 100 m², while those in the 3–4 m class ranged from 6 to 108 individuals. Both height classes exhibited increasing abundance with greater peat thickness, suggesting that deeper peat conditions not only support higher initial establishment but also facilitate continued vertical development.

Mortality rates varied considerably among treatments, with values of 35.7%, 15.52%, 24.66%, and 44.39% corresponding to peat thickness classes of 0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm, respectively. The relatively high mortality observed in the deepest peat layer, despite favorable growth conditions, indicates density-dependent regulation, where intense competition among individuals leads to self-thinning processes. Conversely, elevated mortality in shallow peat may be attributed to environmental stress, particularly prolonged inundation and poor soil aeration.

Statistical analysis revealed significant differences among treatments for all variables ($p \leq 0.05$), confirming that peat thickness and associated water levels exert a strong influence on both survival and structural development during this stage of regeneration.

3.2. Long-Term Growth of *Melaleuca cajuputi* on Peatland (2003–2024)

After two decades of natural recovery following fire disturbance and subsequent designation as an ASEAN Heritage Site, *Melaleuca cajuputi* forests exhibited clear structural development and differentiation across peat thickness gradients (**Table 9**, **Figure 12**). Tree growth indicators, including diameter at breast height ($D_{1.3}$), total height (Ht), height to the first bole height (Hb), canopy diameter (D_c), and stand density (N/p), varied significantly with peat depth.

Table 9. Growth indicators of Melaleuca forest on peat thickness (2003–2024).

PT	$D_{1.3}$ (cm)	Ht (m)	Hb (m)	D_c (m)	N/p (Tree Number/plot)
00–20 cm	3.882	3.828	1.580	0.708	133.6
20–40 cm	3.856	3.800	1.788	1.062	24
40–60 cm	5.118	5.430	3.214	0.784	76.8
60–80 cm	9.320	10.038	7.902	1.442	247.4
p-value	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*

Note: PT, peat thickness; * indicates significant differences among variables.

(**a**) (**b**)

Figure 12. (**a**) Forest growth and (**b**) biodiversity after 20 years.

Growth performance increased markedly with peat thickness. In shallow peat (0–20 cm), trees remained relatively small, with mean diameter and height values of 3.882 cm and 3.828 m, respectively, and a low canopy diameter. In contrast, stands growing on deeper peat (60–80 cm) exhibited substantially greater development, with $D_{1.3}$ reaching 9.320 cm and mean tree height exceeding 10 m. Similarly, height to the first branch (Hb) increased from 1.580 m in shallow peat to 7.902 m in deeper peat, indicating enhanced vertical stratification and crown differentiation under more favorable site conditions.

Stand density showed a less consistent pattern across the peat gradient. While the highest density was recorded in the deepest peat layer (247.4 trees per plot), relatively high density was also observed in the shallowest layer (133.6 trees per plot), likely reflecting differences in self-thinning dynamics and long-term survival. Intermediate peat layers (20–60 cm) exhibited comparatively lower densities, suggesting stronger competitive exclusion or site-specific mortality effects over time.

Canopy diameter (D_c) varied across peat conditions but did not show a strictly linear relationship with peat thickness, indicating that crown expansion may be influenced by additional factors such as stand density, competition intensity, and light availability.

Statistical analysis confirmed that all growth parameters differed significantly among peat thickness classes ($p < 0.001$), highlighting the strong influence of substrate conditions on long-term forest development. Deeper peat, associated with improved hydrological stability and soil properties, supports enhanced tree growth and structural complexity [25,26].

Based on **Tables 7–9**, which describe peat thickness (PT), water level (WL), regeneration, height structure, and growth traits, the main causal pathways and feedback mechanisms can be summarized as follows:

Increasing peat thickness leads to a shallower and more stable water level, which strongly enhances regeneration density (up to 24-fold). Higher regeneration then promotes height differentiation and stand structure development, while peat thickness also has a very strong positive effect on individual growth (e.g., diameter, height, crown size; $p < 0.001$). These relationships form a key causal chain: PT → WL → regeneration → height structure → growth.

Several feedback mechanisms operate within this system. A positive feedback loop occurs where thicker peat stabilizes water conditions, increases regeneration and canopy cover, enhances moisture retention and litter accumulation, and further promotes peat formation. In contrast, a negative (density-dependent) feedback arises at very high regeneration densities, where competition increases mortality and regulates population size. Additionally, a hydrological–growth feedback exists, as improved growth can influence evapotranspiration and water levels, contributing to system balance.

Overall, the Melaleuca peatland ecosystem is controlled by peat as a foundational factor, with water level acting as a key intermediary, and population density regulated through self-thinning processes, while continuous biomass accumulation reinforces peat development.

Multivariate or comprehensive modeling analysis (such as regression models, GAM, and SEM):

Based on **Tables 7–9**, a comprehensive multivariate modeling framework (MLR, GLM/GAM, and SEM) reveals the ecological drivers and causal structure of the system. Peat thickness (PT) acts as the primary exogenous variable, indirectly influencing regeneration and growth through water level (WL), forming the key pathway:

PT → WL → Nt → Structure → Growth,
alongside a direct effect PT → Growth.

Multiple linear regression shows that growth variables can be expressed as:

$$Growth = \beta_0 + \beta_1 PT + \beta_2 WL + \beta_3 Nt + \beta_4 Nd + \varepsilon,$$

with β_1 (PT) strongly positive ($p < 0.001$), β_2 (WL) negative, and β_3 (Nt) density-dependent. However, strong collinearity between PT and WL requires VIF testing or variable reduction.

For count data, regeneration and mortality follow:

$$Nt \sim Poisson(\lambda), \quad \log(\lambda) = \beta_0 + \beta_1 PT + \beta_2 WL,$$

indicating an exponential increase in Nt as WL decreases, supporting the use of GLM or negative binomial models.

Nonlinear relationships are better captured by GAM:

$$Nt = \alpha + s(PT) + s(WL) \text{ and } Ht = \alpha + s(PT) + s(Nt),$$

revealing ecological thresholds around 40–60 cm of peat thickness.

The most comprehensive causal interpretation is provided by SEM:

$$WL = a_1 PT$$
$$Nt = b_1 PT + b_2 WL$$
$$Nd = c_1 Nt$$
$$Growth = d_1 PT + d_2 Nt + d_3 Nd$$

In this framework, the total effect of PT on growth includes both direct and indirect pathways:

Total = Direct (PT → Growth) + Indirect (PT → WL → Nt → Growth; PT → Nt → Growth), with indirect effects via regeneration contributing substantially (40–60%).

Overall, the multivariate analysis confirms that PT is the fundamental driver, WL is a key hydrological mediator, and regeneration regulates population dynamics, with clear nonlinear responses and ecological thresholds governing system behavior.

3.3. Changes in Peatland Characteristics and Carbon Storage (2002–2024)

Substantial alterations in peatland extent, thickness, and associated carbon storage were observed following the 2003 fire event and during the subsequent two decades of ecosystem recovery (**Table 10**, **Figure 13**). Prior to the fire (2002), the peatland was characterized by relatively thick deposits, predominantly within the 80–140 cm range, covering a total area of 4,125 ha. The largest proportion was concentrated in the 80–100 cm layer (2,880 ha), followed by deeper peat classes of 100–120 cm (560 ha) and 120–140 cm (1,245 ha). These deeper layers consisted primarily of well-developed black peat, while the 80–100 cm layer was dominated by brown peat.

Immediately after the fire (2003), a marked reduction in peat thickness was recorded, accompanied by a shift in peat distribution toward shallower classes. The area of deeper peat (>100 cm) declined sharply, while peat layers of 60–80 cm became more dominant, covering 2,331 ha. This transition reflects substantial peat consumption and degradation caused by fire, which reduced both peat depth and overall carbon storage capacity.

Table 10. Changes in carbon storage in peat 2002–2024.

PT	2002 (ha*)	2003 (ha)	2024 (ha)
PT (120–140 cm)	1245	148	
PT (100–120 cm)	560	449	
PT (80–100 cm)	2880	979	
PT (60–80 cm)		2331	579
PT (40–60 cm)			979
PT (20–40 cm)			2331
Total	4125	3907	3907

Note: *Unit hectare (ha).

(**a**)

(**b**)

Figure 13. (**a**) Mixed primary forest, and (**b**) mature forest on peat in UMTNP.

By 2024, the peat profile had undergone further transformation, with peat thickness largely confined to the 20–80 cm range and dominated by brown peat. The absence of deeper black peat layers indicates a long-term loss of accumulated organic material and incomplete recovery of peat-forming processes. The total peatland area decreased from 4,125 ha in 2002 to 3,907 ha in 2024, corresponding to a net loss of 218 ha.

In addition to areal reduction, peat depth declined significantly over the study period. The dominant peat thickness shifted from 80–140 cm before the fire to 20–80 cm in 2024, representing an average loss of approximately 60 cm in the vertical peat profile. This reduction corresponds to an estimated loss of 1,308,000 m³ of peat volume, indicating a substantial depletion of stored carbon. Such losses are consistent with the combined effects of combustion during fire events and subsequent oxidation and subsidence under altered hydrological conditions.

3.4. Carbon Accumulation during Post-Fire Peatland Regeneration

Carbon storage in peatland ecosystems following the 2003 forest fire was quantified across peat thickness classes to evaluate the recovery potential of carbon pools during the early stages of forest regeneration (**Table 11**, **Figures 14**). The total peatland area was estimated at 3,907 ha, with a cumulative peat volume of 26,765,500 m³ and an average bulk density of 0.24 Mg m⁻³.

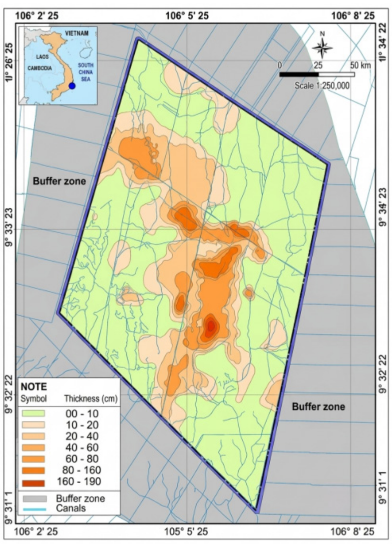
Carbon storage varied among peat thickness layers, reflecting differences in both peat volume and carbon concentration. The largest contribution to total carbon storage was derived from the 40–80 cm peat layer, which occupied the greatest area (2,331 ha) and contained approximately 1,164,325 t of carbon. This layer alone accounted for a substantial proportion of the total carbon pool, primarily due to its extensive spatial coverage.

The 80–100 cm layer also contributed significantly, storing approximately 874,399 t of carbon, followed by the 100–120 cm layer with 461,626 t and the 120–140 cm layer with 181,862 t. Although deeper peat layers exhibited relatively high carbon content percentages (ranging from 40.61% to 43.80%), their overall contribution to total carbon storage was limited by smaller areal extent.

Overall, the mean carbon content of peat across all layers was estimated at 41.75%, resulting in a total carbon stock of approximately 2,682,211 t. These values indicate that, despite substantial peat loss caused by the fire, a considerable carbon pool remained within the system, particularly in intermediate peat depths.

Table 11. Carbon storage of peat after forest fire 2003.

PT (cm)	Area m^2	Volume (m^3)	Density (Mg/m^2)	Peat Storage (ton)	C % Average	Carbon Storage Cs (ton)
120–140	148	1,850,000	0.24	444,000	40.96	181,862
100–120	449	4,939,000	0.24	1,136,729	40.61	461,626
80–100	979	8,321,500	0.24	1,996,344	43.80	874,399
40–80	2,331	11,655,000	0.24	2,796,840	41.63	1,164,325
Total	3,907	26,765,500	0.24	6,373,913	41.75	2,682,211



(**a**) Peat left after forest fire.

(**b**) Peat land map.

Figure 14. Peat land map in 2003 of UMTNP after big forest fire.

3.5. Peat Volume and Carbon Storage in 2024

After two decades of post-fire management and natural recovery, peatland structure and associated carbon storage exhibited substantial changes, reflecting ongoing decomposition processes and incomplete peat accumulation (**Table 12**). By 2024, peat distribution was largely confined to shallow and intermediate layers (20–80 cm), with a total peatland area of 3,907 ha and a cumulative peat volume of 10,738,100 m^3.

Peat storage and carbon stock varied across thickness classes, with the largest contribution derived from the 60–80 cm layer. This layer, despite its relatively smaller area (597 ha), contained the highest peat volume (5,153,100 m^3) and supported a carbon stock of approximately 520,917 t. The 40–60 cm layer contributed moderately, with a carbon stock of 376,067 t, while the 20–40 cm layer—although covering the largest area (2,331 ha)—contained the lowest carbon stock (188,509 t) due to its limited thickness and lower peat volume.

Across all layers, peat bulk density remained relatively constant (0.24 Mg m^{-3}), and the average carbon content was stable at approximately 42.12%. The total peat mass was estimated at 2,577,144 t, corresponding to a total carbon stock of 1,085,493 t. These values indicate a substantial reduction compared to pre-fire conditions, reflecting long-term peat degradation and carbon loss.

3.6. Seasonal Variation in Peat Chemical Properties (2024)

The chemical characteristics of peat soils exhibited clear seasonal variation between the wet and dry seasons, reflecting changes in hydrological conditions and biogeochemical processes (**Tables 13** and **14**). Overall, peat soils remained acidic across all thickness classes, with pH values consistently lower in the dry season compared to the wet season.

During the wet season, pH values ranged from 4.58 to 5.66 and showed a decreasing trend with increasing peat thickness. In contrast, the dry season was characterized by more acidic conditions, with pH declining further to values between 4.10 and 4.47. These differences were statistically significant ($p < 0.01$), indicating a strong influence of seasonal hydrology on peat acidity. The lower pH observed in the dry season likely reflects increased oxidation and acidification processes under reduced water saturation.

Humic acid content was higher in the wet season, with relatively stable values across peat layers, whereas in the dry season it declined significantly with increasing peat depth. This pattern suggests enhanced decomposition and mineralization under drier conditions, leading to a reduction in organic matter quality. The seasonal difference in humic acid content was statistically significant in the dry season but not in the wet season, indicating greater sensitivity to moisture stress.

Table 12. Peat and carbon volume in UMT National Park 2024.

PT (cm)	Area m^2	Volume (m^3)	Average Density (Mg/m^2)	Peat Storage (ton)	Average % C	Carbon Storage Cs (ton)
60–80	597	5,153,100	0.24	1,236,744	42.12	520,917
40–60	979	3,720,200	0.24	892,848	42.12	376,067
20–40	2,331	1,864,800	0.24	447,552	42.12	188,509
Total	3,907	10,738,100	0.24	2,577,144	42.12	1,085,493

Note: Square meter (m^2); Cubic meter (m^3); Miligram/square meter (Mg/m^2).

Table 13. Chemical indicators of peat in the wet season (2024).

PT (cm)	pH (H_2O)	Humic Acid (%)	SO_4^{2-} (mg/L)	P_2O_5 (mg/L)	NH^{4+} (mg/L)	Nt (mg/L)	K_2O (mg/L)	Fe^{2+} (mg/L)
20–40	5.66	17.78	0.030	0.09	17.86	0.66	0.41	2.30
40–60	5.38	15.98	0.027	0.10	16.65	0.98	0.51	2.66
60–80	4.58	17.67	0.029	0.11	19.56	1.03	0.55	2.45
Average	5.21	17.14	0.029	0.1	18.02	0.89	0.49	2.74
p-value = 0.05	<0.01*	0.48*Ns*	0.76*Ns*	<0.05*	0.30*Ns*	<0.05*	<0.05*	0.36*Ns*

Note: *p*-value = 0.05; * significant difference, *Ns*: not significant difference.

Table 14. Chemical indicators of peat in the dry season 2024.

PT (cm)	pH (H_2O)	Acid Humic (%)	SO_4^{2-} (mg/L)	P_2O_5 (mg/L)	NH^{4+} (mg/L)	Nt (mg/L)	K_2O (mg/L)	Fe^{2+} (mg/L)
20–40	4.47	11.60	0.08	0.11	17.06	0.26	0.18	1.18
40–60	4.30	8.60	0.05	0.07	15.40	0.59	0.37	2.74
60–80	4.10	6.80	0.04	0.06	13.37	0.73	0.56	4.09
Average	4.29	9	0.06	0.08	15.28	0.53	0.18	3.41
p-value	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*

Note: PT peat thickness; * significant difference.

Nutrient dynamics also varied between seasons. Concentrations of ammonium (NH_4^+) and TN were generally higher in the wet season, reflecting reduced nitrification and greater accumulation of reduced nitrogen forms under saturated conditions. In the dry season, these values decreased, likely due to increased microbial activity and nitrogen transformation processes. Available phosphorus (P_2O_5) and potassium (K_2O) exhibited moderate variation across peat layers, with some statistically significant differences, suggesting localized nutrient redistribution influenced by peat depth and seasonal water availability.

Sulfate (SO_4^{2-}) concentrations remained relatively stable in the wet season but increased in the dry season, particularly in shallower peat layers, indicating enhanced oxidation of sulfur compounds under aerobic conditions. Iron (Fe^{2+}) concentrations showed contrasting patterns, with relatively uniform distribution in the wet season but a marked increase in deeper peat layers during the dry season, likely associated with redox fluctuations and mobilization of iron under changing water table conditions.

3.7. Seasonal Variation in Water Chemistry on Peatland (2024)

Water chemistry in peatland ecosystems showed pronounced seasonal variation between the wet and dry seasons, reflecting strong hydrological control on nutrient dynamics and redox processes (**Tables 15** and **16**). Across all peat thickness classes, significant differences were observed for all measured parameters ($p < 0.001$), indicating consistent vertical and seasonal gradients.

During the wet season, water pH ranged from slightly acidic to near neutral (5.08–6.31), with higher values recorded in shallower peat layers. In contrast, the dry season exhibited more acidic conditions (4.32–5.40), with pH decreasing consistently with increasing peat thickness. This seasonal decline in pH suggests enhanced oxidation and acidification processes under lower water table conditions.

Table 15. Water chemical indicators of peat in the rainy season 2024.

PT	pH (H_2O)	Humic Acid (%)	Nt (mg/L)	Fe^{2+} (mg/L)	P_2O_5 (mg/L)
20–40 cm	6.31	0.849	0.16	0.26	0.026
40–60 cm	5.37	0.637	0.27	1.08	0.035
60–80 cm	5.08	0.473	0.52	2.27	0.057
Average	5.69	0.653	0.32	1.2	0.04
p-value = 0.05	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*

Note: PT peat thickness; * significant difference at $p < 0.001$.

Table 16. Water chemical indicators of peat in the dry season 2024.

PT	pH (H_2O)	Humic Acid (%)	Nt (mg/L)	Fe^{2+} (mg/L)	P_2O_5 (mg/L)
20–40 cm	5.40	0.2643	16.81	7.49	5.39
40–60 cm	4.59	0.7362	21.57	6.16	6.08
60–80 cm	4.32	1.1938	26.11	4.45	6.56
Average	4.77	0.7329	21.5	6.03	6.01
p-value = 0.05	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*

Note: PT peat thickness; * significant difference at $p < 0.001$.

Humic acid concentrations displayed contrasting patterns between seasons. In the wet season, humic content decreased with increasing peat depth, indicating dilution and leaching under saturated conditions. Conversely, in the dry season, humic acid concentrations increased with depth, likely reflecting the accumulation of dissolved organic matter as water levels declined and decomposition intensified.

Nutrient concentrations exhibited substantial seasonal differences. TN levels were relatively low during the wet season (0.16–0.52 mg L^{-1}) but increased dramatically in the dry season (16.81–26.11 mg L^{-1}), suggesting enhanced mineralization and concentration effects under reduced water volume. Similarly, phosphorus (P_2O_5) concentrations were minimal during the wet season but increased sharply in the dry season, indicating mobilization and reduced dilution under drier conditions.

Iron (Fe^{2+}) concentrations also varied markedly between seasons. During the wet season, Fe^{2+} increased with peat depth, consistent with reducing conditions in deeper, water-saturated layers. In contrast, the dry season showed higher overall Fe^{2+} concentrations but a decreasing trend with depth, likely reflecting oxidation processes and changes in iron solubility under fluctuating redox conditions.

4. Discussions

Forest regeneration following the 2003 fire in U Minh Thuong National Park represents a clear trajectory of secondary succession under peatland conditions. The recovery pathway observed in this study—from seed-based regeneration to canopy closure and eventual stand maturation—aligns with classical succession theory in fire-affected wetlands. The sequential stages identified, including seedling establishment, sapling development, canopy closure, and structural maturation, highlight the resilience of *Melaleuca cajuputi* under appropriate hydrological management. Similar recovery pathways have been documented in fire-prone wetland forests, where regeneration is strongly dependent on residual seed sources and post-disturbance environmental conditions [27,28].

Based on **Tables 7–9**, peat thickness strongly controls the ecosystem by regulating water level, which in turn enhances regeneration, stand structure, and individual growth ($p < 0.001$), forming the key pathway: PT → WL → regeneration → structure → growth. Positive feedback occurs as thicker peat improves moisture conditions, increases vegetation cover, and promotes further peat accumulation, while negative density-dependent feedback regulates populations through increased competition and mortality at high densities. Overall, the Melaleuca peatland system is primarily driven by peat and hydrological conditions, with self-thinning and biomass accumulation maintaining ecological balance.

The successful restoration of forest structure over 20 years demonstrates the critical role of fire prevention and water management in peatland ecosystems. In particular, maintaining high water tables to reduce peat oxidation and fire recurrence has been widely recognized as a key restoration strategy in tropical peatlands [29]. The recovery observed in U Minh Thuong is comparable to restoration outcomes reported in Southeast Asia and represents a significant milestone for conservation, consistent with criteria for designation under UNESCO and ASEAN heritage frameworks.

Tree growth patterns showed a strong dependence on peat thickness, with significantly higher values of diameter ($D_{1.3}$), total height (Ht), and bole height (Hb) in deeper peat layers (60–80 cm). This finding is consistent with studies in both tropical and temperate peatlands, where deeper organic soils provide more stable moisture regimes and improved nutrient availability [30]. In contrast, shallow peat layers are more susceptible to waterlogging fluctuations and nutrient limitations, constraining tree growth. Comparable patterns have been reported in managed peatlands, where reduced flooding and soil amendments significantly enhance growth rates of *Melaleuca* species [31].

Based on **Tables 7–9**, peat thickness (PT) emerges as the key driver of the Melaleuca peatland ecosystem, regulating water level (WL), regeneration, stand structure, and growth through the main pathway PT → WL → regeneration → structure → growth, alongside a strong direct effect on growth ($p < 0.001$). Thicker peat creates more stable, shallow water conditions, significantly increasing regeneration and enhancing individual tree performance. Positive feedback occurs as increased vegetation promotes moisture retention and peat accumulation, while negative density-dependent feedback regulates populations through competition and mortality at high regeneration levels.

Multivariate analyses (MLR, GLM/GAM, and SEM) further support this mechanism. Growth responses follow the model $Growth = \beta_0 + \beta_1 PT + \beta_2 WL + \beta_3 Nt + \beta_4 Nd + \varepsilon$, with PT showing a strong positive effect and WL a negative effect. Regeneration dynamics are well described by $Nt \sim Poisson(\lambda)$, $\log(\lambda) = \beta_0 + \beta_1 PT + \beta_2 WL$, indicating exponential increases under lower WL. GAM results reveal nonlinear responses and ecological thresholds around 40–60 cm of peat thickness, while SEM confirms both direct and indirect effects of PT on growth: *Total = Direct + Indirect* (via *WL* and *Nt*), with indirect pathways contributing substantially (40–60%). Overall, the system is controlled by peat and hydrology, with regeneration and self-thinning processes maintaining ecological balance.

Changes in peat chemistry further reflect the strong influence of hydrological conditions. The observed decrease in pH and humic acid with increasing peat thickness, alongside increases in nutrients such as NH_4^+, P_2O_5, and Fe^{2+}, indicates active biogeochemical cycling influenced by redox dynamics. Similar trends have been reported in peatlands of Central Kalimantan, Indonesia, where seasonal water fluctuations drive nutrient mobilization and organic matter decomposition [32].

Importantly, comparable processes have also been documented in peatland and wetland systems in the United States. In boreal peatlands of Alaska, studies following large wildfires have shown that fire-induced lowering of the water table accelerates peat decomposition, increases nutrient availability, and alters soil chemistry, particularly through increased nitrogen mineralization and iron mobilization [33]. Similarly, research in the Florida Everglades demonstrated that post-fire conditions can lead to increased phosphorus release and changes in water chemistry, affecting long-term ecosystem productivity [34].

Water chemistry results from this study further support these findings. The strong seasonal contrast, with significantly higher nutrient concentrations (N, P, Fe) during the dry season, reflects concentration effects and enhanced mineralization under lower water levels. In U.S. peatland systems, such as the Great Dismal Swamp and northern bogs, similar seasonal dynamics have been observed, where drought conditions increase nutrient release and alter redox-sensitive elements, particularly iron and sulfur compounds [35,36]. These processes can enhance short-term productivity but also accelerate long-term peat degradation.

The loss of peat area (218 ha) and reduction in peat thickness (approximately 60 cm) following the 2003 fire represent a substantial decline in carbon storage capacity. The estimated peat volume loss (1,308,000 m^3) and associated carbon emissions are consistent with global observations of peatland fires as major sources of atmospheric carbon. In the United States, peat fires in Alaska and the southeastern coastal plain have been shown to release large quantities of stored carbon, contributing significantly to greenhouse gas emissions [37,38].

Peatlands are globally recognized as critical carbon reservoirs, storing more carbon than aboveground forest biomass in many ecosystems. This has been well documented in boreal peatlands of North America, where long-term carbon accumulation in peat exceeds that of forest vegetation [39]. The findings from U Minh Thuong reinforce this global pattern, emphasizing the importance of peat conservation for climate regulation.

A key insight from this study is that post-fire peat decomposition may result in greater long-term carbon loss than the initial combustion event. While fire causes immediate carbon release, subsequent drainage, oxidation, and microbial decomposition can lead to sustained emissions over decades. Similar conclusions have been reported in both tropical and temperate peatlands, where altered hydrology leads to persistent carbon loss even after vegetation recovery [10,38].

Finally, the relationship between peat chemistry and forest growth indicates that humic substances play a central role in regulating ecosystem productivity. The strong correlation between humic acid content and growth parameters ($D_{1.3}$, Ht, Hb) suggests that organic matter quality is a key driver of nutrient availability and plant development. This is consistent with findings from peatland studies in both Southeast Asia and North America, where dissolved organic carbon and humic compounds influence nutrient cycling, microbial activity, and vegetation dynamics [36].

Peatland Melaleuca forests are sensitive ecosystems that are highly prone to fire, with fires capable of smoldering underground for several weeks. The direct impacts of fire include the death of seedlings, mature trees, and small fauna, reduction in tree density, alteration of forest structure, drying and nutrient loss in peat soils, and CO_2 emissions that affect the photosynthesis of surviving trees. After a fire, water management under the forest canopy becomes critical for ecological recovery. High water levels during the dry season support tree survival and rapid regeneration while creating wet zones that prevent further peat ignition. Conversely, low water levels increase stress on trees, the risk of smoldering fires, and depletion of aquatic organisms. Thus, fire causes immediate direct damage, whereas water management is an indirect factor that determines the long-term recovery and stability of peatland Melaleuca forests (**Figure 15**).

Carbon loss in peatland Melaleuca forests results (**Figure 16**) from multiple interacting mechanisms. First, biological oxidation and mineralization by microorganisms decompose organic matter, releasing CO_2 and CH_4. Second, water level changes regulate decomposition rates: high water slows oxidation, whereas drainage exposes peat to air, accelerating carbon loss. Third, peat fires directly release large amounts of long-stored carbon as gases. Fourth, leaching and dissolved carbon export via water flows reduce carbon stocks. Finally, these mechanisms interact, highlighting the critical role of hydrological management and fire prevention in carbon conservation and ecological recovery of peatland Melaleuca forests.

Figure 15. Schematic illustrating the direct impacts of wildfire and the subsequent effects of water management.

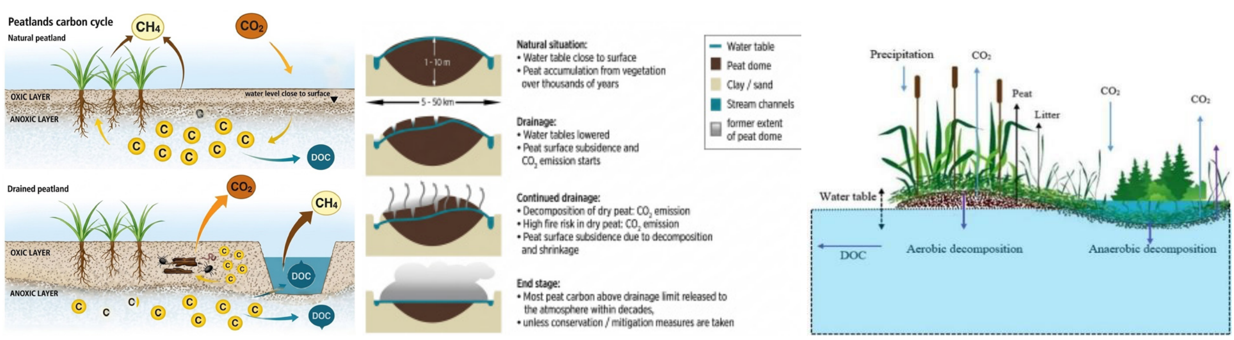


Figure 16. Diagram of Carbon Loss Mechanisms in Peatland Melaleuca Forests.

Integrated diagram illustrating the main mechanisms of carbon loss in peatland Melaleuca forests. Carbon stored in peat is lost through biological oxidation and mineralization by microorganisms, peat fires that release large amounts of carbon as gases, water level changes that control decomposition rates, and leaching of dissolved organic carbon (DOC) via water flows. These mechanisms interact, highlighting the importance of hydrological management and fire prevention for carbon conservation and ecological recovery.

5. Conclusions

The restoration of *Melaleuca* forests in U Minh Thuong National Park demonstrates a strong capacity for natural regeneration from residual seed banks following fire disturbance, facilitating the recovery of pre-primary forest structures consistent with conservation criteria for protected areas. Forest succession proceeds through four distinct stages: (i) post-fire seedling emergence from burned mother trees, (ii) development into young stands

(1–3 m), (iii) rapid canopy closure (3–4 m) within approximately two years, and (iv) long-term maturation over ~20 years, forming a stable forest system comparable to primary conditions.

Forest growth is strongly influenced by peat thickness and hydrological regimes. Growth parameters (DBH, total height, bole height, and canopy diameter) are generally constrained under shallow or irregularly flooded peat, while optimal development occurs in peat layers of 60–80 cm.

Severe fire disturbance resulted in the degradation of 218 ha of peatland, reducing peat thickness and significantly depleting peat volume, biomass, and carbon stocks. Initial peat reserves (26.77 million m^3; 6.37 million t; 2.68 million t C) have declined substantially after 20 years of hydrological management, with remaining stocks reduced to 10.74 million m^3, 2.58 million tons, and 1.09 million t C, respectively. These losses highlight the combined impacts of fire and prolonged water management practices on peat decomposition.

Post-fire peat and water chemistry exhibit clear relationships with peat thickness. Parameters such as pH and humic acid decrease with increasing peat depth, whereas nutrients and ions (SO_4^{2-}, NH_4^+, P_2O_5, total N, K_2O, and Fe^{2+}) show increasing trends. Correlation analysis further indicates that humic acid is strongly associated with peat thickness, while growth variables are influenced by key chemical factors, particularly pH, sulfate, and iron, with weaker relationships observed for canopy diameter.

Overall, peat thickness and associated biogeochemical properties play a critical role in regulating forest regeneration, growth dynamics, and long-term carbon storage in fire-affected *Melaleuca* ecosystems.

Author Contributions

L.T.T. and M.D.: conceptualization, methodology, software, validation, writing—original draft preparation, writing—review and editing, visualization, supervision, project administration, funding acquisition; G.H.P., Q.T.L., H.T.T., and B.M.N.N.: formal analysis, investigation, resources, data curation. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

The research was approved by the ethical review from Faculty of Natural Resources and Environment of Kien Giang University in December 2024 with the number KGU1-B2024.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study. Participation was voluntary, and respondents were informed about the purpose of the research and the confidentiality of their responses.

Data Availability Statement

The data supporting reported results can be found at Kien Giang University, U Minh Thương National Park, Department of Agriculture and Environment in Kien Giang province.

Acknowledgments

The authors would like to thank the Department of Science, Technology and Environment, Ministry of Education and Training Vietnam has supported project KGU1-B2024 (2024–2025), the Faculty of Natural resources and Environment of Kien Giang University, the U Minh Thuong National Park of Vietnam, the Southern Forestry Institute of Vietnam. All of authors also thank help funding from Research Project Number: RP-NASS-2006-015 Ecosystem Funtion Evolution and Sustainable Management under Anthropogenic Disturbances: Acase Study of Cental Asia and Surounding Regions of Nanyang Academy of Sciences (NASSG).

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

The authors declare that no artificial intelligence (AI) tools were used in the research, analysis, or preparation of this manuscript.

References

[1] Tran, V.T., 2016. U Minh peat swamp forest: Mekong River Basin (Vietnam). In: Finlayson, C.M., Milton, G.R., Prentice, R.C., et al. (eds.). The Wetland Book. Springer: Dordrecht, The Netherlands.

[2] Thai, L.T., Tran, T.V., Le, K.V., et al., 2024. Peatmass Change and Water Level Influencing Regenerated Melaleuca Forest after a Fire in U Minh Thuong National Park, Vietnam. Sustainability. 16(2), 620. DOI: https://doi.org/10.3390/su16020620

[3] Dinh Thong, V., Van Viet, N., Van Nha, P., et al., 2025. Remarkable records of mammals and conservation status of Sundasciurus hippurus and Macaca fascicularis from U Minh Ha National Park, southern Vietnam. Journal of Science Natural Science. 70(4), 101–109. DOI: https://doi.org/10.18173/2354-1059.2025-0058

[4] Anh, L.N.T., Diep, N.T.H., Chinh, N.V., et al., 2025. Mapping biomass and carbon reserves of Melaleuca forest (Melaleuca cajuputi Powell) in U Minh Thuong National Park, Kien Giang Province. Electronic Journal of Agriculture and Environment. (17). Available from: https://tapchikhoahoc.nnmt.net.vn/vjae/article/view/370

[5] Nguyen, T.N.T., Huynh, B.A.Q., Nguyen, T.L., et al., 2020. The species composition of fish distributed in surrounding areas of U Minh Thuong and U Minh Ha National Parks. Can Tho University Journal of Science. 56, 185–191.

[6] Vietnam Nature Conservation Center, 2004. U Minh Thuong National Park. In Sourcebook of Existing and Proposed Protected Areas in Vietnam, 2nd ed. Vietnam Nature Conservation Center: Hanoi, Vietnam. Available from: https://thiennhienviet.org.vn/sourcebook/pdf/4%20Mekong%20Delta/U%20Minh%20Thuong.pdf (cited 1 March 2026).

[7] Huat, B.K., 2004. Organic and Peat Soils Engineering. Penerbit Universiti Putra Malaysia: Selangor, Malaysia.

[8] Jauhiainen, J., Takahashi, H., Heikkinen, J.E.P., et al., 2005. Carbon fluxes from a tropical peat swamp forest floor. Global Change Biology. 11, 1788–1797.

[9] Posa, M.R.C., Wijedasa, L.S., Corlett, R.T., 2011. Biodiversity and conservation of tropical peat swamp forests. BioScience. 61, 49–57. DOI: https://doi.org/10.1525/bio.2011.61.1.10

[10] Page, S.E., Siegert, F., Rieley, J.O., et al., 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature. 420, 61–65. DOI: https://doi.org/10.1038/nature01131

[11] Girkin, N.T., Cooper, H.V., Ledger, M.J., et al., 2022. Tropical peatlands in the Anthropocene: The present and the future. Anthropocene. 40, 100354. DOI: https://doi.org/10.1016/j.ancene.2022.100354

[12] Kuwata, M., 2024. Atmospheric emissions, processes, and impacts of tropical peatland fire haze in Equatorial Asia: A review. Atmospheric Environment. 331, 120575. DOI: https://doi.org/10.1016/j.atmosenv.2024.120575

[13] Harrison, M.E., Ottay, J.B., Cheyne, S.M., et al., 2020. Tropical forest and peatland conservation in Indonesia: Challenges and directions. People and Nature. 2(1), 4–28. DOI: https://doi.org/10.1002/pan3.10060

[14] Ngo Bieng, M.A., Finegan, B., Sist, P., 2022. Active restoration of secondary and degraded forests in the context of the UN Decade on Ecosystem Restoration. Forest Ecology and Management. 503, 119770. DOI: https://doi.org/10.1016/j.foreco.2021.119770

[15] Dharma, A.B., Marlinda, P., Adianto, A., et al., 2024. The implementation of peat ecosystems in mitigating the disaster of Riau forest fires. E3S Web of Conferences. 506, 08002. DOI: https://doi.org/10.1051/e3sconf/202450608002

[16] TCVN 14286-2:2024. 2024. Forest Inventory Method – Part 2: Regenerated Tree Layer. Available from: https://thuvienphapluat.vn/TCVN/Nong-nghiep/TCVN-14286-2-2024-Phuong-phap-dieu-tra-rung-Phan-2-Tang-cay-tai-sinh-921593.aspx

[17] Palaghianu, C., 2016. Forest regeneration analysis: Statistical and computational perspectives. arXiv preprint. arXiv:1601.06191. DOI: https://doi.org/10.48550/arXiv.1601.06191 (in Romanian)

[18] Hooijer, A., Page, S., Canadell, J.G., et al., 2010. Current and future CO_2 emissions from drained peatlands in Southeast Asia. Biogeosciences. 7(5), 1505–1514. DOI: https://doi.org/10.5194/bg-7-1505-2010

[19] Gytarsky, M., Hiraishi, T., Irving, W., et al., 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Institute for Global Environmental Strategies: Hayama, Japan. Available from: https://www.ipcc-nggip.iges.or.jp/public/2006gl/

[20] Ratefinjanahary, I., MacKenzie, R., Sharma, S., et al., 2025. Development of soil organic carbon quantifica-

tion model and comparison based on CHN analyser, Loss on Ignition, and Walkley-Black methods for mangrove soils in Madagascar. Estuarine, Coastal and Shelf Science. 317, 109182. DOI: https://doi.org/10.1016/j.ecss.2025.109182

[21] Ziegel, E.R., Polhemus, N.W., 2000. Statistical Analysis Using STATGRAPHICS Plus, Volume 2: Quality Control and Experimental Design. Technometrics. 42(3), 323.

[22] Gazzaz, N.M., Yusoff, M.K., Aris, A.Z., et al., 2012. Artificial neural network modeling of the water quality index for Kinta River (Malaysia) using water quality variables as predictors. Marine Pollution Bulletin. 64(11), 2409–2420. DOI: https://doi.org/10.1016/j.marpolbul.2012.08.005

[23] Tu, S., Li, C., Shepherd, B.E., 2024. Between- and within-cluster Spearman rank correlations. arXiv preprint. arXiv:2402.11341. DOI: https://doi.org/10.48550/arXiv.2402.11341

[24] Bao, H., 2009. Statistics in Forestry: Application of Statgraphics Centurion and MS. Tay Nguyen University: Buon Ma Thuot, Vietnam.

[25] Danh, M., Thai, L.T., Ngo, T.V., et al., 2025. Assessing Sustainable Development of Carbon Stock and Melaleuca Forest Growth in U Minh Thuong National Park after Big Fires Vietnam. Research in Ecology. 7(4), 125–141. DOI: https://doi.org/10.30564/re.v7i4.10232

[26] Quoi, L.P., Truyen, N.T., Thang, T.V., 2016. Restoration of Peatland Ecosystems and Biodiversity in U Minh Region of Mekong Delta, Vietnam. In Proceedings of the 15th International Peat Congress (IPC 2016), Kuching, Malaysia, 15–19 August 2016. Available from: https://peatlands.org/assets/uploads/2019/06/ipc16p445-450a325quoi.truyen.etal_.pdf

[27] Johnstone, J.F., Allen, C.D., Franklin, J.F., et al., 2016. Changing disturbance regimes, ecological memory, and forest resilience. Frontiers in Ecology and the Environment. 14(7), 369–378. DOI: https://doi.org/10.1002/fee.1311

[28] Turner, M., Baker, W., Peterson, C., et al., 1999. Factors Influencing Succession: Lessons from Large, Infrequent Natural Disturbances. Ecosystems. 1, 511–523. DOI: https://doi.org/10.1007/s100219900047

[29] Page, S.E., Rieley, J.O., BanksS, C.J., 2011. Global and regional importance of the tropical peatland carbon pool. Global Change Biology. 17(2), 798–818. DOI: https://doi.org/10.1111/j.1365-2486.2010.02279.x

[30] Brady, N.C., Weil, R.R., 2016. The Nature and Properties of Soils, 15th ed. Pearson: New York, NY, USA.

[31] Giesen, W., 2015. Utilising non-timber forest products to conserve Indonesia's peat swamp forests and reduce carbon emissions. Journal of Indonesian Natural History. 3(2), 17–24.

[32] Wösten, J.H.M., Clymans, E., Page, S.E., et al., 2008. Peat–water interrelationships in a tropical peatland ecosystem in Southeast Asia. Catena. 73(2), 212–224. DOI: https://doi.org/10.1016/j.catena.2007.07.010

[33] Turetsky, M.R., Kane, E.S., Harden, J.W., et al., 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience. 4(1), 27–31. DOI: https://doi.org/10.1038/ngeo1027

[34] Smith, S.M., Newman, S., Garrett, P.B., et al., 2001. Differential Effects of Surface and Peat Fire on Soil Constituents in a Degraded Wetland of the Northern Florida Everglades. Journal of Environmental Quality. 30(6), 1998–2005. DOI: https://doi.org/10.2134/jeq2001.1998

[35] Jiang, D., Nie, T., Yan, J., et al., 2025. Restoration type determines synchronic recovery of soil carbon, nitrogen, and phosphorus in mangrove wetlands. Journal of Environmental Management. 385, 125658. DOI: https://doi.org/10.1016/j.jenvman.2025.125658

[36] Quan, Q., Zhou, J., Hanson, P.J., et al., 2025. Drought-induced peatland carbon loss exacerbated by elevated CO_2 and warming. Science. 390(6771), 367–370. DOI: https://doi.org/10.1126/science.adv7104

[37] Kasischke, E.S., Verbyla, D.L., Rupp, T.S., et al., 2010. Alaska's changing fire regime — implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research. 40(7), 1313–1324. DOI: https://doi.org/10.1139/X10-098

[38] Austin, K.G., Elsen, P.R., Honorio Coronado, E.N., et al., 2025. Mismatch Between Global Importance of Peatlands and the Extent of Their Protection. Conservation Letters. 18(1), e13080. DOI: https://doi.org/10.1111/conl.13080

[39] Gorham, E., 1991. Northern Peatlands: Role in the Carbon Cycle and Probable Responses to Climatic Warming. Ecological Applications. 1(2), 182–195. DOI: https://doi.org/10.2307/1941811