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Assessing Sustainable Development of Carbon Stock and Melaleuca Forest Growth in U Minh Thuong National Park after Big Fires Vietnam

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ABSTRACT

Research conducted in U Minh Thuong National Park to assess carbon storage from fires and water on forest growth and regeneration. In 2003 after forest fire, measures were implemented to promote forest regeneration, afforestation, and rainwater storage, aim to prevent future forest fires. Investigating established in 2023 on the thicknesses of (20–40 cm), (40–60 cm), (60–80 cm) of the 500 m^2 per plot, with 5 replications, measuring growth and analyzing peat chemistry. Contents include: Assessing changes in peat and carbon reserves Melaleuca forests before and after forest fires; analysis of peat and water chemical properties during seasonal floods, assessing Melaleuca growth, and the relationship between soil chemistry and growth due to higher water levels 20 years after forest fire. The results show a large volume of peat and carbon reserves, accumulated over thousands of years, destroyed by forest fires; lost in large quantities due to frequent flooding, leading to organic matter decomposition. Melaleuca grows slowly and death ratio increases after 20 years. Study also determined soil and water chemistry by seasonal flood; relationship between peat chemical indicators and Melaleuca growth on peat thickness. Results assessed the total peat volume and carbon stocks

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ARTICLE INFO
Received: 28 May 2025 | Revised: 06 June 2025 | Accepted: 18 June 2025 | Published Online: 17 September 2025
DOI: https://doi.org/10.30564/re.v7i4.10232

CITATION
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

accumulated over thousands of years of Melaleuca Forest history, the effects of forest fires and water management on growth and chemical relationships, particularly after above-normal water levels were observed for 20 years. Results are research changes in peat.

Keywords: Sustainable Development; Peat; Carbon Stock; Melaleuca Forest; Seasonal Flood Water; U Minh Thuong National Park

1. Introduction

U Minh Thuong National Park (UMTNP) in southwestern Vietnam, with a core zone area of 8,038 hectares [1]. It is home to numerous rare and endangered plant and animal species [1,2]. Biodiversity is very high, with 250 plant species and 225 animal species, including green snakes, crocodiles, large reptiles, yellow parrots, and many migratory birds [3–5]. UMTNP recognized by UNESCO as a World Natural Heritage Site in 2002 [6]. Conservation efforts must focus on promoting sustainable development practices.

Peat is a resource found in natural forests and a cause of forest fires [7]. The properties of peat such as water absorption and spread of wildfires [1,2]. Research of peat and carbon volume in response to forest fires [8,9]. A forest fire in 2003 burned more than 90 % of peat thickness from 100–300 centimeters (cm). After one year, 95 % the burned area was regenerated with Melaleuca trees. After 3 years, regenerating forest is formed, and the reed vegetation develops, creating a risk of forest fires in the dry season. The plan to build a hard embankment around the core zone by area 8038 ha was also completed after 3 years of construction. This dike facilitates the rainwater storage throughout the year for many years to come. The practice of storing water under above normal conditions causes deposition of peat and carbon mass. At the same time, high water levels in the core zone are also unsuitable for the growth conditions of Melaleuca Forest. After 20 years (2003 – 2023), there have been many changes in carbon accumulation mass, changes in the growth status of Melaleuca Forest on peat land. To assess the management of peat flooding that is longer than normal under the conditions of using dykes to store rainwater to fight forest fires over a 20-year period, a study on the current status of peat and forest was conducted to assess the current status of peat loss and forest growth in 2023.

Based on the above hot issues, a research project was set up with title "Assessing sustainable development of carbon stock by flooding effects on Melaleuca Forest growth in U Minh Thượng National Park after dig fires in Vietnam".

2. Material and Methods

2.1. Carbon Assessment

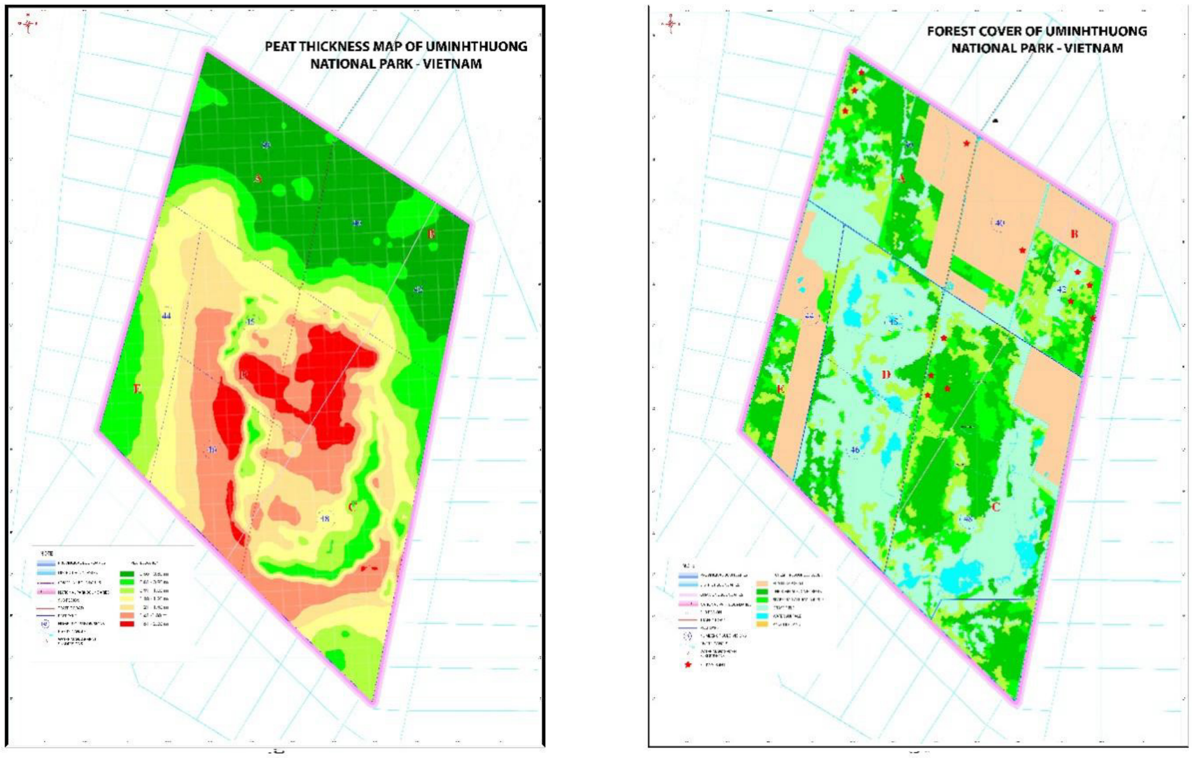
The division of peat thickness (PT) is based on the lowest average thickness of 20 cm and the highest average thickness of 80 cm, resulting in three peat thickness categories as follows:

Collect peat samples, on peat thickness (PT); PT 20 – 40 centimeter (cm); PT (40 – 60 cm); PT (60 – 80 cm); each PT 05 plots, each sample is 1 kg and coded a number UTM1, UTM2, UTM3 then gets to the Laboratory of Southern Institute of Forestry Science for analysis (**Table 1**).

Measure forest growth: Based on the peat and forest map after the forest fire (after 2003–2023) to measure growth of Melaleuca Forest on 3 types PT: PT (20 – 40 cm); PT (40 – 60 cm); PT (60 – 80 cm), each PT 5 plots; plot area 500 m^2/plot (**Figure 1**).

Table 1. Coordinates for Latitude (La.) and Longitude (Lo.) of Forest and Peat Survey Plots.

No peat		**PT (20–40 cm)**		**PT (40–60 cm)**		**PT (60–80 cm)**	
Lo.	La.	Lo.	La.	Lo.	La.	Lo.	La.
105.09498	9.63394	105.08536	9.58129	105.10804	9.60254	105.1097	9.60301
105.09685	9.6395	105.0827	9.57361	105.09251	9.57957	105.10021	9.58504
105.09375	9.62692	105.09087	9.60302	105.09853	9.57647	105.09251	9.58898
105.06385	9.60852	105.09106	9.59796	105.08804	9.56234	105.09556	9.58898
105.06338	9.60273	105.08949	9.58868	105.09719	9.56032	105.09498	9.63394



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

Figure 1. Example Caption (Study Area). (**a**) Peat thickness of UMTNP. (**b**) Research Sites Investigated in UMTNP, 2023.

Diameter of the trunk (D1,3)

$$D1.3 = \frac{C1.3}{\pi} \quad (1)$$

The formula for calculating the area of the trunk cut at a position of 1.3 m (G1.3)

$$G1.3 = \frac{D1.3}{4} * \pi \quad (2)$$

D1.3: The trunk diameter at position 1.3 m

$G_{1.3}$: The area of the trunk cut at 1.3 m

Dc The canopy diameter (m)

Gc: The canopy area (m^2)

Ht: Height to top (m)

f: The volumetric tree coefficient (calculated as 0.5)

N/p: Number trees of plot

Calculate peat and carbon reserves.

Peat volume using formula (Pv):

$$Pv = Pt * Pa \quad (3)$$

$$Pw = Pv * Dw \quad (4)$$

Pv: Peat volume; Pt h: Peat thicknesses (cm); Pa: Peat area (m^2); Dw: weight per volume unit (g/cm^3); Pw: Peat weight of volume (tons).

Carbon volume reserves (Cv):

$$Cv = Pv * Pw \quad (5)$$

(Cv Carbon volume reserves (m^3)

$$Cw = Pw * Rc\% \quad (6)$$

Cw: Carbon weight; Rc%: Rate of carbon per peat unit

Calculation of emissions due to peat oxidation [10].

$$CO2e = Pa * Pdg * Dwl * CO2 - 1 \text{ (ton/year)} \quad (7)$$

Pa: Peat areas; Pdg: Peat area dropped down ground; Dwl: Depth water level

Oxidative emissions of peat based on peat area and groundwater level characteristics. Apply formula Indonesia, 91 tons/ha/year 1 meter per deep [10]. Thus, the total emission is calculated as follows:

$$CO2e = Pa * Pdg * Dwl * CO2 - 1 \text{ (ton/year)}$$

Pa: Peat areas; Pdg: Peat area dropped down ground; Dwl: Depth water level

$CO_2 - 1$: CO^2 emission in depth underground water level = 45.5 ton CO^2/ha/year)

Chemistry and physics of peat include:

pH (H_2O); pH KCl, Humus (%), Nitrogen total (%), P_2O_5 (%), K_2O (%), Fe^2+ (mg/100g), SO_4+ (mg/100g), humic acid (%). The pH (H_2O) and pH (KCl) were determined with a pH meter. Humus content and acid humic evaluated by Walkley Black and total nitrogen by Kjeldahl method [11]; indicates P_2O_5 by colorimetric method.

2.2. Data Analysis

Analysis using t-tests and one-way analysis of variance (ANOVA) to compare the mean differences between peat and forest growth on PT [12]. Correlation analysis using the Pearson correlation coefficient described the interdependence between peat quality and the development of Melaleuca trees. Correlation coefficients (−1) – (+1), with a positive correlation indicating an increase or decrease in two variables and a negative correlation indicating an increase in one variable and a reduction in the other. A correlation is significant when the P value is > 0.05, and the correlation coefficient (r) is significant < 0.5 in absolute value [13]. All analyses using statistical software IBM SPSS 20.0 Windows and Statgraphics Centurion XVI.

Relationship between peat and the growth of Melaleuca forests on PT. Spearman's correlation coefficient used for analysis, and the significance at $P > 0.05$ [14]. If the correlation coefficient variable (peat) levels are significant, the hypothesis is rejected. Data processing tools, including statistical calculations, description, test hypotheses, and using Microsoft Excel, Statgraphics Centurion 19.12, and IBM SPSS Statistics version 20.0 [15].

3. Results and Discussion

3.1. Results of Peat Area Changes on Peat Thickness (PT) Before and After Fire (2002–2003)

3.1.1. Comments (Table 2, Figure 2, Figure 3, Figure 4)

Changes carbon storage in peat 2002 and 2003 (**Table 2, Figure 2, Figure 3, Figure 4**): Before forest fire in 2002, the area in the PT (80 –100 cm) is 2880 ha, PT (100 – 120 cm) is 560 ha, PT (120 – 140 cm) is 1250 ha. After forest fire in 2003 on PT (60 – 80 cm) is 2331 ha, PT (80 – 100 cm) is 979 ha, PT (100 – 120 cm) is 449, PT (120 – 140 cm) is 148 ha. Total area before fire (2002) is 4125 ha, after fire (2003) is 3907 ha; before and after fire the peat area is lost 218 ha; The depth PT (2002) is (80 – 140 cm) and (2003) is (60 – 140 cm).

Table 2. Changes Peat Area Before and After Fire (2002 and 2003).

No.	Peat Thickness (PT)	2002 (ha)	2003 (ha)
1	PT (120 – 140 cm)	1,245	148
2	PT (100 – 120 cm)	560	449
3	PT (80 –100 cm)	2,880	979
4	PT (60 – 80 cm)		2,331
5	PT (40 – 60 cm)		
6	PT (20 –40 cm)		
	Total	4,125	3,907

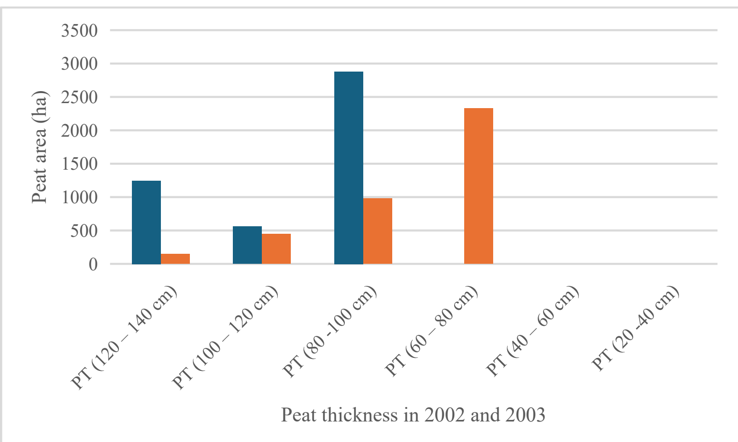


Figure 2. Changes of Peat Area Before and After Fire in 2002 and 2003.

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

Figure 3. This is original Melaleuca forest more than 3000 years with mixed many species. (**a**) Mixed Primary Forest many species; (**b**) Mature Forest of *Melaleuca cạuputi* and *Stenochlaena palustris* on Peat thickness 3 meters in UMTNP.

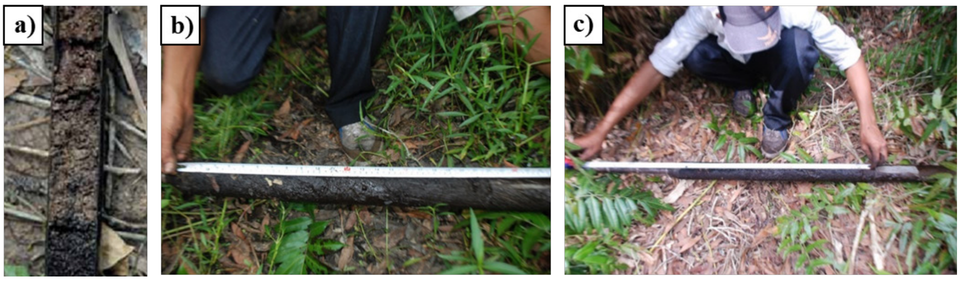


Figure 4. Vegetation on the Peat Layer. (**a**) Peat Thickness 20–60 cm, plant species regernerating on peatland after the 2003 forest fires; (**b**) PT (100–140 cm); (**c**) Peat Status after Forest Fire 2003 with species Stenochlaena palustris.

Peat land before forest fire 2002 with the PT two layers of black and brown peat. Black peat is found at the PT (100 –140 cm), while brown peat is found at the PT (80 – 100 cm). Total remaining peat area is 3907 ha [16,17].

In the annual report of U Minh Thuong National Park 2002, supported by CARE International (**Table 2**, **Table 3**), it is noted that the 2003 fire caused great damage to the area of peat immediately after the fire ended.

Table 3. Changes Area on Peat Thickness in 2003 and 2023.

No.	Peat Thickness (PT)	2003 (ha)	2023 (ha)
1	PT (120–140 cm)	148	
2	PT (100–120 cm)	449	
3	PT (80–100 cm)	979	
4	PT (60–80 cm)	2,331	579
5	PT (40–60 cm)		979
6	PT (20–40 cm)		2,331
	Total	3,907	3,907

3.2. Results of Peat Area and Volume Changes (After Fire 2003)

3.2.1. Comments (Table 3, Table 4)

Result of change area on peat (**Table 3, Figure 5**) In (2003) PT is 3907 hectare (ha) with PT (60 – 80 cm) is 2331 ha, PT (80 –100 cm) is 979 ha, PT (100 –120 cm) is 449 ha, PT (120 –140 cm) is 148 ha; in 2023 PT (20 – 40 cm) is 2331 ha, PT (40 – 60 cm) is 979 ha, PT (60 – 80 cm) is 579 ha. After the forest fire (2003), the area is 3907 ha [18,19]. In 2023, it is 3907 ha; if we compare them, there is no loss of area, but they have lost the PT. After the forest fire, the area of burnt peat land was investigated in 2003 was 3907 hectares. The regenerated forest after that was cared for with higher water level then normal until 2023. The investigation continued and the peat area remained not change, but the peat thickness had collapsed due to peat decomposition, losing up to 60 cm in the peat thickness.

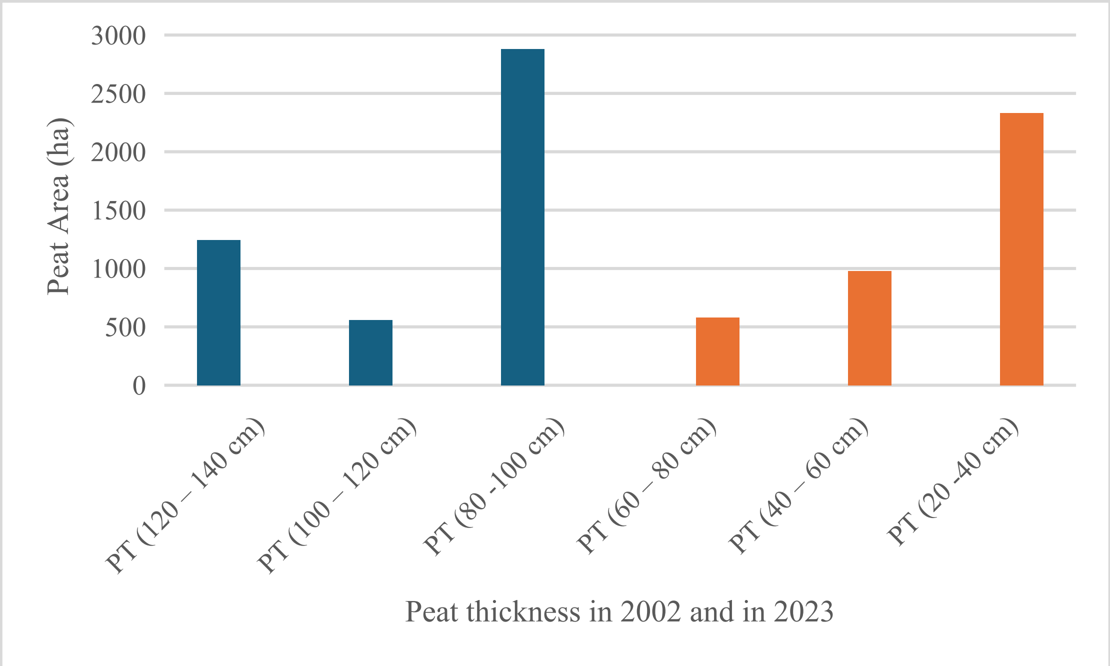


Figure 5. Peat Area Changes on Peat in 2002 and 2023.

After forest fire in 2003 (**Table 4, Figure 6**): On PT (40 – 80 cm) peat area (Pa) is 2331 ha; peat volume (Pv) is 11,655,000 m^3; Density peat weight per volume (Dw) (g/cm^3) is 0.24; peat weight storage (Pw) is 2,796,840 tons; rate of carbon per peat unit (Rc%) is 41.63% and carbon weight storage (Cw) is 1,164,325 tons. PT (80 – 100 cm) Pa is 979 ha; Pv is 8,321,500 m^3; Dw (g/cm^3) is 0.24; Pw is 1,996,344 tons; Rc% is 43.80% and Cw is 874,399 tons. PT (100 – 120 cm) Pa is 499 ha; Pv is 4,939,000 m^3; Dw (g/cm^3) is 0.24; Pw is 1,136,729 tons; Rc% is 40.61% and Cw is 461,626 tons. PT (120 – 140 cm) Pa is 148 ha; Pv is 1,850,000. m^3; Dw (g/cm^3) is 0.24; Pw is 444,000 tons; Rc% is 40.96% and Cw is 181,862 tons. These results show Pa total is 3907 ha, Pv is 26,765,500 m^3, Dw (g/cm^3) is 0.24, Pw is 6,373,913 tons, Rc% is 41.75%, Cw is 2,682,211 tons.

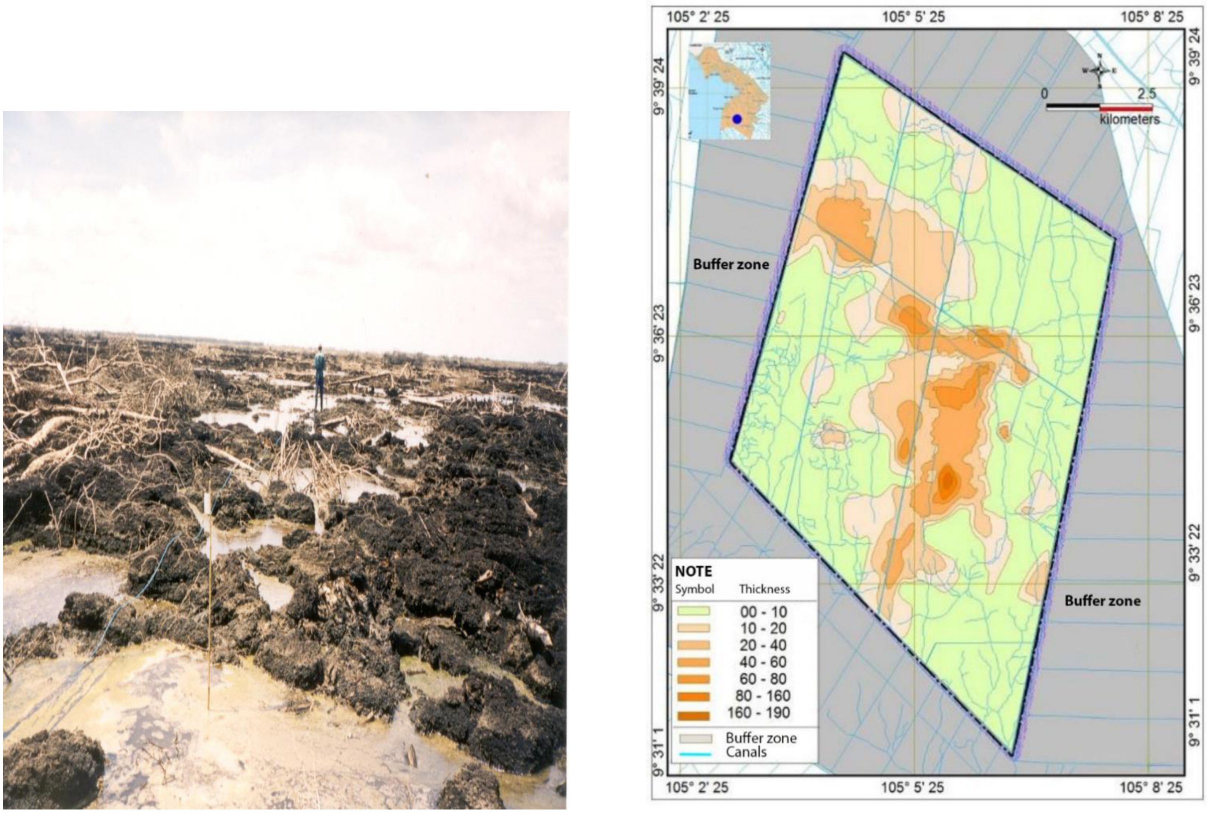
Before the forest fire, peat thickness was determined. After the fire, government policy required a reinvestigation of the area, revealing discrepancies in both the extent and thickness of peat loss (**Table 3**). Based on the lost area and peat thickness, values such as Dw, Pw, Rc%, and Cw were calculated. The resulting losses in peat volume (Pv), peat weight (Pw), and carbon storage were found to be substantial.

Table 4. Volume of Peat and Carbon Storage After Forest Fire 2003.

No.	Peat Thickness (PT) (cm)	Peat Area (Pa) m^2	Peat Volume (Pv) (m^3)	Density Peat Weight per Volume (Dw) (g/cm^3)	Peat Weight Storage (Pw) (ton)	C % Rate of Carbon per Peat Unit (Rc%)	Carbon Weight Storage (Cw) (ton)
1	120 – 140	148	1,850,000	0.24	444,000	40.96	181,862
2	100 – 120	449	4,939,000	0.24	1,136,729	40.61	461,626
3	80 – 100	979	8,321,500	0.24	1,996,344	43.80	874,399

Table 11. *Cont.*

No.	Peat Thickness (PT) (cm)	Peat Area (Pa) m^2	Peat Volume (Pv) (m^3)	Density Peat Weight per Volume (Dw) (g/cm^3)	Peat Weight Storage (Pw) (ton)	C % Rate of Carbon per Peat Unit (Rc%)	Carbon Weight Storage (Cw) (ton)
4	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**) (**b**)

Figure 6. Peat Land Map in 2003 of UMTNP After Big Forest Fire. (**a**) Peat Left After Forest Fire; (**b**) Peat Land Map build after forest fire 2003.

Source: UMTNP.

3.3. Results of Peat Area and Volume Changes (After Flooding Level 2003–2023)

3.3.1. Comments (Table 5)

After 20 years of water level manangement, the decomposition of peat and carbon volume in 2023 as follows (**Table 5**): On PT (20 – 40 cm) peat area (Pa) is 2331 ha, peat volume (Pv) is 1,864,800 m^3, Density peat weight per volume (Dw) g/cm^3 is 0.24, peat weight storage (Pw) 447,552 ton, rate of carbon per peat unit (Rc%) % is 42.12 %, Carbon weight storage (Cw) is 188,509 tons. On PT (40 – 60 cm) with Pa is 979 ha, Pv is 3,720,200 m^3, Dw is 0.24, Pw 892,848 tons, Rc% is 42.12 %, Cw is 376,067 tons. On PT (60 – 80 cm) Pa is 597 ha, Pv is 5,153,100 m^3, Dw peat density g/cm^3 is 0.24, Pw 1,236,744 tons, Rc% is 42.12 %, Cw is 520,917 tons.

From 2003 – 2023 the water level was kept higher in the peatland and extended for a longer period 6 months in the dry season to limit forest fires, this results the collapse and decomposition of the peat thickness (**Table 5**). U Minh Thuong National Park is flooded in the dry season; in some areas, the water level down in six months, so the calculated coefficient is 45 tons/ha/year on 1 meter per thickness [10,20]. In 2023 the annual peat volume survey of U Minh Thuong National Park, calculated on the peat area; calculating PV, Dw, Pw, Rc%, Cw show the actual volume and storage of peat and carbon loss are many times higher.

Table 5. Volume of Peat and Carbon Storage in 2023.

No.	Peat Thickness (PT) (cm)	Peat Area (Pa) (m^2)	Peat Volume (Pv) (m^3)	Density Peat Weight per Volume (Dw) (g/ cm^3)	Peat Weight Storage (Pw) (ton)	Rate of Carbon per Peat Unit (Rc%)	Carbon Weight Storage (Cw)-(ton)
1	60 – 80	597	5,153,100	0.24	1,236,744	42.12	520,917
2	40 – 60	979	3,720,200	0.24	892,848	42.12	376,067
3	20 – 40	2,331	1,864,800	0.24	447,552	42.12	188,509
Total		3,907	10,738,100		2,577,144	42.12	1,085,493

3.4. Peat Chemical After Flooding Level

3.4.1. Comments (Table 6)

Chemical indicators of peat in the wet season (**Table 6**) show: PT (20 – 40 cm) pH (H_2O) is 5.66, Humic acid is 17.78 %, SO_4^{2-} is 0.030 mg/l (milligram per liter), P_2O_5 is 0.09 mg/l, NH^{4+} is 17.86 mg/l, nitrogen total (Nt) is 0.66 mg/l, K_2O is 0.41 mg/l, Fe^{2+} is 2.30 mg/l. PT (40 – 60 cm) pH (H_2O) is 5.38, Humic acid is 15.98 %, SO_4^{2-} is 0.027 mg/l, P_2O_5 is 0.10 mg/l, NH^{4+} is 16.65 mg/l, nitrogen total (Nt) is 0.98 mg/l, K_2O is 0.51 mg/l, Fe^{2+} is 2.66 mg/l. PT (60 – 80 cm) pH (H_2O) is 4.58, Humic acid is 17.67 %, SO_4^{2-} is 0.029 mg/l, P_2O_5 is 0.11 mg/l, NH^{4+} is 19.56 mg/l, nitrogen total (Nt) is 1.03 mg/l, K_2O is 0.55 mg/l, Fe^{2+} is 2.45 mg/l.

After 20 years in flooded conditions, the chemical composition of peat was investigated and analyzed in the rainy season (November 2023) show (**Table 6**) pH(H_2O) decreased with increasing thickness, the indicators humic acid, SO_4^{2-}, P_2O_5, NH^{4+}, Nt, K_2O, Fe^{2+} increased when peat thickness increased.

Table 6. Chemical Indicators of Peat in the Wet Season (15/11/2023).

No.	Peat Thickness (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)
1	20 – 40	5.66	17.78	0.030	0.09	17.86	0.66	0.41	2.30
2	40 – 60	5.38	15.98	0.027	0.10	16.65	0.98	0.51	2.66
3	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		>0.01	0.48	0.76	>0.05	0.30	>0.05	>0.05	0.36

3.4.2. Comments (Table 7)

Chemical indicators of peat in the dry season (**Table 7**) show: PT (20 – 40 cm) pH (H_2O) is 4.47, Humic acid is 11.60 %, SO_4^{2-} is 0.08 mg/l (milligram per liter), P_2O_5 is 0.11 mg/l, NH^{4+} is 17.06 mg/l, nitrogen total (Nt) is 0.26 mg/l, K_2O is 0.18 mg/l, Fe^{2+} is 1.18 mg/l. PT (40 – 60 cm) pH (H_2O) is 4.30, Humic acid is 8.60 %, SO_4^{2-} is 0.05 mg/l, P_2O_5 is 0.07 mg/l, NH^{4+} is 15.40 mg/l, nitrogen total (Nt) is 0.59 mg/l, K_2O is 0.37 mg/l, Fe^{2+} is 2.74 mg/l. PT (60 – 80 cm) pH (H_2O) is 4.10, Humic acid is 6.80 %, SO_4^{2-} is 0.04 mg/l, P_2O_5 is 0.06 mg/l, NH^{4+} is 13.37 mg/l, nitrogen total (Nt) is 0.73 mg/l, K_2O is 0.56 mg/l, Fe^{2+} is 4.09 mg/l.

After 20 years of flooding level, peat investigation in the dry season (June 2023), the result of chemical indicators analysis showed **(Table 7)** pHH2O, humic acid, decreased as peat thickness increased and SO_4^{2-}, P_2O_5, Nt, K_2O, Fe^{2+} indicators increased as peat thickness increased.

Table 7. Chemical Indicators of Peat in the Dry Season (15/06/2023).

No.	Peat Thickness (cm)	pH (H2O)	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)
1	20 –40	4.47	11.60	0.08	0.11	17.06	0.26	0.18	1.18
2	40 – 60	4.30	8.60	0.05	0.07	15.40	0.59	0.37	2.74
3	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

3.5. Water Chemical on Peat

3.5.1. Comments (Table 8)

Water chemical on peat in the wet season (**Table 8**) show: PT (20 – 40 cm) pH (H_2O) is 6.31, Humic acid is 0.849 %, Nt is 0.16 mg/l, Fe^{2+} is 0.26 mg/l, P_2O_5 is 0.026 mg/l. PT (40 – 60 cm) pH (H_2O) is 5.37, Humic acid is 0.637 %, Nt is 0.27 mg/l, Fe^{2+} is 1.08 mg/l, P_2O_5 is 0.035 mg/l. PT (60 – 80 cm) pH (H_2O) is 5.08, Humic acid is 0.473 %, Nt is 0.52 mg/l, Fe^{2+} is 2.27 mg/l, P_2O_5 is 0.057 mg/l.

After 20 years of flooding, the chemical indicators of water on peat analyzed in the rainy season (November 2023) show the chemical indicators of peat water decreased, such as pHH$_2$O, humic acid, and Nt, Fe^{2+}, P_2O_5 chemical indicators on peat increased when increased peat thickness.

Table 8. Water Chemical Indicators on Peat in the Wet Season (15/11/2023).

No.	Peat Thickness	pH (H_2O)	Humic Acid (%)	Nt (mg/l)	Fe^{2+} (mg/l)	P_2O_5 (mg/l)
1	20 – 40 cm	6.31	0.849	0.16	0.26	0.026
2	40 – 60 cm	5.37	0.637	0.27	1.08	0.035
3	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	>0.001	>0.001	>0.001	>0.001	>0.001

3.5.2. Comments (Table 9)

Water chemical on peat in the dry season (**Table 9**) shows: PT (20 – 40 cm) pH (H_2O) is 5.40, Humic acid is 0.2643 %, Nt is 16.81 mg/l, Fe^{2+} is 7.49 mg/l, P_2O_5 is 5.39 mg/l. PT (40 – 60 cm) pH (H_2O) is 4.59, Humic acid is 0.7362 %, Nt is 21.57 mg/l, Fe^{2+} is 6.16 mg/l, P_2O_5 is 6.08 mg/l. PT (60 – 80 cm) pH (H_2O) is 4.32, Humic acid is1.1938 %, Nt is 26.11 mg/l, Fe^{2+} is 4.45 mg/l, P_2O_5 is 6.56 mg/l.

After 20 years of flooding, the chemical indicators of water on peat analyzed in the dry season (June 2023) (**Table 8**) show the chemical indicators of peat water decreased, such as pH, H_2O, humic acid, and Nt, Fe^{2+}, P_2O_5 chemical indicators on peat increased with increased peat thickness.

Table 9. Chemical Indicators of Peat in the Dry Season (15/06/2023).

No.	Peat thickness	pH (H_2O)	Humic acid (%)	Nt (mg/l)	Fe^{2+} (mg/l)	P_2O_5 (mg/l)
1	20 – 40 cm	5.40	0.2643	16.81	7.49	5.39
2	40 – 60 cm	4.39	0.7362	21.57	6.16	6.08
3	60 – 80 cm	4.32	1.1938	26.11	4.45	6.56
	Average	4.70	0.7329	21.5	6.03	6.01
	P-value	>0.001	>0.001	>0.001	>0.001	>0.001

3.5.3. Comments (Table 10)

Growth indicators of Melaleuca forest on the average growth indicators of Melaleuca in the acid sulfat soil with no peat and compare the peat thickness is surveyed in 2023 (**Table 10**) show: Growth of Melaleuca in the acid sulfat soil no peat (D1.3 diameter of stem at 1.3 meter) is 3.88 centimeter (cm), Ht height of tree crown to top 3.88 meter (m), Hub height under branch of tree is 1.58 m, Dc diameter of canopy is 0.708 m, N/p number of trees per plot (t/p) is 133.6; this growth of Melaleuca to understand compare the surving rate of Melaleuca growth on peat thickness flood 20 years. On PT (20 – 40 cm) D1.3 is 3.856 m, Ht is 3.8 m, Hub is 1.788 m, Dc is 1.062 m, N/p is 24 tree per plot. PT (40–60 cm) D1.3 is 5.118 cm, Ht is 5.430 m, Hub is 3.214 m, Dc is 0.784 m, N/p is 76.8 trees per plot. PT (60 – 80 cm) D1.3 is 9.320 cm, Ht is 10.038 m, Hub is 7.092 m, Dc is 1.442 m, N/p is 247.4 trees per plot (t/p). Compare with average growth of Melaleuca on acid sulfate soil and on peat thickness 20 years (2003 – 2023) the indicators of growth on peat thickness include D1.3 is 6.098 cm, Ht is 6.423 m, Hub is 4.301 m, Dc is 1.095 m, N/p is 116 t/p.

On the acid sulfate soil: Survival rate on flooded acid sulfate soils grew slower than on peat, but survival rate was higher in actual investigation. On the peat soil: The survival rate on peat thickness increased. D1.3, Ht, Hub, Dc, N/p also increased due to the seasonal flooding management regime during the year.

After big forest fire in 2003 on the rainy season from *Melaleuca cajuputi* seeds grow into forest regeneration (**Figure 7**) (a) Melaleuca forest the first year iss growing well; (b) forest water management in the following years leading to slow forest growth.

Table 10. Growth Indicators of Melaleuca Forest on PT and 0 cm in the Acid Sulfat Soil (Without Peat) (2003–2023).

No.	Current Forest	D1.3 (cm)	Ht (m)	Hub (m)	Dc (m)	N/p (Tree Number/Plot) (t/p)
	On acid sulfat soil no peat on land					
1	00 cm*	3.882	3.828	1.580	0.708	133.6
	On the peat thickness soil					
1	20 – 40 cm	3.856	3.800	1.788	1.062	24
2	40 – 60 cm	5.118	5.430	3.214	0.784	76.8
3	60 – 80 cm	9.320	10.038	7.902	1.442	247.4
	Average	6.098	6.423	4.301	1.095	116
	P-value	<0.001**	<0.001**	<0.001**	<0.01*	<0.001**

** Significantly different. ** Highly significant different.*

(**a**)

(**b**)

Figure 7. Images of Melaleuca cajuputi forest regeneration after the rainy season were investigated and recorded. (**a**) Forest regeneration after fire on early rainy season; (**b**) Forest water management after fire to growth in the following years.

3.6. Relationship Chemical of Peat with Growth Indicators

3.6.1. Comments (Table 11)

Results of one layer linear regression analysis between chemical indicators for Melaleuca forests according to the correlation formulas:

$$Y = a + bX \quad (8)$$

Relationship shows (**Table 11**): Relationship Humic acid⁻, PT and growth, (Humic acid, PT) R = 0.08; (Humic acid, D1.3) R = 0.0391; (Humic acid, Ht) R = 0.1275; ((Humic acid, Hb) R = 0.0857; ((Humic acid, Dc) R = 0.01776. Relationship Humic acid with all of indicators is not correlation. Relationship Nts, PT and growth; (Nt, PT) R = 0.678; (Nt, D1.3) R = 0.7199; (Nt, Ht) R = 0.807; (Nt, Hb) R = 0.8169; (Nt, Dc) R = 0.2865. the indicators D1.3, Ht, Hb, Dc are strong correlation and Dc is small correlation. Relationship P_2O_5, PT and growth, (P_2O_5, PT) R = 0.904; (P_2O_5, D1.3) R = 0.655; (P_2O_5, Ht) R = 0.8388; (P_2O_5, Hb) R = 0.7967; (P_2O_5, Dc) R = 0.2676. The indicators PT, D1.3, Ht, Hb, Dc are strong correlations; Dc is samll correlation. Relationship K_2O, PT and growth; (K_2O, PT) R = 0.9691, (K_2O, D1.3) R = 0.7241; (K_2O, Ht) R = 0.9038; (K_2O, Hb) R = 0.8903; (K_2O, Dc) R = 0.3318. The indicators PT, D1.3, Ht, Hb are strong correlation; Dc is small correlation. The relationship between chemical indicators related to nutrition for Melaleuca forests on peat thickness (PT), Nt, P_2O_5, K_2O affecting growth was analyzed, showing that humic acid is closely related to peat thickness, growth factors such as D1.3, Ht, Hb and a very small relationship with Dc.

Table 11. Relationship of Melaleuca Nutritional Indicators with Peat Thickness (PT) and Growth.

No.	Chemical Indicators	Growth Indicators	Statistical Parameters
1	Humic acid (Ha)	Peat thickness	R = 0.0807, Fr = 0.07873, α = 0.7838, N = 15 a = 17.3999, b = −0.00475 Y(PT Ha) = 17.3999 − 0.00475X(ha) (Very small correlation)
		D1.3 (cm)	R = 0.0391, Fr = 0.8944, α = 0.8944, N = 15 a = 17.3585, b = 0.0285 Y(D1.3 Ha) = 17.3585 + 0.0285X(ha) (Very small correlation)
		Ht (m)	R = 0.1070, Fr = 0.1275, α = 0.7277, N = 15 a = 16.6368, b = 0.0914 Y(Ht Ha) = 16.6368 + 0.0914X(ha) (Very small correlation)
		Hub (m)	R = 0.0857, Fr = 0.0889, α = 0.7706, N = 15 a = 16.8956, b = 0.0620 Y(Hub Ha) = 16.8956 + 0.0620X(ha) (Very small correlation)
		Dc	R = 0.1776, Fr =0.3909, α = 0.5435, N = 15 a = 16.5535, b = 0.5812 Y(Dc Ha) = 16.5535 + 0.5812X(ha) (Very small correlation)
2	Nt	Peat thickness	R = 0.6784, Fr = 9.3798, α = 0.0108, N =15 a = 0.2560, b = 0.00575 Y(PT Nt) = 0.2560 + 0.00575X(Nt) (Pretty good correlation)
		D1.3 (cm)	R = 0.7199, Fr = 12.9124, α = 0.0036, N = 15 a = 0.0843, b = 0.0721 Y(D1.3 Nt) = 0.0843 + 0.0721X(Nt) (Pretty good correlation)
		Ht (m)	R = 0.8073, Fr = 22.4576, α = 0.000, N = 15 a = 0.1244, b = 0.0612 Y(Ht Nt) = 0.1244 + 0.0612X(Nt) (Very high correlation)
		Hub (m)	R = 0.8169, Fr = 20.0660, α = 0.001, N = 15 a = 0.2619, b = 0.0595 Y(Hub Nt) = 0.02619 + 0.0595X(Nt) (Very high correlation)
		Dc	R = 0.2865, Fr = 1.0733, α = 0.3206, N = 15 a = 0.4236, b = 0.0988 Y(Dc Nt) = 0.4236 + 0.0988X(Nt) (Small correlation)

Table 11. *Cont.*

No.	Chemical Indicators	Growth Indicators	Statistical Parameters
3	P_2O_5	Peat thickness	R = 0.9104, Fr = 58.1385, α < 0.000, N = 15 a = 0.1034, b = −0.0005 Y(PT P_2O_5) = 0.1034 − 0.0005X(P_2O_5) (Very high correlation)
		D1.3 (cm)	R = 0.6554, Fr = 9.0388, α = 0.0109, N = 15 a = 0.1089, b = −0.0048 Y(D1.3 P_2O_5) = 0.10389 − 0.0048X(P_2O_5) (Very high correlation)
		Ht (m)	R = 0.8388, Fr = 28.4912, α = 0.000, N = 15 a = 0.1181, b = −0.0061 Y(Ht P_2O_5) = 0.1181 − 0.0061X(P_2O_5) (Very high correlation)
		Hub (m)	R = 0.7967, Fr = 19.1228, α = 0.001, N = 15 a = 0.1052, b = −0.0061 Y(Hub P_2O_5) = 0.1052 − 0.0061X(P_2O_5) (Very high correlation)
		Dc	R = 0.2676, Fr = 0.9262, α = 0.3548, N = 15 a = 0.0872, b = −0.0088 Y(Dc P_2O_5) = 0.0872 + 0.0088X(P_2O_5) (Small correlation)
4	K_2O	Peat thickness	R = 0.9691, Fr = 18.3745, α < 0.000, N = 15 a = 0.1563, b = 0.0044 Y(PT K_2O) = 0.1563 + 0.0044X(K_2O) (Very high correlation)
		D1.3 (cm)	R = 0.7241, Fr = 13.2254, α = 0.0034, N = 15 a = 0.1014, b = 0.0414 Y(D1.3 K_2O) = 0.1014 + 0.0414X(K_2O) (Very high correlation)
		Ht (m)	R = 0.9038, Fr = 53.5738, α = 0.000, N = 15 a = 0.0314, b = 0.0510 Y(Ht K_2O) = 0.0314 + 0.0510X(K_2O) (Very high correlation)
		Hub (m)	R = 0.8903, Fr = 45.8977, α = 0.000, N = 15 a = 0.1419, b = 0.0506 Y(Hub K_2O) = 0.1419 + 0.0506X(K_2O) (Very high correlation)
		Dc	R = 0.3318, Fr = 1.4847, α = 0.2465, N = 15 a = 0.2780, b = 0.0852 Y(Dc K_2O) = 0.278 + 0.0852X(K_2O) (Small correlation)

Humic acid and PT, D1.3, Ht, Hub, Dc: Relationship of peat chemistry such as humic acid nutrients (Ha) with PT, D1.3, Ht, Hub, Dc are R < 0.1 no relationship of them. Nt and PT, D1.3, Ht, Hub, Dc: Nt with PT, D1.3, Ht, Hub show R < 0.6 – R < 0.9 relationship very high correlation; Dc relationship is small correlation. P_2O_5 and PT, D1.3, Ht, Hub, Dc: P_2O_5 with PT, D1.3, Ht, Hub shows R<0.6 – 0.9 relationship very high correlation, Dc relationship is small correlation. K_2O and PT, D1.3, Ht, Hub, Dc: K_2O with PT, D1.3, Ht, Hub show R < 0.6 – 0.9 relationship very high correlation; Dc is small correlation; studies on the effects of nutrients such as humic acid, Nt, P_2O_5, K_2O on plant also demonstrate that these nutrients affect plant growth [21–23].

3.6.2. Comments (Table 12)

Results of one layer linear regression analysis between chemical indicators of acid sulfate soil properties for Melaleuca forests according to the correlation formulas:

$$Y = a + bX$$

Relationship shows (**Table 12**): Relationship pH, PT and growth; (pH, PT) R = 0.9674, (pH, D1.3) R = 0.7199; (pH, Ht) R = 0.8738; (pH, Hb) R = 0.7805; (pH, Dc) R = 0.3497. The indicators PT, D1.3, Ht, Hb are strong correlation; Dc is small correlation. Relationship SO_4^{2-}, PT and growth; (SO_4^{2-}, PT) R = 0.9430, (SO_4^{2}, D1.3) R = 0.7258; (SO_4^{2-}, Ht) R = 0.9138; (SO_4^{2-}, Hb) R = 0.8993; (SO_4^{2-}, Dc) R = 0.3387. The indicators PT, D1.3, Ht, Hb are strong correlation; Dc is small correlation. Relationship Fe^{2+}, PT and growth; (Fe^{2+}, PT) R = 0.9543, (Fe^{2+}, D1.3) R = 0.7106; (Fe^{2+}, Ht) R = 0.8921; (Fe^{2}, Hb) R = 0.8795; ($Fe^{2+}SO_4^{2-}$, Dc) R = 0.3309. The indicators PT, D1.3, Ht, Hb are strong correlation; Dc is small correlation.

Table 12. Relationship of Chemical Indicators with PT and Melaleuca Growth.

No.	Chemical Indicators	Growth Indicators	Statistical Parameters
1	pH	Peat thickness	R = 0.9674, Fr = 175.2339, α < 0.000, N =15 a = 0. 4510, b = −4.5578 Y(PT pH) = 0.4510 − 4.5578X(pH) (Very high correlation)
		D1.3 (cm)	R = 0.7199, Fr = 12.9124, α = 0.0036, N = 15 a = 0.4564, − 0.0041 Y(D1.3 K_2O) = 0.4564 − 0.0041X(pH) (High correlation)
		Ht (m)	R = 0.8738, Fr = 38.7826, α = 0.000, N = 15 a = 0. 4626, b = −0.0050 Y(Ht pH) = 0.4626 − 0.0050X(pH) (Very high correlation)
		Hub (m)	R = 0.7805, Fr = 18.7072, α = 0.000, N = 15 a = 0.4515, b = −0.0048 Y(Hub pH) = 0.4515 − 0.0048X(pH) (Very high correlation)
		Dc	R = 0.3497, Fr = 1.6723, α = 0.2202, N = 15 a = 0.4391, b = −0.00916 Y(Dc pH) = 0.4391 − 0.00916X(pH) (Small correlation)
2	SO_4^{2-}	Peat thickness	R = 0.9430, Fr = 96.3715, α < 0,000, N = 15 a = 0.0772, b = −0.0046 Y(PT SO_4^{2-}) = 0.0772 − 0.0046X(SO_4^{2-}) (Very high correlation)
		D1.3 (cm)	R = 0.7258, Fr = 13.3631, α = 0,0032, N = 15 a = 0.0838, b = −0.0044 Y(D1.3 SO_4^{2-}) = 0.0838 − 0.0044X(SO_4^{2-}) (Very high correlation)
		Ht (m)	R = 0.9138, Fr = 60.7679, α < 0.000, N = 15 a = 0.0915, b = −0.0055 Y(Ht SO_4^{2-}) = 0.0915 − 0.0055X(SO_4^{2-}) (Very high correlation)
		Hub (m)	R = 0.8993, Fr = 50.7531, α < 0.000, N = 15 a = 0.0796, b = −0.0054 Y(Hub SO_4^{2-}) = 0.0796 − 0.0054X(SO_4^{2-}) (Very high correlation)
		Dc	R = 0.3387, Fr = 1.5549, α = 0.2361, N = 15 a = 0.0651, b = −0.0092 Y(Dc SO_4^{2-}) = 0.0651 − 0.0092X(SO_4^{2-}) (Small correlation)
3	Fe^{2+}	Peat thickness	R = 0.9543, Fr = 122.3928, α < 0.000, N = 15 a = 0.1024, b = 0.0034 Y(PT Fe^{2+}) = 0.1024 + 0.0034X(Fe^{2+}) (Very high correlation)
		D1.3 (cm)	R = 0.7106, Fr = 12.2437, α = 0.0043, N = 15 a = 0.604, b= 0.0320 Y(D1.3 Fe^{2+}) = 0.0604 + 0.0320X(Fe^{2+}) (Very high correlation)
		Ht (m)	R = 0.8921, Fr = 46.7989, α = 0.000, N = 15 a = 0.0047, b = 0.0394 Y(Ht Fe^{2+}) = 0.0047 + 0.0394X(Fe^{2+}) (Very high correlation)
		Hub (m)	R = 0.8795, Fr = 41.0121, α = 0.000, N = 15 a = 0.9067, b = 0.0394 Y(Hub Fe^{2+}) = 0.9067 + 0.0394X(Fe^{2+}) (Very high correlation)
		Dc	R =0.3309, Fr = 1.4759, α = 0.2477, N = 15 a = 0.1960, b = 0.0670 Y (Dc Fe^{2+}) = 0.1960 + 0.0670X(Fe^{2+}) (Small correlation)

pH, SO_4^{2-}, Fe^{2+} are indicators of acid sulfat soil**;** forest trees will be growing difficult this soil as the number increases: A lower pH indicates higher acidity, relationship pH with PT, D1.3, Ht, Hub R < 0.6 – R < 0.9 show pH affecting with indicators are PT, D1.3, Ht, Hub very high correlation; Dc is small correlation. SO_4^{2-} relationship with PT, D1.3, Ht, Hub R < 0.6 – R < 0.9 shows SO42⁻ with these indicators has a very high correlation; Dc shows a small correlation. Fe^{2+} relationship with PT, D1.3, Ht, Hub R < 0.6 – R < 0.9; with these indicators, there is a very high correlation; Dc has a small correlation. Some other research has examined the effects of pH, SO42⁻, and Fe^{2+} on forest trees [24,25].

4. Discussions

Research on peatland in UMTNP in 2003 found that 218 ha of peat area were lost. Peat thickness decreased from 80 –140 cm to 60 – 140 cm. Immediately after the forest fire, this seriously affected the above-ground forest resources of 4,125 ha and the environment of the entire Mekong Delta of Vietnam. Peatland fires destroy above and below ground biomass, impacting health in Indonesia such as Sumatra and Kalimantan [26], increasing hospital admissions, asthma and respiratory diseases.

A forest fire was investigated with peat volume of 26,765,500 m^3; the peat weight is 6,373,913 tons and carbon storage is 2,682,211 tons. This volume contributes to global carbon storage. Peat deposits store more carbon than trees in forested peatlands of the boreal biome [27].

This is a large carbon reserve in the Mekong Delta, immediately after the 2003 forest fire, it lost a large amount of carbon after the forest fire. However, after using rainwater storage measures, it decomposed peat and lost a much larger amount than the forest fire, if compared, the damage to carbon resources was more severe [28].

The growth of Melaleuca forests to the peat thickness flooded seasonally due to irregular rainwater storage is slow growth in D1.3, Ht, Hb and Dc, where the peat thickness is 60 – 80 cm; these indicators grow faster. Study *Melaleuca leucadendron* by was not flooding water level so growth indicators are normal [29].

Peat under long-term flooding conditions, 20 years after a forest fire, was investigated during both the rainy and dry seasons; the indicators that decreased with peat thickness were pH and humic acid and increased with peat thickness were SO_4^{2-}, P_2O_5, NH^{4+}, Nt, K_2O, Fe^{2+}. Study on assessing existing farming systems in the peatland of Central Kalimantan, Indonesia [30].

Water chemistry on peatland burned after 20 years by forest fire in the rainy and dry seasons was investigated. the indirators that decreased with peat thickness were pH and humic acid and increased with peat thickness were Nt, Fe^{2+}, P_2O_5. This chemical residue results in pollution that needs to be treated for use [31].

The relationship between chemical indicators related to nutrients Melaleuca forests such as Ha, Nt, P_2O_5, K_2O are very high correlation with PT, D1.3, Ht, Hub and Dc is small correlation and chemical indicators for acid sulfat soil such as pH, SO_4^{2-}, Fe^{2+} affecting growth was analyzed; such as D1.3, Ht, Hb are very high correlation and Dc is small correlation.

5. Conclusions

A big forest fire destroyed 218 hectares of peatland, reducing peat thickness from (80 – 140 cm) to (60 – 140 cm). Another loss from rainwater management in the core zone for fire prevention purposes caused peat decomposition, lowering the peat thickness from (80 – 140) to (20 – 60 cm).

After 20 years of rainwater management for peat and carbon fire prevention, the remaining peat volumes are 10,738,100 m^3, peat weight is 2,577,144 tons and carbon stock is 1,085,493 tons; compared to peat and carbon reserves lost after forest fire are 16,027,400 m^3, peat weight lost is 3,796,769 tons, and carbon stock lost is 1,596,718 tons.

Peat under long-term flooding conditions, 20 years after a forest fire, was investigated during both the rainy and dry seasons. The indicators that decreased with peat thickness were pH and humic acid and increased with peat thickness were SO_4^{2-}, P_2O_5, NH^{4+}, Nt, K_2O, Fe^{2+}.

The growth of Melaleuca forests to the peat thickness flooded seasonally due to irregular rainwater storage is slow growth in D1.3, Ht, Hb and Dc, where the peat thickness is 60 – 80 cm; these indicators grow faster.

The relationship between chemical indicators related to Melaleuca forests on peat thickness (PT) includes nutrient indicators humic acid (Ha) is small correlation with PT, D1.3, Ht, Hub, Dc; with Nt, P_2O_5, K~~2~~O very high correlation to PT, D1.3, Ht, Hub, small correlation Dc. Chemical indicators such as pH, SO_4^{2-}, Fe^{2+} very high correlation with PT, D1.3, Ht, Hub and small correlation with Dc.

Author Contributions

Conceptualization, L.T.T.; methodology, L.T.T.; software, M.D., T.V.T.; validation, L.T.T., M.D., T.V.T.; formal analysis, L.T.T., T.V.T., T.V.N.; investigation, L.T.T., T.V.T., T.V.N.; resources, T.V.T.; data curation, L.T.T., T.V.T.; writing—original draft preparation, L.T.T.; writing—review and editing, L.T.T.; visualization, L.T.T.; supervision, L.T.T.; project administration, L.T.T. 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 study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of the Faculty of Natural Resources and Environment, Kien Giang University (protocol code KGU1-B2024 and 31st December 2023).

Informed Consent Statement

Not applicable.

Data Availability Statement

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

Acknowledgments

The authors would like to thank 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.

Conflicts of Interest

The authors declare no conflict of interest.

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