FIRE RISK IN MELALEUCA PEAT FORESTS ON POTENTIAL ACID SULFATE SOILS AND PEAT MINING IN U MINH, MEKONG DELTA, VIETNAM

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ABSTRACT

Peat in the U Minh Thuong and U Minh Ha areas of the Mekong Delta is formed on acid sulfate soils and represents a rare ecological and environmental resource. This type of peat has high physical, chemical, and biological adsorption capacity, is rich in nutrients and micronutrients, and contains natural growth stimulants. However, the exploitation or burning of peat, especially in the Melaleuca forest ecosystem where trees contain high levels of essential oils, can lead to serious and irreversible consequences. Such actions not only destroy biodiversity and degrade the environment but also accelerate soil acidification, turning fertile land into “dead land”. Therefore, protecting the U Minh peatland ecosystem is essential to maintaining the integrity of the Mekong Delta wetland environment and ensuring sustainable development for future generations.

Keywords: Peat soil, U Minh area, Melaleuca Forest fire, potential acid sulfate soil, Mekong Delta, environmental degradation.

1. INTRODUCTION

The U Minh Melaleuca Forest, one of Vietnam's most distinctive wetland ecosystems, has long been recognized for its ecological, economic, and environmental importance. This study synthesizes field observations and previous research to highlight the characteristics of the U Minh peatland, its formation process, and the serious environmental risks posed by forest fires and unsustainable peat mining.

Historically, the U Minh forest covered approximately 145,000 hectares, stretching across Kien Giang and Ca Mau provinces. The forest is bounded by the Cai Lon river to the north, the Ong Doc river to the south, the Chac Bang canal to the east, and the gulf of Thailand to the west. However, due to repeated forest fires and agricultural expansion, this once vast ecosystem has been drastically reduced in size gradually [1].

The U Minh ecosystem develops primarily on potential acid sulfate soil and peatland, both highly sensitive to hydrological and chemical changes. The pristine forest exhibits a multilayered structure with a tall canopy, middle layer, and dense understory vegetation. The flora of the U Minh forest belongs to the wetland plant community, characterized by species adapted to periodic flooding such as *Melaleuca cajuputi*, *Diplazium esculentum* (in vietnamese, Dớn vegetable), *Stenochlaena palustris* (in vietnames, Choại vegetable), and other marsh ferns and vines [2].

This unique composition supports a diverse fauna including bees, monkeys, bears, leopards, snakes, turtles, fish, and numerous bird species. Together, these organisms create a balanced and productive ecological network that plays a vital role in carbon sequestration, water regulation, and biodiversity conservation across the Mekong Delta [2].

2. METHOD

The PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) methodology [3] was used to conduct a comprehensive system review and analysis. PRISMA provides a checklist of important items that need to be addressed and ensures full coverage. The author developed a search strategy to identify relevant literature within the scope of the study. Information was collected from these databases: Peat soil, U Minh area, Melaleuca forest fire, potential acid sulfate soil, Mekong Delta, environmental degradation. The database search extended to 2025, encompassing journal articles, reviews, and research reports published in both English and Vietnamese. A screening process was conducted to maintain the quality of the review, and all duplicates were excluded. Included articles were selected by examining abstracts and results containing variables focused on the search title, as well as valid experimental design and statistical analysis. Additionally, for field access, a transect survey method was used, guided by farm staff. Method for analyzing humic acid, according to the guidelines in current Vietnamese standards (TCVN).

3. FORMATION AND CHARACTERISTICS OF THE U MINH PEAT MINE IN THE MEKONG DELTA [4]

Unlike most sedimentary materials, peat soil formation does not involve erosion or transportation. It accumulates directly where vegetation grows, under specific hydrological and environmental conditions. The surface vegetation does not always reflect the composition of the underlying peat layers because peaty soil forms only when several distinct factors coexist.

Water availability: Water is the principal agent in peat formation. The surface of the peat must remain below the water level to prevent excessive oxidation. Water in these regions often contains organic acids secreted by bacteria during the partial decomposition of plants, which in turn inhibit further microbial activity and preserve plant residues.

Hydrological stability: The water depth should not exceed 3 meters, as excessive submergence prevents plant growth and halts peat formation. Moderate, stable water levels coupled with slow flow rates allow plant residues to accumulate and gradually transform into peat.

Sediment clarity: Peat soil develops best in clear water with minimal suspended sediment. Excessive mud or sand interferes with peat formation, producing low-quality peat mixed with clay.

Substrate composition: Clayey substrates favor peat accumulation more than sandy ones, as clay creates anaerobic conditions that slow decomposition.

Climatic conditions: A humid tropical climate with high annual rainfall and even seasonal distribution is ideal for peat formation and preservation.

According to [2], [5], maintaining high water levels in peat areas is crucial to prevent oxidation and preserve existing peat deposits. If groundwater levels drop below the peat layer, oxygen penetrates the surface, stimulating microbial activity that breaks down organic matter and leads to peat loss.

3.1. Development of peat soils in the Mekong Delta

The distribution of peat in the Mekong Delta corresponds to flooded depressions, ancient river channels, and coastal swamps. The process of coastline formation occurred in several stages.

Around 6,000 years ago, sea levels fluctuated significantly. As sea levels dropped from +4 meters to near their current level, the delta gradually expanded into the sea, depositing clay and sand brought by rivers to form mudflats. Mangrove vegetation then colonized these mudflats, creating an environment for the formation of early peat.

As the supply of sediment decreased, coastal erosion and wave action reshaped these areas, separating fine clay and silt from coarse sand and shells. Coarse materials accumulated near the shore, forming sand dunes, while mangrove and swamp vegetation developed behind these dunes. Over millennia, the alternation between sediment-rich and sediment-poor phases created the complex dune-swamp landscape characteristic of the Mekong Delta today.

Peat in delta regions is formed in two main environments [4]

1. Coastal salt marshes (pyrite-containing peat)
2. Freshwater swamps (ancient river peat)

Saltwater swamp peat contains more sulfur and is found in coastal swamp sediments, while freshwater peat typically has lower sulfur concentrations and occurs in riparian depressions.

3.2. Characteristics of peat deposits formed on potential foliate soils in U Minh, Mekong Delta, as a product of decomposition of wild fern plants

Unlike other sedimentary layers, and unlike peatlands on the North European coast, peatlands are not subject to erosion or sediment transport. Peat only accumulates where vegetation grows. The vegetation on the surface does not reflect the vegetation beneath the peat deposit. Peat is formed only by the convergence of the following special conditions:

Water is the primary agent in peat formation. The peat surface must not exceed the water level. Water is usually acidic, possibly due to bacteria secreting during plant decomposition; however, these acids kill the bacteria and thus prevent further plant decomposition. The water depth must be adequate for plant growth, and the flow must be slow so that the bacteria are not washed away.

The maximum water depth should not exceed 3m; furthermore, peat conservation also requires the presence of water. Generally, the growth rate of vegetation is accompanied by an increase in water level. It is important to have a maximum water level limit that affects peat bog development. If the water level rises above the growth rate of vegetation, the peat bog will be submerged due to excessive depth. The vegetation will die, and peat bog development will cease.

For peat to form, the water must be clear, meaning the amount of sediment in the water should be as low as possible. Water rich in mud and sand will hinder the development of peat deposits. In this case, if a peat deposit is formed, it will only exist in the form of peat.

Particle size also affects peat formation. In peat accumulation environments, if the bottom is clay, peat formation conditions are easier than in sandy environments because clay creates an anaerobic environment for bacteria to thrive. This is a prominent feature of the U Minh region (Mekong Delta) because the soil layer beneath the peat deposits has a high clay content (>70%), ensuring the formation of semi-decomposed layers of ferns, two typical species being the D fern and the Choai fern.

In addition, climate also plays a crucial role. Humid climatic conditions, with average rainfall evenly distributed throughout the year, are also very suitable for peat formation.

Water management will reduce peat erosion, sediment deposition, and peat formation. Vo Dinh Ngo (1997) [5] also suggested that water resources should be maintained for peat mines. Maintaining high water levels in peat mines may be related to peat formation.

The peat layer is not higher than the water level; the water prevents air from contacting the plants, and the water usually contains dissolved acids, making the pH acidic, preventing microorganisms from developing and completely decomposing the plants. Also according to Vo Dinh Ngo (1991) [6], the plants that create peat are herbaceous and woody plants; these species cannot live at very great depths, usually not exceeding 3 m.

The current distribution of peat deposits in the Mekong Delta indicates that peat is concentrated in swampy areas. The peat swamps of the Mekong Delta are depressions between fields, ancient rivers, and coastal wetlands.

The formation of coastal swamps is associated with the process of creating land ridges and goes through 3 stages:

Approximately 6,000 years ago, sea levels in the Mekong Delta fluctuated significantly. Sea levels dropped from 4 meters to 2 meters and continued to fall to their current level. With the lowering of sea levels, coastline gradually advanced to the sea, leading to the expansion of the Mekong Delta. At that time, the material carried to sea by the river consisted mainly of clay and sand, forming mudflats where mangrove vegetation grew and the mudflats became increasingly solid. Conversely, if the amount of material carried to sea by the river had decreased sharply, the delta would not have expanded, the coastline would have remained the same or shifted inland due to erosion. This would occur under conditions of reduced sedimentary material, due to the impact of waves and erosion on previously alluvial plains. Fine materials such as clay and silt separate from the clay-silt-sand mass and are carried out to sea, while coarse materials such as sand and shells are redeposited and brought ashore, forming sand dunes or sand ridges.

The repetition of two phases of abundant and scarce deposition of material into the sea during two periods of sea level rise and fall is the main cause of the formation of coastal ridges and swamps. During this phase, the coastal ridge moves inland and covers the swamp sediments behind the ridge.

The erosion process ends when another tidal mudflat sedimentation occurs. The coastline is isolated and becomes an ancient sandbar. On the tidal mudflat, mangrove vegetation continues to grow and becomes a swampy area.

This phenomenon repeats itself in the Holocene period and the sea retreat period of about 6,000 years, creating a series of ridges in the Mekong Delta and due to the formation of ridges, many ridges in the Mekong Delta are blocked and become dead rivers, the rivers become freshwater swamps and on which ancient river peat is formed.

In the Mekong Delta, peat is formed in two environments: saltwater swamps and freshwater swamps, in two forms: vein and ancient river forms. Saltwater swamp peat, also known as pyrite peat, is mainly found in marine swamp sediments in vein form, while freshwater swamp peat has two ancient river forms - meandering river-like forms and vein forms.

Figure 1. Fern (Rau Dớn) *Diplazium esculentum* (Retz),
Source: https://trungtamthuoc.com/duoc-lieu/rau-don [7]

3.2.1. Diplazium esculentum (Retz) D (Vietnamese: Dớn vegetable)

Dớn vegetable is a special wild vegetable, similar in shape to a fern, often growing on the banks of streams, creeks and humid places in the highlands. Dớn vegetable has a crunchy, sweet and slightly slimy taste, bringing many health benefits.

However, for households in the mountains, the Southeast region and areas with slightly acidic soil, this is a familiar vegetable with high nutritional value and many significant health benefits. Not only is it a popular dish in Vietnam, rau dot choai is also widely used in the cuisine of many Southeast Asian countries, especially in vegetarian dishes thanks to its natural sweetness.

3.2.2. Stenochlaena palustris (Burm. f.) Bedd. (Vietnamese: Rau choại, Chại)

Introduction: "Choai" can be considered a type of wild vegetable, known by many different names depending on the pronunciation of each region. Common names used by many people include rau choai, sau chấm choai, rau trầu, or rau răm. "Choai" belongs to the fern family, is a climbing plant, and thrives in abandoned forests, swamps, and especially in slightly acidic soil. A characteristic of this vegetable is its stem, which can grow up to 20 meters long, with roots firmly attached to other trees, typically melaleuca trees. The young leaves of "choai" are feather-shaped, about 1 meter long, brownish-green when young, and often have curved tips, resembling the shape of a millipede [8].

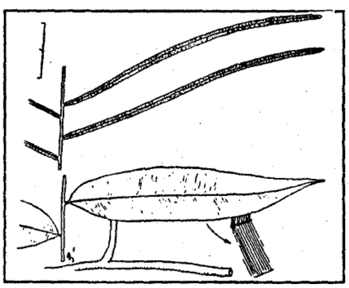

Figure 2. Rau choại (*Stenochlaena palustris)* [8]

Figure 3. Rau choại (*Stenochlaena palustris)*
(Self-taken photo, 1999)

Figure 4. Rau choại (*Stenochlaena palustris*) (Self-taken photo, in U Minh Thuong forest, 1999)

Flora "Choai" is not only a familiar food in some regions but also brings many wonderful health benefits. With a sweet, slightly slimy taste and easy to prepare, Choai vegetable has become a rustic ingredient in many attractive dishes. The following article will help you better understand rau choai as well as the nutritional values that this unique vegetable brings. Choai vegetable is a vine of the fern family, commonly growing wild in forest and swamp areas, especially in places with slightly acidic soil. The vegetable is characterized by a long stem, up to 20 meters, clinging to other trees such as cajuput trees. Young leaves are feather-shaped, the tips of the leaves are curved to look like millipedes. Rau choai is famous for its characteristic flavor, sweet, slightly slimy and is often processed into boiled, stir-fried or soup dishes, especially boiled dishes with chili fish sauce.

3.2.3. Distinguishing between Dớn and Choại

Table 1. Preliminary comparison of the two species Dớn and Choại

Characteristic	Don Flora	Choai Flora
Latin name	*Diplazium esculentum* (Retz)	*Stenochlaena palustris* (Burm. f.) Bedd.
Plant family	Athyriaceae	Palm-leaved fern (Blechnaceae)
Characteristic	The herbaceous plant is 0.5 to 1.0 meter It is commonly found in potential peatlands such as U Minh Thuong and U Minh Ha – acidic sulfate soils or tropical rainforests at altitudes of 1000 to 2000 meters.	This vine can grow up to 20 meters long. It is commonly found in potential peatlands like U Minh Thuong and U Minh Ha – acidic sulfate soils or tropical rainforests at altitudes of 700 m and above.
Use	Laxative As a tonic for women after childbirth.	Regulate blood sugar levels Promote wound healing
Resources	These peat deposits form floating layers, 1.5 to 2.0 m thick, with very low sulfur content and rich in trace elements, which help to enhance soil fertility and the activity of beneficial microorganisms.	These peat deposits form floating layers, 1.5 to 2.0 m thick, with very low sulfur (S) content and rich in trace elements, which help improve soil fertility and the abundance of beneficial microorganisms.

3.2.4. The role of these two wild plant species

These two wild plants are not only naturally growing wild vegetables and a good food source for the local people, but they also have immense value as semi-decomposed organic remains. Over many years, with a lifespan of five thousand years, layer upon layer, they have formed a "floating peat layer" 1.5 to 2.0 meters thick, lying right on the surface of the ground, and its nutritional and commercial value is enormous. A remarkable feature is that beneath this floating peat layer lies a very special type of soil, formed over more than 5000 years, known as the "potential acidic sulfate soil" of the U Minh wetlands in the Mekong Delta, which cannot be found in peatlands of Northern Europe, Africa, or America: It leaves us with an invaluable resource. It is this peat layer that covers and prevents oxygen from coming into contact with pyrite to form jarosite, which is eventually acidified into sulfuric acid, toxic to humans, living organisms, and the environment.

To fully understand the U Minh forest ecosystem, special attention must be paid to the peat layer – the soil layer susceptible to sulfate acidification. This is because, in the soil profile, the surface layer is peat, and beneath it is soil susceptible to sulfate acidification (not yet acidified under current environmental conditions).

The peat layer here is characterized by its thickness, ranging from 1.0 m to 1.5 m, sometimes reaching 2 m. The peat is formed from the semi-decomposition products of *monoculture* and *legume plants* over thousands of years and many life cycles, gradually accumulating on the swamp surface to form a high-quality, low-sulfur peat layer capable of producing growth stimulants, fertilizers, dyes, and many other valuable products. Studies [6] [5] [4] have confirmed that this peat layer lies on a clay layer with high potential acid sulfate content. The total sulfate content in the soil may exceed 5%, but it also exists in the form of latent pyrite (FeS_2) found at depths of 1.0 m to 2.5 m.

Under normal conditions, in its pristine state, for example in the former center of the Bien Bach forest, although the water is dark in color and may be polluted, it has not yet been acidified. This is because peat, especially U Minh peat, has a high moisture retention capacity, extremely high absorption capacity, and very effective filtering properties, forming a special protective layer for the entire inland ecosystem, preventing acidification or salinization, and maintaining a lush green landscape year-round.

However, once these layers catch fire, the situation changes completely, as not only is the forest vegetation destroyed, but the entire environmental ecosystem is also seriously threatened.

In the peatlands of U Minh Thuong and U Minh Ha, from Bien Bach commune to the Bien Bach re-education camp, through An Bien, or the Dong Thap peatlands of the Xang Cat, Gao Doi, and Nha Thuong canals, the peatland area has shrunk, partly due to burning for rice cultivation and partly due to wildfires. Here, people used to grow watermelons and beans very successfully. A watermelon crop of 1 hectare, 2 months old, could yield a profit of 15-20 million VND. But after burning or the loss of peat, strong oxidation occurs, causing the soil to die, the jarosite layer disappears, and the soil rises near the surface. A thick layer of iron oxide powder, 1-3 cm deep, appears on the surface. Particularly, white, transparent aluminum sulfate ($Al_2(SO_4)_3$) salt particles appear on the surface, adhering to clumps, brittle and easily broken when exposed to dry sunlight or moisture, sticky in high humidity, and quickly dissolving in water. If you taste it, your tongue will feel "numb, slightly bitter." This substance is highly toxic because it contains up to 69% aluminum sulfate salt. The land has become barren. Some people in the U Minh region have a custom of burning peat to grow rice. Usually, the rice grows very well in the first year, with plenty of ash and rich in nutrients. But later, the yield decreases: the land has turned acidic.

4. EXTRACTING PEAT FOR USE AS FUEL FOR COOKING OR VEHICLES

After the liberation of South Vietnam, the country faced a very strict embargo, leading to shortages of gasoline and especially natural gas for daily use. Therefore, small boats exploited and transported peat (on land) as fuel at a very cheap and fast rate from the U Minh region via rivers and canals at night to major cities like Can Tho and Saigon [9]. The amount extracted was extremely large. As a consequence, after 5-6 months, the peat layer in U Minh was completely stripped away. The damage caused was the loss of a valuable resource. Because our peat is very valuable, rich in energy, contains little to no sulfur, but is rich in nutrients and growth stimulants such as Gibberellin, Humic acid, fulvic acid, and many other trace elements. On the other hand, the physical and chemical adsorption capacity of peat on the acidic sulfate-containing soil layer keeps the pyrite layer from direct contact with the air, thus preventing the formation of toxins: That is, if there is a layer of peat floating on this soil layer, the ecosystem remains safe. The habitat here remains lush. If this valuable peat layer were removed, the entire area would quickly turn into a wasteland.

Furthermore, this peat layer will prevent tides from entering the fields, thus avoiding salinization.

During this period, gasoline was embargoed, so people came up with the "ingenious" idea of installing stoves to burn peat (or charpeat) to power their vehicles. What an ironic situation!

5. CAUSES OF THE PEAT FIRES AT THE *MELALEUCA* FOREST

The cause is a combination of human activities and natural factors.

The primary cause of forest fires is **human activity**: sometimes fires occur due to accidents, negligence, or sometimes intentionally. For example, during the dry season, with intense sunlight, people often use smoke to drive away bees to prevent them from starving; or carelessly discard cigarette butts or cut branches to create sparks. Sometimes forest fires are caused by traditional practices such as burning fields or hunting rats in abandoned forests, inadvertently allowing the fire to spread. Embers left over from distant fires can also cause wildfires.

Another widely cited cause is drought, primarily due to the El Niño climate phenomenon, which lasted from July 1997 to April 1998 and had not yet ended.

The dry season in U Minh lasts 4-5 months, with the highest average temperature at the end of April (up to 35.9 °C), causing the "upper layer" (dry branches and leaves that have fallen on the ground) to become extremely dry and highly flammable.

Regarding hydrology, during the dry season, low tides cause groundwater levels in each soil layer to decrease, leading to water depletion. The canal system in the forest has both advantages and disadvantages. While it facilitates transportation and can help prevent the spread of fires, it also causes surface water to drain away very quickly. Therefore, the dry season lasts longer than in previous years. Even in the soil, the old groundwater level has dropped significantly, by 0.7m to 1.0m. In addition, the climate of U Minh forest is a tropical monsoon climate. The dry season is usually characterized by southwest winds with speeds of 3 m - 7 m/second. Tornadoes are particularly common, creating strong, sudden gusts of wind lasting from 15-30 minutes, with low air humidity, sometimes only reaching 50-60%.

Another factor is the characteristics of the local vegetation, including *creeping fig*, *cypress*, and melaleuca trees. These trees are highly flammable, not only when dry but also when green. Melaleuca trees, in particular, contain a high concentration of essential oils, making them capable of burning quickly and intensely.

All of the above factors, occurring during the El Niño conditions of 1997-1998 and 2002, made wildfires a very high risk.

6. TYPES OF FOREST FIRES – WHY DO THEY REIGNITE AND SPREAD?

It's widely acknowledged that fires here are very difficult to extinguish; often, when put out in one place, they reignite elsewhere or flare up again after being extinguished. This fact stems from the unique characteristics of fires in the U Minh forest. Three types of fires devastate this forest:

6.1. Fire spread (Vietnamese: Lửa chảy), also known as "boiling fire," typically spreads rapidly to the undergrowth (vegetation under the canopy) and young leaves. This type of fire burns only on the ground, following winding paths between trees. It develops quickly, spreads, and destroys the decaying leaves and woody plants on the ground. If there is wind, the fire will begin to burn the young branches, making the leaves and branches look "boiled," which is why locals call it "boiling fire". However, this type of fire usually occurs quickly and is easily extinguished in areas without peat, causing negligible damage.

6.2. Canopy Fires: These fires burn more slowly but produce larger flames. This occurs in areas with thick topsoil, many dry branches, and melaleuca trees. When encountering tornadoes, these fires can easily flare up, creating large blazes. If a tornado is present, it can even carry embers to another area, creating a larger fire, resulting in a patchy, leopard-skin-like pattern. Conversely, in areas where the fire has just been extinguished, embers are blown back and continue burning at the base. This phenomenon is called re-ignition. The fire trail can spread 700-800 meters from the original source.

6.3. Smoldering Fires: As mentioned above, the U Minh forest mainly consists of forests on peat soil – a type of soil prone to acid sulfate soil formation, so forest fires here mean that the peat layer itself is burning. A prominent characteristic of smoldering fires is that they occur in areas with thick peat layers. The fire smolders are within the dry peat layer. We cannot see the flames, but beneath the trees and soil, the peat continues to burn until the trees fall, smoke rises, and the soft surface layer is burned. This type of fire is very difficult to extinguish because its origin is hard to detect. Sometimes it seems to have been extinguished in one place, but in reality, it spreads to another, and the path of the fire does not follow any clear pattern, leading to the false belief that it has been extinguished when in fact it has reignited. The most effective firefighting measure here is to completely flood the burning area.

7. ECOLOGICAL AND ENVIRONMENTAL DAMAGE CAUSED BY MALELAUCA TREES IN FOREST FIRES ON SULFATE-CONTAINING SOILS

The damage caused by the U Minh forest fires is immense and unpredictable. Here are some key points:

7.1. Loss of Forest Resources and Biodiversity: Forest fires have destroyed the rich and diverse forest resources of this unique "mangrove forest – peat – acid sulfate soil" ecosystem, leading to the loss of invaluable resources. In addition, it has depleted incredibly rich life sources, reducing the number of fish, rabbits, snakes, turtles, softshell turtles, tigers, wild boars, and birds, especially rare species. They either die in the fires, are captured by people fleeing the fires, or, if they survive, migrate to other areas. Furthermore, forest fires lead to the loss of valuable timber, firewood, natural grasses, and mangrove honey. The value of these resources cannot be measured in millions or billions, as they are very difficult to regenerate or restore. Peat, in particular, is a non-renewable resource; once lost, it can never be recreated. For potentially sulfated acidic soils, once acidified, no one knows how long it will take to neutralize the acidity.

7.2. Negative Ecological Changes. First, acidification will inevitably occur. As mentioned, beneath the peat layer lies potentially acidic sulfate soil. When the peat layer is lost, the potentially acidic sulfate soil can be exposed to oxygen, easily acidified, and form active acidic sulfate soil with very high acidity, containing many toxic substances, mainly aluminum, iron, and sulfate (up to 2000 mg/liter), to the point of rapidly killing plants and animals. Acidification is sometimes interspersed with salinization. Although salinity is not as toxic as acidity, it is equally dangerous to the environment. As a consequence, the vegetation will then consist of only a few species:

- Melaleuca trees have the ability to regenerate if the fire is not too intense, because they have a high chance of sprouting from burnt roots or trunks. Furthermore, their seeds dry quickly due to the heat of the fire, and after the fire is extinguished, they disperse rapidly and germinate into new trees.
- In addition, *single-stemmed trees* and reeds are plants with very well-developed underground root systems. After a fire destroys the above-ground parts of the tree, this underground root system helps them regenerate.

However, when wildfires rage, their regenerative capacity is lost. Instead, the vegetation is replaced by species adapted to acidified and saline soils. The ecosystem becomes extremely monotonous: *sedges* and *rushes* grow densely on acidic, sulfate-acid, saline, nutrient-poor soils. If used for rice cultivation, the first year's yield might be good thanks to residual ash, but in subsequent years, yields gradually decrease until harvest is impossible due to the acidity rising to toxic or lethal levels. Thus, wildfires lead to the degradation of the environmental ecosystem. If the fire is mild, only surface-level, and controlled, it can even lead to reforestation (almost like clearing the forest). The complex wetland forest ecosystem on potential sulfate-acid peatlands transforms into a pure mangrove forest ecosystem on acid-contaminated soil. If the fire cannot be controlled, which is very likely to happen at any time during the dry season, it will inevitably lead to the complete destruction of the rich mangrove forest ecosystem, transforming it into a monotonous, highly toxic sulfate-acid soil ecosystem, potentially becoming a "dead zone".

8. SOME MEASURES FOR PREVENTING AND CONTROLLING PEAT FOREST FIRES IN U MINH

- **Strengthening community education is** crucial to help people understand that the U Minh Melaleuca forest ecosystem – peatland – sulfate-acid soil – possesses invaluable potential, in order to prevent any encroachment that could cause forest fires.
- **Invest fully** in building up the forest ranger force, implementing forest fire prevention measures with adequate equipment such as pumps of sufficient capacity, well-maintained, combined with manual tools to extinguish fires.
- **Research and improve the digging of canals and the construction of dams**, regulating and minimizing floodwater at the end of the rainy season to retain water in the forest for as long as possible, and strictly prohibit the digging of additional canals that cause water to drain too quickly.
- **Improve the allocation of land and forests in a rational and responsible manner.**

The phrase means "Perfect hydrological regulations, with clear rewards and penalties," but since "hydrological regulations" can be too technical in English, a more general translation might be more appropriate depending on the context. I'm keeping it as it is for now, but it's worth noting that it may need to be rephrased for a general reader.

- **Establish special conservation areas** to protect threatened ecosystems.

Along with the people of Ca Mau, Kien Giang, and the entire country, we are deeply saddened and worried about the U Minh forest fire. We hope that effective measures will soon be implemented to prevent future fires and protect this invaluable natural resource.

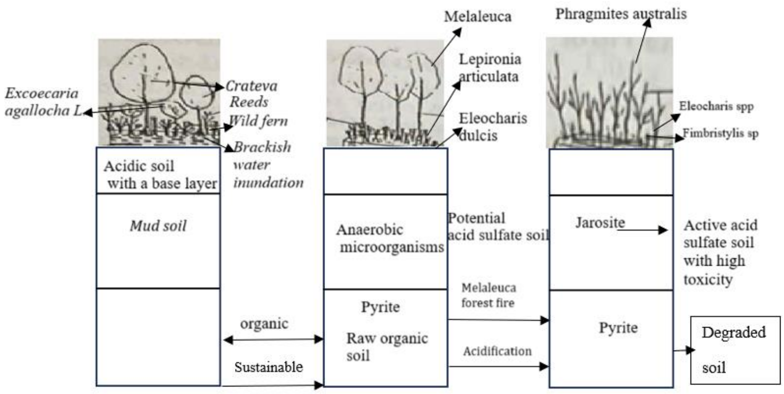

Figure 5. Ecological succession in the U Minh Melaleuca peat forest before and after the fire.

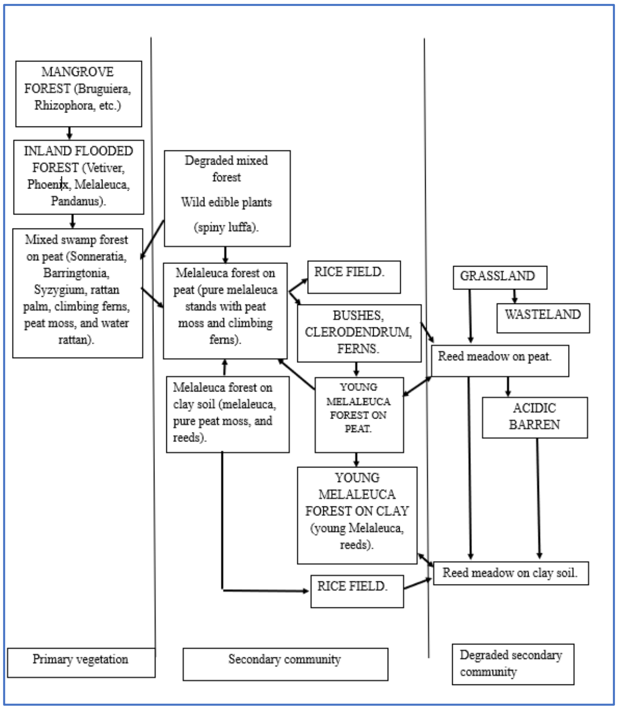

Figure 6. Forest succession of U Minh vegetation due to the impact of forest fires.

9. CLASSIFICATION OF PEAT IN U MINH, MEKONG DELTA

According to Tran Manh Tri (1991) [10], there are 4 bases for classifying peat:

9.1. Classification by origin

Peats of higher plant origin typically have less ash, more resin and wax, and lower humic acid content, while peates of lower plant origin are the opposite. To distinguish between the two, their plant or chemical composition needs to be analyzed.

For the plant components in the lower peat layer, plant residues in the lower layer must account for more than 95% of the peat's organic matter, while plant residues in the upper peat layer must not exceed 5% of the peat's organic matter.

Based on the chemical composition of the groups of substances, it is also possible to determine which type of peat belongs to which category. In addition, the table presents classification criteria based on bitium content, water-soluble and easily hydrolyzable substances, humic acids, cellulose, and non-degradable residues.

Table 2. Classification by origin [10]

Peat	Group of substances	Content of different groups of substances in peat (% organic matter)	
		Medium	Scope
Lowland peat	Bitumen	4.2	1.2-12.5
	Water-soluble and easily biodegradable substances	25.2	9:2-45:8
	Humic acid	40.2	18:6-55:5
	Cellulose	2.4	0-9
	Undecomposed residue	12.3	3.3-26.2
Highland peat	Bitumen	7	1:2-17:7
	Water-soluble and easily biodegradable substances	35.8	9.0-63.1
	Humic acid	24.7	4:6-49:9
	Cellulose	7.3	0.7-20.7
	Undecomposed residue	7.4	0-21.1

9.2. Classification by degree of decomposition

The degree of peat decomposition characterizes the extent to which organic matter in plant residues is transformed to form peat. The higher the degree of decomposition, the deeper the transformation process, and the more compounds such as humic acids, bitumen, and other easily hydrolyzable and unstable compounds are broken down.

Based on the degree of decomposition of each type of peat, peat can be divided into the following types:

Table 3. Classification of peat according to degree of decomposition [10]

Peat	Class	Degree of decomposition
High quality	1	1-15
	2	16-34
	3	> 35
Low quality	1	1 – 20
	2	21 – 34
	3	> 35

9.3. Classification according to the amount of heat released when burned or turned into ash

Table 4. Classification based on the amount of heat released during combustion [10]

Group	Calorie content (Kcal/Kg)
1	≤ 5,200
2	5,210 – 5,600
3	>5,600

9.4. Classification by ash content

Table 5. Classification based on ash content [10]

Group	Ash content (%)
1	5.0
2	6.0 – 10.0
3	11.0 – 15.0
4	16.0 - 23.0
5	24.0 – 35.0
6	36.0 – 50.0

Additionally, according to several authors, peat can be classified based on the determination of organic matter weight.

10. CHEMICAL COMPOSITION OF PEAT ON SULFATE-ACID SOILS, U MINH FOREST, MEKONG DELTA

10.1. Introduction

According to foreign literature, many insect groups inhabit the mudflats of Canada, Germany, and Poland, including 104 species belonging to the Chironomidae family, whose contribution to mudflat formation is significant. However, the mudflats in the Jura Mountains (France) are formed by specific plant species such as Typha, Scirpus, and Sphagnum (long-stemmed aquatic algae).

Peat in the Long Xuyen area, Kien Giang province, consists of two types: ferns (17.3%), gymnosperm pollen (0.35%), and angiosperm pollen (82.5%). Angiosperm pollen includes: Rhizophora sp., Bruguiera sp, Anacardiaceae, Fagaceae, etc. Fern spores include: Polypodiaceae, *Stenochlaena palustris*, *Acrostichum aureum*, Blechnaceae.

Sweet swamp pollen (ancient river type) consists of 76% fern spores, 2.5% gymnosperm pollen, *Stenochlaena palustris*, *Acrostichum aureum*, Blechnaceae, etc. Angiosperm pollen includes: *Melaleuca leucadendron*, Poaceae, Rhizophora sp., Oleaceae, Magnoliaceae, etc.

According to [6], the chemical composition of Kien Giang peat is as follows:

Table 6. General quality of saline swamp peat [6]

Sulfur (S^k)	3.2 – 7.14%	average 4.35%
∑ SO_4^{2-}	52,900 – 139,000 ppm	average 104,517 ppm
N	0.24 – 0.67%	average 0.43%
P_2O_5	400 – 1,900 ppm	average 1256 ppm
K_2O	2,100 – 11,200 ppm	average 4,554 ppm
Humus	30.5 – 55%	average 43.8%
Humic acid	6.25 – 29.39%	average 15.96%

Table 7. General quality of freshwater swamp mud [6]

Sulfur (S^k)	1.57 – 5.36%	On average 3.81%
∑ SO_4^{2-}	21,100 – 145,300 ppm	Average 78,081 ppm
N	0.4 – 1.45%	On average 0.97%
P_2O_5	300 – 2,750 ppm	Average 1,210 ppm
K_2O	500 – 7500 ppm	Average 2,139 ppm
Humus	32.06 – 62.84%	On average 52%
Humic acid	10.5% - 38.69%	On average 21.96%

In addition to organic acids, peat also contains Ca, Mg, Fe, Al, Na, K, Mn, Zn, Cu, and Li.

In the process of studying the chemical composition of peaty soil in Kien Giang province, 5 types of peat were analyzed in the Long Xuyen quadrangle from mines such as Binh Son, Tri Hoa, Binh An, Mop Van Tay and the U Minh Thuong forest peat mine in the Ca Mau Peninsula. Of which, there are 4 types of peat in the form of veins (Binh Son, Tri Hoa, Binh An, U Minh Thuong), 2 types of peat in the form of ancient rivers, Lung Lon and Mo Van Tay.

Through analysis of the chemical composition of peat types, it shows that: All peat types have quite low pH values (pH_{H2O} from 3.36 - 5.57, pH_{KCl} from 3.31 - 5.01), EC conductivity from 0.64 - 3.26 mS/cm, total nitrogen content is high from 0.47 - 1.47%, phosphorus content in the soil is from 0.024 - 0.090%, generally poor in phosphorus. Potassium in peat soil is also poor, ranging from 0.120 - 0.595

%. Total carbon content is quite high, 23.3 - 42.2%. C/N index is 35.2 - 49.6. In addition, the peaty soil also contains many trace elements such as Mn, Cu, Zn, etc. (Table 8).

10.2. Analysis of the chemical properties of humic acid extracted from two types of peat from U Minh and Binh Son

The experiment was conducted in the laboratory of the Department of Crop Science and the laboratory of the Department of Plant Physiology, Faculty of Agriculture, Can Tho University from June to December 1999 [11].

The results show that: The humic acid content of the two types of peat from U Minh and Binh Son is quite high. Binh Son peat has 2.3% humic acid and U Minh peat has 28.57% humic acid. Compared with the research results of Vo Dinh Ngo, Nguyen Sieu Nhan (1991), the humic acid content of peat mines in the Long Xuyen Quadrangle ranges from 15.96 - 21.96%, according to the research results of Schnitzer (1892) is 19.5-26.4%. This may be due to the excess humic acid extraction process while other authors only extracted humic acid once.

The total carbon content of humic acid in U Minh peat is 65.6%, while in Binh Son it is 61.4%.

The relatively low N content of 2.58-2.61% compared with the research results of Schnitzer (1991) is 5 %, possibly because the two types of U Minh and Binh Son mud have different coal compositions, mainly from plants such as *Melaleuca*, parrots, etc. so the composition of humic acid at U Minh and Binh Son Forest is also different. The ash content in the two acids (21.31% at U Minh Forest and 7.71% at Binh Son Forest) is quite high compared to the research results of Schnitzer, on some peat groups it is 7.9%. It is possible that the structural characteristics of peat U Minh and Binh Son are affected by alluvium of the Mekong River, so there is a lot of clay that cannot be removed by the extraction method.

Table 8. Chemical properties of humic acid extracted from two types of peat from U Minh and Binh Son [11]

Type	U Minh	Binh Son
Humic acid content in peat (%)	28.5	32.3
Ash content in acid sample (%)	21.3	27.7
N total (%)	2.61	2.58
C total (%)	65.6	61.4
C/N	25.1	23.8
E_{465} (nm)	2.29	1.41
E_{665} (nm)	0.390	0.230
E_4/E_6	5.80	6.08

Table 9. Optical density of humic acid extracted from two types of peat from U Minh and Binh Son at different wavelengths [11]

Wavelength (nm)	U Minh humic acid	Binh Son Humic Acid
400	3.91	2.73
430	2.55	1.87
465	2.29	1.41
500	1.76	1.07
550	1.15	0.69
600	0.75	0.43
665	0.39	0.23
700	0.28	0.16

All six types of peat surveyed had relatively high acidity (pH2O ranging from 3.36 to 5.57) and medium electrical conductivity. The total nitrogen content in all types was quite high, ranging from 0.47 to 1.47%, while phosphorus and potassium content were low. The total carbon content and C/N ratio were quite high. In addition, peat soaked in alcohol also contained many trace elements such as Mn, Cu, Zn, etc.

The humic acid content in the two types of peat from U Minh and Binh Son is quite high (28.57% - 32.3%). The total nitrogen content in humic acid is also quite high (2.61% for U Minh and 2.58% for Binh Son). The total carbon content is very high, reaching 61.4% (Binh Son) - 65.68% (U Minh). The C/N ratio is high. The E4/E6 index is at an average level (5.80 - 6.08) and the ash content in humic acid is very high, reaching 21.31 - 27.71%.

In nutrient solutions, increasing the concentration of humic acid from 0 to 1000 mg/L increased rice plant height, number of tillers, dry weight, potassium content, and reduced aluminum content in stems and leaves. Conversely, increasing the aluminum concentration from 0 to 200 mg/L in the solution reduced rice plant height, number of tillers, and dry weight, while increasing aluminum and potassium content in stems and leaves. Humic acid extracted from Binh Son mud was more effective than humic acid extracted from U Minh peat in reducing aluminum content and increasing potassium content in rice stems and leaves. In pot-grown experiments using 0-240 g/pot on OM 997-6 rice variety, peat increased the number of grains per panicle, number of filled grains per panicle, 1000-grain weight, yield, phosphorus and potassium content, and reduced aluminum content in stems and leaves. U Minh peat increased the number of seeds/flowers, the number of viable seeds/flowers, and reduced the amount of aluminum in stems and leaves better than Binh Son peat. Conversely, Binh Son peat increased the 1000-seed weight better.

Additional information: Using peat as a base fertilizer for the OM 997-6 rice variety at a dosage of 0 to 8 tons/ha increased the number of panicles/m^2 and the number of filled grains per panicle, leading to increased yield. When using peat, the potassium content in the stem and leaves increased while the aluminum content decreased. There was no difference in phosphorus content in the stem and leaves between the peat-fertilized group and the non-peel-fertilized group. U Minh peat increased the number of filled grains per panicle, reduced aluminum content in the stem and leaves better than Binh Son peat, increased grain weight, and also increased yield.

Field trials and demonstrations showed that using peat-based foliar fertilizer at a dosage of 2 liters/ha or 500 kg of treated peat-based fertilizer/ha increased yield, bringing farmers profits ranging from VND 290,000 to VND 330,000/ha.

11. THE ECOLOGICAL ROLE OF MELALEUCA PEAT FORESTS ON ACID SULFATE SOILS

The U Minh Melaleuca forest ecosystem plays a crucial role in the environmental balance of the Mekong Delta. Its peat layer acts as a **giant carbon sink** , storing thousands of tons of carbon per hectare and regulating water and air quality. The forest canopy and undergrowth slow evaporation and erosion, while biodiversity supports pollination, pest control, and habitat stability for many species.

However, peat is a **non-renewable resource** within the human timescale. The process of peat accumulation takes thousands of years, while a single fire can destroy centuries of ecological accumulation. As peat dries and oxidizes, it releases **CO_2, CH_4, and SO_2,** contributing to climate change and the formation of acid rain.

Causes and consequences of peatland fires

Peat fires are the most serious environmental hazard in the U Minh region. They occur when the groundwater level drops below the peat surface, drying out the organic matter and making it more flammable. Melaleuca trees, which contain volatile essential oils, further increase the risk of fire.

11.1. Causes

1. Hydrological disturbance: Excessive drainage for agriculture lowers groundwater levels and exposes peat to oxygen, leading to oxidation and increased flammability.

2. Human activities: Burning forests for land clearing, honey harvesting, or illegal hunting often causes uncontrollable fires.

3. Prolonged droughts: Climate change and El Niño years significantly increase the risk of wildfires.

4. Infrastructure expansion: Roads and canals cut through forests and alter the natural flow of water, exacerbating peatland drought.

11.2. Impact

Environmental degradation: Burning peat releases enormous amounts of greenhouse gases. Studies show that burning one hectare of peat releases more than 500 tons of CO_2.

High temperatures destroy microorganisms, humus, and soil fertility, turning fertile soil into acidified "dead soil."

Loss of biodiversity: The fires destroy nesting habitats and kill vulnerable species, including amphibians and birds that live in wetlands.

Hydrological imbalance: Burning peat causes it to lose its water-retention capacity, exacerbating flooding during the rainy season and droughts during the dry season.

Socio-economic consequences: The fires damage timber and non-timber resources, disrupt local livelihoods, and threaten ecotourism initiatives.

Field observations following the U Minh Melaleuca forest fire on land with potential for sulfate acid formation.

- Field studies conducted after major fires (2002, 2010) showed that the peat layer was almost completely oxidized, leaving a hard, acidic soil crust. The soil pH dropped from 4.8 to below 3.0, and toxic iron and aluminum ions were released.
- The process of vegetation recovery after the fire has been slow. Melaleuca trees have regrown, but the ferns, mosses, and shrubs that make up the peat layer have almost disappeared. The humus layer, once 1.5–2.0 meters thick, has shrunk to less than 30 cm in heavily burned areas.
- Smoke from burning peat can linger underground for weeks, making firefighting incredibly difficult. Underground fires often reignite even after rain, posing ongoing risks to surrounding communities.

11.3. Discussion about the environment

- The destruction of peatland not only affects local ecosystems but also accelerates climate change at the regional and global levels.

Every ton of carbon released from peat contributes significantly to the concentration of greenhouse gases in the atmosphere.

Furthermore, the sulfate-acid soils beneath the peat layers oxidize upon exposure to air, producing sulfuric acid and iron hydroxides that contaminate surface and groundwater.

- Chemical reaction: acidification of sulfate

$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$

This reaction increases the acidity of the soil, resulting in pH values as low as 2.5–3.0 and making the soil toxic to most crops.

Once oxidized, restoring peat-forming conditions is nearly impossible without large-scale hydrological restoration.

Therefore, protecting peat is a crucial component of climate change resilience in the Mekong Delta. Maintaining groundwater levels, avoiding peat mining, and preventing forest fires are key to preserving the ecological integrity of the U Minh wetland.

12. CONCLUSION

1. The U Minh peatland ecosystem is one of Vietnam's most valuable natural assets, providing essential ecological functions such as water regulation, biodiversity conservation, and carbon sequestration.

2. U Minh peat is a product of the accumulation, decomposition, and transformation of plant remains from the fern family (Don and Choai plants).

3. This peat layer is peat floating on the surface of the earth, forming a peat deposit, and the soil beneath it is soil susceptible to sulfate acid intrusion.

4. Thanks to the thick layer of peat (1-3 m), the soil here does not oxidize into sulfate-acid soil; it also prevents seawater from infiltrating the fields. The freshwater here maintains a pH of 6.5, providing

sufficient calcium and minerals for the daily lives of the people as well as the growth of aquatic and agricultural seedlings.

5. However, unsustainable peat mining and recurring forest fires have severely degraded this fragile environment.

Research demonstrates that peat in U Minh is formed on potentially sulfate-acid soils with high nutrient and humic acid content. When burned or over-exploited, these soil layers undergo irreversible oxidation, releasing greenhouse gases and producing acidic byproducts that render the soil barren.

To ensure sustainable management, the following actions should be taken:

1. **Strict fire prevention and control measures:** Maintain high groundwater levels through improved hydrological management.

2. **Peat mining ban:** Restrict the extraction of peat for fuel or industrial use, especially in areas with large reserves.

3. **Restoring degraded land:** Implementing hydrological restoration measures, replanting native Melaleuca species, and improving soil with organic matter.

4. **Community involvement:** Engaging local communities in forest protection, fire prevention patrols, and ecotourism activities.

5. **Scientific monitoring:** Establish a long-term monitoring system for groundwater levels, peat chemical composition, and biodiversity to guide adaptive management.

Protecting the U Minh peat ecosystem is not only a local issue but also extremely important for maintaining the ecological stability of the entire Mekong Delta and mitigating the impacts of global climate change.

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TÓM TẮT

NGUY CƠ CHÁY RỪNG TRÀM TRÊN ĐẤT THAN BÙN HÌNH THÀNH TRÊN ĐẤT PHÈN TIỀM TÀNG VÀ HOẠT ĐỘNG KHAI THÁC THAN BÙN TẠI U MINH, ĐỒNG BẰNG SÔNG CỬU LONG, VIỆT NAM

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Than bùn ở khu vực U Minh Thượng và U Minh Hạ thuộc Đồng bằng sông Cửu Long được hình thành trên nền đất phèn và là một nguồn tài nguyên sinh thái – môi trường quý hiếm. Loại than bùn này có khả năng hấp phụ cao về mặt vật lý, hóa học và sinh học, giàu dinh dưỡng và vi lượng, đồng thời chứa các chất kích thích sinh trưởng tự nhiên. Tuy nhiên, việc khai thác hoặc đốt than bùn, đặc biệt trong hệ sinh thái rừng tràm, nơi có các loài cây chứa hàm lượng tinh dầu cao, có thể gây ra hậu quả nghiêm trọng và không thể phục hồi. Những tác động này không chỉ làm suy giảm đa dạng sinh học và gây suy thoái môi trường mà còn thúc đẩy quá trình axit hóa đất, biến đất màu mỡ thành "đất chết". Vì vậy, việc bảo vệ hệ sinh thái đất than bùn U Minh là hết sức cần thiết nhằm duy trì tính toàn vẹn của môi trường đất ngập nước vùng Đồng bằng sông Cửu Long và đảm bảo phát triển bền vững cho các thế hệ tương lai.

Từ khóa: Đất than bùn, khu vực U Minh, cháy rừng tràm, đất phèn tiềm tàng, Đồng bằng sông Cửu Long, suy thoái môi trường.