



**POST-FIRE EFFECTS AND HEAT PIPE AS INNOVATIVE SUPPRESSION
TOOL IN PEAT FIRE MANAGEMENT**

By

DAYANG NUR SAKINAH BINTI MUSA

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
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Doctor of Philosophy**

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February 2024

Chairman : Mohd Zahirasri bin Mohd Tohir, PhD
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Peat swamp forest is a globally significant carbon stock and habitat for endemic flora and fauna. However, this ecosystem faces significant threats from fires due to human and environmental factors. This thesis aims to understand fire safety management by focusing on post-fire effects and mitigation strategies in peat swamp forests. To achieve this, Objective 1 examines current approaches in preventing and managing peat fires, emphasizing the need to mitigate the post-fire effects caused by human-induced fires, as discussed in Chapter 3. Mitigating smouldering peat fire is critical and has been recommended, for instance, through the construction of firebreak canals. This approach significantly controls smouldering peat fires by the fire managers along with experienced firefighters; the majority were trained in peat firefighting (77%). Peat fire occurrences have been recorded in the Beaufort peatlands and Raja Musa Forest Reserve, Malaysia, which were chosen as study sites to achieve Objective 2, analysing the peat properties at different post-fire conditions discussed in Chapters 4 and 5. Significant differences in peat properties between pre-fire and post-fire

conditions, and high frequency and low fire frequency areas were recorded near firebreak canals. The findings revealed that repeated fire incidents caused waterlogged conditions at the surface of the peat soil, carbon loss, lower organic matter content, and influenced peat properties such as pH, P, Ca, Na, K, and Mg, showing significant differences ($p < 0.05$) between pre-fire and post-fire areas. Lower moisture content and water table depth will make peat a good below-ground fuel to sustain smouldering peat fires. Subsequently, Objective 3 investigates the importance of moisture availability by the presence of a water table in suppressing smouldering peat fires. The study explored the creation of a safe region within the peat layer enhanced by the role of heat pipes as suppression tools, as discussed in Chapter 6. The findings demonstrate that heat pipes are effective suppression tools that enhance the formation of a safe region from 1.5 cm without heat pipe application to 8 cm and 17 cm in mesh and sealed rigs with heat pipe application, respectively. The findings have demonstrated the significant role of heat pipes in suppression efforts. In summary, effective peatland fire management requires policymaking, suppression actions, and ongoing monitoring to substantially reduce the risks posed by smouldering fires in tropical peatlands. This research provides essential insights for government agencies and firefighters regarding pre-fire mitigation and post-fire impacts on peat properties.

Keywords: Fire effects, heat pipe, innovative suppression tool, peat fire management, smouldering peat fire

SDG: GOAL 13: Climate change

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**KESAN AKIBAT KEBAKARAN DAN TIUB HABA SEBAGAI INOVASI ALAT
PEMADAMAN DALAM PENGURUSAN KEBAKARAN GAMBUT**

Oleh

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Hutan paya gambut merupakan stok karbon yang penting di peringkat global dan juga habitat kepada flora dan fauna. Walau bagaimanapun, ekosistem ini menghadapi ancaman kebakaran disebabkan faktor manusia dan alam sekitar. Tesis ini bertujuan untuk memahami pengurusan keselamatan kebakaran di hutan paya gambut dengan fokus utama terhadap kesan kebakaran dan strategi pencegahan kebakaran. Untuk mencapai ini, Objektif 1 mengkaji pendekatan semasa untuk pencegahan dan pengurusan kebakaran gambut, dengan menekankan keperluan untuk mengurangkan kesan kebakaran yang disebabkan aktiviti manusia, seperti yang dibincangkan dalam Bab 3. Strategi mengurangkan kadar kebakaran gambut adalah penting dan telah dijalankan, contohnya, melalui pembinaan terusan pencegah kebakaran. Pendekatan ini secara signifikan dapat mengawal kebakaran bara gambut yang telah diselia oleh pegawai kebakaran hutan bersama dengan bomba yang berpengalaman, dengan majoriti terlatih dalam pemadaman kebakaran gambut (77%). Kejadian kebakaran gambut telah direkodkan di daerah Beaufort dan Hutan Simpan Raja Musa, Malaysia, yang dipilih sebagai tapak kajian untuk mencapai Objektif 2,

dimana ciri-ciri gambut terhadap keadaan kebakaran yang berbeza telah dianalisis dan dibincangkan dalam Bab 4 dan 5. Perbezaan yang signifikan dalam ciri-ciri gambut antara kawasan sebelum dan selepas kebakaran, dan kawasan kekerapan kebakaran tertinggi dan rendah telah direkodkan berdekatan dengan terusan pencegah kebakaran. Hasil kajian menunjukkan bahawa kejadian kebakaran menyebabkan air bertakung di permukaan tanah gambut, kehilangan karbon, kurangnya kandungan bahan organik, dan memberi impak terhadap ciri-ciri gambut seperti pH, P, Ca, Na, K, dan Mg, dimana terdapat perbezaan signifikan ($p < 0.05$) antara kawasan sebelum dan selepas kebakaran. Kandungan kelembapan yang lebih rendah dan aras air bawah tanah yang rendah menjadikan gambut sebagai bahan bakar yang sesuai untuk mengekalkan keadaan kebakaran bara gambut dalam tempoh yang lama. Seterusnya, Objektif 3 mengkaji kepentingan kelembapan dan aras air bawah tanah dalam mempengaruhi pemadaman kebakaran bara gambut. Hasil kajian mendapati *safety region* (kawasan selamat) telah tercipta di antara lapisan gambut dan telah ditingkatkan dengan adanya tiub haba sebagai alat pemadaman, seperti yang dibincangkan dalam Bab 6. Penemuan baharu ini menunjukkan bahawa tiub haba adalah alat pemadaman yang berkesan yang mempertingkatkan *safety region* daripada masing-masing 1.5 sm tanpa kehadiran tiub haba kepada 8 sm dan 17 sm dalam pelantar jaringan dan tertutup setelah tiub haba diaplikasikan. Penemuan ini menunjukkan peranan tiub haba dalam proses pemadaman api. Secara keseluruhan, pengurusan kebakaran gambut yang berkesan memerlukan polisi, tindakan pemadaman, dan pemantauan berterusan untuk mengurangkan risiko yang ditimbulkan oleh kebakaran bawah tanah yang berlaku di kawasan gambut tropika. Penyelidikan ini memberikan wawasan kepada agensi kerajaan dan bomba mengenai strategi

pencegahan sebelum kebakaran dan impak selepas kebakaran terhadap ciri-ciri gambut.

Kata Kunci: Kesan kebakaran, tiub haba, alat pemadaman inovatif, pengurusan kebakaran gambut, kebakaran bara gambut

SDG: Matlamat 13: Perubahan iklim



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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

%	Percent
°C	Degree celsius
<	Less than
>	More than
±	Plus minus
ASEAN	Association of Southeast Asian Nations
BFR	Binsuluk Forest Reserve
C	Carbon
cm	Centimetre
cmol/kg	Centimoles of charge per kilogram
CO ₂	Carbon dioxide
FFC	Forest Fire Crew
FR	Forest Reserve
g	Gram
g/cm ³	Gram per centimetre cube
ha	hectare
IAC	Initial Attack Crew
IUCN	International Union for Conservation of Nature
K	potassium
KALBAR	Kalimantan Barat
KFR	Klias Forest Reserve
kg	kilogram
Kg.	<i>Kampung</i>
L	Liter
m	meter
m ³	Meter cube

mg	Milligram
Mg	Magnesium
MODIS	Moderate Resolution Imaging Spectroradiometer
NBOS	National Blue Ocean Strategy
NTFP	Non timber forest products
OMC	Organic matter content
P	Phosphorus
PPE	Personal Protective Equipment
PSF	Peat Swamp Forest
RMFR	Raja Musa Forest Reserve
SFD	Sabah Forestry Department
SFM	Sustainable Forest Management
Sg.	<i>Sungai</i>
TGA	Thermogravimetric analysis
TPA	Total Protected Area
USD	United States Dollar
µg/g	Microgram per gram
θ	theta
km ²	Kilometre aquare
PM _{2.5}	Particle matter (2.5)

CHAPTER 1

INTRODUCTION

1.1 Background

Peat swamp forests constitute crucial ecosystems that provide a range of ecological advantages, including carbon sequestration, biodiversity conservation, and hydrology regulation. Furthermore, these forests are essential in supporting local communities through activities like agriculture, fishing, and the collection of non-timber forest products (Freeman et al., 2001). Subsequently, protecting peat swamp forests aligns with Malaysia's goal of allocating 30% of its land area as a Totally Protected Area (TPA), a fundamental initiative aimed at securing the welfare of future generations, the continuity of forest habitats, and the harmonious cohabitation of human communities. Nonetheless, conserving these unique habitats faces an increasing risk from destructive forest fire, which could lead to significant environmental and socio-economic consequences. Indeed, fire emerges as a significant threaten, posing a threat to the local community, wildlife, forests, and environment (Miettinen et al., 2017; Munawi, 2014; Pillai et al., 2021). The development and execution of efficient fire management strategies hold critical importance in protecting the vulnerability of these ecosystems and securing their sustainability.

The necessity to control fires in peat swamp forests arises from their significant environmental impacts and the possibility of widespread catastrophes. Clearly, forest fires potentially destroy the entire peat swamp forest ecosystem (Chen et al., 2014; Wunder et al., 2021). An alarming example is Indonesia's forest fires in

2015, 2018, and 2019 causes problems to business and tourism in Malaysia and Singapore due to the haze and pollution from the fires, which led to financial losses and forest degradation (Miettinen et al., 2017; Munawi, 2014; Phelps et al., 2021; Trihadmojo et al., 2020). It's important to highlight that tropical peat swamps, as seen in Malaysia and Indonesia that experienced thousands of years of development from forest materials and making up around 15-19% of the total peat carbon content (Dommain et al., 2011; Sundari et al., 2012). The various elements of managing peat swamp forest fires include quickly spotting and responding to fires, managing water levels, controlled burning, involving local communities, providing firefighting tools and infrastructure, international collaboration, restoring ecosystems, sustainable land use, and systematic research and monitoring initiatives. It's clear that strategies for managing fires in peat swamp forests significantly impact social and economic aspects, as well as the decision-making processes of institutions (Hamilton & Salerno, 2020). Adopting a holistic and diverse approach to fire management in peat swamp forests has the potential to safeguard these distinct ecosystems and mitigate negative environmental and social effects.

The heat transfer from the heat pipe is efficient as a suppression device that can dissipate heat away from the source. In the context of peat swamp forest fires, heat pipe can be used to extract the heat from smouldering peat layers underground, thus reducing the temperature and mitigating the spread of fires. The safe region formation from the heat pipes facilitates this creation within the peat layer by lowering the temperature sufficiently to prevent combustion. To maintain the water table depth to be used for the heat pipe application. Fire break canal serve as physical barriers and maintaining the moisture of the peat. Fire

break canal strategically position near the degraded area to minimise the potential impact of peat fires.

Recognizing various viewpoints and inputs from fire managers and firefighters contributes to a unified understanding and resolution of the complex nature of fire occurrences. Over the past years, there has been significant academic attention devoted to peat fires, particularly in terms of their post-fire effect and specialized suppression methods (Fawzi et al., 2021; Rochmayanto et al., 2021; Horton et al., 2022; Qin et al., 2022; Nurhidayah et al., 2023). The integration efforts between managers and researchers underscores a common goal: the efficient management of fires and a deeper understanding of their impact on peat swamp forests.

Heat pipes and fire break canals play important roles in peat swamp forest fire management. In the context of this thesis, by localise the use of heat pipes in extracting the heat from the smouldering peat fire, while FBC providing broader containment measures creating the physical barriers to limit the fire spread. Technology can contribute in effective fire safety management for mitigating the risk associated with peat fires.

Fire management in peat swamp forests covers both before and after fire situations. Careful management of peat swamp forests is crucial to prevent fires from spreading and becoming intense. Thorough understanding of pre-fire conditions is essential for effective fire management strategies. The beginning of fire ignitions, be they intentional or accidental, by human-driven constitutes a significant threat to peat swamp forests (Fawzi et al., 2021). The 2017 and 2019

Annual Reports of the Sabah Forestry Department emphasize that human activities, including open burning, intentional arson, and illegal poaching, are responsible for causing fires (SFD, 2017, SFD, 2019). In this means, effective fire prevention measures, public awareness campaigns, and resilient law enforcement mechanisms stand as critical safeguards against human-induced fire episodes. Thus, the public's knowledge of the of the managerial attempts aimed at fire control, particularly concerning preventatives measures (Li et al., 2023) and post-fire rehabilitation initiatives (Mulyasih et al., 2022; Nurhidayah et al., 2023) like the deployment of firebreaks and restoration efforts (Rochmayanto et al., 2021; Volkova et al., 2023), acquires heightened significance. Proficient water table management, achieved through canal blocking or the establishment of firebreak canals, augments conditions conducive to fire resistance by preserving moisture levels (Fawzi et al., 2021; Mezbahuddin et al., 2023). Therefore, addressing the challenges associated with peat swamp forests in Malaysia requires multidisciplinary research efforts and the implementation of science-based management practices to ensure the peat swamp forests are sustained.

1.2 Problem statement

Future research should prioritize interdisciplinary perspectives to understand better the challenges faced by the firefighters (Held et al., 2024). Comprehensive research and effective strategies are essential to address peat swamp forest fires effect on its properties. Understanding peat properties and smouldering fire durations is crucial due to human-induced disturbances (Liu et al., 2023; Volkova et al., 2023). Fires release of preserved carbon nearly 90%

and increase peat vulnerability to fire in supposed waterlogged area (Che Azmi et al., 2021; Darusman et al., 2022). This cause changes in peat properties due to anthropogenic influences, climate change and the duration of plant remains in the peat swamp forests (Murayama and Zahari, 1996; Yule and Gomez, 2009; Bragazza et al., 2013; Starr and Vasander, 2021). For instance, the need is addressing gaps of fire return intervals contributing to comprehensive assessment of recurrent fire impacts such as the waterlogged condition causes the hydrophobicity and water runoff (Mulyasih et al., 2022; Taufik et al., 2019; Volkova et al., 2023).

To reduce the fire impact on peat properties, it is important to address the efficacy of current firefighting techniques (Horton et al., 2022; Nurhidayah et al., 2023) and the difficulties in extinguishing deep-seated peat fires (Ramadhan et al., 2017; Lin et al., 2020; Mulyasih et al., 2022). While, existing fire management approaches have reduced peat fires with minimum ecological and socio-economic impacts in Malaysia (Munawi, 2014; SFD, 2019; SFD, 2020), limited research has been conducted on peat fires and their management, especially about community and deep peat fire studies (Taufik et al., 2020; Fawzi et al., 2021; Rochmayanto et al., 2021; Nurhidayah et al., 2023). Additionally, further research to understand the impacts of the canal systems on peat fires, especially during drought with lower water levels is crucial. Current measures of canal-based rewetting in the burnt area to lower fire frequency for successful restoration ideally achieved around 25 years (Taufik et al., 2023; Warren et al., 2017). Additional research is crucial to understand canal systems, describing management methods accurately and acknowledging their impact on peat fires, especially in droughts with lower water levels (Horton et al., 2022;

Mezbahuddin et al., 2023).

A phenomenological explanation to the moisture contents limiting smouldering is yet to be established (Yermán et al., 2017). Since canals, dike, and dams are significant to prevent fires (Fawzi et al., 2021; Taufik et al., 2023), there is a need to understand the raising the moisture levels in peat from canal blocking can lower the potential of prolonged smouldering peat fires by raise water tables for fire prevention and extinguishment (Schulte et al., 2019); Sutikno et al., 2019; Ward et al., 2021). Implementing effective firefighting measures is needed since the lack of essential firefighting equipment intensifies the difficulties in accomplishing efficient fire control in peat swamp forest (Mulyasih et al., 2022; Nurhidayah et al., 2023).

However, this approach requires human interaction and can be time-consuming for the flooding method and tremendous amount of water needed to be effective. Previous study indicates that 1 kg of peat needed about 6 L of water which needed a water sources availability or short period of violent rain (>50 mm/h) is the most effective to extinguish the peat fire to gradually decrease the peat fire (Ramadhan et al., 2017; Sandhyavitri et al., 2018; Lin et al., 2020; Arisanty et al., 2023). Other study in Riau, Indonesia, shows that the frequency of extreme fire declined by 40% after rewetting (Taufik, Haikal, et al., 2023). Nevertheless, they have proven effective in suppressing peat fires during periods of water shortage. The need for essential firefighting equipment hinders efficient fire control (Nurhidayah et al., 2023). With the potential increase in fire risks due to climate change, a fresh approach to managing fuel becomes crucial for suppressing deep-seated smouldering peat fires (Masarie et al., 2019;

Deane et al., 2022). Overall, enhancing understanding and implementing strategies are essential for safeguarding peat swamp forest and ensuring forest sustainability.

1.3 Research aims and objectives

The main aim of the research is to evaluate multidimensional approaches to current policy, their effects on peat properties, and the potential of suppression tool for sustainable peat swamp forest fire management in pre-fire and post-fire conditions. To achieve this understanding, three objectives were outlined as follows:

Objective 1: To understand the on-ground perspectives of peat fire management suppression strategies and prevention policies.

Chapter 3 of this thesis focuses on the first goal, offering insights into fire incidents, their effects, and ways to manage them based on the perspectives of fire managers and firefighters working in peat swamp forests. A survey with different types of questions will be given to firefighters, covering their knowledge, experiences, firefighting techniques, reasons for fires, outcomes, and safety concerns. Detailed discussions on peat fire management will be held through interviews with specific fire management experts and government authorities. By collecting numbers-based and descriptive information through surveys and interviews, this thesis aims to grasp the complexities of peat fire management better and understand how firefighters see and experience fires in peat swamp forests. **Chapter 3** will extensively detail this goal. The subsequent **Objective 2** concentrates on examining the impact of peat fires on

peat properties to confirm their influence.

Objective 2: To analyse the post-fire peat properties under different fire history conditions.

This objective complements **Objective 1** by analysing the peat properties based on different fire history factors. Peat samples will be collected from areas before and after fires, as well as from places with low and high fire frequencies, and their properties, such as moisture and nutrients, will be examined to understand the impact of fires. The study will also analyse how well peat can hold water after fires and in regions that haven't experienced fires yet. The chemistry of peat properties will be investigated to see if there are any potential effects. This laboratory work will provide important scientific information about peat conditions in different fire situations, aiding in evaluating fire impact for developing effective fire management strategies. **Chapters 4 and 5** will further explore conditions before and after fires, and areas with different fire frequencies, expanding on the objectives mentioned in those chapters. The significance of moisture, essential for preventing fires, is emphasized in this objective. **Objective 3** will then look into how moisture helps prevent slow-burning fires in peat.

Objective 3: To investigate the heat pipe as an early suppression tool for aiding mitigation strategies at different scales of the experimental rig.

Aligned with **Objective 1** and **Objective 2**, this thesis will further discuss the management of peat fire mitigation. Rapid response to peat fires remains crucial, even in the presence of fire break canals as mitigation measures. This objective revolves around the exploration of how newly developed heat pipes

contribute to fire suppression strategies. The experiment will highlight the potential advantages of utilizing heat pipes to control peat fires. Laboratory experiments employing these tools for fire management will provide insights and recommendations for their practical application in peat swamp forests. This sustainable and comprehensive management approach not only safeguards peat swamp forests against destructive fires but also preserves their crucial functions and services. Additional details regarding this objective can be found in **Chapter 6**.

1.4 Research aims and objectives

Peat swamp forests function as natural reservoirs, regulating water flow and mitigating drought events. However, uncontrolled fires can disrupt their hydrology, potentially leading to water shortages. Ensuring proper fire management becomes crucial in maintaining the hydrological balance of these ecosystems. Additionally, these forests offer a range of ecosystem services, catering to local communities' water, food, and raw material needs. The adverse impacts of severe fires can surround through socio-economic channels, affecting livelihoods, agriculture, and regional economies.

This study seeks to clarify the roles of forest fire managers and firefighters within the context of current fire management policies in Malaysia. It is imperative to gauge the efficacy of suppression, mitigation, and impact reduction strategies against peat fires in the peat swamp forest. Existing literature's constrained trials have illustrated the inefficacy of all artificial suppression methods (Lin et al., 2020). Furthermore, academic experts might not possess an equally

effective comprehension of the applicability of solutions in real-world scenarios (Phelps et al., 2021). Quantifying the perspective of the on-the-ground personnel engaged in peat fire issues could contribute to shaping further research directions in the specific context of peat fires.

The fundamental aspects of this research are to accumulate quantitative and qualitative data relevant to peat fires and their management. It is to provide invaluable insights into the complex components indicating peat fire management. The perceptive explanation of the fire-prone area involves navigating a complex-ecological system inhabited by diverse stakeholder groups and managerial entities (Hamilton & Salerno, 2020). It is also important to comprehend the impacts of peat fires on peat properties and the surrounding environment. A comprehensive evaluation of smouldering peat fire behaviour becomes imperative before selecting an appropriate suppression technique (Mulyasih et al., 2022). Nevertheless, the context of the research conducted in this thesis comprise the need for responsive reaction of peat fire suppression by using heat pipe it can prevent the smouldering fire behaviour below ground.

Overall, justifying peat swamp forest fire management, understanding their impact on peat properties, and development the innovation of fire suppression technologies are crucial measures towards safeguarding these invaluable ecosystems and ensuring a sustainable future for both the environment and the communities reliant upon them. Through the coordinated interest of **Objectives 1, 2, and 3**, this thesis aims to compile a comprehensive dataset concerning peat swamp forest fires, their influence on peat properties, and methods for effective fire prevention and suppression strategies. The integrated insights

gathered through these approaches will contribute practically to add knowledge in decision-making, policy making, and sustainable management of peat swamp forest ecosystems.

1.5 Thesis outline

This thesis embarks on a thorough exploration of a comprehensive management of peat swamp forests, with a specific focus on forest fires and their subsequent impacts. The study delves into strategies for enhancing mitigation efforts to strengthen fire suppression actions. Within this thesis, three key aspects have been rigorously examined through experimental studies: peat fire management (**Chapter 3**), the impact of peat fires (**Chapters 4 and 5**), and the utilisation of heat pipes as a tool for suppression (**Chapter 6**).

The outline structure of this thesis comprises five distinct chapters, excluding the introductory and concluding sections. Each of these chapters takes the form of an independent paper, either having been published, submitted and prepared to be submitted to journals or conferences. The primary key points of this thesis include the areas affected by fire, unburned areas, and those subject to varying fire frequencies. The disruption of peat properties following a fire event worsens changes in peat properties and subsequently impacts the water table, contributing to the suppression of peat fires. A visual representation of the research framework employed in this thesis is presented in **Figure 1**.

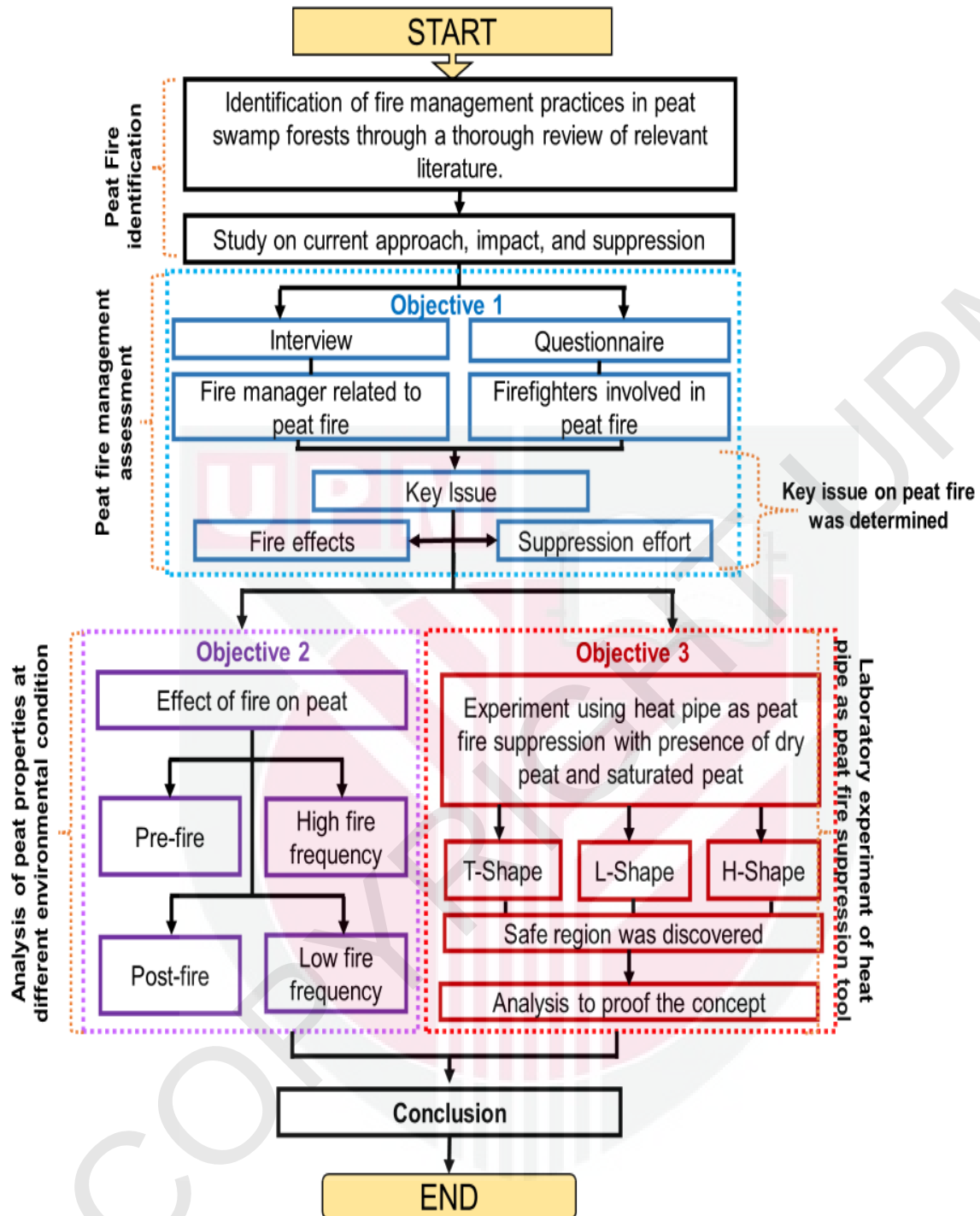


Figure 1: Framework of the research approach of the thesis.

Chapter 3 of this thesis is oriented towards achieving **Objective 1**, which involves gathering comprehensive and structured data from firefighters through a questionnaire study, aiming to glean nuanced insights into peat fire management. The focus is on fire managers who hold specialised expertise,

experiences, and perspectives in dealing with forest fires in peat swamp environments. Within the context of a management plan, the application of a fire break canal in a susceptible region to control fire propagation in a forest reserve underscores the necessity of comprehending the effects of such canals, particularly given the limited research on their fire break functionality to protect the peat.

To account for the inherent variations and outcomes of peat fires on peat properties, this study employs on-site sampling and analysis of peat characteristics in diverse environmental conditions near a fire break canal within a forest reserve. The aim is to address varying fire severity levels and peat fire impacts. **Chapters 4 and 5** of this thesis are dedicated to scientifically exploring the consequences of peat fires on peat properties and the surrounding ecosystem, as specified in **Objective 2**. **Chapter 4** divides the pre-fire and post-fire states of peat properties, encompassing physical and chemical attributes. This section exposes differences between areas with no history of fire and those repeatedly subjected to burning, revealing how fire affects peat conditions, causing waterlogging and changes in its properties. Considering the potential distinctions in fire frequencies and their distinct impacts on peat attributes, **Chapter 5** examines the properties linked to fire occurrence frequencies, offering comprehensive insights into the diverse consequences of peat fires.

To address fire management challenges in peat swamp forests, the exploration of an innovative fire break canal applied to peat swamp forest holds potential, with an importance of reducing dry peat to be vulnerable to fire. The enhancement of firefighting equipment also emerges as a significant possibility

for mitigating fire damage (Wang et al., 2021). This innovative approach could utilise as heat-resistant materials to create a barrier that increasing moisture levels around dry peat, thereby hindering the progression of peat fires and preserving critical peatland habitats. In line with **Objective 3**, **Chapter 6** focuses on the design of specialized tools to enhance fire suppression efforts by increasing the moisture. An experimental laboratory setup is developed to evaluate a novel suppression concept, aiming to address peat fire suppression and ultimately mitigate the peat fire and reduce the workload of firefighters.

Collectively, the insights described from the various chapters, encompassing **Chapter 3, 4, 5, and 6**, offer novel perspectives on the efficacy of peat fire management, both practically and in the area of research. The through combination of diverse methodological approaches, including surveys, interviews and laboratory analyses, augments the comprehension of the dynamics management of peat fire occurrences, their negative impact upon peat properties, and innovative avenues for fire suppression. The outcomes yielded by this research possess the potential to inform grounded fire management policies and operative protocols, thereby practically contributing to the fundamental objectives of peat swamp forest conservation and sustainable management. These insights span across the operational effectiveness of management practices, the execution of firefighting protocols, the physicochemical impacts within the forest reserve, and the introduction of suppression tools to aid in early mitigation strategies.

1.6 Limitation of the study

Through this thesis, there was a particular limitation that may impact the depth of the thesis's findings as follows:

1. **Chapter 3** explores the factors influencing peat fire and the key issues related to current management strategies. This chapter aims to examine peat fire management from the perspective of fire managers and firefighters. However, it does not discuss the involvement of local communities from their viewpoint, even though their contribution to peat fire suppression is discussed.
2. **Chapters 4 and 5** focus on peat properties influenced by different historical fire factors. These variables can lead to variations in fire behaviour. Yet, surrounding factors such as wind patterns and vegetation composition may not be fully addressed within the scope of this study.
3. **Chapter 6** covers the availability of the water table's efficacy to suppress smouldering fire occurrences above-water table region and was enhanced by the application of heat pipes of different designs. A more comprehensive application of heat pipes in a deeper and larger scale of experimental rig could overcome the constraints of the study duration.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Fire is a worldwide phenomenon that happens in every ecosystem, including the forest ecosystem. In Malaysia, the forest ecosystems encompass various types such as mountain, lowland, mangrove, and peat swamp forests. The forests plays crucial roles in supporting livelihoods, acting as a key component in agricultural development, logging, and sustenance for local communities. Additionally, the peat swamp is home to endemic species such as the critically endangered Orang Utan (*Pongo pygmaeus*), as listed in the IUCN Red List. It is also home to one of the rarest birds in Malaysia, the Hook-billed Bulbul, for which this species was only documented in the Peat Swamp Forest of Klias, Sabah (Sheldon et al., 2014).

Peat swamp forests are globally valuable ecosystems with unique hydrological conditions and diverse biodiversity. It is permanently waterlogged and has low organic matter decomposition, leading to peat accumulation (Jackson et al., 2009). In tropical regions, dead leaves and plant materials accumulate, creating peat layers that can reach depths of up to 20 meters (Silvius & Suryadiputra 2002; Nik et al., 2006; Jackson et al., 2009). Alternative viewpoints propose that peat could attain depths of 10 to 40 meters or more of undecomposed plant biomass and accumulation persisted for as long as 100,000 years (Othman et al., 2011; Lindsay & Andersen, 2018). Peat swamp forests are severely threatened by recurrent fires, causing significant environmental and socio-

economic damage. The increasing frequency and severity of these fires in recent years have raised alarm, highlighting the urgent need for effective fire management strategies.

During drought seasons, heightened dryness in peat swamp forests, resulting from elevated temperatures, intensifies evaporation and reduces groundwater levels. Over time, recurring fire incidents have become a significant concern in these forests, occurring annually over recent decades. Human activities, such as starting fires and causing land degradation, present substantial challenges. The deep accumulation of peat becomes vulnerable to smouldering underground during fires, posing threats to endemic species and generating thick smoke. Effective forest management is essential to mitigate impacts like habitat loss, reduced income, and environmental pollution, thereby maintaining stability crucial for climate change mitigation (Posa et al., 2011; Sazawa et al., 2018). Objectively, the peat swamp forest accumulated organic matter for thousands of years to store carbon and mitigate the flood. However, this permanently logged forest will be destroyed once affected by the fire on the surface and spread belowground. The millennia-old peat dome stands as a treasured outcome of accumulated forest debris, with a 40-meter peat dome taking thousands of years to form (Dommain et al., 2011).

Therefore, this chapter will cover a literature review that aims to provide a comprehensive overview of the current state of knowledge regarding peat swamp forest fire management. By exploring existing research, policies, and practices, we seek to gain valuable insights into the challenges and opportunities in mitigating and preventing peatland fires.

2.2 Ecological significance of peat swamp forest

This section delves into the ecological significance of peat swamp forests, elucidating their intricate relationships with biodiversity, the formation, and distribution of these ecosystems across Asia. Understanding this ecosystem's unique characteristics and functions lays the groundwork for identifying the potential impacts of fire incidents on these vital habitats.

2.2.1 Ecological significance of peat swamp forest

Peat, peat soils and organic soils are synonyms. The difference between peat and peat swamp is that peat is a material, and peat swamp is the physiographic or landscape unit, which must be discussed separately (Andriesse, 1988). Organic matter contains over 20% organic matter. Peat swamps are intricate forest ecosystems characterised by naturally accumulated peat layers at the surface (Huat et al., 2014; Priyadi et al., 2006). The typical soil profile in drained organic soils consists of three layers (**Figure 2a**). The layers are the upper layer (20 – 30 cm) of well-decomposed organic materials of the sapric type, the middle layer (30 – 40 cm) of semi-decomposed organic materials of the hemic type, and a lower layer of fibric materials (Mohamed et al., 2002).

The peat is considered dome-shaped, with depths ranging from as low as 1 m to 20 – 40 m, depending on the sampling areas by the researcher. It has been reported that peat swamp domes might cover areas ranging from 5,000 ha to 800,000 ha, which undoubtedly affects the dome's characteristics (Chin & Parish, 2013). Generally, peat domes in the tropics develop between two rivers, where young domes have a limited central plain; however, in older domes, the

swamp plain is very extensive. An example of an advanced dome with an extensive central peat plain is depicted in **Figure 2b**.

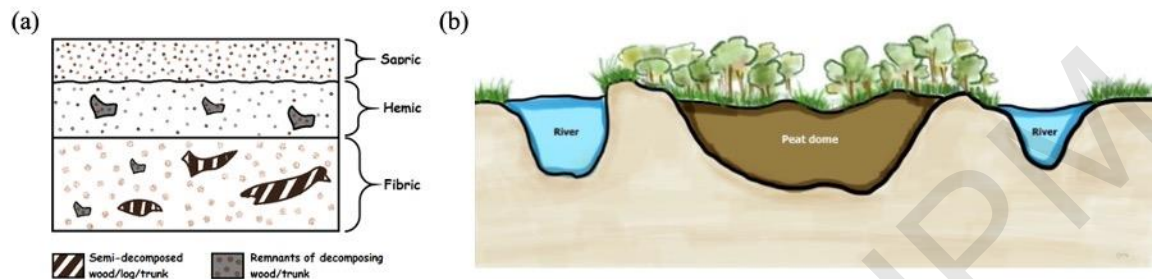


Figure 2: a) Profile morphology of drained organic soils; b) Description of peat dome.

2.2.2 Distribution of peat swamp forest in Asia

This section of the delves into the ecological significance of peat swamp forests Peat, The peat accumulation develops the dome as the sea level increase and the moisture climate increase in early peat formation in Southeast Asia (Dommain et al., 2011). These tropical peat swamps are primarily located at low altitudes in river valley basins, watersheds, and sub-coastal areas, with Southeast Asia hosting 60% of the world's total, estimated at 33 million hectares. Indonesia holds the majority (82%), followed by Papua New Guinea (8.8%) and Malaysia (8.3%) (Nik et al., 2006; Wösten et al., 2006; Posa et al., 2011). Furthermore, there are smaller peat swamps areas found in other Southeast Asia countries such as the Philippines (240,000 ha), Vietnam (183,000 ha), and Thailand (68,000 ha) (Postel & Ritcher, 2012).

The forest cover in Peninsular Malaysia, Sumatra, and Borneo Island (Sabah, Sarawak, and Kalimantan) was predicted to disappear by 2030 as 77% of the

area drastically lessened to 36% from the past two decades with a current rate of deforestation of 4.9% a year-1 (31,000 km²) (Miettinen et al., 2012). However, restoration and new policies have been implemented to protect the area in recent years. For example, Sabah, Malaysia, increased its Total Protected Area by 30% of the land by 2025. Fire has become one of the significant threats to peat swamp degradation. **Figure 3** portrays the peat area covered globally (Xu et al., 2018). Determining the global extent of peat swamps faces challenges due to varying estimations and definitions, but globally, peat swamp forests cover approximately 350,000 km² (Nik et al., 2006; Zoltai & Martikainen, 1996).

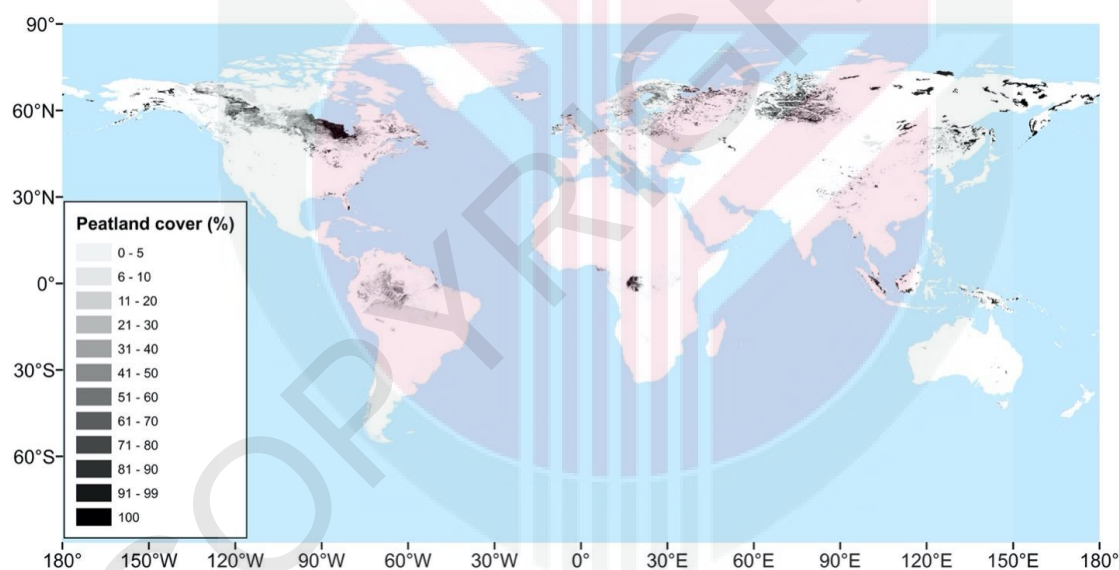


Figure 3: The peatland distribution globally.
Source: (Xu et al., 2018)

2.2.3 Distribution of peat swamp forest in Asia

Peat swamp forests are vital for flood control, climate change mitigation, and carbon storage, while also providing habitats for unique and endangered species. They store approximately 15% to 19% of global peat carbon and offer

various economic benefits due to their multiple uses and functions. From supporting forestry and agriculture to providing recreational spaces and economic resources for local communities, peat swamp forests offer diverse advantages. Recognizing their aesthetic, historical, and cultural significance is essential for preserving their functionality and ensuring their sustainable use.

2.3 Causes leading to peat swamp forest fires

In this section, we assess the primary causes and contributing factors that lead to peat swamp forest fires. Human-induced factors, such as land-use changes, illegal logging, and agricultural activities, often intertwine with natural factors, like climatic variations and drought, amplifying the risk of ignition. Recognising these interconnected triggers is crucial in designing comprehensive fire management strategies.

2.3.1 Peat fire occurrences in Asia

The tropical peat swamp of Asia was mostly in Southeast Asia, in Indonesia, facing significant fire occurrences, with Malaysia, Thailand, and Brunei. These areas have a high probability of burning again because of the accumulation of unburned dead biomass and the presence of fire-prone regrowth vegetation that can act as fuel for the subsequent fire (Siegert et al., 2001; Posa et al., 2011). In Malaysia, a gazetted forest reserve in Raja Musa Forest Reserve, has experienced severe fire incidents recorded since 1996 (Ainuddin & Goh, 2010). Fire incidents in Raja Musa Forest Reserve destroyed 10 ha in 2002, 400 ha in 2004, 12 ha in 2007, 630 ha in 2008, and 29 ha in 2009 (Selangor State Forestry Department, 2014). In another part of Malaysia in the northern part of Borneo

Island, the El-Niño phenomenon was one of the factors for the great fire in 2015/2016, which burned a total of 1585 ha, which Binsuluk (1000 ha) and Padas Damit (585 ha) forest reserves (SFD, 2016). Indonesia also faced significant peat fires, notably in the Merang-Kepahyang peat forest that burned about 69,837 ha in 2015 due to El-Niño (Saputra et al., 2017). Furthermore, a major peat fire event occurred from 1997 to 1998, affecting around 800,000 ha of peat swamp forests in Malaysia and Indonesia, leading to severe smoke haze events (Nik et al., 2006; Yule, 2010; Zacccone et al., 2014).

2.3.2 Forest fire classifications

Forest fires in the peat swamp forest can be classified into three (3) types: surface fire, crown fire, and below-ground fire (smouldering fire) as illustrated in **Figure 4**. These fires often originated from alienated and state land (SFD, 2019, SFD, 2020). Then, the fire igniting as surface fires before it extends to underground and crown fires. The interaction of fire affects the flame height when the fire reaches the forest's crown (Liu et al., 2019). Heat transfers through radiation and convection spread to the tree canopy, and this type of fire spread the fastest compared to underground and surface fire. The high temperature on the surface for about one to two hours and sufficient fuel causing the fire from the surface spread into the underground peat (Page & Hooijer, 2016; Leng et al., 2019).

It holds paramount importance to disrupt one of the components of the fire triangle (heat, fuel, and oxygen) as shown in **Figure 5**. In the peatland area, the fuel supply is the dry peat condition that serves as suitable fuel to be ignited.

The heat will be coming from ignition of prescribe burning or slash and burn activity, arson and the situation will be worsened during prolonged dry condition (Musa & Huang, 2022; SFD, 2017). Despite limited oxygen underground, the smouldering fire can still persistently smoulder underground (Qin et al., 2022; Wyn et al., 2020; Yamazaki et al., 2019).

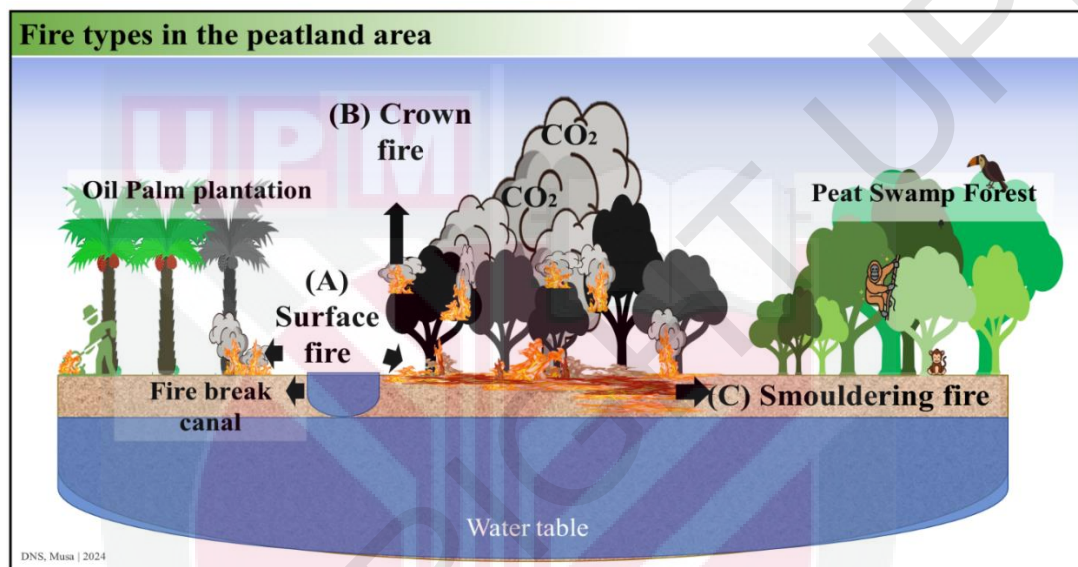


Figure 4: Fire types in peatland area consist of A) Surface fire, that can extend to B) Crown fire and C) Smouldering fire underground.

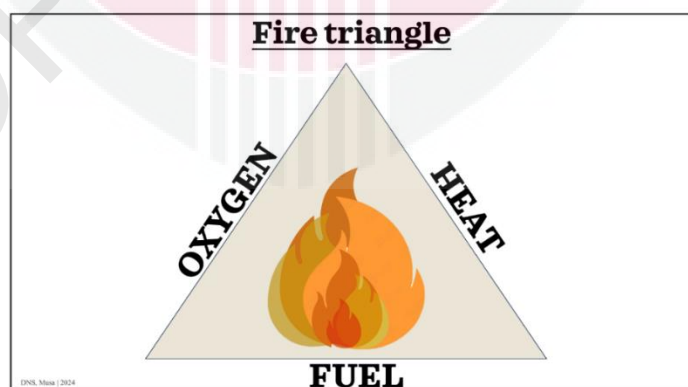


Figure 5: Fire triangle consists of the presence of i) oxygen, ii) heat, and iii) fuel.

Consequently, when the peat, serving as available fuel, is completely consumed, or when heat production is insufficient to sustain vaporisation, the

peat fire is considered extinguished (Leonard et al., 1998). The underground fire is challenging for the firefighters to tackle in peat swamp forest due to invisible and sustainable fire known as smouldering fire. The smouldering fire produces heavy smoke, causing loss of carbon and aerosol to the extent of initiating severe regional haze events (Toriyama et al., 2014; Hu et al., 2018). The Association of Southeast Asian Nations (ASEAN) member countries signed the ASEAN Agreement on transboundary haze pollution on June 10, 2002, in Kuala Lumpur, Malaysia (Hayasaka et al., 2014).

2.3.3 Contributing factors towards peat swamp forest fires

An abundance of fuel and ignition sources in Southeast Asia creates ideal conditions for fires in the peat swamp areas (Page & Hooijer, 2016). The drought season and El-Niño phenomenon exacerbate this situation by reducing rainfall, increasing hotspots, particularly in January, April, and September (Autika et al., 2018). Peat becomes especially vulnerable during this period due to drying and decreased water content (Afdeni et al., 2016; Taufik Arief et al., 2019). Padang Island of Riau Province, Indonesia, became the most prone to fire and was heavily impacted by the 2014 and 2015 peat fires (Susanti et al., 2018). When the water deficit is intense in the drained peat swamps, an enormous drawdown on the water table and massive severity of burning will happen (Granath et al., 2016). Additionally, human activities significantly contribute to peat fires, often ignited intentionally to clear vegetation for agriculture (Murdiyarso et al., 2010). Studies suggest that natural occurrences do not typically trigger peat fires, highlighting human involvement as the primary cause (Handayani & Maswar, 2019). In Indonesia, 30% of the wildfires started

in the oil palm, near the communities, and 70% in the non-forest area (Cattau et al., 2016).

The dry peat increases fire risk, especially during the dry season (Frandsen, 1987; Huang et al., 2015; Lawson et al., 1997). Two types of ignitions are forced ignition by external heating and self-heating by internal exothermic reactions (Drysedale 2011; Taufik Arief et al., 2019). While lightning strikes and volcanic eruptions can directly ignite smouldering fires in peat swamps, surface fires, often initiated by human activities like land clearing and open burning, are the primary cause of most peat fires (e.g., surface fires). A spark from these activities can lead to surface fire and spread to underground fire. Similarly, drainage will lower the water table, which increases the fire risk in Southeast Asia and causes fire naturally during drought and exaggerated by the El-Niño event (Diemont et al., 2002). This disastrous fire changes the peat swamp ecosystem and will undoubtedly cause serious health problems through the emission.

During the dry season, peat fire can self-ignite in a high-temperature and low-moisture environment. Self-ignition is also called auto-ignition, and spontaneous ignition will begin under the precipitation of the self-heating process (Restuccia et al., 2017). As the thickness of the peat layer increases, the temperature of the peat soil rises continuously due to the heat generated from biochemical and oxidation reactions. The limited thermal conductivity of peat further restricts environmental cooling (Khoroshavin et al., 2012). One of the factors that can cause spontaneous combustion of peat is the continuous oxidation of dried leaves (Nugroho 2010). Smouldering peat fire involves

pyrolysis; oxidation and porosity (Huang & Rein, 2017). Continuous oxidation with addition to dry peat as a potential fuel will initiate the fire. In which this transition. This transition process, known as the incubation period of spontaneous combustion, can last for days or even weeks (Khoroshavin, Medvedev, Belyakov, & Bezzaponnaya, 2012; Restuccia et al., 2017). The internal heating mechanism, allow the biochemical exothermic reactions to occur as the temperature reaches 40-60°C, followed by oxidation at 60-70°C, which then reducing the moisture content to 35-45% (Nugroho 2010; Khoroshavin et al., 2012).

2.3.4 The insight of tropical peat fire in Asia

It is important to comprehensively understand various aspects of peat swamp forest fires, including their occurrences, classification, challenges, influencing factors, and impacts on these ecosystems. Previous research has linked peat swamp forest fires with dry peat conditions, drought, and human activities. Particularly in the tropical peat swamp forests of Asia, the El-Niño phenomenon, associated with the Southern Oscillation, has been a key driver of large-scale fires (Hirano et al., 2007; Miyamoto et al., 2021). A fire that involves the El-Niño phenomenon occurred in 1972/73, 1982/82, 1994, 1997/98, 2002, 2006, 2015, and recently 2019 (Hayasaka et al., 2020). This phenomenon tends to reappear every 3 to 10 years and is exacerbated by land use changes such as grazing, crop cultivation, and agriculture. These changes often lead to peat extraction, contributing to greenhouse gas emissions during warm periods and elevating the risk of fires (Page & Hooijer, 2016). Additionally, severe drainage of peat swamp areas renders them more vulnerable to fires, increasing the potential for

high fire severity (Granath et al., 2016).

While previous research has explored the impacts of fires on peat and the environment, it has also extended its focus to encompass the effects on communities and firefighters. Investigations into the impacts of fires on biodiversity, communities, and deforestation have been conducted. However, there is an opportunity for further research from various perspectives, such as fire frequencies, which can contribute to a more comprehensive understanding of the impacts of fires on peat ecosystems.

2.3.5 Peat fire effect on peat properties

Tropical peat has low bulk density, high porosity, low pH, high OM accumulation, and high water table which maintains by the interaction between biomass and hydrology adjacent to the peat surface (Ledger et al., 2023). Water, mineral, and organic carbon are the four main components of peat related and dependent on each other (Wetlands International, 2010). Peat is very acidic (< 6 pH value), with low nutrient cycling as they depend on the natural high-water levels. This situation also acts to prevent the peat from drying out. The physical and chemical properties of the different peat types are the results of both the original plant material and the degree of decomposition (Calvert et al., 1991). Drainage and land conversion significantly change selected peat properties (Anshari et al., 2010). For climatic reasons, rainfall plays a significant role in influencing the properties of tropical conditions (Syaufina et al., 2004).

The physical properties of different peat layers need to be improved, which is essential to assessing the critical groundwater depths and fire hazards (Taufik et al., 2019). Moreover, peat properties affect the combustion time as the inorganic content and porosity are related to the smouldering rate (Dianti et al., 2018). Besides that, fire affects peat up to 300 cm in-depth and discussed the physical and morphological characteristics of the peat (Musa and Ramli 2017; Irah et al., 2020; Musa et al., 2020). The smouldering fire causes changes in peat characteristics. As it creeps underground and is hard to detect, it eventually affects the structure of the peat.

2.3.5.1 Moisture content

Moisture content or water content, indicates the amount of water in soil (Andriesse, 1988). It is calculated as a percentage (%) oven-dried mass will be determined by oven drying peat sample at 105°C at least 16 hours or until no change in mass after further drying above 1-hour (ASTM) 1993; ASTM D 2974-00 2011). Peat naturally has an extremely high moisture content (> 100%) and is significantly affected by temperature, which can reduce moisture content and influence the peat's water absorption ability leading to peat drying (Kechavarzi et al., 2010; Razali et al., 2013; O'Kelly & Sivakumar 2014; Taufik Arief et al., 2019). The summary of the moisture content in the previous study is summarised in **Table 1**.

Peat swamps may be more than 90% water by volume when fully saturated. The peat swamp ecosystem could absorb up to 13 times its water weight (Taufik Arief et al., 2019). Also, rainfall and a higher percentage of organic matter are

related to high moisture contents (Sa'don et al., 2015; Syaufina et al., 2004). Water content measurement is fundamental to many soils' agricultural, forestry, hydrological, and civil engineering investigations (Smith and Mullins, 1991).

Table 1: Summary of peat moisture content (below the surface) in the tropical peat swamp forest

Region	Area	Moisture content	Citations
Sarawak, Malaysia	Batu Kawa (Hemic)	607-926%	(Sa'don et al., 2015; Shien et al., 2011)
	Kota Semarahan (Hemic)	246-817%	
	Kota Semarahan	853% to 1138%	
Southeast Palangkaraya, Indonesia	<i>Sub-surface peat burns</i>		(Wooster et al., 2018)
	0-10 cm	245±30 g g ⁻¹	
	10-30 cm	459±43 g g ⁻¹	
	<i>Sub-surface peat fire</i>		
	Surface (O horizon)	165±6 g g ⁻¹	
	0-10 cm	364±16 g g ⁻¹	
	10-30 cm	350±13 g g ⁻¹	
	<i>Flaming scrubby vegetation atop peat</i>		
	0-10 cm	206±19 g g ⁻¹	
	10-30 cm	259±9 g g ⁻¹	
	<i>Sub-surface peat</i>		
	0-10 cm	258±1 g g ⁻¹	
10-30 cm	223±2 g g ⁻¹		
Sabah, Malaysia	Binsuluk Forest Reserve		(Musa and Ramli 2017)
	50 cm;	209.88±0.18%;	
	100 cm;	249.29±0.12%;	
	150 cm;	332.46±0.18%;	
	200 cm	1013.51±1.39%	
West Aceh, Indonesia	Forest -Simpang	717%	(Handayani & Maswar, 2019)
	Forest -Cot Gajah Mati	978%	
	Oil palm plantation -Suak Raya	678%	
	Oil palm plantation - Suak Raya	734%	
	Oil palm plantation -Cot Gajah Mati	985%	
	Oil palm plantation -Suak Puntong	548%	

The peat maturity will influence the moisture content, wherein fibric has the highest water content, followed by hemic and sapric, 540-1187%, 268-480%, and 106-242%, respectively. The high moisture content can prevent the peat

fire to smoulder underground. It is crucial to maintain the moisture content because 100 to 125% moisture still increases the risk of fire on peat swamps (Handayani & Maswar, 2019). A study on the effect of rewetting on smouldering combustion of tropical peat in Indonesia indicates that the dry peat has irreversible drying properties that lead to loss of water mass and provide a gap in oxygen supply to accelerate combustion (Dianti et al., 2018).

As peat properties such as moisture will influence the physical properties of the peat, it is crucial to understand the peat properties relationship in lowering the rate of combustion during the suppression process. However, (Handayani & Maswar, 2019) argue that high moisture content reduces the rate of combustion, which is essential during suppression. Further study on the rewetting on peat method is needed to understand its importance during fire suppression.

2.3.5.2 Bulk density

The bulk density of peat is well studied previously. It is determined as the dry mass of organic soil, and it refers to the weight of a given volume of soil and is usually expressed on a dry weight basis in grams per cubic centimeter (Andriesse, 1988; Binkley & Fisher, 2012). Peat occurs in different stages of decomposition, and when it decomposes, the mineral and moisture contents at the sampling time will influence the density (Silc and Stanek 1977; Andriesse, 1988). The peat sample will be taken using soil core methods for bulk density. It measures the weight (mass) per unit volume (Hossain et al., 2015). The sample will undergo oven-dry at 105°C for 72 hours and expressed in g cm⁻³.

The peat's bulk density determines the water deficit in the water table and moisture content (Granath et al., 2016). (Dianti et al., 2018) mentioned that during combusting or evaporating, peat will have low water absorption. It will result in a high-water holding capacity which is crucial to regulating the water in the tropical region (Leng et al., 2019).

Table 2: Summary of bulk densities of peat in tropical peat swamp

Location	Bulk Density	Land Use	Peat Type	References
West Kalimantan, Indonesia	0.10-0.15 g/cm ³ ; 0.09-0.16 g/cm ³ ; 0.12-0.13 g/cm ³	Thinned forest; Rubber plantation; Disturbed forest	-	(Comas et al., 2015)
Central Kalimantan, Indonesia	0.01-0.197 g cm ⁻³	Forest	-	(Lampela et al., 2014)
Sarawak, Malaysia	0.4-0.8 g cm ⁻³	-	Sapric	(Padmanabhan et al., 2013)
Sungai Karang Forest Reserve, Tanjong Karang, Selangor, Malaysia.	0.16±0.03 g/cm ³ (Burned area); 0.17±0.03g/cm ³ (Unburned area)	Forest	-	(Syaufina et al., 2004)
Pelalawan, Indonesia	0.11 to 0.13 g/cm ³	-	Fibric	(Saharjo & Nurhayati, 2003)
Stapok Research Station, Sarawak, Malaysia	0.15 g/cm ³ (0-15cm); 0.13 g/cm ³ at (15-30 cm)	Cultivation	Sapric	(Tie & Kueh, 1979)
Kalimantan, Indonesia	<0.1 g/cm ³ ; >0.2 g/cm ³	-	Fibric; Sapric	(Driessen & Rochimah, 1976)
Sarawak, Malaysia	0.12 and 0.09 g/cm ³	-		Andriesse (1974)
West Indonesia				
Simpang,	0.05 g/cm ³		-	
Cot Gajah Mati	0.06 g/cm ³	Forests; Oil palm plantation		(Handayani & Maswar, 2019)
Suak Raya	0.08 g/cm ³			
Suak Raya	0.12 g/cm ³		-	
Cot Gajah Mati	0.26 g/cm ³			
Suak Puntong	g/cm ³			

Fire can increase the bulk density, and the porosity will be low (Maher et al., 2019; Sinclair et al., 2020). Hence, increase the peat compaction as the water holding capacity and the moisture content are reduced. The bulk density of Malaysia and Indonesia peat is summarised in **Table 2**. High bulk density also decreases the velocity of the smouldering, but the airflow for transition increases as the porosity and permeability decrease (Yang et al., 2019). When peat is heated, water evaporates, and ash content increases (Khoroshavin et al., 2012). Artificial drainage and cultivation reduced the moisture content and increased bulk density (McLay et al., 1992).

2.3.5.3 Porosity

Peat's physical properties depend on porosity (Huat et al., 2011). It is the fraction of the total soil volume occupied by pore spaces (Nimmo et al., 2013; University of Minnesota, 2016). Most peats have large pores that actively transfer water formed by the remains of the plant cells (Leng et al., 2019). The moisture will be high, and density will be low when the porosity level is high. The peat structure influenced the higher porosity during the wet and dry seasons. The swelling and shrinking movement of the peat surface occurs caused by the microbial habitats activity that produces CO₂ emission and XH₄ fluxes in the peat area (Rezanezhad et al., 2016).

Peats shrink during the dry season. Low water levels can reduce the water content, decreasing subsidence and shrinking the peat volume as the peat becomes soft and has a lower carrying capacity (Taufik Arief et al., 2019). The shrinkage causes the macropores to enlarge and create new macropores, while

the swelling closes and reduces the size of the macropores (Nimmo et al., 2013). For that reason, the peat is vulnerable to fire once it dries since high evaporation happens on the surface of the peat, where it is highly flammable (Melling and Tang 2019; Taufik Arief et al., 2019). The surface can evaporate in the open areas because of lower groundwater levels (Marryanna, 2020). Besides that, porosity level can increase the area contact with oxygen, gas exchange, chemical properties of peat, product composition during the pyrolysis process, presence of catalyst and formation of carbonous residues (Khoroshavin et al., 2012). The surface soil was porous and had low water-holding capacity; ascending soil water can bring up labile underground OM to the hollow surface, and much of the OM might have been left on the ground when the water table descended underground (Sundari et al., 2012).

2.3.5.4 Organic matter content

Loss of ignition is a quick method to determine the amount of soil organic matter in organic soil (Ben-Dor & Banin, 1989). In this method, the sample is burnt after oven-drying at a temperature of $\pm 800^{\circ}\text{C}$, and some use 480°C . It is expressed as a percentage (Baize, 1993), and a sample's weight loss after temperature reach 500°C to 575°C is proportional to the organic matter content (Gandois et al., 2013; Wright et al., 2008). It was studied that high organic matter will lower the bulk densities ranging from 0.2 to almost 1.9 g/cm^3 (Binkley & Fisher, 2012).

As peat decomposes of organic material, fire will reduce the organic layer of the peat. Saharjo and Nurhayati (2003) stated that the forest fire encouraged the regrown of the new vegetation because of the rich nutrient. However, a severe

burning will cause soil erosion that causes organic matter loss Sazawa et al., (2018) added in their research that the subsurface layer of the burned soils produced charred materials and significantly decreased the organic matter content of the surface. Organic content will influence the peat acidity to a pH value of 3 to 4 when the organic content decreases (Sa'don et al., 2015).

2.3.5.5 Peat acidity

Peat usually has a low pH and is considered strongly acidic, with pH values of 2.5-3.6 (Khoroshavin et al., 2012). Cooper et al., (2019) found that the pH value for peat in the forest is 3.4 in Selangor, Malaysia (Cooper et al., 2019). Peats in Southeast Asia have pH levels as low as 3.5 (Wetlands International, 2010). Page et al. (1999) supports the previous statement that the peat in Kalimantan Indonesia ranged from 3.0 to 3.6 pH value (Page et al., 1999). Similarly, the Indo-Malayan peat range from 2.9 to 4 pH (Yule, 2010). Wet peat is considered a semiconductor, and dry peat is an insulator. Because of those characteristics, the acidic compound leaching from the peat forms when it interacts with the humic acid and the peat will become mainly negatively charged (Khoroshavin et al., 2012). Peat will also influence peat maturity and peat decomposition (Handayani & Maswar, 2019).

Peat is acidic because of poor drainage and moor-humus and due to the presence of a wide range of acidic functional groups which can release H⁺ into the surrounding peat environment, particularly the carboxyl (COOH) and phenolic hydroxyl (OH) groups (Domineco, 1996; Simpson, 1983). Another study found that peat in the deforested area has a higher pH value than in peat

swamp forest due to the existence of ash and release of basic cations such as Ca, Mg, and K from the peat resulting from drainage, oxidation and burning (Radojevic & Tan, 2000; Sulistiyanto et al., 2007). Thus, the deforested area is less acidic because of drainage, oxidation, and burning. Besides, the mean pH value for burned and unburned peat of Sungai Karang Forest Reserve, Tanjung Karang, Selangor was found to be 3.4 and 3.5, respectively (Syaufina et al., 2004). Burning will increase the pH value and make it less acidic.

2.3.5.6 Carbon content

The carbon content in forest ecology results from climate, soil moisture, soil temperature, plant species, nutrient availability, soil texture, and disturbances regimes (Bhatti et al., 2002). On a global scale, peat swamp forests contribute to the storage of atmospheric carbon in which large quantities of carbon are stored in tropical peat swamps to slow global warming (Nik et al., 2006). It is estimated that 5,800 tonnes of carbon per hectare can be stored in a 10-meter-deep peat swamp compared to 300-500 tonnes per hectare for other tropical forests.

The peat swamp from the Southeast Asia region is responsible for 30% of global carbon dioxide (CO₂) emissions from the 11-14% of global peat carbon (Couwenberg et al., 2010; Page et al., 2011). Peat has a complex chemical and phase composition that involves carbon, oxygen, hydrogen, nitrogen, sulphur, and lignin, and it is highly dependent on the peat type (Khoroshavin et al., 2012). Indonesia has the most significant low carbon containing 65% (57.4 Gt), and Malaysia is 10% (9.1%) of the total global peat carbon (Page et al., 2011). **Table**

3 summaries carbon losses in the tropical region because of forest fire in the peat swamp area.

Determining organic carbon content in organic soils is essential, particularly for calculating the C/N ratio of the material, which is relevant for agricultural development purposes (Mohamed et al., 2002). The C/N ratio also indicates the degree of humification of organic materials. The organic carbon content of peat can vary from 12 to 60% (Andriesse, 1988).

Table 3: Summary of carbon losses in a peat swamp area in the tropical peat swamp

Area	Type	Carbon emission	Year	Citations
Central Kalimantan, Indonesia	-	-602 g C m ⁻² Yr ⁻¹	2002	(Hirano et al., 2007)
		-382 g C m ⁻² Yr ⁻¹	2003	
		-313 g C m ⁻² Yr ⁻¹	2004	
Tropical peat swamp	Drained burned land	94 mg C m ⁻² h ⁻¹	-	Ishikura et al., 2018
	Drained forest	241 mg C m ⁻² h ⁻¹)		
Tropical region	Drained peat swamp	13 t C ha ⁻¹ to 114 t C ha ⁻¹	-	(Konecny et al., 2016)

It was reported that there was a significant difference in the total carbon of peat swamp forest in Batang Igan Sibul, Sarawak before (48.8%) and after timber harvesting (48.30%) (Salimin et al., 2010). Previous research reported that the mean content of carbon in the San Pon Sak peat swamp of Panama ranged from 481 mg C g⁻¹ to 502 mg C g⁻¹ (Sjögersten et al., 2011). Besides, it was previously reported that the organic carbon content in central Kalimantan was a minimum of 54.2% and a maximum of 64.8%, respectively (Lampela et al., 2014). A past study also reported that the mean peat carbon in a tropical peat

swamp in Indonesia ranged from 41.60% to 59.33% (Comas et al., 2015). The research conducted in Katingan Peat Swamp Forests, Central Kalimantan, indicates that carbon stocks are higher in the northern part ($1894.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$) compared to the southern part ($1351.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$).

Drainage and burning can disturb the carbon accumulated over centuries or millennia is rapidly released into the atmosphere contributing to the greenhouse effect and climate change (Wetlands International, 2010). Carbon stored will be released into the atmosphere when a fire happens in this area. Organic carbon is lower in burned soils than in unburned peat soils (Sazawa et al., 2018). This way, the peat swamp areas become a vulnerable carbon pool (Page & Hooijer, 2016). The carbon released during the forest fire in 1997-98 equals 41% of worldwide fossil fuel used and affects public health (Cochrane, 2003). The brown smoke from peat fires carries harmful impurities such as sulphur oxide, carbon monoxide gas and volatile resins, which worsen when the fire affects the peat swamps with irrigation (Khoroshavin et al., 2012).

The carbon emission in a burnt forest area with a mean of groundwater -0.14 m will produce $372 \text{ g C m}^{-2} \text{ yr}^{-1}$ as cited by Wakhid et al., (2017) in Hirano et al., (2014) study. Moreover, CO_2 flux is said to be significantly promoted by lowering the moisture and pH where the drained forest has a higher CO_2 flux ($241 \text{ mg C m}^{-2} \text{ h}^{-1}$) compared to drained burned land ($94 \text{ mg C m}^{-2} \text{ h}^{-1}$) in the tropical peat swamp (Ishikura et al., 2018). Carbon dioxide balance in Kalimantan shows that the Net ecosystem CO_2 production (NEP) was highest in 2002, followed by 2003 and 2004 with a value of -602, -382 and $-313 \text{ g C m}^{-2} \text{ Yr}^{-1}$, respectively. Their study suggests that the higher negative NEP values in 2002 show it has low

photosynthetic photon flux density (PPFD), which is caused by the dense smoke from large fires during the drought season and becomes a source of carbon dioxide (Hirano et al., 2007). In recurrent drained peat swamp in a tropical region, the dry mass of peat fuel consumes (with carbon losses) 206 t ha⁻¹ (114 t C ha⁻¹), 115 t ha⁻¹ (64 t C ha⁻¹), 69 t ha⁻¹ (38 t C ha⁻¹) and 23 t ha⁻¹ (13 t C ha⁻¹) for initial, second, third and successive fires respectively (Konecny et al., 2016).

2.3.5.7 Peat thermal properties

In **Table 4**, the summary is compatible with (Nugroho 2010) providing information on the critical temperature for peat to self-ignite. In the study of peat self-ignition, it has been found that the critical temperature for peat to self-ignite is a temperature of 171°C with an energy value of 44 kJ/Mol. This experiment indicates that the peat is more likely to react with oxygen even at a low temperature when the water content is low. In addition, a study on smouldering fire found that smouldering can self-propagate through the packed bed with a peak temperature close to 327°C (Yang et al., 2019). The peak temperature of pyrolysis can be raised to 600°C, which will decrease the char production and at a temperature of 870°C, it might correspond to the decomposition of content (Khelkhal et al., 2021).

In a dry form, peat has relatively high thermal insulation properties as it becomes a good insulator (Khoroshavin et al., 2012). The thermal properties of peat can be caused by the seasonal swelling and shrinking of the peat surface (Waddington et al., 2010). Moisture and rate of spread are part of the thermal

properties that help us understand the flammability in managing, controlling, and suppressing peat fire in the recurrent burnt area in peat swamp forests (Nuruddin et al., 2016). The study on the ignition temperature can identify the actual peat fire condition as the information on weight loss (TG signal) and rate weight loss (DTG signal) as a function of temperature will be recorded (Hayasaka et al., 2016; Sutcu, 2007).

Table 4: Summary of temperature of peat from TGA analysis

Region	Type	Lowest Temperature	Peak temperature	References
South Sumatera, Indonesia	1m peat	101.63°C	213.68°C	(Taufik et al., 2019)
	2m peat	133.13°C	196.33°C	
	3m peat	147.59°C	212.28°C	
	4m peat	115.26°C	191.30°C	
Central Kalimantan, Indonesia	-	171°C	-	(Nugroho, 2010)
Lab experiment	-	327°C	-	(Yang et al., 2019)
China	peat	27°C	627°C	(Zhao et al., 2014)

The smouldering combustion of peat was controlled by thermal decomposition kinetics and oxygen diffusion, where the char oxidation and fuel gas oxidation reaction in porous pores (Yang et al., 2019; Zhao et al., 2014). Another study about peat energy was conducted using calorimetry (Khoroshavin et al., 2012). They discovered that the calorific value produced from the peat would increase at 0.42–1.67 kJ by 10% of the degree of decomposition (Khoroshavin et al., 2012). Increasing the degree of decomposition will increase the density and fibre content will decrease. Chemical content such as sulphur has more than 60%, which might influence the smouldering fire (Dianti et al., 2018).

2.4 Peat swamp forest fire management

This section will review and explore the current state of peatland fire management practices employed globally. This review will encompass the evaluation of fire suppression techniques, early warning systems, community engagement, and cutting-edge technologies such as remote sensing and GIS. Understanding the effectiveness of these strategies can provide valuable insights for refining existing approaches and developing novel solutions. The development of new techniques or tools for peat fire suppression is crucial to aid in mitigation efforts and reduce the fire risk to the peat swamp forest ecosystem.

The forest fire protection plan and its implementation in the peat swamp forest have been summarized into preventive measures and suppression strategies. This section discusses the preventive efforts undertaken by forest fire managers, which involve various stakeholders including firefighters, forest officers, and both government and non-government sectors. Furthermore, the section delves deeper into the suppression strategies that have been implemented, including the types of strategies and the individuals responsible for their execution.

2.4.1 Prevention measures

Implementing prevention measures to protect peat swamp forests and prevent the extinction of listed species is of crucial importance. Maintaining a higher water table is essential to reduce the risk of fire and prevent its rapid spread. It is important to emphasize the significance of addressing the fire issue within

peat swamp forests especially in Malaysia, highlighting the primary causes and impacts of forest fires on swamp ecosystems. The ensuing discussion will offer comprehensive insights into the post-fire implications and proposed management strategies, providing a comprehensive review of peat swamp forest fires in Asia. The chapter covers various aspects of peat swamp forests, including their characteristics, threats, and management strategies, encompassing approaches to rehabilitation and protection.

Prevention measures represent a fundamental component of forest fire management and contribute to overall fire protection programs. Fire prevention plays a vital role in safeguarding carbon stocks, biodiversity, and other ecosystem services provided by forests (Page & Hooijer, 2016). For instance, one method employed to mitigate the spread of fires in peat swamp forests is the construction of firebreak canals. While these canals are typically built for agriculture and logging purposes, they accidentally create possibilities for fires to ignite due to human activities such as hunting, fishing, and land clearing for rubber, pulpwood, and oil palm plantations (Whitehouse & Mulyana 2004; Sinclair et al., 2020).

These activities lead to the drainage of the peat swamp area, lowering the water table and drying the peat's surface, thus oxidising it and making it susceptible to fire (Chin & Parish, 2013; Khakim et al., 2020). Additionally, these actions eventually increase the bulk density of the peat and reduce its porosity (Lennartz & Liu, 2019; Melling & Tang, 2019). However, Susanti et al., (2018) propose a different perspective, emphasising that drainage does not necessarily cause peat swamp dryness and fire-prone conditions during the dry

season, although the area may become flooded during the wet season (Susanti et al., 2018). This inconsistency happens because the purpose of the canal, is for fire prevention that align with the specific objectives of its construction. For instance, canals built in oil palm plantations need to maintain the water level between 40 and 50 cm from the surface to ensure the palms can withstand the water-table level (Othman et al., 2011). However, when the canal's purpose is solely for serving as a firebreak, it varies from agricultural objectives and focuses on preventing fire spread without intentionally lowering the peatland's water table. In Malaysia's peat swamp forest, such canals serve as one of the most effective preventive measures, acting as firebreaks to protect the land from fire spread, especially within forest reserve areas.

Evidence from previous studies indicates that the water table plays a pivotal role in regulating surface fluctuations in peat. Subsidence occurs during dry periods following water table drawdown, while swelling ensues after increases in the water table due to heavy rainfall (Imran et al., 2022). The biannual rainfall cycles, coupled with dry seasons, alter hydraulic conductivity, causing peat to shrink and swell in response to water inputs. This pattern is observed with the highest water table levels occurring near or above the surface in October to November 2019 and the lowest levels in June to September 2019 in Selangor, Malaysia (Ledger et al., 2023). Additionally, a study in Johor, Malaysia, highlighted a correlation between reduced rainfall and decreased groundwater levels, with the lowest levels recorded in October and the highest in December 2015. In Selangor, the scarcity of significant water sources during the dry season increases the area's susceptibility to fire incidents. Maintaining the peat in a moist state serves as a critical preventive measure against forest fires

(Ghazali et al., 2020).

A precautionary approach using a canal has been implemented in the forest reserves area in Malaysia (**Figure 6**), which will be referred to as a fire break canal. The fire break canal will control the fire spread from nearby land such as agricultural land and settlement areas, into the forest reserve. Another advantage of the fire-break canal construction is helping the firefighters during fire suppression by pumping the water from the fire-break canal using a water pump and assisting in fire suppression. Apart from the fire break canal as a water source, the forest manager also takes the initiative of a tube well to store the water as part of precautionary to take the example of the inferno incident in 2016 which is depressing and difficult to control. The water was stored in the tube well to help peat fire suppression near the Kg. The Lumat in Beaufort district in Sabah, Malaysia which is part the peat swamp area, as shown in **Figure 6**.

The tube well was installed by the Ministry of Natural Resources and Environment (NRE) of Malaysia as one of the programs to manage the recurrent fire in the peat area. This method will help table regulation with a rewetting method to maintain and restore the peat moisture (Dianti et al., 2018). It is important to making sure the peat is in a liquid state to prevent peat fire is the best method (Marryanna, 2020). Thus, managing the water is one of the best keys to maintain the water table depth from dropping at no less than 50 cm below the surface (Chin & Parish, 2013).



Figure 6: (a) Canal implemented in Klias Forest Reserve as a fire break to prevent fire spread from state land and plantation nearby; (b) District Forest Officer of Beaufort, standing beside the tube well in Kg. Lumat, Beaufort, and Sabah to help in fire suppression.
(Source: Dayang Nur Sakinah Musa)

Monitoring constitutes a crucial part of preventive measures applied to detect forest fires early within peat swamp forest areas. For instance, the Sabah Forestry Department (SFD) has undertaken several steps to achieve early fire detection by employing the Fire Danger Rating System (FDRS). These measures encompass: (1) Collecting daily weather data, considering variables such as rainfall, temperature, humidity, and wind speed (this data collection is continuously carried out across all 27 districts of Sabah), (2) Conducting ground and air surveillance, and (3) Monitoring hotspots. Additionally, the implementation of fire danger mapping in fire-prone areas allows for proactive firefighting planning, enabling remote monitoring of fire occurrences via the internet (Hamzah et al., 2021). In Malaysia, the Sabah Forestry Department of the Sabah region has developed a novel mobile FDRS that can be updated in real time, directly to the headquarters, facilitating immediate action when necessary.

2.4.2 Forest fire suppression strategies

Implementing a strategy to suppress peat fires is essential for minimizing their impact and altering the fire pattern during such incidents. Previous studies have emphasised the undeniable difficulty in controlling smouldering fires that occur underground. These fires present significant challenges in terms of detection, monitoring, and suppression. Determining the precise location of a smouldering fire is often not feasible, although firefighters attempt to distinguish its presence through smoke observation, albeit successfully only in certain situations. Moreover, it is not uncommon for a fire to reappear on the peat surface after a few days.

One of the methods employed to suppress peat fires is the flooding technique. Flooding is used in peat swamp forests to mitigate the potential for underground fire. This approach requires a substantial volume of water to cover the burning area. In Malaysia, the flooding technique has been employed in targeted areas, as illustrated in **Figure 7**. Water is pumped, and hoses are directed toward areas where smoke is visible, ensuring that the peat becomes sufficiently wet, thus preventing the reoccurrence of fire. It was estimated that the smouldering requires about 1 to 2 liter of water per kilogram of the burning fuel to suppress it (Rein, 2016). From previous research, for 1m³ size of peat requires about the same volume of 1m³ of water for the suppression, then it will absorb 5% to 8% of water and dries immediately during the fire extinguishing process (Khoroshavin et al., 2012). That is why even heavy rain was pouring, the smouldering peat fire is still hard to control. A laboratory experiment was conducted to determine the rain effect on peat fire suppression (Lin et al., 2020). According to the study, a light rain (4mm/h) cannot suppress the smouldering

peat fire, but a violent rain of 50 mm/h can quickly cool down the burning soil. Their research found that the shallow-layer peat fire was suppressed by rain for seven (7) minutes, while a small flaming wood could be extinguished by rain in 20 seconds. It is an indication that the smouldering took longer to suppress than the surface fire. However, for a larger-scale peat swamp forest, it might take longer and corresponds to the current situation of peat fires that can take months to suppress fully. From the experiment, we also understood that pure water does not wet the peat but only cools it. Thus, a large amount of water is needed to make the peat combustion fades, reducing the exothermic reaction leading to thermal destruction (Khoroshavin et al., 2012).

Other than flooding method, water-based suppression such as water bombing also used (**Figure 7**). It was understood that the suppression of peat fire is best using a water-based suppression technique. The water will reduce the heat of the peat as fuel and reduce the temperature to emit combustible gases. Lower moisture of peat in about 200–300% will contribute to the potential of higher fire severity (Grau-Andrés et al., 2018; Leonard et al., 1998). Rein (2016) refers to experiments conducted by Hadden & Rein (2011) and Tuomisaari et al. (1998) on three water suppression methods and different extinguishing agents on coal and smouldering wood chips. In summary, their findings show that the shower suppression method is the most efficient method for water suppression, and CO₂ injected from the bottom was the most effective for water with additives. Further study on the real-time appliance on active suppression time, water application rates, and location enhance wildfire behaviour's quantitative measurement (Penney et al., 2019).



Figure 7: (a) Water-pump use during fire suppression; (b) An Initial Attack Crew (IAC) suppress the smouldering fire; (c) Water bombing was applied to fight peat fire in the Beaufort peat swamp in 2016.
(Source: Sabah Forestry Department)

Other than water-based method, a waterless method such as fire retardants and hand tools are widely used. Fire retardants is considered to fight the forest fire (Penney et al., 2019), for instance, in Central Kalimantan Province, Indonesia, the foam was used as a barrier between smouldering peat fire and the air to stop the oxygen supply (Ratnasari et al., 2018). This barrier is a fire-break method to separate the burning area and unburned area as illustrated in **Figure 8**. To bolster the suppression methods, fire break canals have been introduced as barriers and water sources for extinguishing purposes in both Indonesia and Malaysia. Meanwhile, in Russia, water and barriers are utilized as methods to prevent fire spread (Drapalyuk et al., 2019). These measures are integral to management efforts aimed at preventing the fire from advancing into forests or other types of land. In addition to the management aspect of suppression strategies, fire suppression training is conducted. Such training is essential to ensure that firefighting crews possess the requisite knowledge of fire suppression methods and the skills necessary to manage forest fires effectively.

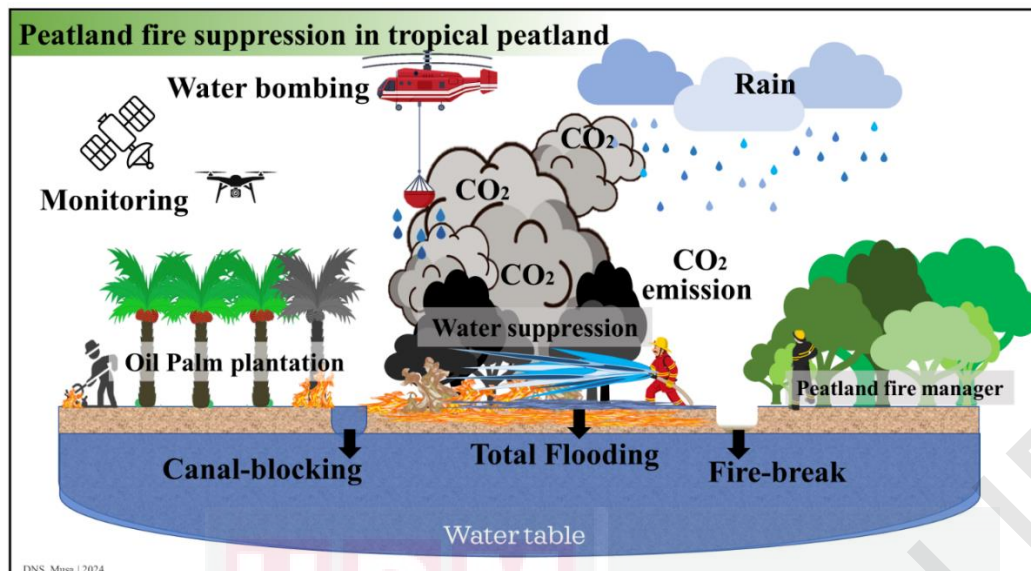


Figure 8: Peatland fire suppression strategies in the Malaysia includes total flooding, canal-blocking, fire break, and water bombing.

2.4.3 Impact on the groundwater level

The peat swamp forest naturally maintains a waterlogged condition, often serving as an indicator of drier peat and increased potential for ignition. A waterlogged state occurs when the groundwater level reaches the surface (Taufik et al., 2019). Understanding the influence of groundwater levels on peat fires and the suppression process is crucial. Maintaining the groundwater table approximately 20 cm to 30 cm below the surface, or even higher, is essential to prevent peat from drying out. During the rainy season, the water table may extend above the surface (Ohkubo et al., 2021). However, hydrological drought and worsening by the El-Niño phenomenon can lead to the groundwater level sinking as low as 150 cm below the surface, causing the upper layers near the surface to dry up (Taufik et al., 2019). In such circumstances, the peat becomes more susceptible to ignition, which can hinder the suppression process.

Changes in solar radiation, atmospheric humidity, and temperature can also

impact the peat water balance (Dadap et al., 2022). To address this, pond construction is carried out during fire incidents when the groundwater level is low and even canals have dried out, as illustrated in **Figure 9**. These ponds aid in the firefighting process, as water sources pose a significant challenge when combating peat fires, primarily due to accessibility issues. As depicted in **Figure 9(a)**, accessibility problems arise, where only a four-wheel drive can transport fire crews and equipment to affected areas in Malaysia.

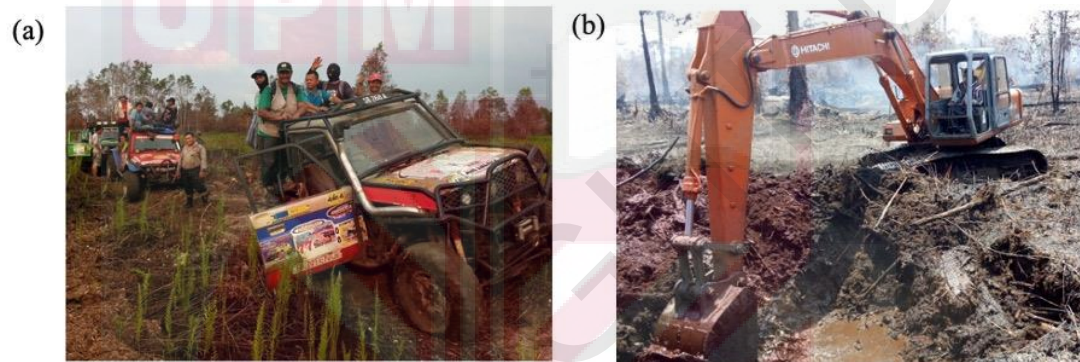


Figure 9: (a) 4x4WD transport the Fire Crews and equipment to the affected areas; (b) A pond was constructed to store water for firefighting purposes in the Binsuluk Forest Reserve because of the great fire in 2015-2016

(Source: Sabah Forestry Department).

Land changes to agricultural land was linked to the drier peat and lower ground water level in the peat swamp forest. The forest conversion to oil palm plantation for instance has no effect on the ground water level due to fire based on Handayani & Maswar (2019) research. However, their findings still show that the forest has statistically higher moisture compared to the oil palm area, with 717–978% and 505–985% moisture, respectively (Handayani & Maswar, 2019), yet indicates land change has lower moisture content.

The ground water table lowered, and peat surface layer become more

vulnerable to fire in the agricultural land (Wiggins et al., 2018). This situation is similar to Malaysia peat swamp forest, wherein the low water table makes the peat flammable due to fire spread from the alienated land and state land (Musa & Huang, 2022). Hence, a ground water level monitoring was conducted to monitor the fluctuations in the peat swamp forest (Marryanna, 2020). For instance, the Malaysia ground water level fluctuates temporally and spatially in different areas of the peat swamp forest reserve. A lack of drainage network will influence the fluctuation which will increase the fire incident during the dry season (Wiggins et al., 2018). In Malaysia, the average ground water level from September 2018 to September 2019 has a minimum level of -136 cm, and a maximum of 23 cm were recorded (Maryani et al., 2020).

2.5 Policy and governance framework

A review of policy and governance frameworks concerning peatland fire management at the national, regional, and international levels will elaborate further in this section. Effective governance plays a pivotal role in coordinating efforts among diverse stakeholders and ensuring the implementation of resilient fire prevention and control measures. The comprehensive management of forest fires in peat swamp forests holds the potential to mitigate impacts on the ecosystem, particularly the peat soil.

2.5.1 Peat fire impacts in Asia

Forest fires had positive and negative effects on peat swamp forest conditions. In terms of the positive effects, the fire increased nutrient availability and helped grow. For the adverse effects, fire will decrease hydraulic conductivity, and

increase surface runoff and land erosion. Generally, it will reduce the canopy cover and species richness, decrease tree and sapling density, and destroy the vegetation covers underground and seeds bank (Page et al., 2011; Yeager et al., 2003). The fire intensity and frequency also play a significant role. The larger burn intensity and frequency will lower the big trees and dominate low-growing plants (Posa et al., 2011). Consequently, it will suppress certain endemic species, promote other species, and cause vegetation changes as the succession patterns are altered, reducing the soil microorganism, and changing soil bacterial composition (Syaufina & Ainuddin, 2011). Fire impacts on peat are more critical than other types of soil that will repeatedly become enlarged – especially during the drought season (El-Niño cycles in particular) (Lailan et al., 2004; Hirano et al., 2012). Therefore, dried peat increases are more likely to fire like in the 2015 El-Niño-related dry season (Khakim et al., 2020).

In addition, the peat purpose of storing carbon can be difficult at this moment. The amount of carbon stored in the world's peat swamps exceeds the carbon stored in the world's vegetation, phytomass and the atmosphere (Scharlemann et al., 2014; Lindsay & Andersen, 2018). Therefore, a fire in this area becomes a massive source of carbon released into the atmosphere. The function of the peat swamp as carbon storage changes immediately at that moment. For example, deforestation has huge after-effects for the local community, leading to the extinction of peat swamp forest endemic species, global carbon emissions and tonnes of other greenhouse gasses, particulates and aerosols in the Malaysia and Indonesia region (Miettinen et al., 2012; Putra et al., 2019).

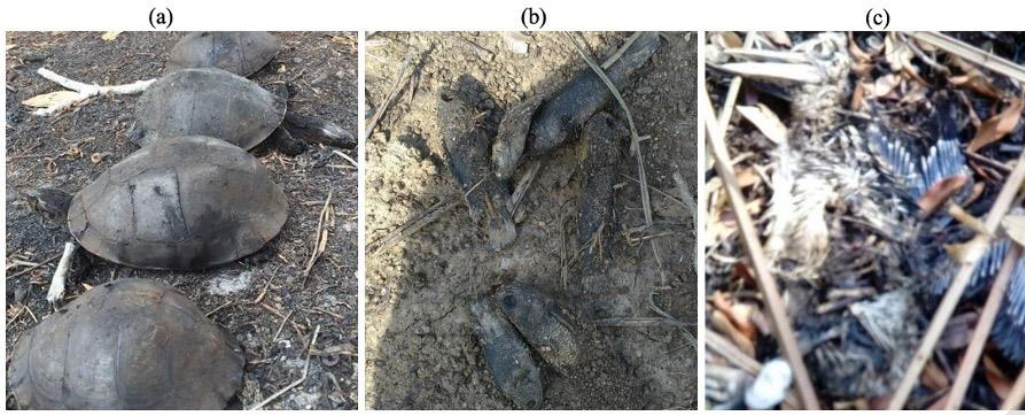


Figure 10: Animals were burned beside the trees and peat in Binsuluk Forest Reserve, Sabah. (a) tortoise; (b) fish; (c) bird.

(Source: Sabah Forestry Department)

It was agreed that the peat swamp forest wildfires impacted the invertebrate biodiversity (Neoh et al., 2015). In Malaysia, the burned (a) tortoises, (b) fishes, and (c) birds because of the great fire are shown in **Figure 10**. It was described that birds could not escape from the area, and water was dried until the fishes in the nearby canal were burnt. A tortoise is well known to dig the soil to save itself from fire. However, a smouldering fire made it impossible to escape.

2.5.2 Challenges in peat swamp forest fire

Forest fire in the peat swamp is challenging and more critical than other soil types (Syaufina et al., 2004). Based on previous research, drought is the main environmental condition that contribute to the forest fire in the peat swamp forest. The cases will worsen and be extra challenging for the firefighters with the upcoming El-Niño phenomenon. In most cases, fires repeatedly enlarge out of control during the prolonged drought season, particularly during El-Niño cycles, because of the increased dried peats (Khakim et al., 2020; Hirano et al., 2012). At this point, it will be tough to look for a water source when the condition is very dry. Peat fires are difficult to extinguish without restoring the naturally

high-water levels (Nik et al., 2006). The difficulty is due to forest fire continuing in the deep, challenging layers of peat.

Other challenges in the peat swamp include logging, drainage, land conversion to agriculture with possible ignition from lightning, self-heating, arson, or accidental ignition from human activity (Yule, 2010; Posa et al., 2011; Rein, 2016). Due to forest clearance, these activities pressured the land and resulted in declining Malaysia's peat swamp forests over the past 50 years (Wösten et al., 1997; Lailan et al., 2004; Yule, 2010). Moreover, the conversion involves drainage, open burning, and fertilisation, dramatically influencing peat properties (Yule, 2010). It will be challenging once the peat is dried and become highly flammable. Fire occurrences in peat swamp areas due to open burning have also happened in the recent year in 2020 (**Figure 11**). Indonesia also faces a similar condition wherein the degraded peat swamps are due to the drainage canal (Chin & Parish, 2013).

Draining peat swamps can increase fire frequency as dried peat is easily ignited, and a large fuel load burns down several metres below the surface (Knicker, 2007; Rein et al., 2008). This abundant biomass and dry peat spread the fires faster by contributing as flammable material (Wösten et al., 2006). Once the fire ignited in the deep peat, it can persist for months and is difficult to extinguish despite extensive rainfalls, the weather changes or fire-fighter attempts, and this makes fires the most significant threat to peat swamp forests (Posa et al., 2011; Zacccone et al., 2014); Klias Forest Reserve Conservation Plan, 2007).

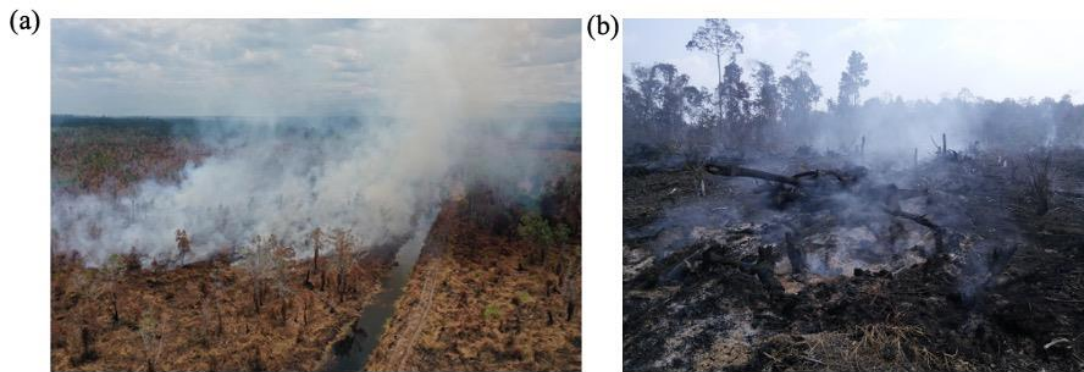


Figure 11: (a) Peat fire in Beaufort, Sabah, because of open burning captured using a drone in March 2020 (b) Smoke appears because of the smouldering fire at Sg. Tenggi, 2013.

(Source: (a) Sabah Forestry Department; (b) Dayang Nur Sakinah Musa)

Additionally, selective logging causes changes in forest structure and composition, such as a lack of regeneration of valuable timber such as the Ramin tree (*Gonystylus bancanus*), which is listed as vulnerable on the IUCN Red List (Posa et al., 2011; SFD, 2014; Bruenig & Droste, 1995). Further discussion on the example of tropical peat swamp forest in Asia is the North Selangor Peat Swamp Forest (NSPSF), Malaysia that changes from logging area to gazetted as forest reserve. The number of ignitions initially increased near the settlement, which counters the claim that the fire started from an oil palm plantation (Cattau et al., 2016) because multiple human disturbances interrupt the balance among vegetation, peat and peat and hydrology, and the peat swamps (Posa et al., 2011).

2.5.3 Peat swamp forest management

Forest management constitutes a crucial operational system for governing and monitoring forest areas, encompassing forest fire management to achieve sustainability. In peat swamp forests, effective forest fire management plays a pivotal role in preventing, controlling, and suppressing fires. Dealing with fires

during prolonged drought seasons poses a significant challenge for fire managers. The year 2016, marked by the El-Niño phenomenon, mainly tested the managers' abilities in fire control. Hence, prevention assumes paramount importance in reducing fire intensity and frequency. Measures such as law enforcement, information campaigns, and patrolling are vital to forest fire prevention in peat swamp forests. Due to limited enforcement capabilities, implementing practices like zero-burning or controlled burning becomes challenging (Chin & Parish, 2013).

Fire safety and monitoring practices in the peat swamp forest management in Asia are particularly in Malaysia identify to have effective strategies within the strength of its own policies. With frequent forest fire occurrences especially in the peatland, Malaysia closely monitors the approaches adopted by neighbouring countries in Asia to mitigate fire risks and enhance monitoring capabilities. For example, an Internet of Things (IoT) system that was developed to measure and identify the fire risk factors in peat swamp forest and to predict the peatland forests' Fire Weather Index (FWI) (Li et al., 2023). Developing a benchmark dataset for forest fire monitoring in Asia is crucial, as it requires addressing challenges like managing remote sensing data, identifying key factors, incorporating field validation, and spanning varied prediction tasks, advocating for standardized benchmarks, and leveraging big data platforms for effective monitoring (Chew et al., 2022).

2.6 Existing research and trends in peat swamp forest

Existing research gaps and emerging trends in peat swamp forest fire

management were reviewed on fire dynamics and their effects on peat properties. It holds importance in stimulating future research efforts and policy development to tackle the evolving challenges presented by peatland fires. It is significant to identify research gaps, such as the effects of fire at different frequencies and compare them to pre-fire conditions in near to mitigation strategies like firebreak canals.

2.6.1 Fire dynamics

The smouldering peat fire slowly consumes the peat and burns for a long time deeper in the peat, which burnt repeatedly to react with the moisture content (Page & Hooijer, 2016; Rein, 2016). The refined fuel during the dry season for both deeper and upper layers of peat will emit heat during the combustion causing the slow burning underground (Khoroshavin et al., 2012; Sandhyavitri et al., 2016). An experiment was conducted previously that supports the slow burning theory, findings indicate that smouldering can last from 6 to 48 hours for a peat sample of 30 cm depth or 20 cm x 20 cm area (Benscoter et al., 2011; Huang et al., 2016; Huang & Rein, 2017). The burning duration significantly increases with the soil moisture content and the burning depth. This type of fire is flameless, burns constantly, and spreads in all directions (Dianti et al., 2018). As it can be burned almost entirely, the mixture has become ash and charred particles from plant materials (Khoroshavin et al., 2012). It will then release the old carbon stored deep in the peat swamps (Rein, 2013; Rein & Huang, 2021). **Figure 11** is an excellent example of a smouldering peat fire underground that emits smoke.

The smouldering peat fire is initially endothermic and eventually becomes exothermic when the temperature reaches a pyrolysis state (a part of the combustion zone). The combustion zone is divided into three stages: i) evaporation of moisture from fuel, ii) distillation or pyrolysis of volatile matter from fuel and subsequent combustion, and iii) combustion of fixed carbon or char (Frandsen, 1997; Patel, 2012; Rein, 2013). At the final stage of the smouldering process, glowing will show, and only a little or no smoke will be present (Leonard et al., 1998). The propagation rate of smouldering peat fire can vary from ~1 cm per hour or ~1 m per week (Rollins et al., 1993; Neary et al., 1999; Huang & Rein, 2017; Palamba et al., 2017). The different rate of the smouldering fire spread is due to different peat decomposition levels and fire intensity as the amount of heat is transferred downward during combustion (Leonard et al., 1998; Saharjo, 2006). An oxidation reaction will occur because of oxygen availability in the air until the oxidation chemical reaction increases and increases temperature (Nugroho 2010; Rein, 2013; Huang & Rein, 2014). Based on a review of emissions from smouldering peat fires by Hu et al., (2018), smouldering peat fires produce massive atmospheric pollutants. There were two approaches for total emission calculation. First, using satellites combined with modelling techniques enabled to estimate of the global peat fire emission on an annual basis annually. Second, an approach involves the ground study of the amount emission estimation of gas per unit of burned fuel. Based on the literature, the peat origin was divided into boreal, temperate, and tropical peat.

The tropical peat has an average of 56% carbon content, and the boreal and temperate has approximately 44.2% carbon content based on a lab-scale experiment which might contribute to different emissions. The boreal and

temperate peat emit more PM_{2.5} (EF = 19.17 g kg⁻¹) than tropical peat (EF = 17.3 g kg⁻¹). The emission factors (EF), such as organic carbon (OC), constitute 71% of the aerosols from tropical fire and naturally offset the warming effects of GHGs and BC. Fire also emits black carbon (BC) and brown carbon (BrC) in the trace amount of boreal and temperate peat fire. More studies on the tropical peat fire will fill the gap of black carbon in tropical peat. As the large carbon pool can affect the estimation results of total emission, it is important to improve the detection technologies, especially the remote sensation detection when a smouldering fire underground occurs.

2.6.2 Fire extinguishment

To extinguish the smouldering peat fire, three fundamental approaches can be used based on the fire triangle, (1) smothering by removing the oxygen, (2) starving or burnout by removing the peat soil, and (3) quenching or cooling by removing the heat as illustrated in **Figure 12**. Smothering is impractical to suppress large-scale peat fires because it is impossible to remove the oxygen, and the smouldering fire can sustain in shallow oxygen concentration (Huang & Rein, 2016).

In real fire scenarios, if the peat is sufficiently wet with dry-mass moisture content higher than 100~200% (Frandsen, 1997), the peatland will be fireproof. However, the moisture profile will significantly reduce in the dry season. Nevertheless, in the case of a fire, water is still the most widely used cooling agent in fighting peat fires (Blake et al., 2012; Lin & Huang, 2020; Ramadhan et al., 2017). Alternatively, building a firebreak or barrier could be more effective

in controlling and mitigating the hidden peat fires (Migalenko et al., 2018). The principle is to remove the fuel, similar to the prescribed burning (Lin et al., 2021). Removing fuel, quench the oxygen supply and cool the reaction zone are the way of extinguishing smouldering fire (Mikalsen et al., 2019).

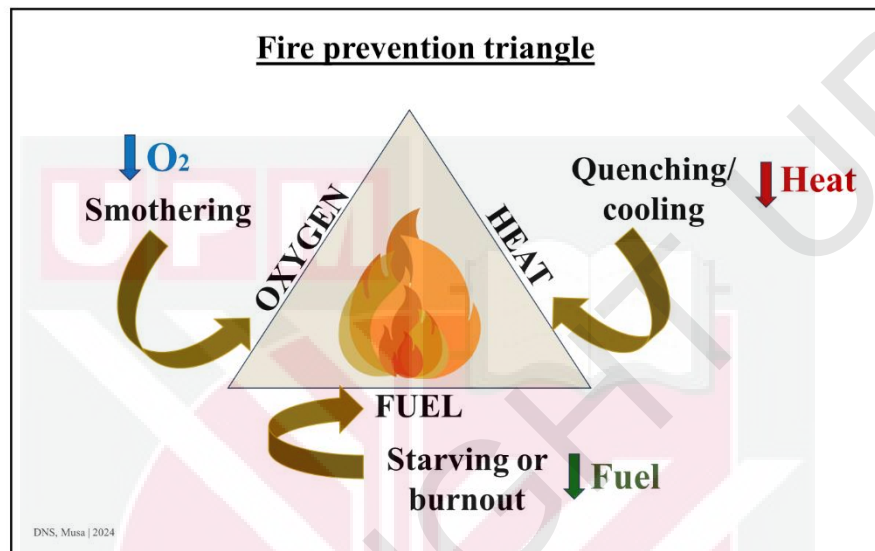


Figure 12: Fire prevention triangle

Based on the concept presented in Figure 12, cooling method is one of the prevention strategies to quench the heat. Peat burning when filled wot water can increase the efficiency of extinguishing and reduce water consumption by when wetting agent is present (Chernik et al., 2021). Therefore, the future implementation of quenching smouldering fire such as water flow inserted into the ground to absorb the heat as potential prevention, control, and extinguishment of smouldering fire (Mikalsen et al., 2019). Apart from metal pipe to transfer water, utilising heat pipe in the future can act similar patter as previous research by Mikalsen et al., (2019) by applying copper heat pipe. Heat pipe known to transfer heat and has high permeability but lower capillarity, which are fully distributed in both evaporation and condensation sections

(Huang et al., 2021).

2.7 Conclusion of chapter

In conclusion, this chapter review addresses the issues of peat swamp forest fire management. Tropical peat swamp forests are vital for both environmental and economic necessities in their surroundings. Local communities' benefit from the roles these forests play in supporting food and generating income. Simultaneously, the flora and fauna depend on these habitats for their needs. By developing sustainable strategies to protect these ecosystems is important. However, peat swamp forests fires pose significant threats to biodiversity, hydrological processes, as well as environmental and socio-economic impacts.

The status of peat swamp forest, including degradation and challenges have been recorded in the past. Peat swamp degradation was deliberated upon to understand better its implications for the state's economy, food security, and the needs of local villagers. Additionally, discussions encompass concerns about logging activities, land clearing, and fires, all of which alter peat properties. Therefore, human activities and natural events contribute to the complexity of fire management. Forest fire results in environmental pollution and increased carbon release, contributing to climate change.

Various fire management practices are in place globally, including technological advancements such as the Fire Danger Rating System and watch towers. Other efforts by the managerial are the implementation of the fire break canal, monitoring through FDRS, and watch towers are current mitigation efforts to

mitigate fire spread into peat swamp forests. Policy and governance frameworks are crucial for coordinating fire management efforts. Effective governance mechanisms are essential to harmonize regional and international cooperation, ensuring the implementation of consistent fire prevention and control measures. Further studies could explore the perspectives of fire managers on policies and governance from the ground level. Despite efforts, fires in peat swamp forests persist, although incidents reduced during the pandemic.



CHAPTER 3

INSIGHT OF MALAYSIA'S FIRE MANAGERS AND FIREFIGHTERS IN MANAGING PEAT SWAMP FOREST FIRE

3.1 Summary of Chapter

This chapter thoroughly examines Malaysia's current fire management methods, including factors, mitigation strategies, and suppression techniques. It offers data that complements laboratory research on peat swamp forest fire management. Additionally, it elaborates on the roles of forest fire managers and firefighters, bridging the gap between ground practices and laboratory experiments discussed in **Chapters 4 and 5**, which pertain to peat properties in varying post-fire history conditions. Given Malaysia's human-induced fire challenges, it underscores the need to enhance prevention, early detection, and suppression efforts. Monitoring and restoring peat swamp forests play a crucial role in preventing and controlling peat fires, and Chapter 6 presents innovative peat fire suppression methods by increasing moisture content to emphasise public safety through prevention and prompt response to peat fire.

3.2 Introduction

Malaysia, located in Southeast Asia, features diverse and valuable forests of significant economic, environmental, and cultural importance. The tropical rainforests experience substantial annual rainfall and are classified into various types, including peat swamp forests. These peat swamp forests hold great value for supporting local communities through agricultural, fishing, and non-timber forest product activities (Freeman et al., 2001). However, Malaysian

forests, particularly the peat swamp variety, confront numerous challenges including deforestation, illegal logging, encroachment, and fire. Fires, triggered by natural phenomena like lightning, strong El-Niño influences, and human activities, significantly affect the forest landscape, cultural and historical values, flora, water quality, and firefighter safety (Hamilton & Salerno, 2020; Grebner et al., 2022). Consequently, fire emerges as one of the major threats to local communities, wildlife, forests, and the environment (Miettinen et al., 2017; Munawi, 2014; Pillai et al., 2021). These fires lead to ecosystem degradation, haze pollution, carbon emissions affecting humans and animals, and economic losses (Miettinen et al., 2017; Munawi, 2014). For instance, the haze originating from Indonesian fires in 2015, 2018, and 2019 significantly disrupted business and tourism activities in Malaysia and Singapore, sparking debates about peat swamp forest fire management policies within ASEAN countries (Trihadmojo et al., 2020; Phelps et al., 2021).

Forest fire management includes strategies and practices aimed at preventing, mitigating, and managing forest fires, with a particular focus on peat swamp forests in Malaysia. Considering the implications of peat swamp forest fire management policies, forest fire management plays a pivotal role in influencing decisions across social, economic, and institutional areas (Hamilton & Salerno, 2020). Fires within peat swamp forests can have far-reaching impacts on the entire forest ecosystem (Chen et al., 2014; Wunder et al., 2021). Despite some discussion on Malaysian peat fire management practices among forest managers and firefighters in previous reports and articles, further exploration from their perspectives is warranted. As academic 'experts' might not possess an equally practical grasp of solutions (Phelps et al., 2021), investigating into

the viewpoints of forest fire managers and firefighters can broaden our understanding of peat fire suppression, encompassing prevention and post-fire management during the implementation phase. For instance, in a short-term analysis, hydrological control by managers on smouldering fires in peatland areas was connected to soil moisture, contributing to long-term peat wetness enhancement (Schulte et al., 2019).

3.2.1 Peat swamp forest fire

Peat swamp forest is characterised by waterlogged, acidic, and high organic content soil, also known as peat. The peat swamp forest in several regions, including Southeast Asia, is particularly prevalent in Malaysia and Indonesia. Several factors can lead to peat swamp forest fires. These include human activities such as illegal logging, draining, and slash-and-burn method practised by local villagers in Malaysia and Indonesia, contributing to fire ignition. The slash-and-burn method is one of the most popular land-clearing approaches among local villagers. It will burn the undesirable grass or trees and increase the nutrient necessary for their plantation. In Bhutan, fire cases have declined due to the ban on slash-and-burn agriculture, with improved fire prevention strategies such as forest fire training and better firefighting equipment helping reduce fire damage (Wang et al., 2021).

The forest is important to the local people, who still depend on non-timber-forest products (NTFP) for daily needs. The prone fire area, especially the forest area, is considered a complex-ecological system as it involves the stakeholder groups and the management (Hamilton & Salerno, 2020). Efforts to prevent and

manage the peat fire by implementing fire prevention measures and restoring the peatlands should be enhanced to reduce the risks and impact of peat fires. Therefore, avoiding ignition and fire spread potentials is required (Dadap et al., 2021; Wunder et al., 2021). The changes in peat fire patterns can be seen during the 2020/21 Covid-19 pandemic related to fire reduction. Researchers need to understand the role of human activities related to peat fire cases (Musa & Huang, 2022). Addressing the peat swamp forest fires requires a multi-faceted approach involving government agencies, local communities, NGOs, and international cooperation. Through concerted efforts and effective management, Malaysia strives to preserve sustainable forests for future generations.

3.2.2 Frequency of fire occurrences

The frequency of forest fire occurrences in peat swamp forests varies depending on the climate and human activities in the area. In the tropical regions, human-induced fire, seasonal changes, and climate change were observed to contribute to forest fires' frequency. The human-induced increases in drought severity in Indonesia lead to peat dryness and fire susceptibility (Taufik et al., 2020). Fire seasons usually occur during drought or extended dry seasons in seasonal changes. They will worsen due to climate change when the temperature rising, changes in precipitation patterns, and prolonged drought. For example, in the 2016 El-Niño season in Sabah, about 20,000 ha of forest, farm and plantation were destroyed. However, this amount is statistically reduced through good fire management comparable to the El-Niño season in 1982/1983 and 1997/1998 (SFD, 2016).

Human-induced contributing examples are uncontrolled agricultural practices, land clearing for farming, and arson, which can highly influence the frequency and severity of forest fires. Malaysia and Indonesia recorded fire in the 1970s, 1982/83, 1998, 2010-2016, 2018, 2019, and 2020 (Musri et al., 2020; Rochmayanto et al., 2021; SFD, 2016; SFD, 2021). Considering the frequent fire occurrences in Malaysia and Indonesia peat swamp forests, it is important to recognise the role of forest fire management in controlling the peat fire, specifically in the peat swamp forest. The repeated fire occurrences were due to the extent of human activities, such as open burning and illegal poaching (SFD, 2016; SFD, 2019). The incident was reported as the fire from the state and alienated land was spread towards the forest reserve that was supposed to be protected. A similar situation also happened in Indonesia, as forest fire management will manage the fire for land clearing by imposing laws and regulations (Rochmayanto et al., 2021). It is important to note that fire frequency and intensity increases can pose significant challenges to ecosystems, human settlements, and the environment. Efforts in fire management prevention and raising awareness are crucial in mitigating the negative impacts of forest fires and ensuring long-term forest sustainability. Therefore, the fire service must have in-depth knowledge of forest fire management to mitigate peat fires.

3.2.3 Objective

This chapter will cover the first objective of the thesis, which is to understand the management approaches towards peat fire suppression strategies and prevention policy from per ground perspective. It is important to gain a comprehensive understanding of peat fires, their causes, impacts, and

dynamics to develop effective strategies and practices for preventing, controlling, and mitigating the occurrences and effects of peat fires. This chapter's key objective is understanding peat fire occurrences, effects, and mitigation strategies from the perspective of the forest fire managers and firefighters involved in peat fire. The fire manager's activities include the preventative, operational, and investigative areas of the work done by the fire service. An important part of this chapter is identifying an area within the current policies that could be used. This chapter is also relevant for firefighters or others working within or with the fire service. Therefore, this chapter will recognise the practitioners' viewpoint to widen the researchers' interpretation of the in-practice peat fire suppression. To achieve the goal of this chapter, three (3) specific objectives were developed as follows:

1. Knowledge of peat fire prevention, early detection, suppression, and post-fire management.
2. Effectiveness and efficiency of firefighting operation specific to peat fires
3. Understanding the contributing factors to peat fire vulnerability.

3.3 Methodology

This research is a systematic study where two different approaches were applied. Firstly, an interview study was conducted among fire managers within the Sabah Forestry Department and Fire and Rescue Department. Secondly, a questionnaire was distributed to the Sabah Forestry Department and Fire and Rescue Department firefighters. These two methods' results are discussed, and conclusions are drawn.

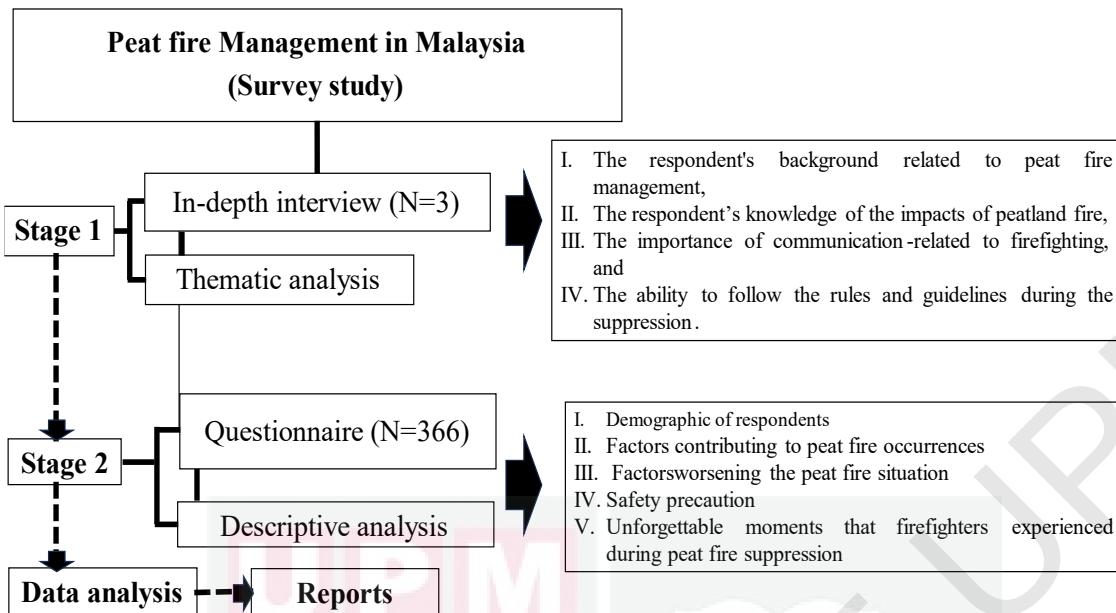


Figure 13: Research framework of the study to achieve Objective 1

3.3.1 Description of the interview study

Fire In this chapter, the research begins by identifying and selecting participants with direct involvement and expertise in Malaysia's peat swamp forest fire management. The interview study was conducted with people working in the fire service or closely related to forest fire management in Malaysia which are from Sabah Forestry Department and Sarawak Fire and Rescue Departments. The interviews were video recorded with the participants' consent to ensure accurate data capture. The participant's identities will be kept confidential, and their consent will be sought before conducting the interviews. This interview was a primary investigation of the forest fire policies implemented in the peat swamp forests that cover a wide range of topics related to forest fire management. The interviews are typically conducted in a semi-structured format, allowing for open-ended questions and in-depth discussion. The purpose of the interview study was to get insight into the following:

1. Compilation of information on the existing methods, approaches, and strategies in peat swamp forest fire management, including current policies, prevention, early detection, post-fire management, and suppression strategies.
2. Identifying the key challenges in managing the peat swamp forest fires, such as limited resources, technical difficulties, climate change and success stories on peat fire monitoring
3. Exploring the experiences and lesson learned from past peat swamp forest fire incidents, including successful management strategies and practices, factors contributing to peat fire occurrences and mitigating the fire risks.
4. Discussing the innovative approaches, technologies, and research advancement in peat swamp forest fire management based on the current status and condition of forest fire in Malaysia.

The prospective interviewees preferred are the ones with a good understanding of forest fire management and peat fire theory to get proficient feedback. The interviewees were therefore selected based on their competence, knowledge, and experience in the areas of fire management issues in the peat swamp forests. Thus, interviewees are selected from the senior fire managers with extensive experience handling peat fires. The interview was conducted in December 2021 and January 2022, and the results and discussion are described in section 3.4.

Thematic analysis was employed to identify the interview transcripts' patterns, themes, and critical findings (see detailed summary of the interview in

Appendix A). The data will be systematically coded and organised to identify commonalities and divergences in the fire manager's perspective as participants. The emergent themes will be analysed to draw meaningful conclusions and extract valuable insights. The data collected from interviews contributed to the existing knowledge base, informing policy decisions, improving fire management strategies, and identifying areas for further research and development in peat swamp forest fire management.

3.3.2 Description of the questionnaire study

A questionnaire study on peat swamp forest fire management was constructed based on the interview results of firefighters involved and experienced in peat fire suppression. The questionnaire involves designing and administering structured questions to firefighters involved in or knowledgeable in peat swamp forest fires. It was conducted to implement the interview findings based on their experience with peat fire during their fire service operations. More specifically, the questionnaire intended to support the policies implemented for peat fire prevention and mitigation strategies. The questionnaires were open-ended and closed-ended questions. The questionnaire was distributed to the fire brigade from the Sabah Forestry Department and Fire & Rescue Department of Sarawak of 366 respondents based on the snowball sampling method, in which the respondents were instructed by the fire managers. The questionnaire is carefully designed to cover the key areas of the peat swamp forest fires. Thus, the following are the identified interpretation based on the firefighter's perspectives.

1. Gathering basic information about the participants, such as their level in peat fire suppression, organisational affiliation, and training knowledge.
2. Assessing the current practices and strategies employed related to peat fire management, including prevention measures, post-fire rehabilitation, firefighting techniques, and awareness related to community engagement programs as part of mitigation strategies.
3. Determining the perceived effectiveness of current strategies and practices in preventing and managing peat swamp forest fires and the impacts of peat of swamp forest fire.
4. Examining the level of preparedness and training among the personnel, including their knowledge of fire behaviour, use of equipment and technology, understanding of the best practice, and the ability to follow the rules and guidelines during the fire suppression.

The questionnaires were distributed electronically via Google form to the targeted respondents. In this questionnaire, the respondents were asked to rank 1 to 5 for each criterion for judging statement (5=strongly agree, 3=natural, 1=strongly disagree), and for judging factor (5=mostly important, 1=least important). The ranking was considered to determine the weight of each parameter that will contribute to peatland fire. The data collected from the questionnaires are then analysed using thematic analysis to identify the trends and patterns among the responses. The analysis took several rounds of refining the categories. To assess the factors and impact on several categories, statistical analysis using SPSS software (IBM SPSS V.28) by comparing the nominal data on a 95% confidence level. The outcome and discussion of the questionnaires are presented in section 3.4. The findings from this chapter

provide quantitative insights into peat swamp forest fire management, helping inform decision-making, and guide future strategies and interventions (see details in **Appendix B**).

3.4 Results and Discussion

In this section, the results and discussion of an interview and questionnaire study on peat swamp forest fire management provide a comprehensive analysis and interpretation of the data collected from participants. Through the analysis of the collected data, this chapter will elaborate on the key findings, highlight significant patterns, and offers insights into the various aspects of peat swamp forest fire management. The findings from this chapter provide a comprehensive understanding of the challenges, perspective, and potential solutions for managing peat swamp forest fire. The results were divided into an interview study and a questionnaire study.

3.4.1 In-depth interview with fire managers on peatland fires

Peat swamp forests are unique ecosystems characterized by waterlogged peat soil, making them prone to fires that can be challenging to control. The interview-based study in this chapter explores fire managers' experience, knowledge, and recommendations to inform effective peat swamp forest fire management. Also, this interview study is used for questionnaire-based study for the firefighters. This section will cover insight into the forest fire policies implemented in Malaysia.

3.4.1.1 Description of interview and interviewees

An interview study was conducted with interviewees from Sabah Forestry Department, Representative A and Representative B, who manage peat fires. Both interviewees from Sabah Forestry Department, Malaysia are the head and deputy of the Sustainable Forest Management (SFM) division that governs the forest fire management unit. The forest fire management unit also manages the forest firefighters known as Initial Attack Crew (IAC) and Forest Fire Crew (FFC). Meanwhile, another interview session was conducted with the head of the Fire and Rescue Department Sarawak, which will be known as Representative C in this chapter—the Fire and Rescue Department combat in both buildings and forest fires. Thus, we have a wide perspective on handling forest fires, specifically peat fires in Malaysia. Hence, understanding the perspective of those involved in fire management and firefighting is crucial for improving strategies, enhancing preparedness, and minimising the impacts of these fires. This section of interview study will summarise the interview and categorised it to forest fire management operation, challenges, prevention measures, awareness, monitoring, and suppression strategies from 3.4.1.2 to 3.4.1.7 sub-sections.

3.4.1.2 Forest fire management operation in Malaysia

Malaysia forests were divided into three (3) regions, the Peninsular Malaysia, Sabah, and Sarawak regions. Every region has a forestry department to manage the forests to achieve forests sustainability, protect the wildlife, forest operations, etc. Forest fire management in Malaysia involves various strategies to prevent, control, and mitigate forest fires, especially in forested areas and

peatlands. The measures are crucial to prevent further degradation in peatlands to protect the environment, biodiversity, and human settlements near the peatlands area. The Fire and Rescue Department is the foremost practitioner for peat fire suppression in Peninsular Malaysia and Sarawak regions. Sabah region on the other hand, acquire a forest firefighter known as Initial Attack Crew (IAC) as a front liner of forest fire defense (SFD, 2019; SFD, 2020), which works along with the firefighter from Fire and Rescue Department.

Forest fire management operations require extensive planning, monitoring, rehabilitation, and suppression strategies to control this zombie-like fire and achieve an integrated management plan. The zombie-fire term was used in the previous study for that persistently smouldering underground, which can reignite on the surface during the dry period contributing to prolonged fire season, for example (Hurst & Grahn, 2021; Irannezhad et al., 2020; Kuklina et al., 2022; O'Sullivan et al., 2023). Thus far, the forest managers have been working on the mitigation plan and monitoring to predict the potential fires in peat swamp forest (Schulte et al., 2019). Prevention, monitoring, and suppression are part of the management effort to control the fire and immediate response to enhance the firefighter's efficiency in suppressing the fire. For example, monitor the hotspots area, tube well installations, and fire break constructions. They also maintain firefighting tools and equipment such as heavy machinery, water pumps, hoses, shovels, chainsaws, and helicopters that are vital for peat fire suppression.

To achieve integrated peat swamp forest management, the forest fire management in Malaysia's peatland requires a comprehensive approach such

as early detection and monitoring, controlled drainage, community engagement, firefighting infrastructure, and international collaboration. Representative A highlighted that in peat fire management, *“Sabah Forestry Department had strengthening: i) monitoring, ii) crew, iii) equipment, and iv) suppression techniques”*. Integrated fire management addresses fire preparedness and response by considering the context of stakeholder’s management to improve the capability of reacting in case of fire (Bacciu et al., 2022; Jurvélius, 2004). Also, fire prevention strategies that target awareness can reduce ignition risks and diminish fuel loads (Munawi, 2014; Wunder et al., 2021). Representative C stated that the prevention the peat fire is very challenging and highlighted that *“Prevention is better than cure.”* Also, *“Construction of a canal in the Klias Forest Reserve in Sabah is effective to prevent the fire spread into the forest, thus similar approach has been implemented in Binsuluk Forest Reserve”* as summarised from Representative A and B.

Other than that, post-fire management involves rehabilitation of the forests and peat accumulation. An initiative to regenerate the area through a forest restoration programme involved a government agency cooperating with non-government and public education. Global Environment Centre (GEC) is an example of a non-government agency that has contributed to peat restoration programs and research on peatlands. One of the initiatives is a tree-planting program in Raja Musa Forest Reserve to restore the repeatedly burnt area, as shown in **Figure 14**. The recovery process allows the regeneration of the land in the burned area, which resulted in variability in the forest regrowth process, which recommended long-term monitoring (Chen et al., 2014).



Figure 14: Tree planting initiative to rehabilitate the degraded area and as part of the million trees planted mission by the Malaysian government in peat swamp forests.

(Source: Dayang Nur Sakinah Musa)

3.4.1.3 Challenges in peat fire management

The forest fire occurrences in peat swamp forests are very challenging to confront. Malaysia presents several challenges due to the unique nature of peatlands and the specific conditions that facilitate the peat fires. The key challenges in peat fire managements in Malaysia are summarised into peatlands characteristics, underground fire, inaccessibility, water availability, depth of peat, air pollution, weather condition, deforestation, and land use change. These crucial situations are interrelated and connected with each other. The best practice of peat fire management is essential to prevent the affected forest and pristine forest that will cause further degradation to the land (Miettinen et al., 2017). In Sabah, current approaches that the Sabah Forestry Department has implemented since the 1980s are considered effective in controlling forest fire incidents despite the influence of the El-Niño phenomenon.

Representative A elaborate that *“The total area affected by the forest fires*

during the El-Niño phenomenon decreased from 1,000,000 ha (the year 1982/83) to 190,000 ha (the year 1997/98), and the recent El-Niño phenomenon on the year 2016 that burn down 19,118 ha". The reduction was due to fast mobilisation for the SFD forest fire suppression teams in collaboration with Fire and Rescue Department by implementing the National Blue Ocean Strategy (NBOS) to conduct joint forest fire suppression operations (SFD, 2016). A severe fire in 2015 is happening because of the El-Niño event, wherein fires escalated from July onwards and reached the climax in most areas in the peatlands in September and October (Miettinen et al., 2017). However, according to Sabah Forestry Department Annual Report 2016, the event escalated to its climax in December and continued to worsen till June 2016 (SFD, 2016). It is similar to the situation in Sarawak, where Representative C summarised that "... the number of fire incidents in the peatland is decreasing".

The environmental condition worsens the fire situation, but humans cause 95% of the fire (Jurvélius, 2004). However, we must remind ourselves not to further conclude by blaming anyone for the fire that occurs straightaway (Miettinen et al., 2017). Farmer initially uses fire to remove crop residues which implies risks for unintended fire spread due to a lack of knowledge regarding these issues (Wunder et al., 2021). It is essential to understand the main aspects and potential alarming characteristics of fire distribution by geographical, political, or cultural context and sources of ignitions (Miettinen et al., 2017).

The recent covid-19 pandemic has reduced human activity in the peat swamp forest, especially for land clearing using a fire (Musa & Huang, 2022). It shows several reduction cases for both Malaysia and Indonesia peat fires. For

example, the peat swamp forest fire reduction in 2020 and 2021 due to lockdown (SFD, 2020; SFD, 2021). Fire-preventive actions by fire managers rarely receive credit for fixing and preventing problems that the community might overestimate their suppression potential (Wunder et al., 2021).

Peat fire management in Malaysia requires comprehensive and integrated approaches to address these challenges further. Based on the interview, prevention, awareness, monitoring, and suppression are the crucial management strategies and further elaborated in following sub-sections of 3.4.1.4, 3.4.1.5, 3.4.1.6 and 3.4.1.7, respectively. Peat fire management is a dynamic field, ongoing research and innovations are essential to enhance the effectiveness of fire prevention and control measures in peatland ecosystem.

3.4.1.4 Prevention measure in Malaysia's peat swamp forests

Fire is associated with a drought season which is particularly difficult to handle even with fire management to protect the land (Miettinen et al., 2017). The first line of defense against forest fires is prevention, therefore, prevention practices were educated to the public, villagers, and workers in the peatland area. Preventing peat fires requires a combination of strategies that focus on maintaining the natural forests and minimising human activities that lead to degradation and increased fire risk. From the interview, this chapter has summarised the various measures for forest fire management to address the issues on prevention strategies included i) establishing a fire break canal, ii) fire prevention education (discussed in 3.4.1.5), iii) providing regular training to forest fire crews iv) fire break, v) restoration and rehabilitation, vi) research and

innovation and vii) monitoring forest fire indicators daily through Fire Danger Rating System (FDRS) and hotspots (discussed in 3.4.1.6 Forest fire monitoring policies).



Figure 15: The Initial Attack Crew of Sabah Forestry Department was trained to construct fire break using the McLeod hand tools.
(Source: Sabah Forestry Department)

The best practice of peatland management and fire prevention efforts is crucial in this region, showing efficient fire practice and control (Miettinen et al., 2017). One example of the prevention strategies applied in Malaysia are fire break and training the Initial Attack Crew and regular firefighters. *“This is our elite team, and everyone is well trained for peat fire suppression,”* said Representative A, referring to the Initial Attack Crew fire brigade. Representative B added *“We ensure that the incident command system as a safety measure to be followed by the personnel, and our crew is in a good spirit during the suppression”*. Implementing a fire break is an essential strategy to reduce the risk of peat fires. It is a physical barrier that creates a gap in vegetation or other flammable materials, effectively interrupting the fuel continuity and preventing fires from

spreading from one area to another as shown in **Figure 15**. It is important to note that other prevention measures are important to be integrate into the overall fire management plan to protect the peat swamp forest.

Another example of a pre-fire prevention strategy is fire-break canal construction adjacent to the alienated and state land (SFD, 2019), as shown in **Figure 16**. However, further discussion on land-use change to the extent of drainage canals is unknown to carbon emission (Dadap et al., 2021). Neighbour country Indonesia also implements the similar approach which is canal blocking to help maintain the water level, preventing excessive drying by proper water management to keep peat moist (Sutikno et al., 2019; Ward et al., 2021).



Figure 16: Fire-break canal as part of prevention method for fire spread towards the forest reserve area from the alienated or state land.

(Source: Dayang Nur Sakinah Musa)

Representative A and Representative B justified that “... *the fire-break canal in the peat swamp forests does not function similarly to agricultural purposes*”. The

agricultural canal will depend on the plantation, and mining activity will dry the peat, which increases the fire risk (Munawi, 2014). By implementing fire break canal and other measures, Malaysia aims to mitigate the risk of peat fires, preserve its unique peat swamp forest, and protect the valuable ecosystem services they provide.

3.4.1.5 Prevention measure in Malaysia's peat swamp forests

Forest fire awareness in peat swamp forests is crucial to prevent and mitigate forest fire risk, specifically peat fires. Creating awareness among the general public, local communities, land owners, and stakeholders is essential to promote responsible behaviour and fire prevention practices. Since forest fire will heavily influence the community, it may cause distrust of governments and corporations and may foster social tensions, including the social implications for those affected; investigate how people understand wildfires-their causes, consequences, and how to mitigate them (Lidskog et al., 2019). Hence, the involvement of the local community and increasing their awareness is important as part of prevention measures.

An example of public inclusion is students from the university, as shown in **Figure 17**, in which they visited the degraded area in Sabah's peat swamp forests. From the visit, students can learn the post-fire effect on the peat and environment resulting from the fire spread from the alienated and state land towards the forest reserve area (SFD, 2019).



Figure 17: Universiti Malaysia Sabah's students visited Sabah's peat swamp forest to learn the post-fire impact and strategies applied to tackle the peat fire.

(Source: Dayang Nur Sakinah Musa)

Other than educational campaign, community engagement and collaboration with local authorities to spread peat fire awareness messages effectively and ensure a coordinated response to fire incidents. Peatland is a source of economy for the local community nearby by providing fish, timber, non-timber forest products and other resources for local communities (Davies et al., 2010). Thus, a resilient community in preventing peat fire will be created by involving the locals in peat firefighting together. Representative C asserted that *"Sarawak has initiated a program with the local community known as 'The Champion' to increase awareness and to aid in fire suppression. The Champion programme was begun to allow the local people to participate in tackling the fire and assist in preventing the fire from spreading"*. This is an important platform since humans are the main reason due to arson and open burning (SFD, 2017; SFD, 2019; SFD, 2020), and it will be hand in hand to control the issue.

The community mobilisation and training as part of the plan will increase their

awareness of forest fires and their impacts (Sonam et al., 2021). Representative B also elaborates on “*Campaign with local community to raise their awareness,*” e.g., Awareness Program in Kg. Kukut Padas Damit, Kg. Suasa, and Kg. Binsuluk (SFD, 2016) to strengthen and create awareness about the potentially harmful effects of open burning on human health and environment. Increasing farmers’ awareness of the negative consequences of burning behaviour could be a means of intervening in this problem behaviour (Trihadmojo et al., 2020). This action will influence the decision-making generally on doing the prescribed burning (Hamilton & Salerno, 2020). Awareness through community engagement is one of the best prevention and emergency management in integrated fire management (Bacciu et al., 2022).

3.4.1.6 Prevention measure in Malaysia’s peat swamp forests

Forest fire monitoring policies are critical for preventing and managing peat fires in peat swamp forests. The previous discussion particularises that humans induce fire such as slash and burn activity. The specific policies and strategies for monitoring peat swamp forest fires can vary depending on the country and region. However, it commonly included early warning systems, ground-based monitoring, community involvement, firefighting infrastructure, legal measure, and research and data collection. As technology advances, it is expected that early detection is to be expanded (Zhang et al., 2019). Thus, Representative A stated that “... *the FDRS system was improved by developing a new mobile application technology. The improved technology will collect a daily input of weather (humidity, rain, wind speed and temperature) from 27 districts in Sabah*”. It is important to link the weather, vegetation fire, topography, and

anthropogenic influence the spread of fire on the objects, people, or concepts (Wunder et al., 2021).

Local weather observation, environments, and human behaviour characteristics were highly correlated to forest fire occurrences (Pillai et al., 2021). Representative C also added that “... *they would monitor the hotspots area through satellite, drone, and helicopter*”. In 2015, the fire hotspots detected in Miettinen et al., (2017) study was 4,460, with 13.5 fire density detected per 1000 km². Their study also determines that the number of hotspots in peatlands is 1,488, which covers 7.6% of Malaysia's total peatland area. However, it is much lesser hotspot density covered in pristine PSF than the degraded PSF (Miettinen et al., 2017).

Other than monitoring the weather through FDRS to predict the potential fire, a ground monitoring for the water level at fire break canal and fire tower were conducted. The interviewees stated that other monitoring efforts to monitor the peat fire besides FDRS were also important. Examples of monitoring effort by the government were shown in **Figure 18** to control the peat fire situation in the peat swamp forest. Monitoring the water level is important in the post-fire area to make sure the peat is not drying to prevent peat susceptible to fire. Low water level increase fire risk, an immediate action to flood the area from the stored water in tube well to area will be performed. Furthermore, a fire tower is part of the ground monitoring to confirm if smoke appears in the hotspot's location. It is important to monitor the peat fire on the ground to be able prove the fire is happening and take suppression action immediately.



Figure 18: (a) Initiative to monitor the water level to maintain the peat water table level – blue: good condition (low risk), green: intermediate risk, and yellow: high risk; (b) A fire tower to monitor fire occurrences in the peat swamp forests.

(Source: Dayang Nur Sakinah Musa)

3.4.1.7 Prevention measure in Malaysia's peat swamp forests

Peat fires can be highly challenging to suppress due to its unique characteristics. In Malaysia, the interviewees described that the fire suppression techniques require special consideration and could be done directly and indirectly. Early detection such as satellite monitoring and ground-based sensors can help in identify fire outbreaks at their inception, thus quick response and successful containment can be achieved. An example of direct suppression method is flooding techniques that require working on the fire's edge or on top of the smouldering fire. Water shortage is the main problem during the prolonged dry season in peat swamp forests (Jurvélius, 2004). In this case, fire can enlarge, and the firefighters exposed to heat, flames, and extensive smoke.

Other challenges such as transportation and firefighter safety concerns lead to the requirement to handle the massive fire by an indirect attack method. For example, they were building firebreaks as a barrier that can halt and slow down the fire spread. Additionally, firefighting teams and equipment should be emphasising such as well-trained firefighting equipment such as water pumps and fire hoses (**Figure 19**) which are essential for combating peat fires. A water bombing by using a helicopter to suppress the fire also widely used in suppressing tropical peat fires.



Figure 19: Initial Attack Crew doing mopping up as part of post-fire effort to reduce smouldering fire re-occurrences on the surface by using water pump and fire hose.

(Source: Sabah Forestry Department)

It is also discussed that the peat fires produce thick smoke during huge fires. At this time, waiting for the rain to pour down is another precaution taken for the firefighter's safety. It was summarised from the interview with the Representatives A, B and C wherein, "*Rain is helpful in suppressing peat fires. Peat fire can re-appear after suppression or rain.*" The rain is the best option to

control the blaze and sometimes the only option although most of the non-firefighting community was difficult to accept and understand (Steelman, 2021). Wetter sites would have lower fire vulnerabilities through the integrated effects of site-specific soil moisture and short-term water level (Schulte et al., 2019). It took lengthy patrolling and suppression of the burned peat area because of the smouldering fire (Jurvélius, 2004). A mopping up will be done to ensure that the smouldering fire is dead, unable to spread further and prevent fire reoccurrence on the surface (**Figure 19**) in the area where smoke appeared.

Prevention and early intervention are key to minimising their impact on the environment and surrounding communities as part of comprehensive peat swamp forest management. Therefore, regular training is important to ensure firefighters are familiar with the hand tools and suppression strategies for peat fire. So, the questionnaire study will observe a perspective on the training significance for firefighters.

3.4.2 Questionnaire for firefighters on peatland fires

The questionnaire study is conducted to gain valuable insights into peat swamp forest fires from firefighters' perspective. The responses contribute to better understanding the challenges faced and the effectiveness of current firefighting techniques in peat swamp forests on the frontlines, which is crucial to improving fire management strategies and overall response efforts. This chapter have included the forest fire brigade that exclusively tackle forest fire as the frontliners (SFD, 2017; SFD, 2019; SFD, 2020) and Fire and Rescue Department's firefighters to control the peat fire issue. This section will present the results and

discussion on the understanding of the firefighters on the current policies, experience during peat fire occurrences, and the method used to fight the peat in Malaysia.

3.4.2.1 Socio-demographics of the Malaysian firefighters

Total of 366 respondents participated are selected from Sabah Forestry Department and the Fire and Rescue Department Sarawak that experienced peat fire suppression, as shown in **Table 5**. From the table, the participating firefighters were mainly 31-40 years old (39.6%), and only 1.4% of the respondents are less than 20 years old. Moreover, this work also measured the respondents' experience with peat fire suppression on the field. Most respondents had an experience of about 11-20 years (30.9%) in peat fire suppression, followed by 3-10 years of experience (29.2%).

Table 5: The socio-demographic of the respondents.

Demographic	Description	Respondents (%)
Age	< 20	1.4
	21-30	16.9
	31-40	39.6
	41-50	23
	51-60	19.4
	> 60	0
Years of experience	< 3	13.7
	3-10	29.2
	11-20	30.9
	21-30	13.9
	>30	13.1
Trained in peat fire suppression	Trained	77
	Not trained	23

Remarkably, 13.1% of the respondents have experience of more than 30 years in peat fire suppression indicates a wide knowledge of the respondents. Extensive experience in this field is practical to foresight in the suppression

process. Moreover, regular training is important to ensure the firefighters familiarity in this unique ecosystem. The respondents are mainly trained in peat fire suppression for 77% of total respondents. Meanwhile, 23% were not specifically trained on peat fire suppression. Training is important as part of the safety precaution to firefighters as the suppression is very challenging as the structure of the forest is also different from different types of forest.

3.4.2.2 Questionnaire for firefighters on peatland fires

Peat swamp forest fires are complex and challenging to manage, and a combination of preventive measures is needed to deal with them. The respondent's perspectives on the current approach in Malaysia's peat fire conditions is discussed (b). In the interview section, rising issues related to prevention methods are identified and included in the questionnaire. During firefighting, 69.9% of respondents strongly agree that high fire intensity is the major challenge. Therefore, the rotation hours during the service were important at that time to reduce stress, and 72.7% of the respondents agreed. Intense heat during firefighting is a very challenging environment to work in, and understandably, the firefighters feel concerned about the previous statement. Better management in rotation hours helps the firefighters reduce fatigue and increase their determination during the service. Energy was needed for the crew to control the fire, e.g., to establish a fire break to prevent the fire from spreading.

The respondents strongly agreed that local villager's involvement (67.5%) helps control peat fire incidents along with the current policy (48.6%) to prevent and

reduce fire occurrences. It was in line with the statement from the representative in the interview section that people assisting with firefighting are critical. Examples of people involvement are The Champion programme in Sarawak and Awareness Program in nearby villages in Sabah. The public awareness campaign was strengthened as open burning and arson are the leading causes of the 2016 forest fire (SFD, 2016). Since humans cause 95% of fires (Jurvélius, 2004), prevention to mitigate peat fire is important. Loss of forest can significantly reduce the live hood sources and adaptive capacities (Wang et al., 2021). The pandemic proves that human activity in the peat swamp forest, especially for land clearing using fire, was highly reduced. Hence, 59.8% of the total respondents strongly agreed that the pandemic proves that humans are the main contributor to peat fire incidents; the case reduction confirmed it since the Malaysian Movement Control Order was implemented (Musa & Huang, 2022).

Table 6: Current approach and peat fire situation regarding the forest fire in the peat swamp forest in Malaysia.

	Statement	Percentage (%)				
		Totally disagree	Disagree	Neutral	Agree	Strongly Agree
1	Current policy can prevent the peat fire occurrences	5.7	3.6	15.6	26.5	48.6
2	The pandemic situation in Malaysia proves that human is the main contributor to peat fire	3.3	1.9	14.5	20.5	59.8
3	Local villagers can help prevent peat fire on their own by proper training	2.2	1.6	9.6	19.1	67.5
4	High fire intensity is the major challenge during the firefighting	1.1	0.5	8.5	19.9	69.9
5	Rotation during firefighting can reduce the stress	2.2	1.1	11.7	12.3	72.7

Based on **Table 6**, the respondents have elaborated their moments related to the past peat fire suppression, summarised and coded in **Table 7**. The respondents mainly shared water shortage moments, which is also a moderate factor that worsens the case but also affects firefighter suppression efforts discussed in **Table 8**. The narrative of the respondents shared that effort also can be diverted when equipment to help in fire suppression is not enough, and sometimes the hose is burned during the suppression. It will also prolong the period for the firefighters to extinguish the peat fire. Controlling and suppressing the peat fire is tough without water. The extended operation during peat fire suppression will force them to work at night and sleep in the forest.

The respondents shared vivid memories of past events involving international collaboration in peat fire suppression between Malaysia and Indonesia. Malaysian firefighters aided during the Kalimantan Barat (Kalbar) fire suppression in 1997/98, a period marked by severe peatland fires from June 1997 to June 1998. According to our respondents, this year stands out as one of the most devastating, generating an extensive amount of smoke that resulted in significant transboundary haze pollution. Smoke emissions contain various toxins and carcinogens, posing health risks to both firefighters and local populations (Stockwell et al., 2016). It represented a historical peak in emissions for a single nation during that time (Rainforest Action Network 2010).

The catastrophe of 1997/98 only began to abate by the end of November 1997, with a gradual decrease in the number of fires. Although some were partially extinguished by December, certain fires continued to burn for at least six more months. As Mathews (2000) indicates, the 1997 catastrophe was triggered by

the El-Niño phenomenon, which induced widespread peat fires that rain failed to quench. Economically, the fire inflicted substantial damage, amounting to 10 billion USD, and impacted over 10 million hectares of land.

In Kalimantan alone, 750,000 hectares of peat swamp forests were decimated. The situation deteriorated when the haze reached Malaysia and Singapore by July, worsening further through September of the same year. This deterioration even contributed to a ship collision in Malacca, Malaysia, tragically claiming the lives of 29 individuals. Moreover, the haze not only reduced visibility, causing harm, but also led to the emergence of respiratory, eye, and skin illnesses among people. In response to this global crisis, Malaysian volunteers stepped up to assist.

The challenges posed by higher fire intensity during firefighting efforts were discussed, encompassing both physical and mental health issues. In correlation with the high-intensity fires outlined in **Table 7**, the respondents recounted inhaling smoke, experiencing fatigue, thirst, difficulty in breathing, and stress due to the heavy equipment they had to carry. This elevated physical exertion also had an impact on their mental well-being (Britton et al., 2013; Lui et al., 2014; Miranda et al., 2010).

There was a scenario where the firefighters revealed was trapped in fire because of the high fire intensity, which require more mental strength to overcome the situation. Another related issue is related to not having enough manpower when the fire intensity is high is challenging. Because of that, respondents shared about an incident of losing a crew or a friend during their

service indirectly impacted them. In 2020, a peat fire broke out in Sabah, one crew dies while fighting the peat fire which has become a devastating moment for the fire managers and the firefighters. Their group believed the decease was suffocated and found unconscious at the scene (Gonzales, 2020).

Table 7: Unforgettable moments the respondents experienced during peat fire suppression in peat swamp forest in Malaysia.

Code	Summary
Water shortage	Water shortage during peat fire suppression worsens the situation as no water supply to extinguish peat fire
Past events	Most firefighters mentioned the places that do peat fire suppression previously.
Physical and mental issues	Inhale smoke, fatigue, thirst, hard to breathe, stress, and carry heavy equipment A small group of firefighters extinguish a large area Losing a friend Work at night did not shower and sleep in the forest
Long operation hour	Long hour operation and stand-by up to 2 months
Trapped in fire	Almost trapped because of a huge fire and thick smoke (surrounded by fire).
International Collaboration	Assist in peat fire suppression in Kalimantan Barat, Indonesia. 'Operation KALBAR 1997 Indonesia' are mentioned frequently
Equipment issue	Not enough PPE for firefighters during suppression, although some think their PPE is suitable. Equipment to help in suppression is not enough Some firefighters burnt their hose during suppression
Other issues related to peat fire suppression	Come across venomous animals and insects; not enough manpower; strong friendship develops; fire in oil palm plantation; a tree falls in front of them; lost communication.

3.4.2.3 Questionnaire for firefighters on peatland fires

The discussion revolves around the contributing factors to peat fires, with

human activities identified as the primary drivers behind peat swamp forest fires. A summary of the contributing factors and situations that exacerbated these occurrences is presented in **Table 8**. Gaining a comprehensive understanding of the origins of peat fire incidents holds paramount importance in enhancing our comprehension of fire propagation in tropical peatlands.

Table 8: Malaysian firefighter's perspective on contributing factors and situations that worsen the peat fire event.

Issue	Factors	Respondents' perspective	(%)
Contributing factors	Open burning	Most important	36.1
	Man-made canal	Moderately important	34.4
	Agricultural activities	Moderately important	32.2
	Arson	Moderately important	33.1
	Fishing	Least important	35.0
	Forest Encroachment	Moderately important	35.5
Worsen the situation	Strong wind	Most important	34.4
	High temperature	Most important	35.8
	High humidity	Moderately important	33.1
	Haze	Moderately important	28.4
	Water shortage	Moderately important	29.2
	Small population in the area	Moderately important	33.3

The interviews pinpointed six factors responsible for peat fires in Malaysia: open burning, man-made canals, agricultural activities, arson, fishing, and forest encroachment. The practice of using fire to clear land has persisted for decades (Anshari et al., 2010). Respondents concurred that open burning stands out as the most influential factor contributing to peat fire incidents, aligning with reports from the forestry department (SFD, 2020). While man-made canals, agricultural activities, arson, and forest encroachment are of moderate significance, they still bear relevance to the occurrences of peat fires.

Arson and forest encroachment are human activities, wherein arson

deliberately setting fire to the land and intrusion of human activities to forested area. The ignition of fires is believed to have stemmed from activities undertaken by forest companies, as their limited knowledge and experience in dealing with large-scale wildfires became apparent (Lidskog et al., 2019). Conversely, fishing activity emerged as the least significant factor in causing such incidents (Lidskog et al., 2019). Fishing serves as a crucial part of local villagers' livelihoods, yet instances where bushes are burnt to clear areas or fires are left inadequately extinguished after on-site cooking have led to fire-related episodes (Akbar, 2022).

The weather and surrounding conditions are critical conditions that cannot be ignored. Strong wind and high temperature during the peat fire event are the most critical factors that worsen the incidents. Since Arctic influence on the low-latitude precipitation demonstrated in this chapter implies the possibility that heavy precipitation in East Asia may continue or even shift to increase the influence of tropical warming in the future (Nakamura & Sato, 2022). Other environmental conditions, such as humidity and haze, are considered moderately important factors to worsen the scenarios. Even though these factors do not affect the peat fire incident much, they affect the firefighters the most. Similarly, water shortage conditions and a small population are considered moderate factors to worsen the case but also affect the firefighter suppression efforts corresponding to the respondent's experience in **Table 7**. An awareness campaign involving the local people was conducted to assist with firefighting.

Smouldering peat fire is dangerous, and it is important to ensure the zombie-

like fire is fully suppressed. The term zombie fire is used for the arctic peat fire, which describes the re-occurrence of fire on the surface after winter, indicating that smoldering fire stays underground in the winter (Hurst & Grahn, 2021; Rein & Huang, 2021; Kuklina et al., 2022). It is very crucial to understand the zombie fire that disappear in the surface and come back to life afterwards and its effect on the environment, particularly during extreme drought (Irannezhad et al., 2020; O'Sullivan et al., 2023).

In a tropical country like Malaysia, peat fire can re-appear after suppression since smouldering peat fire cannot be fully distinguished. To distinguish the peat fire, one of the indicators is the presence of smoke (**Figure 20**). Malaysian firefighters agreed that no smoke on the surface indicates a fully suppressed peat below ground compared to the no visible flame or ember presence (**Figure 21**). Additionally, the peat was ensured to be in a wet condition where the smoke appeared as part of to make sure the smouldering fire was suppressed.



Figure 20: Smoke on the peat surface due indicates the peat fire underground in the peat swamp forest.
(Source: Dayang Nur Sakinah Musa)

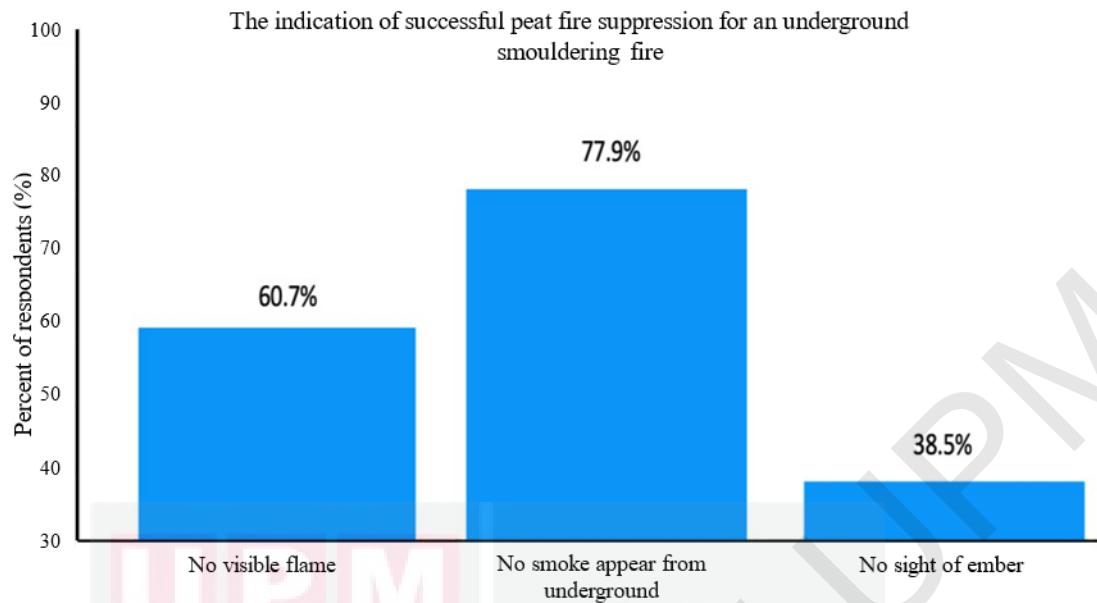


Figure 21: Malaysian firefighter's perspective on the fully suppressed peat fire below ground.

3.4.2.4 Questionnaire for firefighters on peatland fires

The safety issues in the peat swamp forest involved in combating peat fires are highlighted and summarised in this chapter. Safety precautions during the operation are for the role of PPE to reduce hazards, ensuring that firefighters have the necessary tools and support for their safety. It corresponds to experience sharing in Table 9 on equipment issues, in which insufficient PPE and tools to suppress peat fire affect the suppression time. Respondents agreed that PPE is the most important factor (74%) to keep them safe other than hand tools (69.1%), water back pump (65.6%), and communication gear (68%). Communication mats are affected by the limited visibility, increasing the risk of accidents and injuries. Insufficient training, lack of equipment, funds, water, and remote location were often cited as the reason for failure in past peat fire events (Emily, 2002). Therefore, the respondents also stated that transportation towards the peat fire location (73.5%) and training to suppress the peat fire (71.9%) is most important to control the peat fire. Peat swamp forests typically

has swampy terrain, which can impede movement of firefighting personnel and equipment and hinder the effective firefighting efforts.

Table 9: The most important subject for safety precautions according to Malaysian firefighters during peat fire suppression.

Items	Respondents (%)
Safety suit (PPE)	74.0
Hand tools	69.1
Water back-pump	65.6
Communication gear	68.0
Transportation	73.5
Training for peat fire suppression	71.9
Rotation hour	70.2

Rotation hour is a very important safety precaution according to respondents wherein 70.2% agreed it is most important safety precaution during peat fire suppression. The rotation hour also correlated to the extended operation hour, and stress level of the respondents discussed in this chapter. As peatland fire suppression is challenging, proper training and rotation hours are crucial to getting familiar with and reducing fatigue during the service. Continuous training will refresh and enhance the fire crew's skills and knowledge in handling the forest fire equipment and conducting fire prevention and suppression (SFD, 2016). Proper training can prepare the firefighters to combat fire in the hot and humid condition that can lead to heat stress and exhaustion due to prolonged exposures.

Personal protective equipment (PPE), such as firefighting suits and footwear, serves a critical role in ensuring the safety and comfort of firefighters by shielding them from hazards like heat, fire, and sharp objects (Kang & Lee,

2018; Parmar, 2017). This equipment coherence of the story. Landscape and micrometeorological factors significantly impact moisture levels in peat soils, influencing wildfire spread and the susceptibility of organic layers to severe smouldering (Little et al., 2024). Integrating fire management strategies into forest management planning processes can effectively bridge the gap between long-term planning goals and short-term fire response actions (Schultz et al., 2019). Schultz et al., (2019) emphasize the critical importance of addressing current policies to enhance fire management practices for the future. Previous study identified properly fitting gear for firefighters not only reduces injuries but also enhances performance (Sokolowski et al., 2022). However, there remains a lack of understanding regarding the relationship between physiological parameters, physical exertion, and exposure, underscoring the necessity for comprehensive studies integrating physiology, local geography, and exposure to inform fire management and decision-making (Held et al., 2024)

3.5 Conclusion of Chapter

Sustainable forest management is crucial for safeguarding forests for future generations and preventing further degradation, especially when strategies prioritize promoting species richness, allowing burned areas to regenerate naturally (Chen et al., 2014). This chapter concludes that insights from fire managers and firefighters in Malaysian peat swamp forests can serve as a theoretical foundation for more integrated peatland management. It also offers insights into better fire suppression methods, particularly for firefighters. Interviews have demonstrated that anthropogenic impacts have contributed to peat fire occurrences, with a significant reduction during the pandemic,

especially in forest reserve areas. Questionnaire-based studies aim to gather valuable firsthand data from firefighters who have faced the challenges of combating peat swamp forest fires. The insights gathered from this chapter will enhance our understanding of the complexities of peat fires and inform future fire management practices, ensuring firefighter safety and the preservation of the valuable peat swamp forest ecosystem.

Considering the significance of peat swamp forests as critical ecosystems and carbon sinks, the Malaysian government collaborates with non-governmental organizations, international agencies, and local communities to effectively implement prevention measures. Safety measures, such as training and equipment, are essential for firefighter efficiency and accident prevention. Prevention and early intervention are vital in minimizing peat fire impacts, necessitating comprehensive, adaptive management strategies. Insights from respondents and interviewees aid in identifying influential factors contributing to peat fire occurrences and safety measures, with further studies warranted to explore post-firefighting effects on Malaysian firefighters.

CHAPTER 4

PRE-FIRE AND POST-FIRE HISTORY EFFECT ON PEAT PROPERTIES IN A FOREST RESERVE

4.1 Summary of Chapter

Chapter 3 underscores that human activity is the primary cause of fire threats in the peat swamp forest, with settlements close to the forest reserve. Recognizing how peat soil is affected post-fire holds significance for rehabilitation and reforestation. Mitigation efforts and their effects are broadly discussed in **Chapter 3**. This chapter covers the post-fire impact on Malaysia's peat swamp forest within the forest reserve. It evaluates how fire alters peat's physical and chemical properties from the surface down to -150 cm. Given prolonged fire exposure, as detailed in **Chapter 4**, understanding post-fire peat property differences is crucial. The findings here will extend to the fire frequency's impact, addressed in **Chapter 5**. This informs post-fire management regarding smouldering peat fire effects on properties, essential for mitigation. Subsequently, **Chapter 6** elaborates on tools to suppress fires and minimise impact. Thus, this chapter solidifies the importance of previous and upcoming chapters, highlighting the value of millennia-old peat as a national treasure.

4.2 Introduction

Malaysia encompasses 8.3% of Southeast Asia's 33 million hectares of peat swamp forests, with the majority, around 82%, located in Indonesia (Wösten et al., 2006; Posa et al., 2011). Nevertheless, Malaysia's share remains significant

for carbon storage and flood mitigation. Both pristine and rehabilitated peat swamp forests play a crucial role in maintaining their substantial value. Notably, in 1997 and 1998, fires across 800,000 hectares of peat swamp forests in Malaysia and Indonesia resulted in the massive haze that affected not only the originating countries but also their neighbouring nations (Leete, 2006; Yule, 2010; Syaufina and Ainuddin 2011; Zacccone et al., 2014). These large fires were frequent in Peninsular Malaysia, Sumatra, and Borneo Island (Ohkubo et al., 2021). Consequently, it becomes imperative to assess the impact of peat fires on peat properties in post-fire areas compared to pre-fire conditions. This examination is essential for understanding the peat soil's state after frequent fires, a topic that will be further elaborated upon in this chapter.

4.2.1 Effects of drought in Peat Swamp Forest

Peat has been extensively studied for its global carbon balance, its responses to ongoing environmental changes, and its potential uses for energy purposes, attracting the attention of chemists and geologists alike (Andriess, 1988; Rein et al., 2009). During periods of drought, the water table of peat becomes lower, causing the near-surface peat to dry up. Dried peat is susceptible to surface burning, leading to smouldering peat fires that can persist for hours (Goldstein et al., 2020). This type of slow combustion contributes to the evaporation of moisture from the peat, ultimately changing the structure and composition of the forest understory, including the peat soil itself (Patel, 2012; Syaufina & Ainuddin, 2011). Earlier studies have indicated that burning processes can result in evapotranspiration, leading to lowered water tables and increased fire risks (Krivtsov et al., 2008). The relationship between water table conditions and

fire occurrences is illustrated in **Figure 22**.

A fire events eventually increase surface runoff and affects peat's properties such as soil organic matter, density, soil moisture, pH and macro and micronutrients and eventually drop the water table from 11.2 cm to 53.9 cm (Lailan et al., 2004; Verma and Jayakumar 2012; Kusin et al., 2020; Graham et al., 2022). It is crucial to pay attention of the weather, soil, water table depth, and complex fuel availability interactions (Taufik et al., 2022). The peat properties are complicated and depend on the weather conditions of that time and anthropogenic threats. These interactions are fundamental and vary depending on the plant species, leaves, bark, ground litter, moisture content, and fuel load (Yule, 2010; Possell and Bell, 2013).

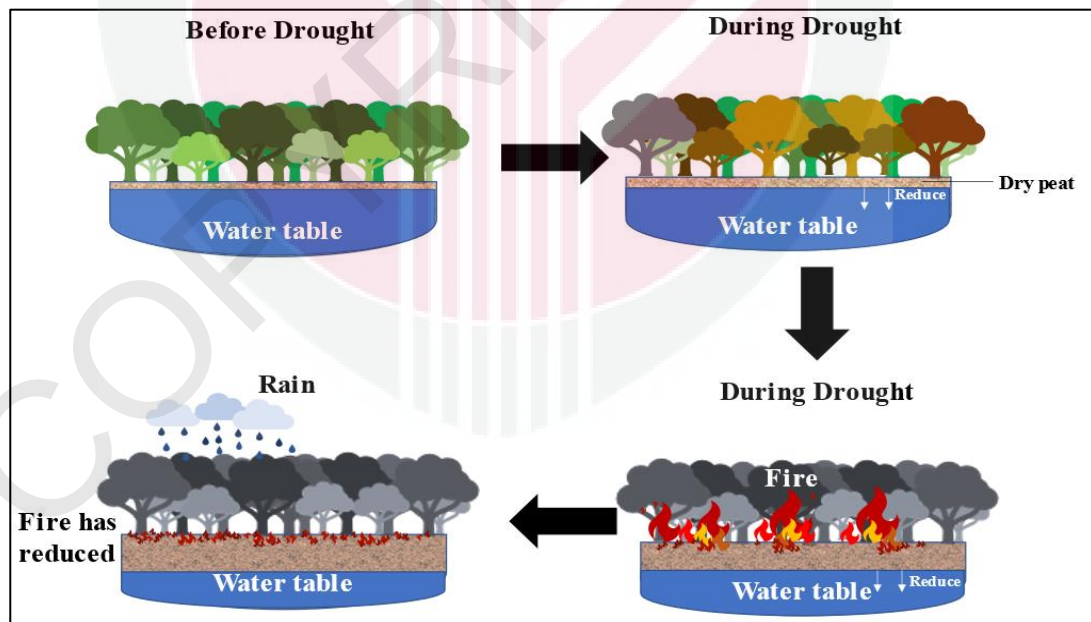


Figure 22: Drought season will reduce the water table and reduce the moisture and make it susceptible to fire. Rain will help reduce the fire in the peat swamp, however, a smouldering fire is yet to be known to be entirely suppressed.

4.2.2 Fire history in Raja Musa Forest Reserve

Raja Musa Forest Reserve (RMFR), covering an area of 35,656 hectares, was subjected to logging activities during the 1950s before being officially designated as a forest reserve in the 1990s (Munawi, 2014). RMFR is categorized into forest production (70%), forest sanctuary (27%), and research purposes (3%). This reserve is subdivided into 102 compartments, serving as territorial units for its comprehensive management, monitoring, and documentation. The maximum peat depth within RMFR has been reported to reach 5.2 meters, with an average of 3 meters above the layer of grey marine clay (Yule and Gomez, 2009; Ainuddin & Goh, 2010). Such peat depth qualifies as deep peat soil, characterized by a thickness exceeding 5 meters, whereas shallower peat is defined as being less than 3 meters deep (Sutejo et al., 2017). The classification of Malaysia's peat predominantly falls under the Saprist category in the USDA Soil Taxonomy or Histosols classification according to FAO/UNESCO (Yew, 2017).

Recorded fire incidents within Raja Musa Forest Reserve, dating back to 1996, depict a concerning pattern of destruction: 10 hectares (2002), 400 hectares (2004), 12 hectares (2007), 630 hectares (2008), 29 hectares (2009), 5.44 hectares (2011), 406.5 hectares (2012), 139.85 hectares (2013), and a staggering 1208.58 hectares (2014), occurring nearly every year (Ainuddin & Goh, 2010; FDPM, 2013; Selangor State Forestry Department, 2014). Notably, these fire events frequently centered around Compartment 99 and its adjacent zones. Consequently, this chapter utilizes the fire history of the area as a basis for categorizing fire occurrences into pre-fire conditions (indicating zero fire

cases) and post-fire conditions (denoting repeated fire incidents).

4.2.3 Objective

Fire effect on peat properties has been significant research for many years. In this chapter, a different fire history is explored in response to the second objective of the thesis, which is to investigate the peat condition at different fire history conditions. This chapter identified that the post-fire and pre-fire areas and hypothesised have different peat soil properties, which tested this hypothesis in the present study. This chapter also studies the effect of rain, which is hypothesised to affect the peat properties after the rain pours in pre-fire and post-fire areas. This work will be important to understand the peat changes for future rehabilitation and fire prevention. To achieve the thesis second objective, this chapter aims to highlight the following specific objectives:

1. To analyse the physical and chemical properties of the peat from the surface until -150 cm below the surface.
2. To identify the peat properties in pre-fire and post-fire conditions of the forest reserve
3. To determine influence of rain on the peat properties in pre-fire and post-fire area

4.3 Methodology

4.3.1 Description of the study area

The Raja Musa Forest Reserve (RMFR) was chosen as the study area was

gazetted in the 1990s and managed by the Selangor forestry department (**Figure 23a**). RMFR was identified to have compartment zones that matched the post-fire area, which repeatedly burnt, and a pre-fire area, where fire occurrences are still zero in which will implement this chapter aims to determine the peat properties at different fire history areas under the forest reserve. Based on the report, we have identified two (2) zoned compartments suitable for peat sampling to represent the post-fire and pre-fire history areas as shown in **Figure 23b**.

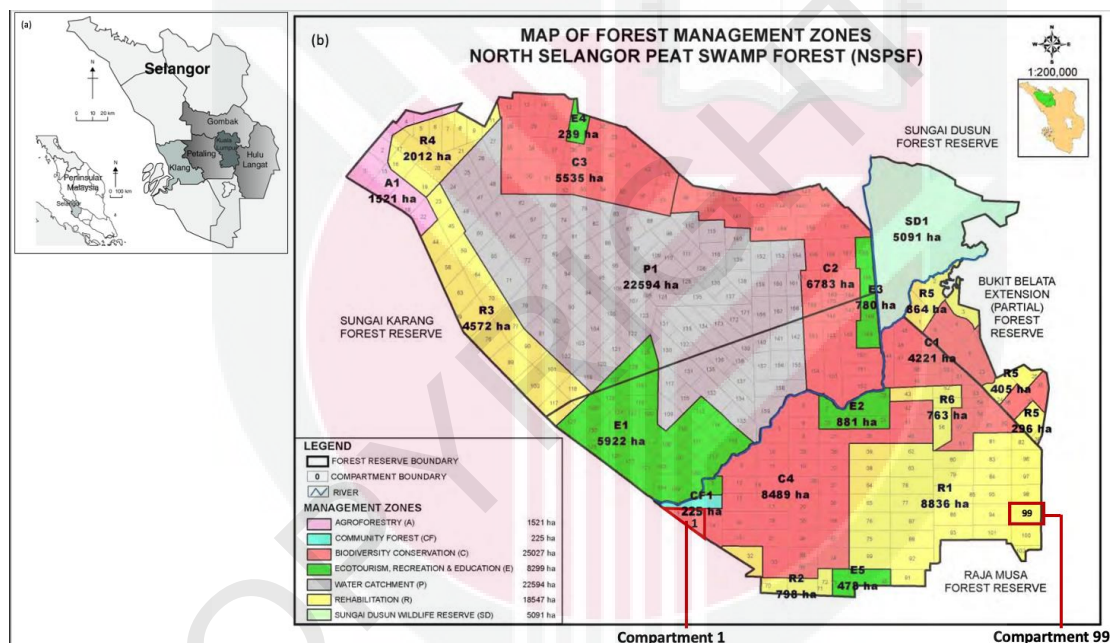


Figure 23: (a) Malaysia map and Selangor state where the RMFR was located (b) Study area of post-fire (Compartment 99) and pre-fire (Compartment 1) areas (in red) in Raja Musa Forest Reserve, Selangor, Malaysia.

(Source: (a) Hamid et al., 2017; (b) Munawi, 2014)

Two areas of pre-fire and post-fire conditions were selected in the RMFR are as follows:

- Compartment 1: Pre-fire history: Compartment 1 is part of the conservation zone and is relatively in good condition, which has not been

severely logged and represents the relative authenticity of the peat swamp forests. The canal was present in this area (Munawi, 2014).

- b) Compartment 99: Post-fire history: Compartment 99 is dominated by herbaceous vegetation with little tree regeneration (Davies et al., 2010). It is part of the rehabilitation zone as it was a fire-prone area for over 10-20 years.

4.3.2 Description of the sampling period

The sampling areas were chosen near a canal and a fire break canal, namely Kunci Air Sungai Burung and Parit 4, respectively. The canal and fire break canal functioned to maintain the water table depth and was important as a water source and acted as a firebreak during firefighting operation corresponding to an interview in **Chapter 3**. The water table was based on the Kunci Air Sungai Burung, the main irrigation canal for compartment 1, and Parit 4 canal for compartment 99 (**Appendix D**). Meteorologically, this area has the highest rainfall from April to May and October to November, with an average temperature of 28°C, humidity is 77%, and lower plant diversity compared to the west coast of Peninsular Malaysia and Sarawak (Yule and Gomez, 2009). Thus, the sampling period was conducted in two different months based on the weather observation (**Appendix C**):

- a) Before-rain

The collected samples are referred to as 'before-rain' samples, representing the peat after the fire happened in the post-fire area due to drought. Less rain, mostly haze, and low water-table depth were observed in February, considered

the dry season. Thus, the before-rain sampling was carried out in February of the drought season.

b) After-rain

The samples were referred to as 'after-rain' as precipitations were observed after the fire happened in the post-fire area due to the rainy season. The water table increased because of the light rain and thunderstorm observed in May, acknowledged as the rainy season during sampling. So, the after-rain sample sampling was collected in May of the rainy season.

4.3.3 Description of plots and sample preparation

For the purpose of post-fire sampling, data collection was conducted in Compartment 99, while pre-fire data was collected from compartment 1, in accordance with permissions granted by the authors (see **Appendix E**). Each compartment was equipped with four designated plots, illustrated in **Figure 24**. According to Sinclair et al., (2020), peat samples were collected by digging one to four pits at each site, with this study collecting three pits per plot, specifically between trees or shrubs in forests. In which in this study, the plots were positioned along the canal, maintaining a 50-meter distance between each plot within the designated area.

The peat auger and corer were used for sampling, then bagged in a plastic bag, and stored in the laboratory for physical and chemical analysis. The auger was used to collect peat for chemical analysis, and the corer was used for physical analysis. In each plot, four different peat depths are sampled 4 different levels

(Figure 25) and were classified as follows:

- a) 0 cm;
- b) -50 cm;
- c) -100 cm;
- d) -150 cm.

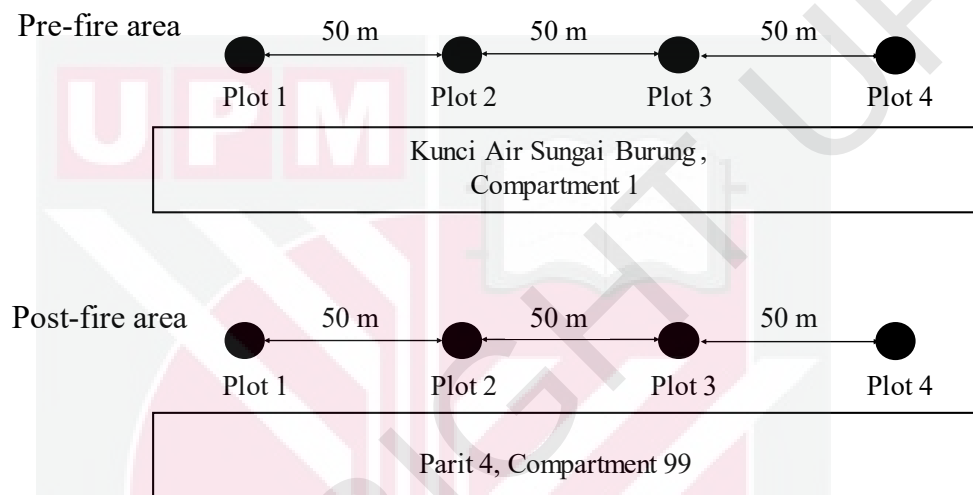


Figure 24: The plot was established in post-fire (Compartment 99) and pre-fire areas (Compartment 1) of the RMFR. Kunci Air Sungai Burung is the canal representative in the pre-fire area, and Parit 4 is the canal representative for the post-fire area.

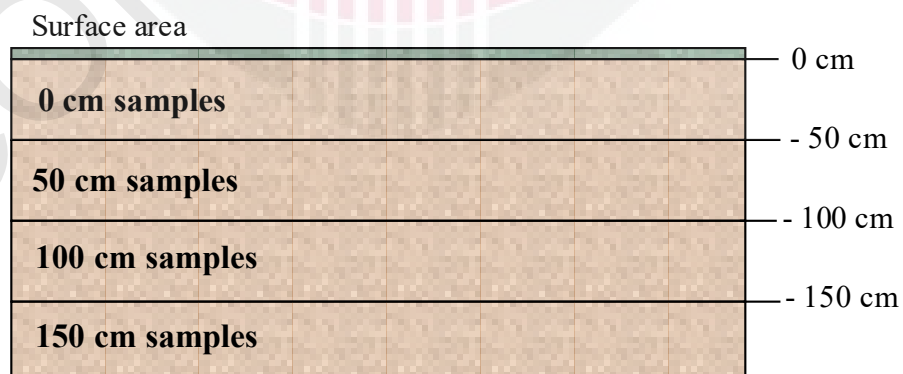


Figure 25: Illustration of the samples collected at four levels of peat depth (0 to -150 cm) from the surface, classified as 0 cm (surface), -50 cm, -100 cm, and -150 cm samples at each plot.

To prepare the peat for further analysis, the peat samples were dried before conducting the physical and chemical properties (Dettmann et al., 2021). For chemical analysis, the samples were oven-dried at 60°C until they reached a constant weight (Chen and Twilley, 1999; O'Kelly, 2005; Gandois et al., 2014). For physical properties of bulk density and moisture content, these properties were determined using the core method and oven-dried at a temperature of 105°C (Aina & Periaswamy, 1985; Dettmann et al., 2021; Lal, 2009).

4.3.4 Description of peat properties evaluation

Dry bulk density, wet bulk density, moisture content, and organic matter content were analysed for the physical properties of peat in this chapter. The Dry (D_b) and wet (D_{bw}) densities were calculated from the experiment as follows:

$$D_b = \frac{\text{Mass of solids}}{\text{Vol. of peat}} \text{ kg/m}^3 \quad \text{Equation 1}$$

$$D_{bw} = D_b + \theta \text{ kg/m}^2 \quad \text{Equation 2}$$

where θ = volumetric water content

$$\text{Moisture content} = \frac{\text{Mass of wet peat} - \text{Mass of Dry peat}}{\text{Mass of Dry peat}} \times 100\% \quad \text{Equation 3}$$

As per the peat chemical properties, the properties that were selected to be important factors determining the importance of peat are:

- a) Acidity (pH);
- b) Cation exchange capacity (CEC);
- c) Total nitrogen (N), phosphorus (P), carbon (C), and;
- d) Extractable ($\mu\text{g/g}$) of potassium (K), magnesium (Mg), sodium (Na), and calcium (Ca).

4.3.5 Description of the statistical analysis

A Shapiro-Wilk test was performed to determine the distribution of the peat samples ($p < 0.05$). Based on the outcome, further statistical analyses were conducted to compare the post-fire and pre-fire peat samples (Mann-Whitney test) and the Kruskal-Wallis's test to summarise the peat samples of post-fire and pre-fire peat properties. The statistical analysis will also be presented in individual tables of **Table 10** and **Table 12** for physical analysis and **Table 11** and **Table 13** for chemical analysis. The results and discussion of the pre-fire area's physical and chemical properties assessment will be presented in section 4.4.1, and the post-fire site will be presented in section 4.4.2.

4.4 Results and discussion

4.4.1 Pre-fire history peat properties

The pre-fire area has a history of zero fire occurrences (**Appendix F**). The finding will contribute to the idea of a pristine peat swamp forest in Malaysia before the fire happened. In this chapter, we hypothesised that the peat properties would differ before and after rain. Thus, this section discussed peat conditions before and after rain for chemical and physical properties. The physical properties of dry bulk density, wet bulk density, organic content, and moisture content are presented in **Table 10** in sub-section 4.4.1.1. Besides, the chemical properties for pre-fire history conditions are explained in **Table 11** in sub-section 4.4.1.2.

4.4.1.1 Physical properties of pre-fire peat

The pre-fire peat samples indicate that the dry bulk density (D_b) ranges from 251 ± 1 to 266 ± 3 kg/m³ for the samples taken before the rain and 242 ± 11 to 285 ± 4 kg/m³ for the samples taken after the rain (**Table 10**). The mean score of the D_b is 23.00 for the surface, 10.50 for -50 cm, 13.38 for -100 cm, and 19.13 for -150 cm depth. For wet bulk density (D_{bw}), it ranges from 502 ± 6 to 556 ± 11 kg/m³ for the samples taken before the rain and 529 ± 11 to 539 ± 3 kg/m³ for the samples taken after the rain. The mean score of the D_{bw} is 5.88 for the surface, 20.38 for -50 cm, 19.50 for -100 cm, and 20.25 for -150 cm depths. The findings in this chapter were similar to previous research, ranging from 200 kg/m³ to 236.5 kg/m³ (Lailan et al., 2004; Katimon and Melling, 2007). A more diverse forest in Sarawak, Malaysia, and Pelalawan, Indonesia, has a statistically lower bulk density, which ranges from 110 to 146 kg/m³ (Saharjo and Nurhayati, 2003; Melling et al., 2005; Yule and Gomez, 2009). A dry density was determined to understand soil density in a dry state to compare the density of peat samples, which was linked to the moisture content as the moisture was removed from the dry density.

The Kruskal Wallis test suggested that the dry bulk density ($p=0.035$) and the wet bulk density ($p=0.003$) were statistically significant. The pattern was portrayed in **Figure 26**, showing the statistically significant ($p<0.05$) of the dry and wet bulk densities for both samples taken before rain and after rain. The peat samples' wet density increases by increasing moisture content. Moisture increases because expanding past samples with water will make them denser (Huang & Rein, 2016).

Table 10: The mean values (n=4) of physical properties of peat in the pre-fire area.

Type	Properties	Depth (cm)			
		0 (Surface)	-50	-100	-150
Pre-fire before rain	D_b (kg/m ³)*	266 ± 3	251 ± 1	251 ± 4	258 ± 4
	D_{bw} (kg/m ³)*	502 ± 6	556 ± 11	543 ± 5	545 ± 11
	Organic matter content (%)	86 ± 3	81 ± 2	82 ± 3	84 ± 1
	Moisture content (%)	528 ± 48	443 ± 20	448 ± 18	501 ± 16
Pre-fire after rain	D_b (kg/m ³)*	266 ± 3	259 ± 5	263 ± 3	267 ± 4
	D_{bw} (kg/m ³)*	513 ± 12	529 ± 11	535 ± 4	539 ± 3
	Organic matter content (%)	80 ± 5	82 ± 1	81 ± 1	82 ± 2
	Moisture content (%)	525 ± 49	464 ± 41	482 ± 27	594 ± 46

Note:
 D_b = Dry density of peat; D_{bw} = Wet density of peat
 *=The mean was a statistically significant value within the depth (Kruskal-Wallis H test)

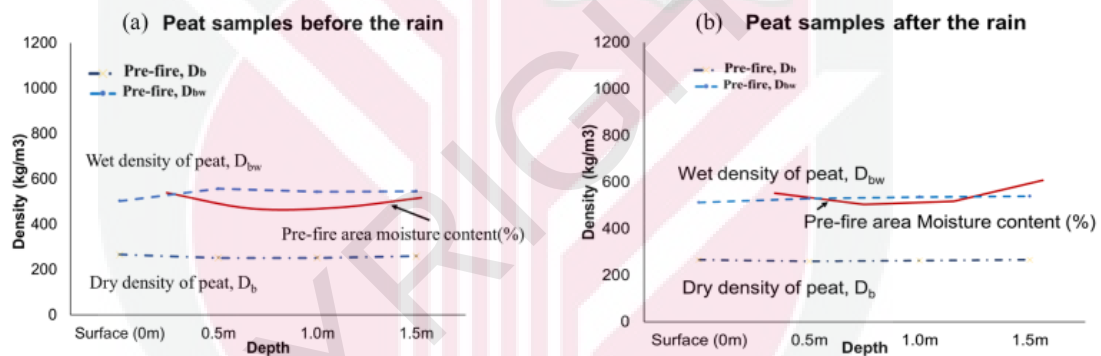


Figure 26: Wet density of peat (D_{bw}) and Dry density of peat (D_b) VS moisture content (MC, %) in pre-fire areas ($p < 0.05$) during the (a) Peat samples taken before the rain and (b) Peat samples taken after the rain.

In the pre-fire area, peat samples show that the moisture content for the samples collected before rain is $443 \pm 20\%$ to $528 \pm 48\%$, and $464 \pm 41\%$ to $594 \pm 46\%$ for the samples collected after rain. Also, moisture content has a significant difference ($p = 0.014$) within the depth with the mean rank of 8.13 (surface), 16.13 (-50 cm), 18.75 (-100 cm), and 23.00 (-150 cm). Peat has high water retention to store water six times its dry weight, making it suitable for water storage (Perdana et al., 2018). High moisture is related to the high organic matter, minerals, and air, making it very soft, crumbly, and dark brown (Calvert

et al., 1991; Mohamad et al., 2020). Both study areas have high moisture content, suggesting no different values between the areas ($p>0.05$). Peat may exhibit a sponge effect, such as efficiently removing oxidised sulphate by wet deposition, soaking up rain during the rainy season, and slowly releasing moisture in the dry season (Krivtsov et al., 2008).

Malaysia's hot weather can influence the peat's decomposition rate, which is related to the organic matter content of peat. In Malaysia, peat is classified as having high organic content under permanent water saturation (Mohamad et al., 2020). The decomposition degree of peat depends on the peat-forming environment; peat that develops in a hot and dry climate is more likely to be highly decomposed (Jinming & Xuehui, 2009). Thus, the organic matter content in the pre-fire area ranged from $81\pm2\%$ to $86\pm3\%$ (peat samples collected before rain) and $80\pm5\%$ to $82\pm1\%$ (peat samples collected after rain).

The findings also suggested that the peat samples within the depth do not have a significant difference in their values ($p=0.729$). It might be due to the decomposition of the peat soil organic matter succeeds by interacting with the abiotic and biotic factors such as climatic and time length of the plant remains, which alters the physical and chemical properties and anthropogenic influences (Murayama and Zahari 1996; Yule and Gomez, 2009; Bragazza et al., 2013; Starr and Vasander 2021). The peat acidity also influences the total carbon and organic matter content (Azizan et al., 2021). Thus, the chemical properties of the peat, such as pH values, are important to be identified.

4.4.1.2 Chemical properties of pre-fire peat

In previous literature, the pH values of peat ranged from 2.6 to 4.6 and might decrease down the depth in waterlogged, nutrient-poor, anaerobic peat swamps (Melling et al., 2005; Yule and Gomez, 2009; Grozav and Rogobete 2010; Huat et al., 2011; Khadiran et al., 2014). However, this chapter found that the pH value did not have a significant value ($p>0.05$) down the depth. In this chapter, the pre-fire area's pH values were statistically lower, ranging from 3.5 ± 0.1 to 3.6 ± 0.1 for the samples of peat collected before the rain, and increased to 4.1 ± 0.0 to 4.2 ± 0.0 pH values after the rain. Based on the findings, moisture content might contribute to the less acidic peat samples after the rain. The rain is also related to peat samples' higher cation exchange capacity when they become more alkaline, ranging up to 8.6 pH value (Purnamasari et al., 2021).

The cation exchange capacity (CEC) is important in peat soil as it functions to hold the exchangeable nutrition as it is related to pH buffering, wherein higher CEC have an increased ability to absorb and provide nutrients when the pH is high (Altland et al., 2014; Purnamasari et al., 2021). The pre-fire area indicates the CEC ranges from 49.2 ± 1.3 to 58.4 ± 2.1 cmol/kg for the peat samples before the rain and increases to 107.1 ± 13.6 cmol/kg to 143.5 ± 39.5 cmol/kg for the peat samples after the rain. The high rainfall increases the organic matter and allows the peat to undergo rapid decomposition with their fungi communities, such as Ascomycota (Fatubarin & Olojugba, 2014; Mishra et al., 2021).

Nitrogen (N) is of the most abundant elements in the peat soil besides carbon

and sulphur but is primarily not available in organic forms (Håkan & Jeglum, 2013). The organic nitrogen content is a fraction of the soil's organic compound containing carbon. In the nitrogen cycle, inorganic nitrogen follows the process of fixation and denitrification, wherein fixation converts dinitrogen gas to a chemically reactive form. Denitrification is the conversion of nitrate to the various gaseous form of nitrogen in the atmosphere under oxygen-limiting conditions in the presence of carbon (Peterson et al., 2022).

This work determines the total N content of the peat samples, which is bound in soil organic matter and consist of organic forms and inorganic forms such as ammonium (NH_4^+) and nitrate (NO_3^-), wherein the inorganic nitrogen is liberated from the organic nitrogen sources such as proteins and amino sugars. The pre-fire nitrogen content will contribute to understanding the peat nitrogen content in the pristine peat swamp forest. The findings indicate a statistically higher nitrogen content compared to the post-fire area, which ranges from $1.2 \pm 0.0\%$ to $1.6 \pm 0.0\%$ for the dry season and $1.3 \pm 0.0\%$ to $1.6 \pm 0.1\%$ for the rainy season. Further analysis to determine the significant difference within the depth suggested that the peat depth has different values ($p < 0.001$) with mean ranks from 28.5 for surface, 14.00 for -50 cm, 11.69 for -100 cm, and 11.81 for -150 cm depth. The P and K are lower in forested land or pre-fire area, comparable to the post-fire area of compartment 1 (Salim et al., 2021). Thus, the pre-fire site has a significant value difference within the depth ($p < 0.05$). Findings on the pre-fire peat samples show statistically lower P content that ranges from 0.02 ± 0.0 to $0.1 \pm 0.0\%$ (before rain) and 0.02 to $0.04 \pm 0.0\%$ (after rain).

The phosphorus level is affected by the rain. Additionally, further analysis to

determine the statistical difference within the depth shows that surface to -150 cm depth has different values ($p < 0.001$) with mean values of 27.75 (surface), 14.13 (-50 cm), 11.69 (-100 cm), and 9.38 (-150 cm). The potassium of the pre-fire area indicates that the peat ranged from 56.1 ± 15.0 to 268.3 ± 12.0 $\mu\text{g/g}$ (before rain) and 13.3 ± 6.8 to 140.6 ± 29.6 $\mu\text{g/g}$ (after rain). There is a significant difference within the depth ($p = 0.001$) with the mean value of 27.88 (surface), 14.31 (-50 cm), 12.69 (-100 cm), and 11.13 (-150 cm) for the potassium content. The summary of the N, P, and K significantly different on the surface compared to the underground (-50 cm to -150 cm) were presented in **Figure 27**.

Table 11: The chemical properties of peat in the pre-fire area according to peat depth.

Type	Properties	Depth (cm)			
		0 (Surface)	-50	-100	-150
Pre-fire before rain	pH	3.5 ± 0.1	3.6 ± 0.0	3.5 ± 0.1	3.6 ± 0.1
	CEC (cmol/kg)	58.4 ± 2.1	50.5 ± 0.4	49.2 ± 1.3	52.7 ± 0.9
	C %	43.8 ± 0.9	44.5 ± 1.1	46.1 ± 1.8	47.5 ± 3.8
	N %*	1.6 ± 0.0	1.2 ± 0.0	1.2 ± 0.0	1.2 ± 0.1
	P %*	0.1 ± 0.0	0.02 ± 0.0	0.03 ± 0.0	0.02 ± 0.0
	K ($\mu\text{g/g}$) *	268.3 ± 12.0	69.2 ± 11.3	78.7 ± 16.3	56.1 ± 15.0
	Ca ($\mu\text{g/g}$)	188.7 ± 89.7	111.8 ± 104.4	113.3 ± 97.7	234.3 ± 123.0
	Mg ($\mu\text{g/g}$)	354.2 ± 14.5	273.3 ± 31.0	302.5 ± 38.0	324.5 ± 29.5
	Na ($\mu\text{g/g}$)	146.2 ± 12.2	133.7 ± 6.8	151.6 ± 12.8	135.2 ± 1.8
Pre-fire after rain	pH	4.1 ± 0.1	4.1 ± 0.0	4.1 ± 0.0	4.2 ± 0.0
	CEC (cmol/kg)	107.1 ± 13.6	118.9 ± 19.5	138.8 ± 13.5	143.5 ± 39.5
	C %	42.1 ± 2.2	45.1 ± 1.0	44.7 ± 0.6	46.2 ± 1.4
	N %*	1.6 ± 0.1	1.3 ± 0.0	1.3 ± 0.0	1.3 ± 0.0
	P %*	0.04 ± 0.0	0.03 ± 0.0	0.03 ± 0.0	0.02 ± 0.01
	K ($\mu\text{g/g}$) *	140.6 ± 29.6	32.3 ± 21.1	13.3 ± 6.8	16.8 ± 10.1
	Ca ($\mu\text{g/g}$)	107.4 ± 22.2	90.3 ± 27.3	116.0 ± 27.2	102.0 ± 10.8
	Mg ($\mu\text{g/g}$)	53.5 ± 13.4	69.2 ± 18.7	64.2 ± 17.1	53.7 ± 7.9
	Na ($\mu\text{g/g}$)	124.0 ± 8.2	150.9 ± 7.7	138.9 ± 8.6	144.8 ± 5.4

Note:

*=The mean was a statistically significant value within the depth (Kruskal-Wallis H test)

The calcium of the pre-fire peat for the peat samples before the rain ranges from 111.8 ± 104.4 to 234.3 ± 123.0 $\mu\text{g/g}$, wherein the rain reduces the Ca content to

90.3±27.3 to 116.0±27.2 µg/g. The peat depth from the surface of -150 cm depth shows no significant difference within the depth, $p=0.783$. Similar to N, P and the extractable K and Ca content also show significant values between the burnt and unburnt areas ($p<0.05$), as summarised in **Figure 28**. The CEC influences the absorption of large quantities of calcium (Ca). Nevertheless, when the Ca levels are too high, some plants accumulate, depressing the uptake and reduction of the amount of K (Håkan & Jeglum, 2013).

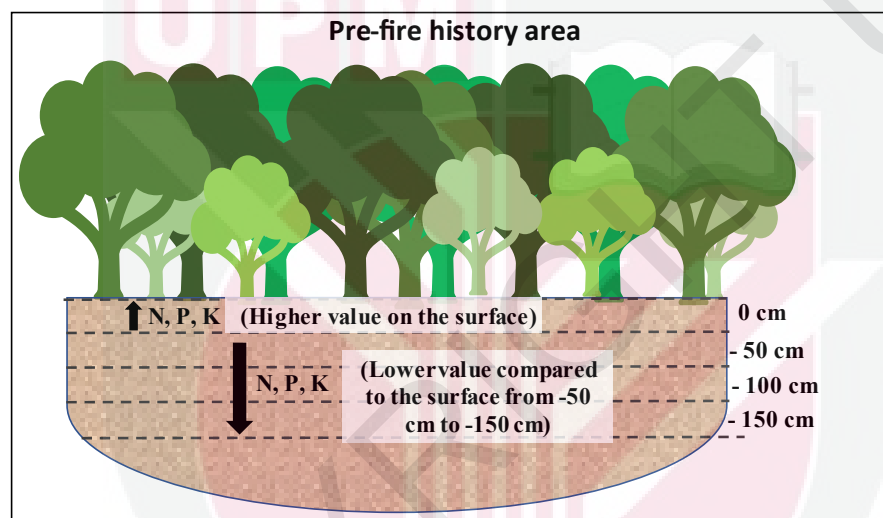


Figure 27: Summary of the chemical properties which significantly different within the depth ($p<0.05$).

The acidic peat will affect the availability and number of macronutrients such as Exchangeable K, Ca, Mg, Cu and Zn (Maftu'ah & Nursyamsi, 2019). Higher CEC will influence the nutrient content of the peat (Sundari, 2022). In this case, there are almost similar findings of the peat during the dry season, where (Yule and Gomez, 2009) found that the magnesium content was from 300 µg/g to 600 µg/g. In the pre-fire area, peat samples collected before the rain have higher Mg content that ranges from 273.3±31.0 to 353.2±14.5 µg/g and reduced to 53.5±13.4 to 69.2±18.7 µg/g after the rain.

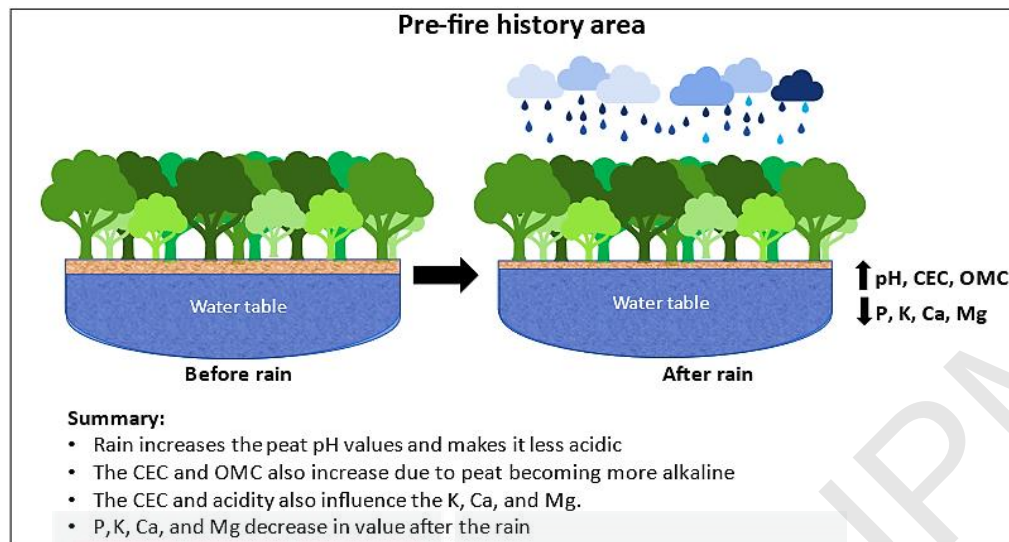


Figure 28: Summary of the effect of rain on the peat chemical properties in the pre-fire history area.

Moreover, no significant differences within the depth ($p > 0.05$) were analysed, suggesting that the peat samples' Mg content was about the same. On the other hand, the rain does not impact the Na content in the pre-fire area. The samples collected before rain range from 133.7 ± 6.8 to 151.6 ± 12.8 $\mu\text{g/g}$, and 124.0 ± 8.2 to 150.9 ± 7.7 $\mu\text{g/g}$ after the rain. Also, further analysis using Kruskal Wallis suggested no significant difference within the depth ($p > 0.05$).

4.4.2 Post-fire history peat properties

The post-fire condition has a repeated fire occurrence history, which is an almost yearly event (**Appendix F**). Thus, the finding will contribute to the idea of the disturbed peat swamp forest in Malaysia after the fire happened. In this chapter, we hypothesised that the repeated fire area's peat properties would differ before and after rain. Thus, this section discussed peat conditions before and after the rain for chemical and physical properties. The physical properties of dry bulk density, wet bulk density, organic content, and moisture content are

presented in **Table 12** in sub-section 4.4.2.1. Besides, the chemical properties of post-fire history conditions are shown in **Table 13** in sub-section 4.4.2.2.

4.4.2.1 Physical properties of post-fire peat

The post-fire area dry bulk density (D_b) ranged from $242 \pm 11 \text{ kg/m}^3$ to $344 \pm 78 \text{ kg/m}^3$ (**Table 12**). Due to fire impact, no significant changes within the peat samples taken before rain and after rain it ranges from $255 \pm 8 \text{ kg/m}^3$ to $344 \pm 78 \text{ kg/m}^3$ and $242 \pm 11 \text{ kg/m}^3$ to $285 \pm 4 \text{ kg/m}^3$, respectively. Meanwhile, the wet bulk density (D_{bw}) in the post-fire area ranges from $504 \pm 4 \text{ kg/m}^3$ to $727 \pm 175 \text{ kg/m}^3$ (before rain) and 457 ± 39 to $592 \pm 18 \text{ kg/m}^3$ (after rain). Further analysis indicates that there was a statistically significant difference in dry density depths ($p=0.003$), with a mean D_b score of 7.00 (Surface), 14.88 (-50 cm), 21.13 (-100 cm), and 23.00 (-150 cm). For D_{bw} , it shows a statistically significant difference ($p=0.005$), wherein the mean score for the D_{bw} is 8.50 for surface (0 cm), 13.13 for -50 cm, 22.63 for -100 cm, and 21.75 for -150 cm depth.

The moisture content of peat is an essential element for the peat to prevent it from drying. Mann-Whitney test indicates that the moisture content has an almost similar value for post-fire and pre-fire areas ($p>0.05$). For post-fire areas, it ranged from 494 ± 128 to $839 \pm 207\%$ for the sample taken before the rain and ranged from 338 ± 42 to $1053 \pm 112\%$ after the rain. For peat depths, further analysis suggested that the peat depth does not have a significant difference ($p=0.288$). Wösten et al., (2006) pointed out that fire emits significant gaps in the forest, leading to increased wind circulation and greater sunlight penetration to the forest floor, which might contribute to the findings of moisture and density.

As a result, temperature and humidity increase, and soil moisture on the surface decreases, making it vulnerable to fire. The ignition probability depends on the moisture content of dried peat (Krivtsov et al., 2008). **Figure 29** shows that moisture content was statistically higher by the depth, parallel to the wet density increases by the depth.

Table 12: The mean values (n=4) of physical properties of peat in post-fire area (0 cm to -150 cm)

Type	Properties	Depth (cm)			
		0 (Surface)	-50	-100	-150
Post-fire; Before rain	D_b (kg/m ³)*	255 ± 8	255 ± 15	344 ± 78	278 ± 5
	D_{bw} (kg/m ³)*	523 ± 24	504 ± 4	727 ± 175	546 ± 5
	Organic matter content (%)	70 ± 11	67 ± 5	72 ± 9	61 ± 8
	Moisture content (%)	494 ± 128	561 ± 79	746 ± 130	839 ± 207
Post-fire; after rain	D_b (kg/m ³)*	242 ± 11	276 ± 1	282 ± 5	285 ± 4
	D_{bw} (kg/m ³)*	457 ± 39	551 ± 5	577 ± 20	592 ± 18
	Organic matter content (%)	44 ± 15	83± 2	83 ± 4	86 ± 1
	Moisture content (%)	338 ± 42	724 ± 23	945 ± 84	1053 ± 112

Note:
 D_b = Dry density of peat; D_{bw} = Wet density of peat
 *=The mean was a statistically significant value within the depth (Kruskal-Wallis H test)

Heat impacts the peat by reducing its organic matter (Ibrahim et al., 2019). However, this chapter indicates that the pre-fire and post-fire areas have similar organic matter content values ($p>0.05$). The difference in peat depth also did not have significant values ($p>0.05$), as shown in **Table 12**. The post-fire areas organic matter content ranged from 61±8% to 72±9% and 44 ±15% to 86±1% for the before-rain and after-rain peat samples, respectively. Further analysis of the peat samples within the depth indicates that the peat depth in the burnt area

does not have a significant difference, $p=0.424$.

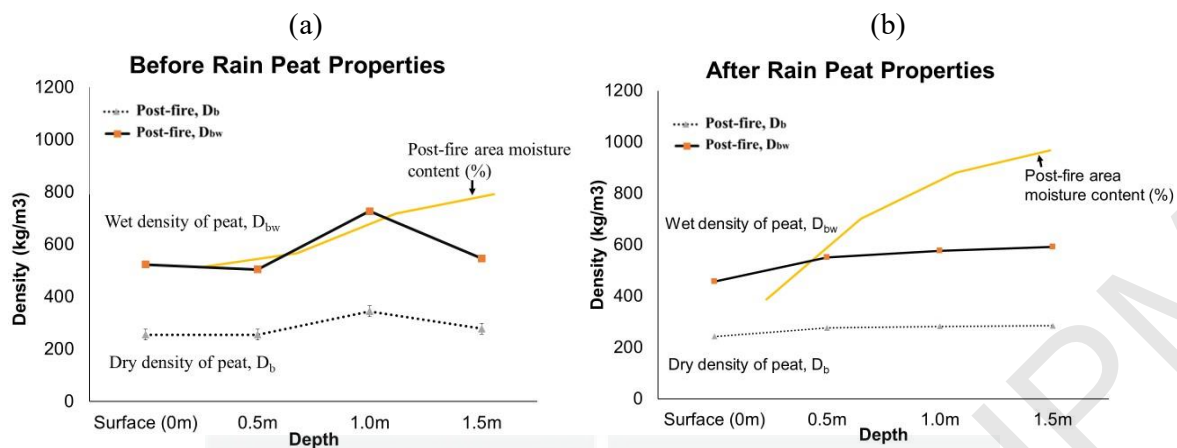


Figure 29: Wet density of peat (D_{bw}) and Dry density of peat (D_b) VS moisture content (MC, %) in post-fire areas during the (a) Peat samples taken before the rain and (b) Peat samples taken after the rain.

4.4.2.2 Chemical properties of post-fire peat

Peat is acidic, with a low pH level of about 5.5 -3.8, similar to Malaysia's peatland water, which is reported as low as 2.6 to 3.5 (Yule and Gomez, 2009; Könönen et al., 2015). Pre-fire and post-fire area in this chapter suggest that the pH value is statistically significant ($p<0.001$), wherein the post-fire peat becomes more alkaline (**Table 13**). It was perhaps due to the increase in ash deposition at the surface of the peat after burning, which influenced the peat acidity. Fire can increase the pH level by leaving ashes behind, reducing peat acidity by 6% (Goforth et al., 2005; Ibrahim et al., 2019; Sulaeman et al., 2021). The results also shows that the peat pH values were the same from 0 cm to 150 cm depth ($p>0.05$), in which it ranges from 4.8 ± 0.1 to 4.9 ± 0.2 pH value (before rain) and 5.2 ± 0.1 to 5.4 ± 0.1 pH value (after rain). A vertical movement of dissolved cations into the soil will increase the bacteria activity and groundwater level, which will have a pH of about 6 when the flow is high (Fatubarin & Olojugba, 2014; Jackson et al., 2009; Yli-Halla et al., 2022).

Table 13: The chemical properties of peat in post-fire area according to peat depths

Type	Properties	Depth (cm)			
		0 (Surface)	-50	-100	-150
Post-fire before rain	pH	4.8 ±0.4	4.9 ±0.1	4.9±0.2	4.8 ±0.2
	CEC (cmol/kg)	43.6 ±4.6	45.8 ±1.5	46.3 ±4.0	46.6 ±4.2
	C %	36.3 ±6.3	37.8 ±4.7	43.1 ±2.6	46.4±2.5
	N %*	1.0 ±0.2	1.1 ±0.1	1.0 ±0.1	1.0 ±0.1
	P %*	0.1 ±0.0	0.1 ±0.0	0.04 ±0.0	0.1 ±0.0
	K (µg/g) *	167.1 ±22.5	168.7 ±6.6	171.1 ±14.4	160.0 ±22.5
	Ca (µg/g)	1619.6±380.4	1846.5 ±254.4	1243.7±386.5	1408.4±315.6
	Mg (µg/g)	195.3 ±8.9	233.2±13.4	223.5 ±5.6	201.0 ±13.0
	Na (µg/g)	56.4 ±6.2	68.6 ±8.4	61.3 ±3.3	60.1 ±2.3
Post-fire after rain	pH	5.4 ±0.1	5.2 ±0.1	5.2 ±0.1	5.2 ±0.1
	CEC (cmol/kg)	54.8 ±12.1	101.6 ±10.3	95.0 ±12.8	91.5 ±13.8
	C %	27.3 ±9.2	47.5 ±1.3	47.1 ±2.0	48.2 ±1.3
	N %*	0.9 ±0.2	1.1 ±0.1	1.1 ±0.1	1.1 ±0.1
	P %*	0.04±0.0	0.04 ±0.0	0.1 ±0.0	0.04 ±0.0
	K (µg/g)*	141.7±30.6	112.9±22.7	103.7 ±21.9	79.1±27.0
	Ca (µg/g)	83.0 ±5.2	71.6±5.6	72.6 ±11.8	208.7 ±41.9
	Mg (µg/g)	51.1 ±3.7	49.6 ±2.4	52.4 ±4.7	56.0 ±6.6
	Na (µg/g)	44.7 ±2.8	51.0±1.5	57.0 ±2.7	48.5 ±1.7

Note:
 *=The mean was a statistically significant value within the depth (Kruskal-Wallis H test)

The increase in pH values is also associated with the eluvation involvement, leaching losses of the exchangeable bases that leave behind H and Al, carbon dioxide, and humic acid from the decay organic material (Huat, 2004; Isola et al., 2015). Thermal destruction of organic matter is one reason the CEC vanishes in the post-fire area and will be restored as biomass and rebuilds humus (Ulery et al., 2017). For the post-fire area, the CEC ranged from 43.6± 4.6 to 46.6± 4.2 (before rain) and 54.8 ±12.1 to 101.6 ±10.3 cmol/kg (after rain). Further analysis determining the significant values within the depth suggested that the post-fire peat samples do not have a significant difference within the depth from the surface to -150 cm depth ($p>0.05$).

Carbon (C) loss is very significant in areas that experience fire occurrence and were lengthily described in this paragraph. Burning in the peat swamp forest will release the carbon stored into the atmosphere (Posa et al., 2011; Rosenburgh et al., 2013). It is estimated that 5,800 tonnes of C per hectare were stored in a 10 m deep and, when released into the atmosphere during burning, contributed to climate change (Leete, 2006; Davies et al., 2010). Therefore, the role of C storage will be changed to a C source in the atmosphere (Hirano et al., 2012). The lower C content on the surface (**Table 11**), might be due to the sun's exposure and reduced amount. The sampling area is also near the fire break canal (Parit 4), which might influence the findings. The results show that the total carbon content (%) of the peat samples in post-fire areas ranged from $36.6 \pm 6.3\%$ to $46.4 \pm 2.5\%$ for the samples taken before the rain and $27.3 \pm 9.2\%$ to $48.2 \pm 1.3\%$ for the after the rain peat samples. The statistical analysis shows that the peat depth significantly differs ($p=0.011$) within the depth, with a mean rank of 10.63 for the surface, 15.50 for -50 cm, 18.38 for -100 cm, and 21.50 for -150 cm. It is in line with the findings in this chapter, wherein the C content is lower on the surface (0 cm) for $36.6 \pm 6.3\%$ (before the rain) and reduced to $27.3 \pm 9.2\%$ for the after the rain peat samples. Azizan et al., (2021) suggests that canopy loss results in greater exposure of the surface to the air and increased oxidative decay that leads to increased C loss. A fire that occurs causes the release of a significant amount of C into the atmosphere and changes the peat chemistry (Krivtsov et al., 2008; Mishra et al., 2021). Nevertheless, the peat concentration increases with depth in the forest area, which is relatively invariable with depth in the open sites (Könönen et al., 2015). Rainfall might flush the C downwards as the post-fire area is an open site directly hit by rain, wind, and sunlight.

Microbial activity also increases when the soil is rewetted and affects the soil C dynamics and N content which are then affected by the mouldering fire afterwards (Blazewicz et al., 2014; Fatubarin & Olojugba, 2014; Turetsky et al., 2015). Organic compounds such as phosphorus and nitrogen increase after burning (Saharjo & Nurhayati, 2003). The high phosphorus content increases as the bacteria, such as phosphate solvent, grow after the fire and other bacteria that have a role in nitrogen cycles (Syaufina & Ainuddin, 2011; Too et al., 2021). Brief views in the N, P, and K impact on the surface and lower ground (-50 cm to -150 cm) were illustrated in **Figure 30**.

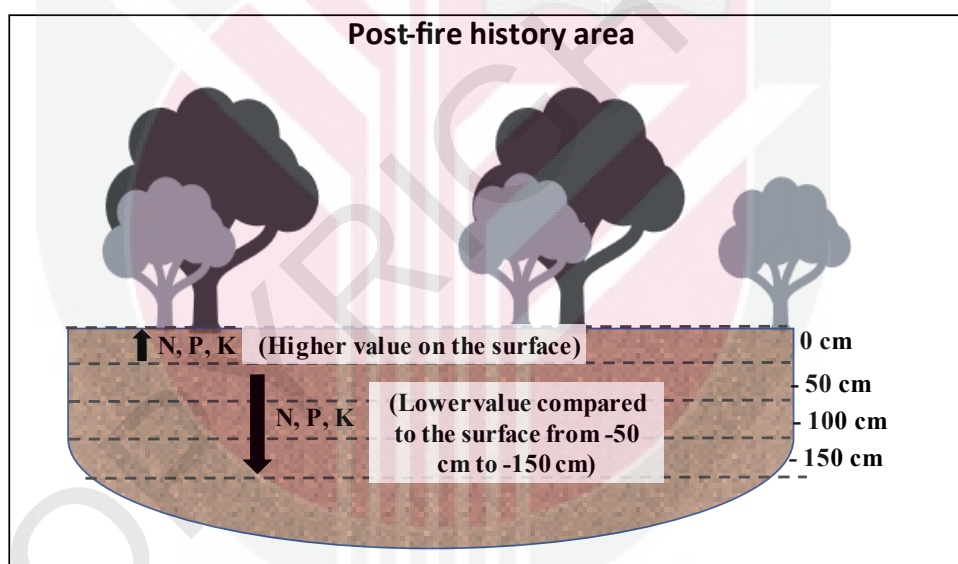


Figure 30: Summary of the chemical properties which significantly different within the depth ($p < 0.05$).

Before the rain peat samples range from 1.0 ± 0.1 to $1.1 \pm 0.1\%$, which statistically lower for the after-rain peat samples that ranges from 0.9 ± 0.2 to $1.1 \pm 0.1\%$. Further analysis suggested that the peat depth has no significant difference, $p = 0.807$ within the peat depth from the surface to -150 cm. The results suggest that the amount of nitrogen in from surface until -150 cm depth is almost the

same. It was observed in a previous study that the nitrogen content would decrease by about 6% because of volatilisation after a fire which is similar to this chapter (Sulaeman et al., 2021; Verma & Jayakumar, 2012). The volatilisation mentioned is related to the ammonia NH_3 loss not retained in soil and influenced by the moisture content, pH, precipitation, wind and other factors, wherein warm and moist peat is ideal for the ammonia loss (Peterson et al., 2022). Short-term degradation might increase the nutrients such as N, P and other micronutrients will happen after degradation but not in the long term (Mishra et al., 2021).

The phosphorus (P) content in the post-fire area ranges from $0.04 \pm 0.0\%$ to $0.1 \pm 0.0\%$ for before-rain and after-rain. Based on the Kruskal-Wallis's test, have no significant difference within the depth ($p=0.104$). However, the post-fire peat shows differently, wherein the peat depth has significant values ($p>0.05$) within the depth. From these findings, the fire had increased the amount of potassium (K) in peat because when it was burnt, it would return to the peat in the form of ashes (Pérez-Cabello et al., 2009). Thus, fire can change the chemical properties of peat. Compared to the pH value influence on the P availability, the pH has less impact on the K content of the peat (Håkan & Jeglum, 2013). The peat samples show no significant difference within the depth ($p>0.05$) for post-fire areas. The K ranges from 160.0 ± 22.5 to $171.1 \pm 14.4 \mu\text{g/g}$ for the dry season and 79.1 ± 27.0 to $141.7 \pm \mu\text{g/g}$ for the rainy season. The calcium (Ca) in the post-fire area were ranged from 1243.7 ± 386.5 to $1846.5 \pm 254.4 \mu\text{g/g}$ for the before-rain and 71.6 ± 5.6 to $208.7 \pm 41.9 \mu\text{g/g}$ for the after-rain. The Ca content in the post-fire area will increase because the pH value and the microbial activity are increasing (Wahyu et al., 2005; Binkley & Fisher, 2012). However, the rain

flushed the Ca content, which resulted in lower Ca content in the samples collected after the rain. The summary of the effect of rain on the chemical properties in the post-fire area is illustrated in **Figure 31**.

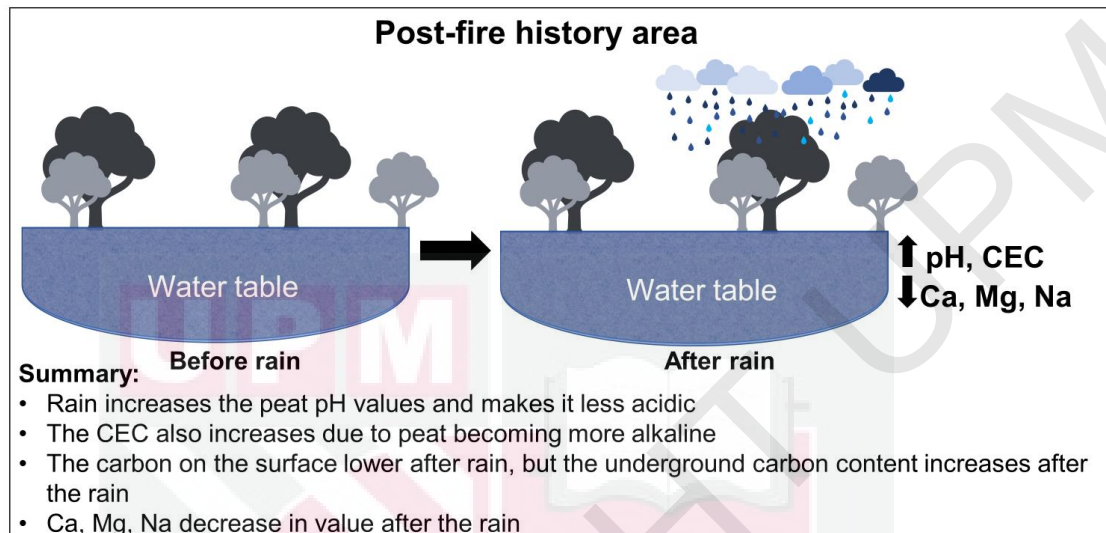


Figure 31: Summary on the effect of rain on the peat chemical properties in the pre-fire history area in RMFR.

The magnesium (Mg) content derived from past vegetation indicates a high exchangeable Mg (Ono et al., 2015). Therefore, less vegetation cover in the post-fire area might contribute to less Mg in post-fire peat samples. The results indicate that the Mg content in this area ranges from $195.3 \pm 8.9 \mu\text{g/g}$ to $233.2 \pm 13.4 \mu\text{g/g}$ for the before-rain and $49.6 \pm 2.4 \mu\text{g/g}$ to $56.0 \pm 6.6 \mu\text{g/g}$ for after-rain. The sodium (Na) availability in the post-fire area ranged from $56.4 \pm 6.2 \mu\text{g/g}$ to $68.6 \pm 8.4 \mu\text{g/g}$ for the peat samples collected before-rain and $44.7 \pm 2.8 \mu\text{g/g}$ to $57.0 \pm 2.7 \mu\text{g/g}$ for the after-rain. Degraded land with intensive agricultural activity is statistically lower compared to the forest area (Salim et al., 2021), which is a similar pattern to this chapter. The Na content was not different in value within the depth in this area using the Kruskal Wallis ($p > 0.05$).

4.5 Conclusion of Chapter

Conservation and sustainable management of Malaysia's remaining peat swamp forests are pressing concerns (Mohd Azmi et al., 2009). The findings of this research in this chapter make a substantial contribution to the region by conducting physical and chemical analyses of pre-fire and post-fire areas. The results presented in this chapter encompass various physical and chemical properties including density, moisture content, organic matter content, pH values, cation exchange capacity, total carbon, nitrogen, phosphorus, and extractable potassium, calcium, magnesium, and sodium content. These analyses hold potential for understanding the short-term effects of restoration plans, which are essential for plant growth, encompassing nutrients such as N, P, S, C, and N (Ibrahim et al., 2019; Nurulita et al., 2016; Sundari, 2022). Peat nutrient content is influenced by external and internal factors, impacting surface and vertical profiles (Bragazza et al., 2013; Könönen et al., 2015). Slash-and-burn practices common in Southeast Asia temporarily enhance soil fertility but lead to short-lived benefits (Ibrahim et al., 2019).

The findings reveal significant differences between pre-fire and post-fire areas, with rainfall affecting post-fire peat properties. Dry bulk density is notably higher post-fire due to water evaporation and peat densification. Wet bulk density remains similar, suggesting comparable rewetting abilities. Ash deposition from underground fires and rainfall affect peat pores (Ibrahim et al., 2019; Jinming & Xuehui, 2009). Furthermore, the findings suggest that the CEC (cation exchange capacity) differs significantly between post-fire and pre-fire peat samples, with $p=0.017$. The research also demonstrates that total N content is

significantly lower ($p < 0.05$) in post-fire peat samples compared to pre-fire samples, attributed to ammonia loss as indicated by the Mann-Whitney test. Similar to nitrogen, phosphorus content also exhibits a significant difference ($p < 0.001$) between post-fire and pre-fire areas. Statistical analysis reveals higher Mg content in the pre-fire area than the post-fire area, with no significant depth-related differences ($p > 0.05$), indicating similar Mg content within the peat sample. Additionally, significant variations in calcium content are observed between burnt and unburnt areas ($p < 0.001$). While calcium content is higher in the burnt area, differences within the depth of burnt and unburnt peat samples are not statistically significant ($p > 0.05$).

Summarizing the peat properties of the samples, it becomes evident that properties such as pH, Np, P, Ca, Na, K, and Mg exhibit significant differences ($P < 0.05$) between pre-fire and post-fire areas. Furthermore, rain impacts properties in both areas, with significant effects on pH, CEC, calcium, magnesium, carbon and sodium content. Physical properties show significant differences in burnt areas' dry and wet density within the depth, while properties like nitrogen, phosphorus, and moisture content exhibit depth-related variations in both areas. These insights are crucial for peatland restoration efforts, serving as benchmarks for monitoring progress and guiding further research (Nurulita et al., 2016; Sławski et al., 2022). Restoration interventions have shown variable success rates (Mishra et al., 2021).

CHAPTER 5

LOW AND HIGH FIRE FREQUENCIES PEAT PROPERTIES ADJACENT TO FIRE BREAK CANAL IN PEAT SWAMP FOREST

5.1 Summary of Chapter

Fire is a substantial threat to peat swamp forests due to both arson and accidental burning spreads into the forest reserve (**Chapter 3**). **Chapter 4** examines fire's impact on post-fire peat properties compared to pre-fire conditions, and this chapter investigates how varying fire frequencies affect the post-fire peat swamp. Canal implementation is highlighted for mitigation, and this chapter further studies peat properties near fire break canals. Frequent fire areas have waterlogged surfaces, unlike regions with fewer fires. The previous chapter noted that there needs to be more understanding of peat properties' impact on moisture. This chapter explores a deeper understanding of the peat properties that are vital to understanding moisture's post-fire importance, adding to **Chapter 6**'s moisture enhancement strategies.

This chapter was based on Musa, D.N.S., Mohd Tohir, M.Z., Huang, X., Abdullah, L.C., Md Said, M.S., Sulaiman, M.F. (2024). Tropical Forest Reserve's Peat Properties Adjacent to Fire-break Canal. **Journal of Forest Research**. 29, 35(1). <https://doi.org/10.1007/s11676-023-01679-2>.

5.2 Introduction

Fire poses a global threat, recurrently affecting various types of land, including forests. In Malaysia, the nation's forest types encompass diverse ecosystems,

such as mangrove and peat swamp forests (Omar, 2023). Tropical peat is composed of decomposed dead plant material and functions like a sponge, readily absorbing water and becoming fully saturated. However, during drought periods, peat can easily dry out, rendering it more susceptible to ignition. The resulting peat fires release greenhouse gases and particles, contributing to haze. Thus, constructing fire-break canals to curtail fire spread into forest reserves becomes imperative. Tropical peat swamps are inherently prone to poor drainage, leading to a waterlogged and swampy surface layer on the peat soil. This waterlogged condition originates from the decay of plant residues, a process that typically occurs at an accelerated pace (Taufik et al., 2019).

5.2.1 Effect of smouldering fire

Previous studies have examined how fires can alter peat properties, driven by slow spread rates and low temperatures characteristic of smouldering fires (Huang et al., 2015; Rein, 2009; Santoso et al., 2021). Forest fires occurring in peat swamp forests are closely associated with underground smouldering peat fires. These peat fires exhibit remarkable persistence and can endure for extended periods (Rein, 2013; Rein & Huang, 2021). Notably, an incident in Sabah endured for about six months due to the El-Niño phenomenon and approximately two months without El-Niño influence (SFD, 2017; SFD, 2020), resulting in substantial damage to the peat swamp ecosystem and impeding forest recovery (Davies et al., 2013).

The moisture content of peat tends to decrease significantly during intense water deficits caused by the drawdown of the water table and extensive burning

(Afdeni et al., 2016; Granath et al., 2016; Taufik et al., 2019), primarily during drought periods. While most studies have focused on fire impacts on physical properties such as density and moisture content, data regarding other chemical properties, such as lignin and cellulose content, are often lacking. While changes in lignin and cellulose content have been observed in boreal and temperate peat, their occurrence and impact on tropical peat subjected to varying fire frequencies remain unexplored.

Given that smouldering represents incomplete combustion (Rein, 2009; Hu et al., 2018), peat properties might indeed vary based on the duration of smouldering (Liu et al., 2023). A previous study by Sinclair et al., (2020) on peat properties in relation to distance from a canal primarily focuses on bulk density farther from the canal. Existing research on canal blocking is primarily cantered around smallholder farmers and large companies using agricultural land to control water levels for crop yield (Ward et al., 2021). The peat bulk density in post-fire areas is correlated with moisture content, influencing ignition and burn depth (Nelson et al., 2021). It is important to note that fire-induced changes in peat properties are influenced by the slow spread rate and low temperature characteristic of smouldering fires within peat (Huang et al., 2015; Rein, 2009; Santoso et al., 2021). The post-fire effects can be discerned by examining the physical and chemical properties of post-fire peat samples, which typically exhibit altered nutrient content (Könönen et al., 2015; Handayani & Maswar, 2019).

5.2.2 Beaufort Peatland and its fire history

In Malaysia, the peat swamp forest was gazetted as a forest reserve to protect the forest, in which Malaysia pledged to maintain 50% of the forest cover (Omar, 2023). The Sabah's peat swamp is unique and distinct from other peat swamps in Borneo; thus, high potential for research and conservation at an international scale can be achieved (Basintal et al., 2007). Studies show that fires frequently happen because people provide ignition sources (Sinclair et al., 2020). Human activities such as agriculture and land development can threaten this unique ecosystem. Anthropogenic factors cause fire to spread from the state land and alienated land to the forest reserve (FR). Based on the Annual Report of the Sabah Forestry Department (SFD, 2020), open burning and arson contributed to major fire cases, such as land clearing, which was set on fire (SFD, 2019; SFD, 2020). Based on the Annual Report by the Sabah Forestry Department of Malaysia, the peat swamp forest reserve burned annually for 706 ha (2015), 20,000 ha (2016), 60 ha (2017), 279 ha (2018), 1313 ha (2019), and 556 ha (2020) due to arson and open burning. Fire also can come from land clearing (SFD, 2019; SFD, 2020).

Therefore, a management effort by the Malaysian government is to construct a fire break canal (Munawi, 2014) near the repeatedly burnt area to reduce fire impact on peat. The fire break canal could also affect the peat properties, thus, further investigation on fire break canal impact at different fire severity is important. In this work, the fire break canal was implemented in Sabah, Malaysia, by the Sabah Forestry Department to isolate the forest reserve from nearby land as part of a mitigation effort in Beaufort peatland (**Figure 32**).



Figure 32: Above - The photo was taken after peat fire occurrences in Binsuluk Forest Reserve, 2019; Below - El-Niño phenomenon in 2016 affecting the Binsuluk Forest Reserve.
(Source: Sabah Forestry Department)

5.2.3 Objective

This chapter will complete the second objective of the thesis, which is to analyse the post-fire peat properties at different fire history conditions. Pre-fire and post-fire areas were discussed in **Chapter 4** regarding the peat properties in pristine forests and repeatedly burnt forests. The peat initially in fibric state with high organic matter content and lower bulk density turned into a sapric condition after burning. Thenceforth, further investigation on the impact of fire frequencies on peat properties will be covered in this chapter. This chapter also identified the

importance of fire break canal in reducing the effects of peat fire by comparing lower and higher fire frequency.

The objective of this chapter is to complement the findings in Chapter 4 and allocate information on peat properties at different fire frequencies in forest reserves and their effect on peat properties. This chapter hypothesised that the peat properties examined would be related to fire frequency. Also, it is hypothesised that the properties would change as the distance from the canal increased. However, this chapter expected that the fire frequency would influence the peat properties changes more than the distance from the canal. This chapter also hypothesised that the surface of the peat would be impacted the most to have significant changes and would pass through the peat. Thus, by examining the peat properties in post-fire areas with higher and lower fire frequencies near fire break canal, a wide knowledge of the impact of peat fire of peat can be understood. The importance of fire break canals to lower the fire frequency can be acknowledged to reduce the fire frequency. Therefore, this work aims to highlight the influence of different fire severity on peat properties near the fire-break canal in forest reserves on the specific objective as follows:

- 1) To analyse the properties of the peat from surface until -150 cm below the surface adjacent to fire break canal
- 2) To determine the impact of peat fire on peat at high fire severity area and low fire severity area; and
- 3) To investigate the changes in peat properties respective of distance from the canal.

5.3 Methodology

5.3.1 Description of study area

Beaufort peatland was chosen as study area for this chapter as it has the required condition for low and high fire frequencies occurrences in peat swamp forest. Based on the Sabah Forestry Department Annual Report, several fire cases affecting forest reserves area in Beaufort peatland. Therefore, to determine further the impact on the post-fire conditions to represent the impact of post-fire at different fire frequencies, Klias Forest Reserve and Binsuluk Forest Reserve (FR) are chosen as specific study areas to represent the different fire frequencies, the description of the area was as follows:

1. Binsuluk Forest Reserve: High Fire Frequency (HFF): 88% of fire occurrences from 2013-2020 were observed, with less forest cover and in waterlogged conditions due to repeated burning. In 2020, the Binsuluk FR was burned for 80 ha due to clearing land during hot weather, causing the fire to be out of control and spread to the FR, which took two months to be extinguished (SFD, 2020). Fire Information for Resource Management System (FIRMS) indicates that the Binsuluk FR fire happened from February to April (Appendix G-Year 2020).
2. Klias Forest Reserve: Low Fire Frequency (LFF): 25% of fire occurrences from 2013-2020 were observed, and forest cover was intact and not waterlogged due to fewer fire occurrences. No fire incident occurred in Klias FR in 2020. FIRMS reported that the BFR is frequently burned compared to KFR since 2013-2020 (refer to **Appendix G**).

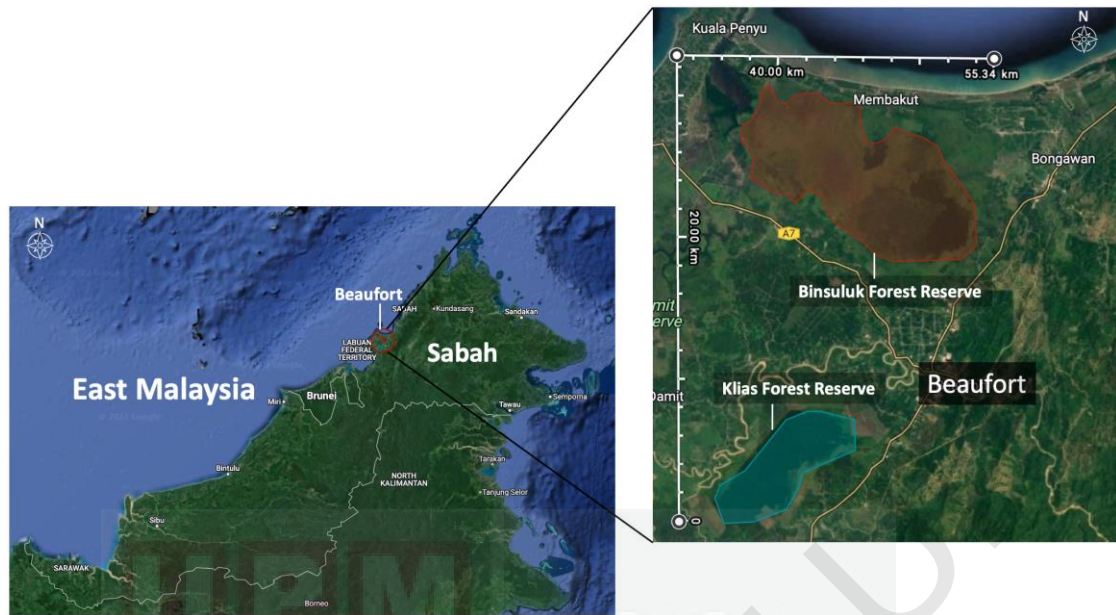


Figure 33: Beaufort peatland located in East Malaysia. The Binsuluk FR can be seen with less forest cover, and Klias with intact forest cover from the map.

Based on FIRM's hotspots within selected months from 2013-2020, it was summarized that 23 months of the fire history shows that 25% occur in Klias FR and 88% occur in Binsuluk FR. The outcomes help in the selection of Klias FR with a minimum fire incident as low fire frequency and Binsuluk FR that is frequently on fire as high fire frequency (**Figure 33**).

5.3.2 Description of the sampling area

The sampling area for high fire frequency and low fire frequency based on its vegetation cover and surface conditions were explained and shown in **Figure 35**, an illustration of **Figure 34** shows the condition of high fire frequency and high fire frequency. The tall grasses and ferns are signs of fire occurrences in an area. In the high fire frequency area, the vegetation cover was low, with fewer trees and covered by tall grasses as a pioneer species. In the high fire frequency area, the vegetation cover is intact, and a specific area of the

sampling area can be seen with tall ferns.

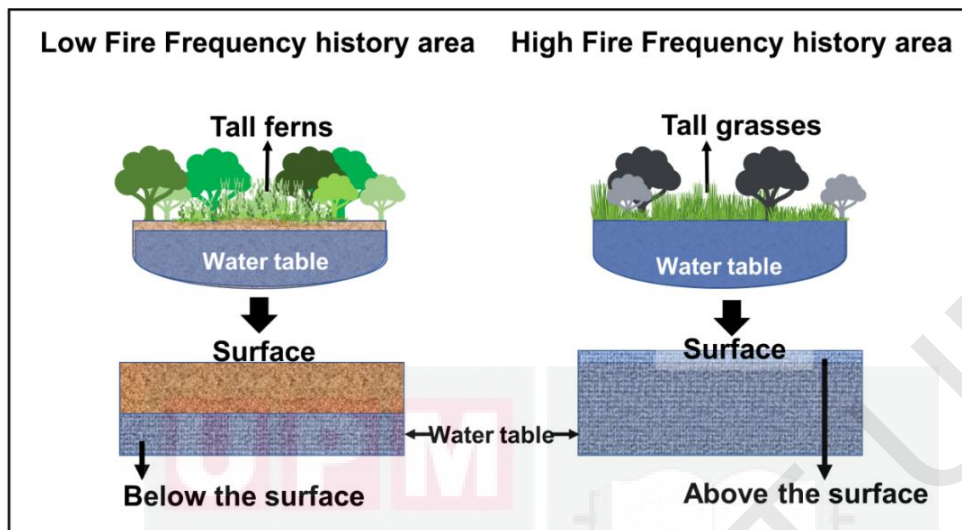


Figure 34: The surface condition of the lower fire frequency was almost similar to the pristine forest, meanwhile the repeatedly burnt forest of high fire frequency area were in a waterlogged state¹.

The previous literature indicates that the surface of the peat will be in a waterlogged condition in repeated fire incidents, thus, this chapter observe the surface of the peat in both high fire frequency and low fire frequency areas. The observation indicates that the low fire frequency area was similar to pristine forest wherein the surface of the peat is not waterlogged. Meanwhile, the high fire frequency is similar to previous literature, wherein the surface is waterlogged due to burning experiences.

In the high fire frequency area (**Figure 35**), the forest was still intact. However, there is a spot for the tall ferns in this area, indicating a fire has occurred. Similar to the high fire frequency area, the high fire frequency, repeated fire in the high fire frequency area results in a waterlogged state due to the peat being

¹ The illustration best describes the waterlogged condition and spotting tall ferns/grasses in each site presented in Figure 34.

considered a capric type at this stage. Typically, the density will increase and lower the OMC.

(a) Low Fire Frequency Area
Klias Forest Reserve



Vegetation cover

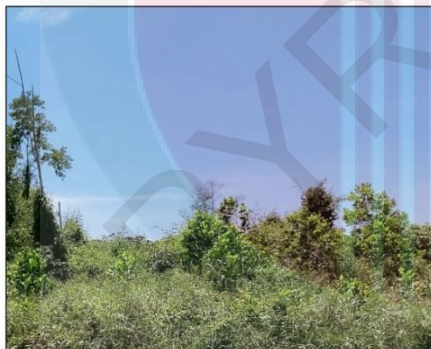
Large trees are visible, ferns are dominating the burned spot, and less tall grasses can be spotted in this area.



The peat surface

The water table is below the surface, causing it to be spongy when stepped but not waterlogged. The peat was similar to sapric or hemic condition which is similar to pristine peat swamp forest.

(b) High Fire Frequency Area
Binsuluk Forest Reserve



Vegetation cover

Large trees are not visible, tall grasses are the majority pioneer in this area, and ferns can be found dominating the certain area with burnt experience.



The peat surface

The water table is above the surface, causing it to be waterlogged. The peat was similar to sapric condition after the fire.

Figure 35: a) Intact Forest cover in Klias FR (LFF); b) Waterlogged condition on the surface in Binsuluk FR (HFF).

5.3.3 Description of plots and sample preparation

Comparable to the plot establishment that was along the fire break canal in

Chapter 4, four (4) plots near the fire break canal (**Figure 36**) in both forest reserves were constructed. However, due to the concern about the impact of the fire break canal on peat by distance, a transect line was aligned from the riparian zone of the fire-break canal further to 300 m long.



Figure 36: Right: The fire break canal that was constructed to reduce fire spread to the forest reserve from the alienated/state land to Binsuluk FR; Left: The fire break canal was constructed to reduce fire spread to the forest reserve in Klias FR, resulting in lower fire frequency occurrences.

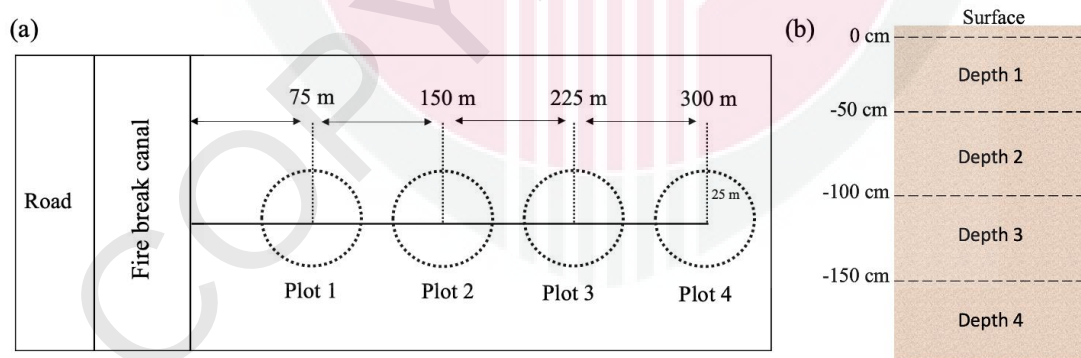


Figure 37²: a) Plot constructed near the fire-break canal at both study sites (HFF and LFF) for peat samples collections b) Samples of peat collected at a different level.

The four (4) plots were located at 75 m (Plot 1), 150 m (Plot 2), 225 m (Plot 3),

² The figure illustrated was not drawn to scale. It was illustrated to describe best the plots and sampling locations

and 300 m (Plot 4) as shown in **Figure 37a**. Each plot has three random sub-plots as sampling replications within a 25 m radius. A 100 cm square pit and -150 cm deep was dug at each sub-plot for peat samples collections at 0 cm, -50 cm, -100 cm, and -150 cm (see **Figure 37b**). The peat sampling was conducted in May for both areas. The peat sample is collected using a peat auger for chemical analysis (n=48) and a bulk density core ring (V=98.17cm³) for physical analysis (n=48). Thus, the samples collected are 4 (plots) x 4 (depths) x 3 (replications), resulting in 96 samples for each HFF and LFF areas.

Table 14: Description of the number of peat samples collected in the Klias and Binsuluk Forest Reserves, Beaufort (n=96).

Analysis	Descriptions	
	Depth	Plot
Physical analysis *	1. 0 cm, 2. -50 cm, 3. -100 cm, 4. -150 cm	5. Plot 1 (75 m from the canal) 6. Plot 2 (150 m from the canal) 7. Plot 3 (225 m from the canal) 8. Plot 4 (300 m from the canal)
Chemical analysis *	1. 0 cm, 2. -50 cm, 3. -100 cm, 4. -150 cm	5. Plot 1 (75 m from the canal) 6. Plot 2 (150 m from the canal) 7. Plot 3 (225 m from the canal) 8. Plot 4 (300 m from the canal)
*Note: For each analysis, the samples were counted as: 4 plots x 4 depths x 3 replication, n=48		

As for sample preparation, the peat samples were determined further from the canal to achieve the objective and hypothesis of this chapter. The peat sample collected for each plot are divided into physical and chemical properties as elaborated in **Table 14**, then stored in a plastic bag to be carried to the laboratory for further analysis.

5.3.4 Description of properties evaluation

Corresponding to **Chapter 4** findings, this chapter understood that peat moisture is important in peat. Therefore, this chapter will further investigate the physical properties of bulk density, moisture content, organic matter content, and porosity. Moreover, the chemical properties covered in this chapter will further determine the ash content and organic carbon content to see how the fire frequency influences these chemical properties. Also, the fibre content was determined to see how the moisture was influenced by the peat fibre content.

5.3.4.1 Description of properties evaluation

The peat samples were weighed (M_w) before oven-drying for 24 hours at 105°C. The oven-dried samples were weighted (M_s) after 24 hours. The bulk density (kg m^{-3}), moisture content (%), moisture regain (%), and porosity (%) will be calculated using the following formula:

$$\text{Bulk density} = \left(\frac{M_s}{\text{Volume of soil samples}} \right) \text{ kg m}^{-3} \quad \text{Equation 4}$$

$$\text{Moisture content} = \frac{(M_w - M_s)}{M_s} \times 100\% \quad \text{Equation 5}$$

$$\text{Moisture regain} = \frac{(M_w)}{M_s} \times 100\% \quad \text{Equation 6}$$

$$\text{Porosity (\%)} = \frac{\text{Total volume} - \text{volume of solid}}{\text{Total volume}} \quad \text{Equation 7}$$

5.3.4.2 Chemical properties

This part is divided into i) Acid detergent fibre method to analyse the decomposed peat fibre content ($n=32$) and ii) Loss on ignition (LOI) method

(n=48) to determine the ash content (%), organic matter content (%), and organic carbon content (C_{org}) (Agus et al., 2011). The fibre analysis covers the peat cellulose and lignin content for 32 samples (2 area x 4 plots x 4 depths). The calculations for the LOI method are as follows:

$$\text{Ash content (inorganic content)} = 100\% - C_{org}\% \quad \text{Equation 8}$$

$$C_{org} (\%) = (100\% - \text{Ash content}) \div 0.58 \quad \text{Equation 9}$$

(*0.58 is the conversion factors from OM to C_{org})

$$\text{Organic matter content (\%)} = \frac{(\text{Powder sample (g)} - \text{ash (g)})}{\text{Powder sample (g)}} \quad \text{Equation 10}$$

5.3.5 Description of statistical analysis

This chapter delves further into the investigation of various physical properties, including density, moisture content, organic matter content, and porosity. Additionally, the chemical properties under scrutiny encompass ash content and organic carbon content. These analyses aim to ascertain how fire frequency influences these chemical properties. Moreover, the study examines the influence of moisture on fibre content within peat. To fulfil the objectives and hypotheses of this chapter, peat samples were specifically chosen from locations further away from the canal rather than along it.

The statistical analyses for bulk density, moisture content, porosity, ash content, organic carbon content, organic matter content (n=48), as well as lignin, cellulose, moisture regain, and moisture content_b (n=32), were performed using IBM SPSS software (IBM SPSS V.28). Statistical comparisons involving both plots and depths were conducted through two-way variance analysis (ANOVA)

at a 95% confidence level. To compare means between the independent HFF and LFF groups, a T-test was employed. Furthermore, a Pearson correlation analysis was carried out to identify potential relationships between the various properties. Microsoft PowerPoint software was utilized for compiling and organizing the results.

5.4 Results and Discussion

5.4.1 Peat Properties at High-frequency Fire Area (HFF)

This section provides a comprehensive exploration of both the physical and chemical properties of peat within the high-frequency fire area (HFF) and the low fire frequency area (LFF). The examination aims to bridge the research gap existing in this chapter by considering the compaction of peat properties across layers and distances from the fire-break canal. The investigation particularly focuses on peat properties adjacent to the fire-break canal, an integral part of fire management to minimize fire incidents. The implementation of the fire-break canal was initiated following a series of fires to prevent fire spread into the LFF region. As a result, this chapter aimed to discern the compaction of peat properties across layers and distances within this area.

For the physical properties in the HFF region, bulk density values ranged from 0.14 g cm^{-3} to 0.22 g cm^{-3} , statistically lower than in the LFF area. Correspondingly, moisture content within this region was notably higher than in the LFF area, ranging from 354% to 1284% (**Table 15**). These two properties were interconnected, with HFF peat samples displaying statistically higher

porosity levels than LFF samples. The exceptionally low density of peat in the swamp leads to increased water-holding capacity, crucial for water regulation, especially in tropical climates (Leng et al., 2019).

Table 15: The peat properties in High Fire Frequency (HFF) area (n=48) based on distance from the fire-break canal

Distance from Canal (m)	Depth (cm)	Physical properties				Chemical properties	
		Moisture content (%)	Bulk density (kg m ⁻³)	Porosity (%)	OMC (%)	Ash content (%)	C _{org} (%)
75	0	1285 ^b	200 ^a	81	85 ^a	16 ^a	49 ^a
	-50	354 ^a	250 ^a	80	87 ^a	14 ^a	50 ^a
	-100	571 ^a	180 ^a	80	90 ^a	11 ^a	52 ^a
	-150	602 ^a	160 ^a	82	78 ^a	22 ^a	46 ^a
150	0	1072 ^a	220 ^b	76 ^a	71 ^a	29 ^b	41 ^a
	-50	1112 ^a	90 ^a	91 ^{ab}	92 ^b	8 ^a	53 ^{ab}
	-100	617 ^a	160 ^{ab}	86 ^b	93 ^b	7 ^a	54 ^b
	-150	925 ^a	110 ^a	87 ^b	84 ^{ab}	16 ^b	49 ^b
225	0	407 ^a	210 ^a	82	89 ^a	11 ^b	52 ^a
	-50	696 ^a	140 ^a	85	95 ^b	5 ^a	55 ^{ab}
	-100	482 ^a	200 ^a	80	94 ^b	7 ^{ab}	54 ^{ab}
	-150	889 ^b	100 ^a	89	89 ^a	11 ^b	52 ^b
300	0	560 ^a	170 ^c	86 ^a	98 ^c	2 ^a	57 ^a
	-50	657 ^{ab}	150 ^{bc}	90 ^b	98 ^{cb}	3 ^{ab}	57 ^{ab}
	-100	846 ^{bc}	120 ^b	90 ^b	96 ^{ab}	4 ^{bc}	56 ^c
	-150	1027 ^c	90 ^a	91 ^c	95 ^a	6 ^c	55 ^{bc}

Note:

1. The different letters indicate a significant difference ($p < 0.05$) within the depths of each plot from the ANOVA analysis (Tukey's post hoc test)

The environmental conditions, as shown in **Figure 33b**, have also influenced the results of the peat samples. The scarce forest cover exposes the HFF region to direct sunlight, rain, and wind, contributing to the saturation of the peat

surface during the rainy season and its susceptibility to drying during droughts. Consequently, the HFF area demonstrated surface saturation or waterlogging during peat sampling due to factors such as high moisture during sample collection and the maintenance of water table depth by the fire-break canal. Furthermore, moisture content on the peat's surface at 75 m and 150 m was significantly higher compared to that at 225 m and 300 m. In contrast, ash content exhibited a statistically decreasing trend farther from the fire-break canal, indicating that fires typically originated along the fire break canal line. The possibility of fire spread might be attributed to spotting fires, allowing flames to extend into the FR areas.

The fire-break canal played a pivotal role in maintaining moisture levels around 0.4 m or higher relative to the peat surface (Ward et al., 2021), influencing the recorded moisture content exceeding 1000% MC at 75 m and 150 m plots. Thus, these findings suggest that the higher moisture at the surface could be influenced by the presence of the fire-break canal, which sustains the water table at the surface to prevent dehydration. Additionally, waterlogged conditions on the peat surface may decrease from the water holding capacity and water repellence due to peat fires. Higher porosity in peat layers within the HFF area enables water absorption and increases ash content indicates water-repellent characteristics reduces from slow burning (Dlapa et al., 2013). The waterlogged condition, marked by diminished oxygen levels, might obstruct near-surface macropores, impacting peat hydrology—an aspect known as the hydrophobic condition (Duchaufour, 1982; Noble et al., 2017). This condition could potentially influence fire suppression efforts when extinguishing subterranean peat fires.

The fire is also related to lower OMC in HFF, which produces char, which increases the ash content and acts as a water repellent. The water repellent caused by the char presence will change the burnt peat into a hydrophobic state up to 90%, wherein it will increase the water drop perception time (Kettridge et al., 2014). The OMC content in HFF was statistically lower than in LFF because of the severe fire incidents in this area. The OMC was lower than 58%, proving the fire consumed the organic layers of the peat. In Indonesia, the rewetted site and the undrained site show 51.2% and 52.7% carbon content; in the rewetted site, a canal network is present in the rewetted area.

The soil organic carbon is associated with peat depth, and the presence of a canal can reduce carbon loss as the carbon input is preserved from the waterlogged conditions (Darusman et al., 2022). As the fire consumes the organic matter intensively, it will impact the lower organic carbon content as it is the main deposit in the tropical peatlands, where almost 90% of the carbon losses are related to the burning of organic soils (Che Azmi et al., 2021). In this chapter, the C_{org} was lower in LFF than in the HFF area. However, the distance from the fire-break canal does not extensively influence ($P > 0.05$) the properties of the peat based on the ANOVA analysis. For the depths of 0 cm, -50 cm, -100 cm, and -150 cm, the study shows a significant difference ($p < 0.05$) between the layers in each plot.

5.4.2 Summary of Chapter

Analysing **Figure 35a** reveals that intact forest cover in the LFF (low fire frequency) area yielded statistically higher bulk density and lower moisture

content compared to the HFF (high-frequency fire) area, ranging from 172% to 924% (**Table 16**). In the Beaufort peatland of Sabah, Malaysia, the LFF area took the lead in implementing a fire-break canal as part of management endeavours to curb fire propagation into the FR (fire-resistant) region. **Figure 33a** supports these findings, indicating that intact forest cover in the LFF area resulted in statistically higher bulk density and lower moisture content than observed in the HFF area, spanning a range of 172% to 924%. The porosity level in the LFF area is also statistically lower (56% to 90%) than in the HFF area, influencing the moisture accessibility of the peat samples.

These results accurately mirror the real conditions of the LFF area, where surface waterlogging is not common. Another parameter reinforcing the lower incidence of fires in the LFF area is the higher OMC (organic matter content) in comparison to the HFF area, ranging from 82% to 99%. Reduced fire occurrences translate to decreased consumption of organic layers by fire, consequently resulting in lower carbon loss compared to HFF (48% to 58%). Under saturated conditions, peat exhibits slower decomposition rates, aiding in the preservation of organic carbon (Szajdak et al., 2020). Burning peat releases various gases, including CO₂, CO, CH₄, and particulate matter, with implications for both the environment and human health (Hamada et al., 2016). Variations in vegetation between LFF and HFF can introduce noteworthy small-scale disparities in soil organic matter properties (Girkin et al., 2019).

Remarkably fewer fire instances in the LFF area translate to lower ash content (0.5% to 18%). For instance, a burnt plank of wood (**Figure 38**) was found 225 m from a depth below the surface of -50 cm (Ash content: 11.3%; OMC: 89%;

MC: 297%). However, this finding does not contribute to surface waterlogging, as observed in the HFF area. The diminished ash content in LFF area signifies reduced water repellence, a consequence of lower fire frequencies. Despite moisture content not surpassing that of the HFF area, the LFF region experiences fewer fire incidents, which underscores the fire-break canal's effectiveness in mitigating fire spread. However, the canal's ability to fully prevent fire spread to this area is limited. Firebrands from adjacent land can still reach the FR due to wind, necessitating more research.

Table 16: The peat properties in Low Fire Frequency (LFF) area (n=48) based on distance from the fire-break canal.

Distance from Canal (m)	Depth (cm)	<i>Physical properties</i>				<i>Chemical properties</i>	
		Moisture content (%)	Bulk density (kg m ⁻³)	Porosity (%)	OMC (%)	Ash content (%)	C _{org} (%)
75	0	412	160 ^a	78	82	18.0	48
	-50	329	180 ^a	72	99	0.5	58
	-100	172	370 ^a	65	99	2.0	57
	-150	299	260 ^a	75	99	1.0	58
150	0	276 ^a	200 ^{ab}	77 ^a	90	1.0	57
	-50	162 ^a	410 ^b	56 ^{ab}	98	2.1	57
	-100	292 ^a	260 ^{ab}	75 ^{ab}	99	1.1	57
	-150	916 ^b	110 ^a	80 ^b	99	1.2	58
225	0	186 ^a	200 ^a	60 ^a	99	1.3	57
	-50	297 ^a	220 ^a	70 ^{ab}	89	11.3	51
	-100	924 ^b	110 ^a	90 ^c	99	0.8	58
	-150	543 ^{ab}	180 ^a	80 ^{bc}	99	0.2	58
300	0	329 ^a	160 ^a	74	99	1.4	57
	-50	414 ^a	160 ^a	90	99	1.4	58
	-100	402 ^a	200 ^a	83	99	0.8	57
	-150	569 ^a	190 ^a	81	99	1.0	57

Note:

1. The different letters indicate a significant difference ($p < 0.05$) within the depths of each plot from the ANOVA analysis (Tukey's post-hoc test)



Figure 38: A plank of burnt wood from the sampling site to prove that the area experienced fire incidents although the fire frequency is lower.

A rehabilitation approach such as tree planting (SFD, 2019) will recover the area, contribute to the land's recovery, and improve peat properties. However, the survival rate of the seedling depended on the tree's adaptation towards waterlogged conditions, drought, and fire (Tata & Pradjadinata, 2016). A prevention measure for the implementation of the fire-break canal can help reduce the fire threat and help rehabilitate the area. A previous study in Riau, Indonesia, shows that the frequency of extreme fires declined by 40% after rewetting (Taufik et al., 2023), which is important for rehabilitation. Based on the simulation analysis by Warren et al., (2017), the optimal peat swamp forest condition can be achieved over 25 years with complete restoration, including drainage similar to the state of the study area of this chapter (Warren et al., 2017). Based on the study plot, a fire-break canal does not influence the presence of peat properties; thus, the distance from the canal did not have a significant difference in the physical and chemical properties.

5.4.3 Relationship Between the HFF and LFF Properties

The soil properties cannot be completely independent, and many interrelations between the properties can be described statistically (Borůvka et al., 2002). Therefore, a detailed analysis of the relationships between variables is presented in this chapter to demonstrate the variables' interactions, especially on moisture availability. In this finding, a higher correlation between two (2) variables indicated by $r=1.000$, and variables with $r \leq 0.200$ will not be considered correlated. The hypotheses are:

Ho: There is no relationship between two variables ($r = 0$)

Ha: There is a linear relationship between the two variables ($r = 1$)

Understanding the physical and chemical properties influenced by fire frequency is crucial to understanding the relationships between the variables. The findings suggest that porosity plays a vital role in influencing the bulk density and moisture content in both areas (**Figure 39**). In the HFF area, the repeated fire cases suggest that porosity does not correlate ($r \leq 0.200$) with the chemical content such as ash, OMC, and C_{org} contents. Notably, the fire-break canal in the HFF area does not dry the area as it has a reasonably strong relationship with bulk density ($r=0.988$) and a moderate relationship with moisture content ($r=0.584$). As moisture is the main control of smouldering propagation (Nelson et al., 2021), it is crucial to understand the properties that influence moisture availability. This situation will affect the significantly high moisture content on the surface (0 cm), indicating that weak peat can retain the water (Perdana et al., 2018) known as a hydrophobic condition because of a

previous fire event. In HFF, the porosity level and moisture content have a moderate relationship (0.584) but still indicate that peat's three fundamental properties depend on each other.

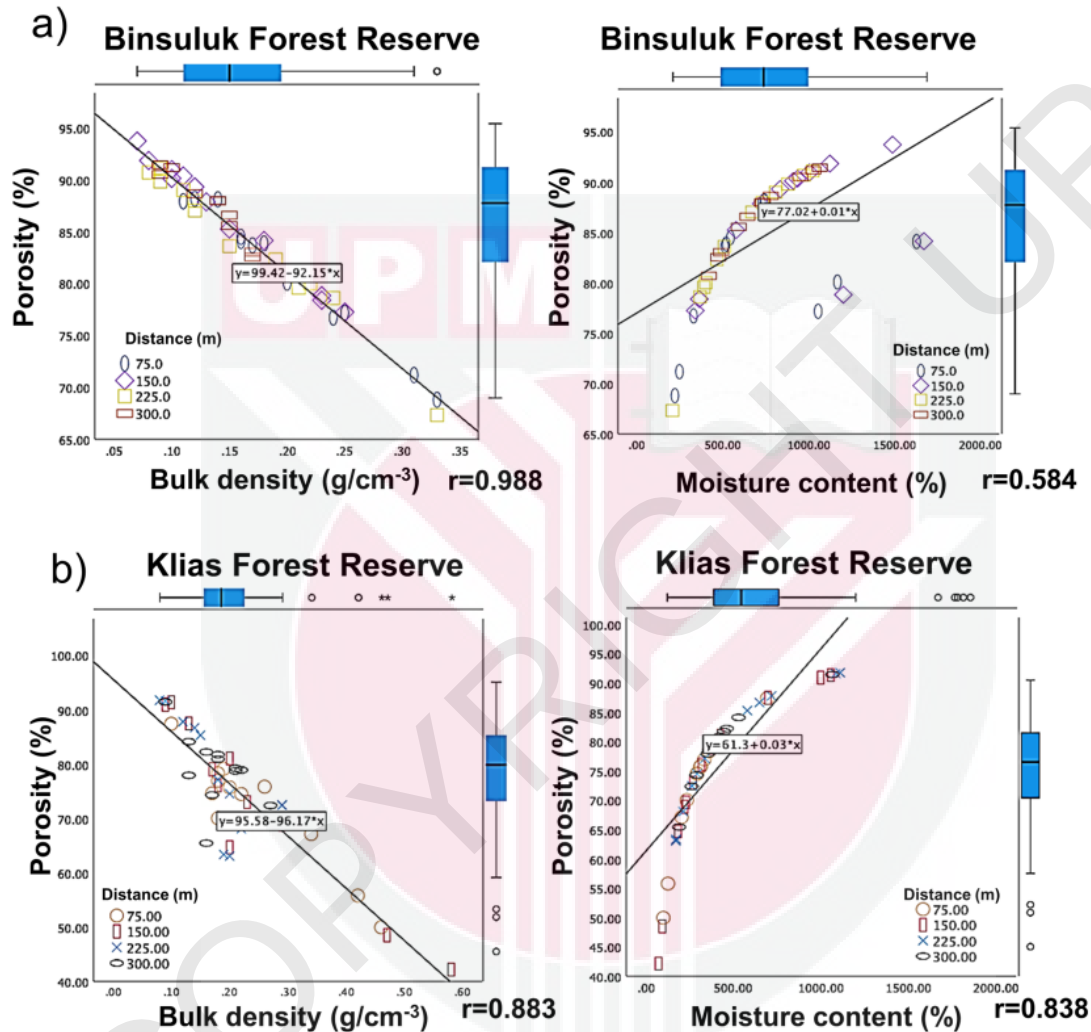


Figure 39: a) Influence of distance on peat physical properties of porosity (%), bulk density (kg m^{-3}) and moisture content (%) of Binsuluk FR; b) Influence of distance on peat physical properties of porosity (%), bulk density (kg m^{-3}) and moisture content (%) of Klias FR.

The physical properties correlation-regression analysis in the LFF area shows that the moisture content and porosity have a strong correlation coefficient of 0.838, or 70% of the moisture content depends on the peat's porosity ($p = 0.002$). Furthermore, based on the graph, the high correlation in the LFF area proves

that this area has not been influenced by smouldering fire to a large extent. There is a relationship between bulk density and C_{org} (<0.001 , 2-tailed) in the HFF area but not in LFF. This relationship indicates that by increasing C_{org} , the bulk density will be lower. The relationship between the density and C_{org} means that denser soil is more susceptible to storing the C_{org} based on its structure.

Despite the fire history, the chemical properties correlated to each chemical variable for both study areas (**Figure 40**). In the HFF area, this chapter can see that the organic carbon content and organic matter content are scattered with a strong positive correlation (0.998) and a strong negative correlation between Ash content - Organic carbon content and organic matter content. The LFF area's chemical properties in this chapter have a strong relationship ($r=1.000$). The LFF area experienced peat fire, but it was not frequent as the fire-break canal was implemented to prevent the fire from spreading as the fire did not change the properties too much with additional restoration efforts. The chemical properties of OMC, C_{org} , and ash content were also strongly correlated ($r=1.000$) in LFF. OMC is a major component of the peat which causes water repellence (Szajdak et al., 2020), and then it influences the compaction of the peat in the HFF area. Nevertheless, the moisture content was not affected by the OMC as other variables contributed to the presence of moisture in this area.

The findings suggest that all chemical variables are dependent on each other. Ash content was studied to identify the area burnt before showing that it was present from 0 cm to -150 cm and up to 300 m further from the canal. Based on the analysis of variance, the significant difference between the depth for the HFF area was shown at 150 m, 225 m, and 300 m plots by the distance from

the fire-break canal. From the analysis, the findings have found that the peat properties were not influenced by the distance from the fire-break canal but by the depth of the peat.

The correlation regression analyses were used to relate each chemical property studied. The peat's total organic matter content in the HFF area varied from 71.43% to 98.04% at a 75 m distance from the canal, which indicates no significant difference ($p>0.05$) between the depths. The HFF area shows a strong correlation ($r=0.998, 0.998, 1.000$) for OMC, C_{org} , and Ash content relationship in the Pearson correlation analysis. The findings were similar to LFF, where the variables have a strong ($r=1.000$) relationship and were expected to have no difference within the depth despite the distance from the canal ($p>0.05$). The LFF area findings do not influence much of the chemical peat properties on these content, organic carbon content and organic matter content. From the results, lower fire frequency shows that the results gathered and point in similar places in the graph, which contributes to the high correlation ($r=1.000$). Even though a higher frequency indicates a high correlation of $r=0.998$, the pattern is straight. From the pattern, the lower fire frequency does not influence notably compared to the higher fire frequency.

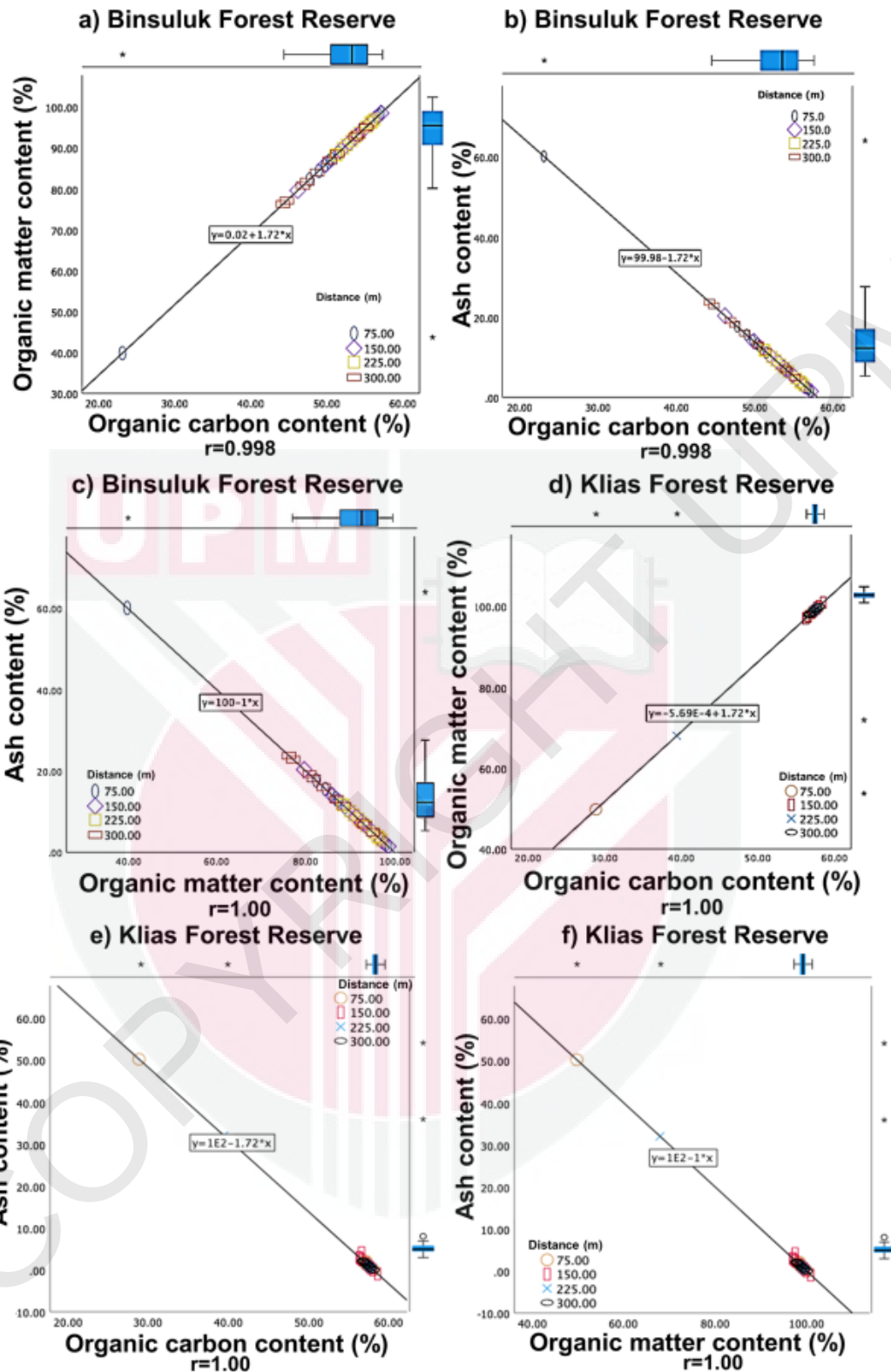


Figure 40: The correlation-regression of the chemical properties of peat-based on the distance from the Canal in both Binsuluk FR - a) Organic matter content (%) - Organic carbon content (%); b) Ash content (%) - Organic carbon content (%); c) Ash content (%) - Organic matter content (%) and Klias FR - d) Organic matter content (%) - Organic carbon content (%); e) Ash content (%) - Organic carbon content (%); f) Ash content (%) - Organic matter content (%).

5.4.4 Fibre analysis and moisture regain (%) of HFF and LFF areas

The peat was associated with a high-water table content, so this chapter wanted to explore the role of fibre content in influencing the peat's moisture. Subsequently, a fibre analysis (n=32) was conducted to understand the role of the fibre content of the lignin and cellulose related to the high moisture content of the decomposed peat near the fire-break canal (**Table 17**). The peat was made up of accumulated peat of decomposed wood; therefore, this chapter wanted to understand this. Spatial variations in litter, temperature, and humidity result in diverse peat fibre compositions across sites, indicating that classification based solely on fibre content is inadequate; it should be complemented with factors like ash content or water retention capacity (Johari et al., 2016). In poorly humified peat, the lignin is expected to have higher lignin and cellulose content (Mcmorrow et al., 2002). As moisture plays an important role in protecting the peat from drying, the ability to regain moisture after peat samples were dried was also studied (**Figure 34**).

Within the context of peat, which is characterized by decomposed woody material in tropical regions, the examination of lignin and cellulose content emerges as crucial Lignin's hydrophobic nature suggests its potential to repel water, while cellulose's hydrophilic properties indicate its capacity for water absorption. This study focuses on understanding the potential of fibre consist of lignin to repel water and hydrophilic cellulose content. The water holding capacity is related to the fibre content as it will decrease with increased water retention (Taufik et al., 2019). In the findings, the proportion of cellulose was lower in the LFF area and affected water retention.

Table 17: Moisture regain after drying for HFF and LFF areas (n=32) based on distance from the fire-break canal.

Distance from Canal	Depth (cm)	HFF				LFF			
		Moisture content _b (%)	Regain moisture (%)	Lignin (g kg ⁻¹)	Cellulose (g kg ⁻¹)	Moisture content _b (%)	Regain moisture (%)	Lignin (g kg ⁻¹)	Cellulose (g kg ⁻¹)
75 m	0	1285 ^b	522.85 ^a	227	69	412	512.36 ^a	244	102
	-50	354 ^a	513.81 ^a	283	130	329	376.34 ^a	186	99
	-100	571 ^a	507.154 ^a	237	93	172	285.50 ^a	248	98
	-150	602 ^a	559.92 ^a	376	110	299	429.28 ^a	137	85
150 m	0	1072 ^a	454.01 ^a	310	117	276 ^a	429.08 ^{ab}	304	109
	-50	1112 ^a	1212.25 ^b	326	114	162 ^a	261.50 ^a	321	131
	-100	617 ^a	796.14 ^{ab}	332	189	292 ^a	397.09 ^{ab}	210	161
	-150	925 ^a	756.60 ^{ab}	356	194	916 ^b	513.48 ^b	215	106
225 m	0	407 ^a	671.43 ^a	379	307	186 ^a	272.46 ^a	384	259
	-50	696 ^a	717.01 ^a	354	303	297 ^a	391.89 ^a	269	143
	-100	482 ^a	581.84 ^a	343	131	924 ^b	1023.49 ^b	311	258
	-150	889 ^b	945.79 ^a	380	430	543 ^{ab}	501.49 ^a	287	117
300 m	0	560 ^a	702.15 ^a	414	438	329 ^a	398.66 ^a	334	154
	-50	657 ^{ab}	1024.95 ^{ab}	386	432	414 ^a	1016.19 ^a	367	280
	-100	846 ^{bc}	988.87 ^{ab}	400	433	402 ^a	642.46 ^a	402	297
	-150	1027 ^c	1127.26 ^b	404	325	569 ^a	668.82 ^a	427	319

Note:

1. Depth: HFF: Surface ($p < 0.05$) to -50 cm, -100 cm, and -150 cm; LFF: Surface, -50 cm, -100 cm, to -150 cm ($p < 0.05$).
2. Lignin and cellulose (g kg⁻¹) show a significant difference ($p < 0.05$) between the plot for distance from the Canal

In this work, moisture regain was also determined to understand the role of decomposed peat in regaining moisture after drying (Equation 6). The moisture regains compared with the initial moisture content expressed as a water percentage of the total weight of the material. As the samples for the fibre analysis were chosen randomly, the ability of the dry peat to regain moisture related to rewetting was presented in this chapter, and the fibre content was determined in this chapter. Rewetting peat soil, revegetating with native species, and revitalizing livelihoods are crucial for reducing fires and peatland

oxidation, with successful rewetting dependent on providing equitable and sustainable livelihood options for affected communities (Mendham et al., 2024). In previous research, the ability of moisture to increase after rewetting process up to 60% to 90% MC since drying will affect the ability of the peat to absorb water (Dianti et al., 2018). The moisture content and the ability for the dry peat to regain moisture can explain that although the moisture content in HFF was statistically higher with higher fibre content, the ability of the peat.

A dry state of peat to regain moisture is not the same. The study in this chapter also found that the areas HFF have a significantly higher ability to regain moisture ($755 \pm 40\%$) than the LFF peat sample's ability to restore moisture after drying ($507 \pm 39\%$), $t(94) = 4.385$, $p < 0.001$. In comparison of the dry basis moisture content for the HFF, it was statistically lower ($p = 0.09$) with a mean of $655 \pm 41\%$ compared to the ability of the peat samples to regain moisture or re-wet ($755 \pm 41\%$). That has corresponded to the waterlogged condition in the HFF as the fibre content contributes to this action. Moreover, in the LFF area, findings also found that no significant difference ($p = 0.07$) between the moisture content ($407 \pm 39\%$) and the ability of the dry peat to regain moisture ($508 \pm 39\%$). Based on the ANOVA analysis, there is no significant difference ($p > 0.05$) between the plot for HFF and LFF, which indicates that the ability of the peat to gain moisture after drying in overall are similar. In contrast, distance from canal play a significant role in influencing the regain moisture availability of peat. It was significantly greater ($p = 0.03$) at the furthest plot from the fire-break canal (300 m) compared to 75 m, 150 m, and 225 m peat samples collected in the LFF area. Thus, the increasing ($p < 0.05$) of the lignin and cellulose content by the distance from the fire-break canal contributing to the findings.

On the other side, for the HFF area, the ability to regain moisture is similar by the distance and was not influenced ($p>0.05$) by the fibre and cellulose content. The findings might be resulted from the HFF area despite the fibre content. Despite that, the findings are also considered to be the effect of repeated fire occurrences on the peat samples to regain their moisture. The Pearson-correlation analysis for the HFF area shows no relationship between cellulose and moisture content and a weak relationship between lignin content and moisture content, $r=0.280$ (**Figure 41**). However, the LFF area indicates that lignin and moisture content have a moderate relationship ($r=0.451$), which is a fair relationship with $r=0.692$ between cellulose and moisture content that contributing to the increasing of the moisture content availability by the lignin and cellulose presence. The significantly higher ($p<0.05$) lignin and cellulose content in HFF is considered to contribute to the statistically higher moisture at 0 cm (surface) and lowest at 100 cm, where the water table is usually situated.

The presence of lignin in peat is higher than cellulose, wherein lignin will reduce with the high groundwater level but not the cellulose content, which does not depend on the groundwater level (Iglovikov & Motorin, 2019). Warren et al., (2017) stated that lignin depends on reduction as the groundwater occurrences increase in depth. This work was similar to the statement by Warren et al., (2017), wherein the higher moisture at the surface of the HFF area increases in depth for the LFF area, which could influence the moisture certainty as the lignin is statistically higher. However, the peat fire underground might change water absorption as the properties change at slow burning. Burning the dead material might contribute to these changes as the HFF shows no relationship between the moisture content with lignin and cellulose.

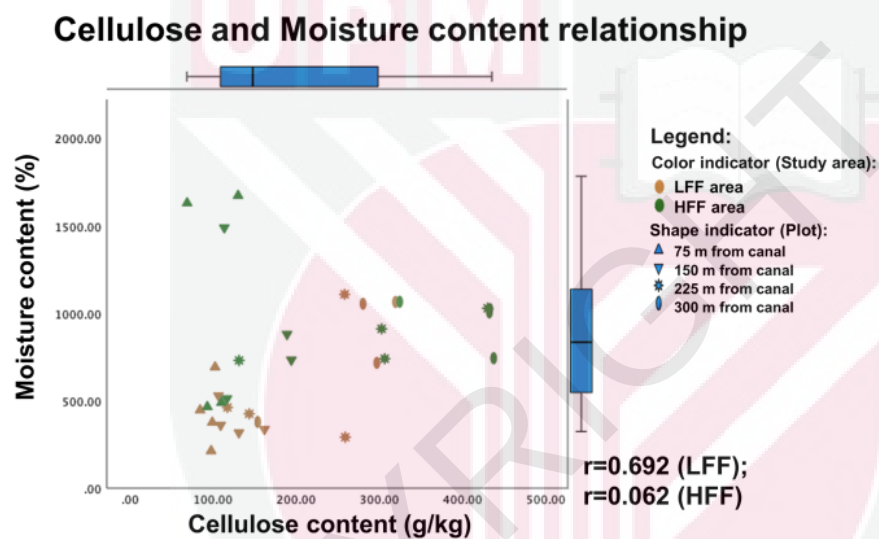
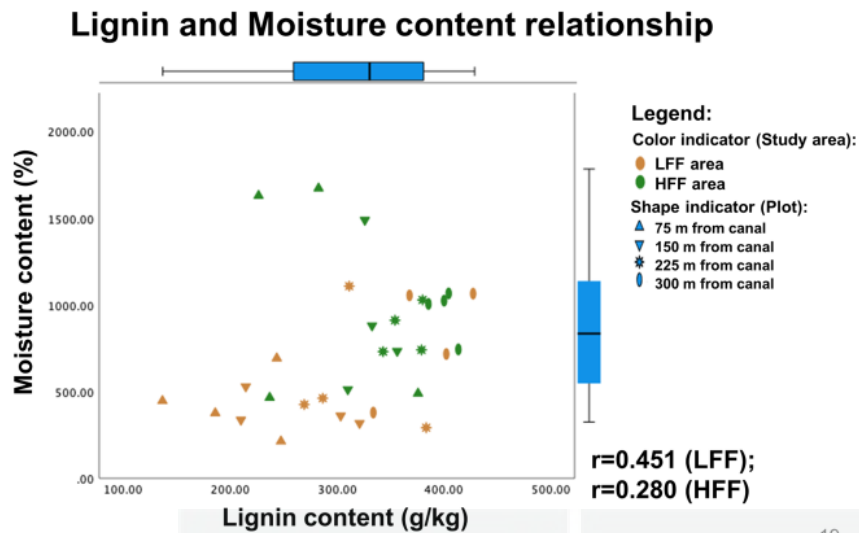


Figure 41: The relationship of lignin content ($r=0.451$) and cellulose content ($r=0.692$) with moisture content in both Klias FR; The relationship of lignin content ($r=0.280$) and cellulose content ($r=0.062$) with moisture content in both Klias FR.

The research on the tropical peat properties was limited to the impact near the fire break canal at lower and higher fire frequency areas. Malaysia's fire management effort on the fire prevention measure on the fire break function and its impact on the peat properties will help improve our knowledge of the post-fire properties for future conservation (Basintal et al., 2007). Since the fire break canal implementation has reduced the fire cases in the forest reserve area (SFD, 2019; SFD, 2020), the research conducted in this chapter is

important for global views of distinct peat swamp forests in Borneo (Basintal et al., 2007) near the fire break canal. The findings also add the limitation on the importance of the canal-blocking study of tropical peatland in Indonesia, which is similar to the fire break canal function in this chapter, which is to rewet and restore the area (Sutikno et al., 2019; Ward et al., 2021). Findings on the physical and chemical properties are crucial for future restoration efforts for peat and forest rehabilitation. Further research on the restoration in post-fire areas near the fire break canal should be conducted.

5.5 Conclusion of Chapter

To date, less attention has been given to the physical and chemical properties of peat-based land-use changes (Könönen et al., 2015). This chapter centers on the peat properties adjacent to fire-break canals in two distinct FRs representing HFF and LFF. Peat fires release a substantial amount of carbon into the environment, contributing to local carbon emissions (Davies et al., 2013). Ash content is significantly higher in the HFF area by 8%, indicating carbon loss; however, due to the fire break canal's presence maintaining the water table depth, the moisture content remains high. Nevertheless, changes in peat properties and environmental conditions suggest heightened vulnerability to fires when they spread from outside the FR. When comparing HFF and LFF areas, no significant differences are noted in physical and chemical properties ($p > 0.05$), except for peat porosity ($t_{72.908} = 5.066$, $p < 0.05$). The mean porosity in the HFF area is 9% higher than in LFF peat, contributing to higher moisture by 434% in the HFF area, coupled with lower bulk density and OMC by 0.05 g cm⁻³ and 8%, respectively. Lower OMC in HFF leads to statistically lower C_{org}

by 5% compared to the mean properties of the LFF area.

Analysing the mean lignin and cellulose content in the fibre content analysis, the HFF area demonstrates significantly higher levels of lignin and cellulose at 397 g kg^{-1} and 54 g kg^{-1} , respectively, than LFF peat. Notably, moisture content does not influence on moisture availability in the HFF area, despite the observed increase in lignin and cellulose content, especially further from the fire-break canal. Conversely, in the LFF area, the rise in cellulose and lignin content moderately influences peat moisture content and regain moisture availability. Other peat properties might also influence moisture content in each area. Pearson correlation analysis indicates that ash, organic matter, and organic carbon content do not correlate with LFF moisture content. These findings address a gap in peat research, as varying depths and maturities produce differing water contents (Junedi et al., 2021). This chapter's insights suggest that the distance from the fire-break canal does not impact moisture content, but peat depth up to -150 cm from the surface at varying fire frequencies affects moisture availability.

In summary, forest cover and fire frequency near the fire-break canal uniquely influence peat properties. It is challenging to discern the fire-break canal's effects on peat properties in forested areas with differing fire frequency and environmental conditions. This chapter's significance lies in representing the protected peat swamp forests in Malaysia and furnishing information about soil properties near fire-break canals in diverse hydromorphic settings. Identifying type-specific threats and deriving implications for conservation, cultivation, and restoration (e.g., rewetting) are crucial outcomes (Gabriel et al., 2018). While a

fire-break canal construction may not significantly impact physical and chemical properties, fire frequency's influence suggests that varying FRs exhibit different properties during frequent fire occurrences. Repeated burning alters peat properties alongside its structure. Therefore, this chapter contributes to understanding the changes brought about by fire outbreaks and how they influence future fire recurrences. Consequently, increased vulnerability to future fire incidents becomes apparent. Restoration efforts and minimizing fire incidents could enhance peat properties. Familiarity with physical and chemical properties near fire-break canals provides soil scientists and land managers with essential information about these peat soil attributes. Further investigation should explore strategies to mitigate smouldering peat fires and minimize their impact on peat properties, which will be covered in the following chapter.

CHAPTER 6

INTEGRATING HEAT PIPE AS SUPPRESSION TOOL INTO PEAT FIRE MITIGATION STRATEGIES

6.1 Summary of Chapter

This chapter focuses on the relationship between the peat swamp forest and fire threats. The effects of fire on peat properties were explored in **Chapters 4** and **5**, while **Chapter 3** discussed fire managers' and firefighters' efforts to minimise impacts. Contributing factors and mitigation strategies were also detailed in **Chapter 3**, shedding light on fire managers' roles in peat swamp forest fire management. Addressing peat fires is crucial for its carbon storage, flood control, and community sustenance. The forest's organic layer, built up over thousands of years, can be ruined by fires spreading underground. Previous chapters emphasise the urgency of peat fire mitigation, particularly in protected forest reserves. Considering the concerns in **Chapters 3, 4, and 5** regarding swift fire suppression and impact reduction, **Chapter 6** expands the study to peat fire mitigation using heat pipes for protection. Its importance lies in demonstrating early fire suppression to safeguard peat, complementing outlined future mitigation efforts.

6.2 Introduction

In forest fire management, fire mitigation is interconnected with fire suppression and is crucial for managing and reducing the impact of forest fires, especially peat fires. Fire mitigation encompasses proactive measures to prevent, reduce, and minimise fire severity and its potential impact. Fire suppression, on the

other hand, refers to the immediate response and actions taken to control and extinguish peat fires, particularly once they start. While fire suppression focuses on addressing active fires, fire mitigation aims to prevent and minimise the impact of future fires. Applying these concepts in tropical peat swamp forests is crucial due to the need for more research and data to address this issue effectively.

In the tropics, peat forms slowly over thousands of decades as plant material decomposes, creating a spongy material that absorbs water. This formation favours areas with high precipitation and lower temperatures, similar to boreal peat environments. Peat swamp forests maintain their peat moisture based on the water table. Therefore, implementing fire mitigation practices such as maintaining water tables through fire break canals and tube wells, along with immediate suppression tools, can enhance the effectiveness of fire suppression efforts and increase overall fire resilience. The relationship between the water table and the smouldering peat fire effect in a laboratory experiment has yet to be investigated. Thus, this chapter further explores the importance of water tables and how they contribute to peat fire suppression. It's important to note that both strategies are essential for effective peat fire management and for reducing their impact on peat properties, communities, and the environment.

6.2.1 The role of water table depth

The water table depth plays a crucial role in preventing peat soil from drying out by maintaining its moisture content. Dry peat is susceptible to ignition, but maintaining an adequate water table depth decreases the likelihood of

smouldering in peat by keeping it wet. However, water table fluctuations can be influenced by the forest's condition, such as pristine and disturbed forests, such as post-fire and logging areas. These environmental differences can lead to variations in the peat surface, with some areas being flooded and swampy, where the water table is above the surface or approximately -7.5 cm to -30.1 cm below the surface (Górecki et al., 2021; Zainorabidin & Mohamad, 2016). In post-fire areas, the water table can drop significantly, reaching depths of -26 cm to -63 cm below the surface (Hooijer et al., 2014). Under these circumstances, the peat surface can rapidly dry out, increasing its susceptibility to ignition. These water table fluctuations underscore the complex connection between forest conditions, water levels, and peat's fire vulnerability. Managing the water table appropriately is crucial for successful peat fire prevention and suppression strategies.

The prolonged drought condition worsens the peat swamp forest condition by decreasing water table depth more rapidly. The rapid transition from saturated peat to dry state will make it highly flammable. The drier state of the peat surface has higher risks of ignition, wherein the fire that occurs at this stage is caused by human activities such as open burning and arson (SFD, 2019). The worst-case scenario is when the fire spreads to the forest reserve area—for example, peat fire occurrences in nearby oil palm plantations in Kg. Binsuluk is spread to the Binsuluk Forest Reserve, as shown in **Figure 42** (SFD, 2019; SFD, 2020). The fire occurrences in the forest reserve caused peat swamp degradation and haze that impacted the air quality, which exposed millions of people, including the neighbouring country, to the original fire area (Karthik et al., 2017; Kiely et al., 2020). Intense smoke on the surface is caused by smouldering fire, which

highlights the need to monitor and maintain the water table to curb underground spread. Indonesia used canal blocking to raise water levels and prevent peat fires (Sutikno et al., 2019; Ward et al., 2021). Peat fires in Malaysia spread from both alienated and state land toward forest reserves. To address this, fire break canals were constructed in repeat fire areas like Binsuluk, Klias, and Raja Musa Forest Reserves. These canals monitor and control water tables (**Figure 43**).



Figure 42: The burnt oil palm plantation near Kg. Binsuluk, Sabah, risk the fire spreading to the adjacent Binsuluk Forest Reserve.
(Source: Sabah Forestry Department)



Figure 43: Monitoring the water table of the canal in frequently burned areas to helps regulate peatland water levels.
(Source: Dayang Nur Sakinah Musa)

6.2.2 Suppression on the underground peat fire

Consistent with the effect of the dried peat when the water table is low, peat is easily ignited and smoulders underground. Peat fire that smoulders belowground can be sustained for an extended period as it is more persistent than a flaming fire (Huang et al., 2016; Rein, 2013). In **Chapter 4** and **Chapter 5**, the post-fire condition was discussed, and the current practice to control the peat fire was elaborated in Chapter 3, including the fire break canal and tube well. The issue with peat fire is the complexity of evaluating the suppression progress, especially in the deep soil layer (Lin & Huang, 2020). The smouldering peat fire is not visible, unlike the flaming fire; therefore, the smoke has become an indicator for the firefighters to suppress the smouldering fire. Peat as carbon storage is crucial for managing climate emergencies, wildlife habitats, and local people's needs.



Figure 44: Construction of a pond for water supply during the prolonged drought in addition to El-Niño, which was present in 2016 affected most areas of Sabah including the Binsuluk Forest Reserve.
(Source: Sabah Forestry Department).

Current practices to control peat fires are monitoring through satellites, fire danger rating systems, ground monitoring, fire towers, fire breaks, and installing tubes to flood the area. These practices are able to reduce the number of peat fires thus far. This approach requires human interaction to handle the flooding method to increase the water table depth, and it is time-consuming yet effective in suppressing the peat fire. However, water shortage can still occur during the El-Niño season; for example, in 2016, the forest fire managers in Malaysia constructed a temporary pond to store water to suppress the peat fire since the nearby water sources are not available (**Figure 44**). Due to the water table dropping significantly during the drought, the water table must play an important role in preventing the smouldering fire from spreading.

During drought, the peat fire is able to reappear on the surface after suppression carried out. The re-appearance of the fire on the surface is known as zombie fire, similar to the Arctic peat fire. However, this term is mainly used in the artic fire (**Figure 45**) to explain the re-occurrence of fire on the surface after the smouldering fire stays underground for a long time during winter (Hurst & Grahn 2021; Rein & Huang, 2021; Kuklina et al., 2022). The tropic zombie fire is illustrated in **Figure 46**, as this situation is related to the discussion in **Chapter 3**, the re-appearance of the fire after suppression happened after 2 or 3 days. Generally, water table depth conservation is important to maintain peat moisture, prevent peat fires, and reduce fire re-occurrences during the drought. It is critical to explore on water table maintenance through fire break canal as fire mitigation during the drought when water sources are limited.

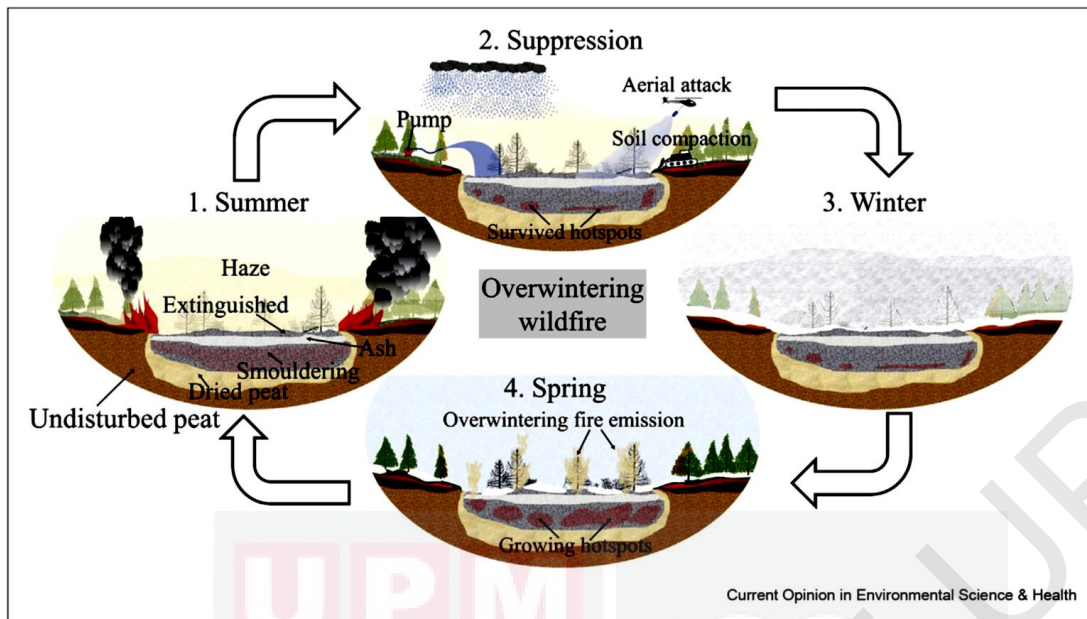


Figure 45: The four stages of an overwintering wildfire caused by smouldering combustion in the Arctic. It is a longer cycle than the Tropic smouldering fire re-appearance in the figure below.
(Source: Santoso et al., 2021 cited in Rein & Huang, 2021)

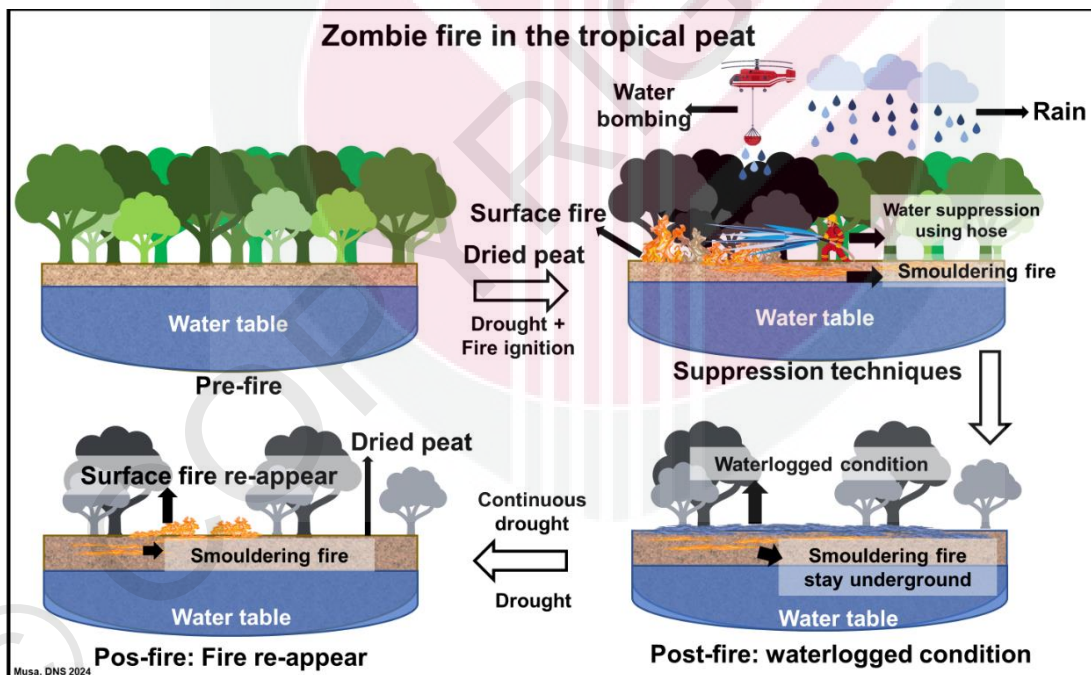


Figure 46: Zombie fire in the tropical fire condition after fire led to waterlogged conditions after suppression. However, according to the firefighters and fire managers during peat fire combat, this zombie fire can stay underground and reappear after a few days.

6.2.3 Objective

Fire mitigation and suppression have been significant areas of research for many years. Various strategies and technologies to prevent and control the peat fire should be explored. Fire suppression technique is the key area to address the current issue related to peat fire and was previously explored on using water, fire retardants, and chemical agents as method of suppression. This chapter identified the importance of early suppression to emphasize the current approaches to fire mitigation. Innovation on fire mitigation and suppression are essential for developing more effective management strategies and mitigating the devastating effect of wildfires. Research on maintaining peat moisture when water table fluctuation is unpredictable during drought and water availability is limited. It is important to protect the peat once the smouldering fire is initiated below the surface.

The objective of this chapter is to investigate the heat pipe as an early suppression tool at different scales of the experimental rig to complement the peat fire mitigation effort. This chapter will fulfil the aim of the thesis which is to understand the fire safety management of peatland fire for post-fire and pre-fire conditions. It is important to note that fire suppression is important to immediately respond to peat fires, although fire break canals as fire mitigation practices were implemented in the fire-prone areas in the forest reserve. The heat pipe will act as an early aid tool to suppress and control the peat fire spreading with the presence of a water table to increase overall fire resilience. This chapter hypothesised that the peat fire would consume all the dried peat with no presence of saturated peat. Thus, the fire resilience of the peat can be

increased using the heat pipe by enhancing the role of the water table or saturated peat in small-scale laboratory experiments. Using heat pipes as an early suppression tool measures to extinguish the fire still needs to be discovered. We also hypothesised that the saturated peat would be dried when the smouldering fire was present. However, we also hypothesised that the saturated peat would help protect the dried peat above the saturated peat level from being consumed by the smouldering fire. Therefore, by examining the water table situation during the smouldering fire, a broad understanding of its role in protecting the dried peat can be understood as a proof of concept. The importance of the fire break canal in maintaining the saturated peat moisture can be acknowledged. Thus, this chapter aims to highlight the following specific objectives:

- 1) To investigate the safe region formation in the dry peat by the presence of saturated underneath in an experimental rig.
- 2) To determine the influence of the heat pipe as an aiding tool to suppress and increase the moisture in the dried peat a form of suppression.
- 3) To determine the importance of maintaining the water table as a peat fire mitigation effort through a fire break canal

6.3 Methodology

6.3.1 Preparation of peat samples

Before the experiment on heat pipe application, this chapter will start with the role of saturated peat and its effectiveness in preventing fire spread in-depth of the peat. The peat used in this experiment will be commercial peat with constant

physiochemical properties. There are two preparations of peat for this experiment (**Figure 47**). The first is the preparation of dry peat, which is oven-dried peat for 48 hours at 90°C until the moisture content becomes 10% moisture content (MC). Second, preparation of saturated peat with $900 \pm 50\%$ MC. The samples were soaked with water until fully saturated to meet the actual saturated peat condition. The saturated peat was continuously soaked with water to maintain its moisture during the experiment.

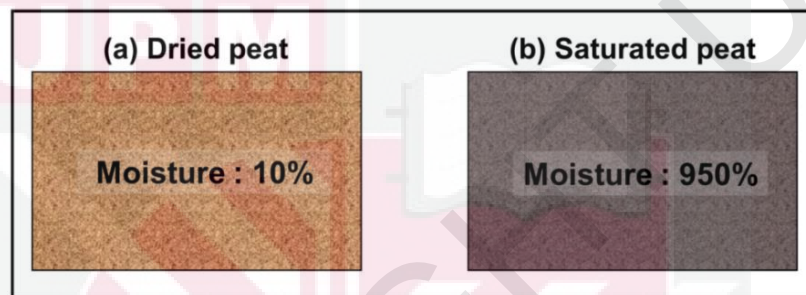


Figure 47: (a) dried peat with a moisture of 10% used in this experiment; (b) saturated peat with a moisture of 950%MC for the research in this chapter.

6.3.2 Experimental designs

To achieve objective 3 of this thesis, the laboratory experimental design illustrated in the experiment taken in this study are shown in **Figure 48**, which divided into i) without heat pipe application, ii) heat pipe application (10 cm), iii) heat pipe application (20 cm), and iv) heat pipe application 30 cm.

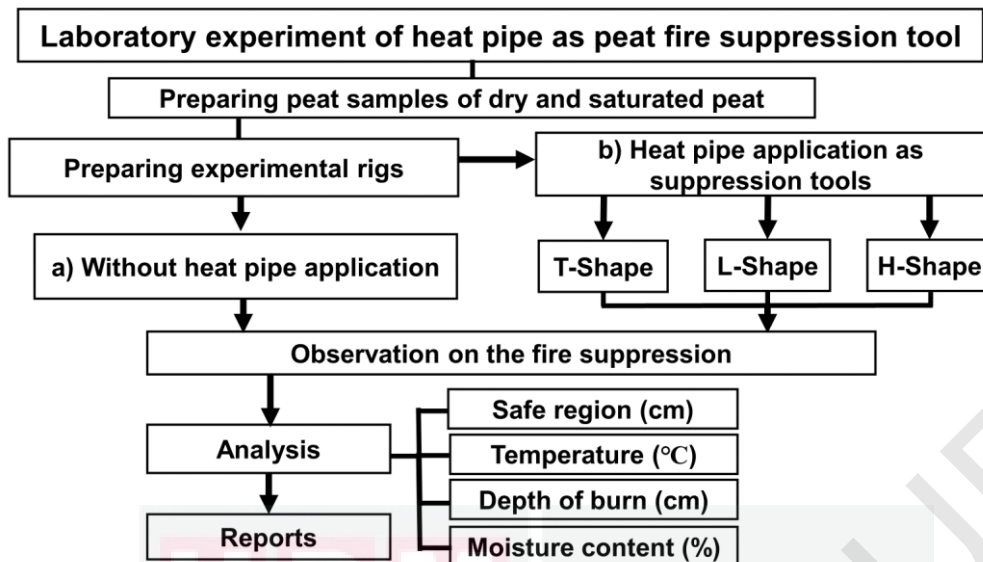


Figure 48: Experimental designs of the heat pipe as suppression tools experiments.

Further explanations of the experiments on the safe region discovery, the mechanism of the heat pipe and the heat pipe application are as follows:

i) Safe region discovery

The design for the experiment without the heat pipe application - The peat sample was placed in a mesh of cylindrical shape with a diameter of 8 cm and a height of 20 cm as a preliminary experiment to understand the safe region formation. An additional experiment was conducted on a rectangle-shaped sealed experimental rig with a height of 35 cm, 30 cm length and 15 cm width, as presented in Figure 43, to understand the safe region formation.

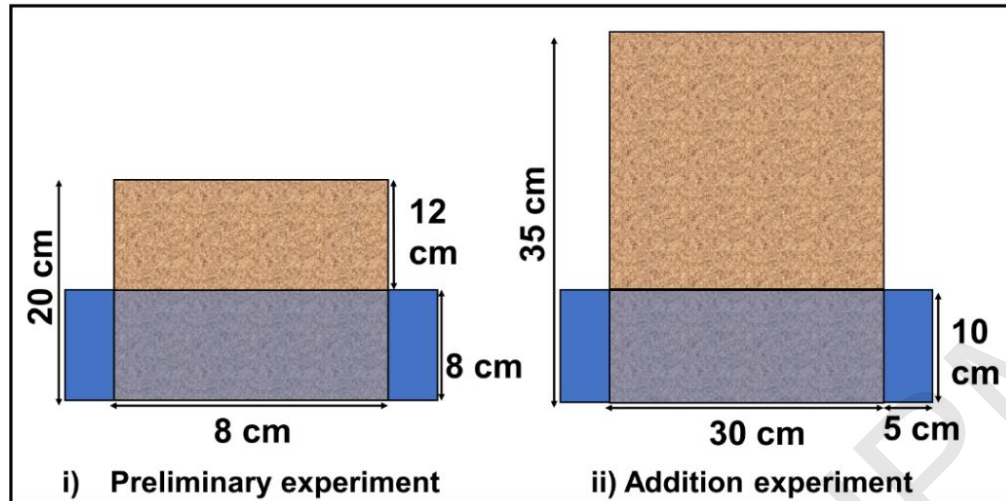


Figure 49: i) Preliminary experiment as proof of concept of the function of saturated peat to protect the dried peat in a mesh; ii) Addition experiment to prove the function of saturated peat to protect the dried peat in a sealed experimental rig.

ii) Heat pipe mechanism

The successful operation of heat pipes relies on their ability to evaporate water from saturated peat and condense water vapor in dry peat regions. This process is crucial because the loss of water mass from wet peat creates a gap in oxygen supply, which accelerates combustion (Dianti et al., 2018). As moisture content increases, there is a corresponding need to elevate the oxygen concentration, as wetter fuels decrease the smouldering spread (Huang & Rein, 2016). In our experiment, we anticipate that the moisture content in the dry region will increase from an initial 10% MC to over 175% MC to effectively suppress smouldering peat fires. Previous studies indicate that ignition, on a dry basis, can occur within the range of 90 to 175%MC, as self-sustaining smouldering conditions depend on comparable rates of smouldering and moisture evaporation (Hadden et al., 2013; Yermán et al., 2017).

Figure 50 demonstrates that increasing the number of heat pipes results in

lower temperatures, confirming the effectiveness of the heat pipe's mechanism for water evaporation from saturated peat and condensation in dry peat regions. By separating the evaporation and condensation sections, heat pipe performance is enhanced (Huang et al., 2021). In our study, we have designed heat pipes with T-shape, L-shape, and H-shape configurations to separate the evaporator and condenser sections as detailed in this section. While the capillary limit of the heat pipes may be constrained due to the horizontal placement of the condensation section in horizontal position (Huang et al., 2021) in the T-shape design without gravitational assistance, the proposed L and H shapes may mitigate this limitation, which will be explored in our study. The dimensions of the heat pipes are tailored to fit the experimental rig's diameter perfectly.

The envisioned approach with heat pipes involves them functioning as heat-triggered water pumps, allowing water vapour to condense in dry peat areas. This would preserve the organic layers, limiting their consumption by smouldering fires and reducing smoke pollution. Elevated moisture content in dry peat areas would facilitate early fire mitigation and supporting suppression approach in real scenarios.

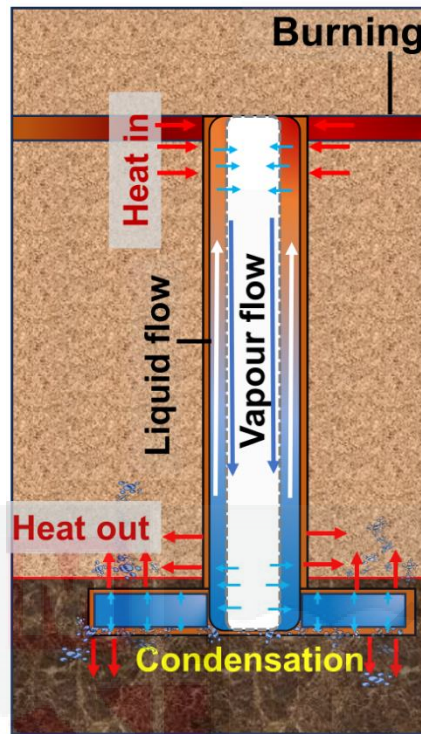


Figure 50: Mechanism of heat pipe to fully suppress the smouldering peat fire underground.

ii) Heat pipe application (10 cm)

For the first experiment on the heat pipe application, a cylindrical shape with a diameter of 8 cm and height of 20 cm was used, similar to the preliminary experiment in i) safe region discovery-preliminary experiment. In this experiment, the saturated peat was placed on the below part of the mesh up to 8 cm to prove the heat pipe concept to support the water table depth role. The experiment rig was soaked in water to retain moisture to maintain the saturated peat. Then, the dry peat was placed on top of the saturated peat (12 cm height) for 24 hours before burning. The moisture was measured after 24 hours resulting in $15 \pm 5\%$ MC. In this experiment, two (2) design of heat pipe was used, namely i) L-shape and ii) T-shape designs with a height of 10 cm and 10 mm diameter (**Figure 51**). This heat pipe was placed between the saturated and dried peat (**Figure 52**). Furthermore, this experiment was ignited using a coil

ignitor for 15 minutes.

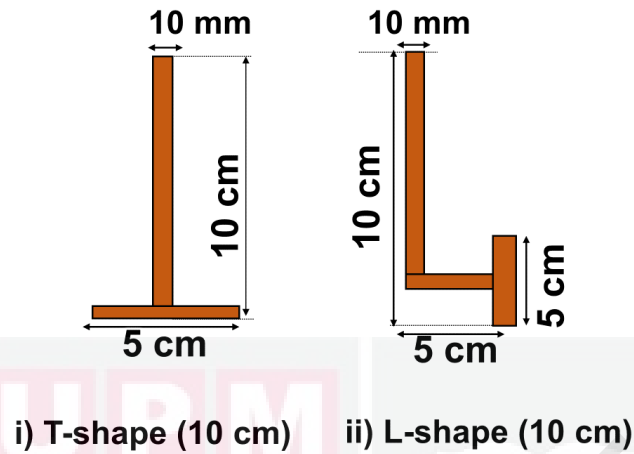


Figure 51: i) T-shape design of 10 cm height; ii) L-shape design of 20 cm height used in the first experiment with heat pipe application.³

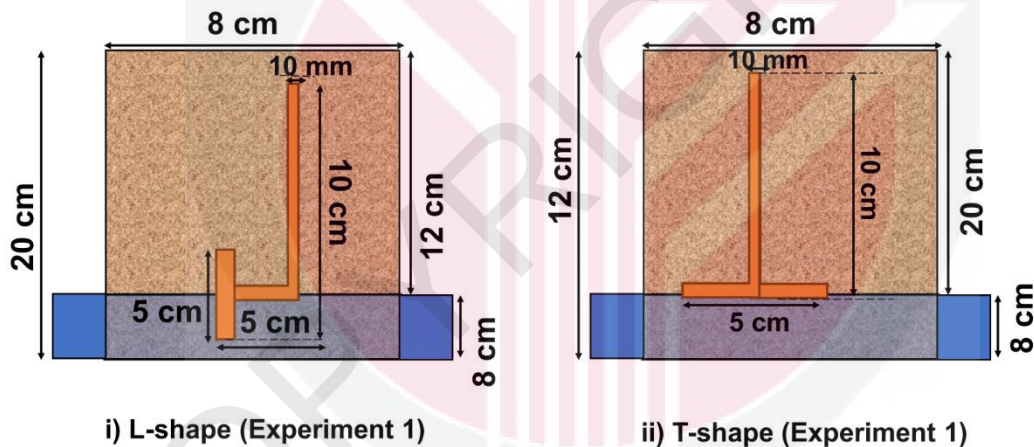


Figure 52: The experimental set-up of 8 cm diameter and 20 cm height. The heat pipe of 10 cm was used for the first experiment on the heat pipe application⁴.

The peat sample was placed in a mesh of cylindrical shape with a diameter of 8 cm and a height of 20 cm (Figure 52). The saturated peat was placed below part of the mesh up to (8 cm). Then, the dry peat was placed on the saturated peat for 24 hours before burning. The moisture content was then measured after

³ The measurement is for illustration to describe better the actual heat pipe used in Experiment 1

⁴ The measurement is not according to scale; it is to describe better the experimental rig used in this chapter.

24 hours, where the moisture was $15\pm 5\%$ MC. This experiment used different shapes of heat pipe design to observe the influence of heat pipe design on the formation of safe regions. The measurement of the heat pipe is 10 cm long and placed between the saturated and dry peat (**Figure 51**).

iii) Heat pipe application (20 cm)

For the second experiment on the heat pipe application, a cylindrical shape with a diameter of 30 cm and height of 35 cm was used similar to the preliminary experiment in i) safe region discovery. In this experiment, the saturated peat was placed on the below part of the mesh up to 9 cm to prove the heat pipe concept to support the water table depth role. The experiment rig was soaked in water to retain moisture to maintain the saturated peat. Then, the dry peat was placed on top of the saturated peat to fill in the 27 cm height. The moisture was measured after 24 hours resulting in $15\pm 5\%$ MC. In this experiment, two (2) design of heat pipe was used, namely i) L-shape and ii) T-shape designs with a height of 20 cm (**Figure 53**). To understand the role of the diameter of the heat pipe, this experiment will have i) 5 mm and ii) 10 mm diameters. This heat pipe was placed between the saturated and dried peat (**Figure 54**). Furthermore, this experiment was ignited by using embers for 5 minutes.

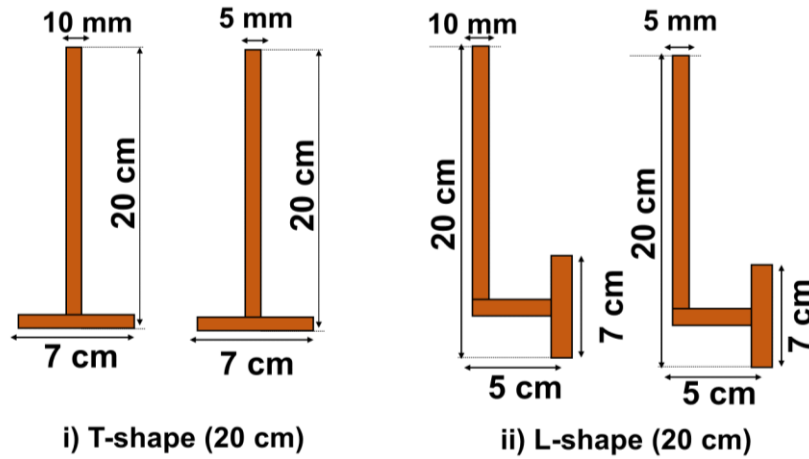


Figure 53: ⁵Different designs of heat pipes of 20 cm used in the second experiment; i) T-shape and ii) L-shape .

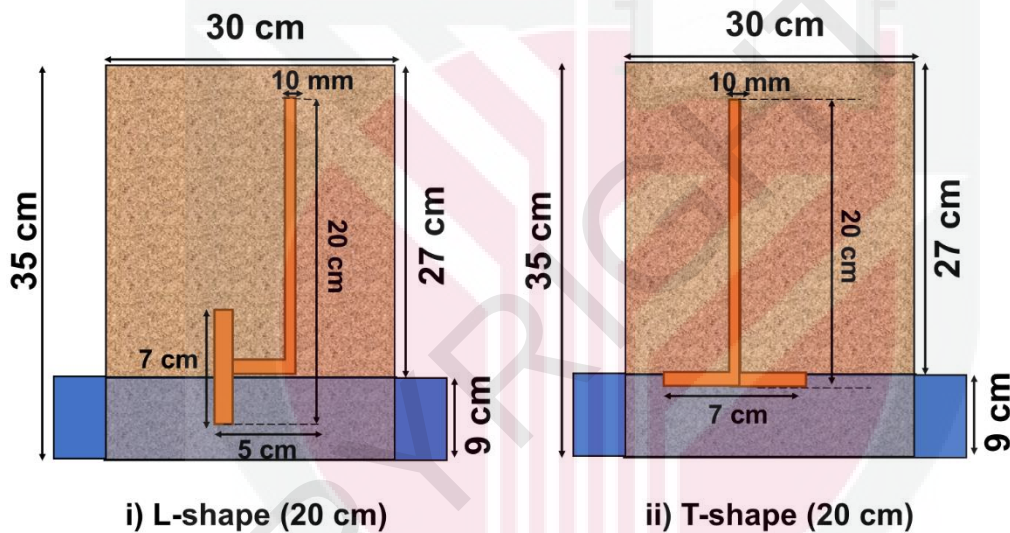


Figure 54: ⁶The experimental set-up of 30 cm diameter and 35 cm height. The heat pipe of 20 cm was used for the heat pipe application in the second experiment.

iv) Heat pipe application (30 cm)

For the third experiment on the heat pipe application, a rectangle shape size of 30 cm (length) x 35 cm (height) x 15 cm was used similar to the preliminary experiment on the 6.4.1 i) safe region discovery. In this experiment, a sealed experimental rig was conducted to prove the concept of heat pipes as early

⁵ The measurement is for illustration to describe better the actual heat pipe used in Experiment 2.

⁶ The measurement is not according to scale; it is to describe better the experimental rig used in Experiment 2

suppression tools for peat fire mitigation, similar to the compressed and tight condition of the peat underground. Therefore, a dried peat of 25 cm in height was placed above the saturated peat that was 10 cm on the below part of the rig, similar to the first and second experiments with heat pipe application. This rig can accommodate 6 kg of dried peat (30 cm x 25 cm x 15 cm), allocated above the saturated peat.

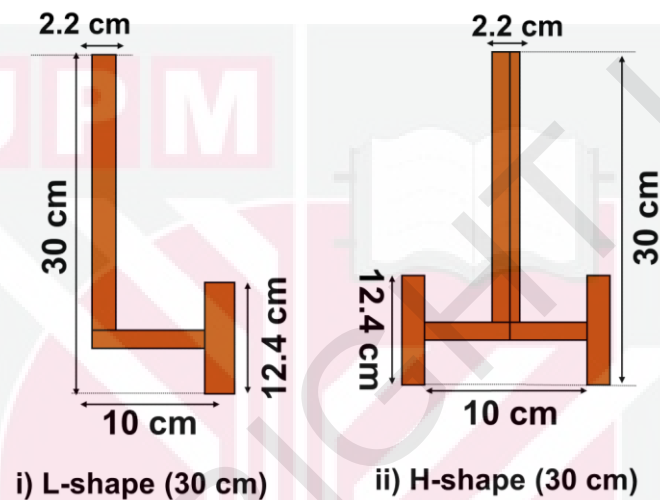


Figure 55: ⁷Heat pipe used in the third experiment: i) L-shape heat pipe of 30 cm; and ii) H-shape heat pipe for 30 cm height.

Since an L-shape heat pipe contributes to the best results in aiding the smouldering fire suppression, this experiment will continue to use the L-shape. Specifically, two (2) designs of heat pipe were used, namely i) L-shape and ii) H-shape designs with a height of 30 cm and 2.2 cm diameter (**Figure 55**). The heat pipe was placed between the saturated and dried peat. Furthermore, this experiment was ignited by using embers for 5 minutes, which is explained further in **Figure 57**. In addition to the third experiment on heat pipe application, the experimental rig added a section to imitate the canal to monitor the water table drop, as illustrated in **Figure 56**, which will be referred to as canal

⁷ The measurement is for illustration to describe better the actual heat pipe used in Experiment 3.

imitation.

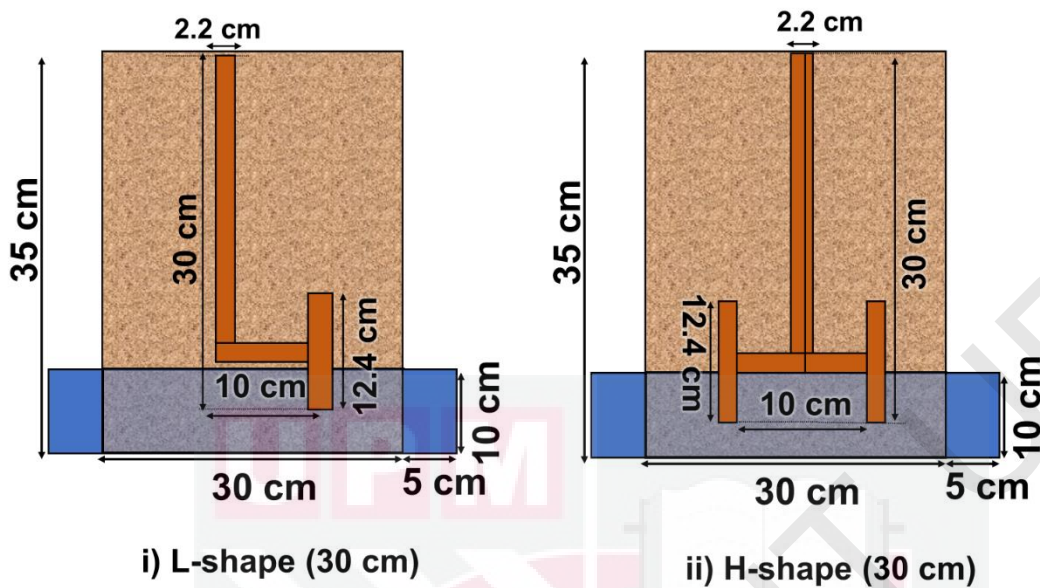


Figure 56: ⁸The experimental set-up of a rectangle shape (35 cm x 30 cm x 15 cm) for the third experiment of heat pipe application. The heat pipe of 30 cm was used in this experiment: i) L-shape and ii) H-shape.

6.3.3 Peat fire ignition

Two (2) type of ignition was used in this experiment. First, a coil ignitor was used in i) the preliminary experiment without heat pipe application and the first experiment with heat pipe application. The coil igniter was buried near the surface of the dry peat to start the smouldering fire. The ignition power was fixed to 60 W (Lin et al., 2020) for 15 minutes and will let smoulder until the temperature reached 30°C to end the experiment. The temperature was monitored by using a thermocouple. Second, ember was used for the ii) addition experiment without heat pipe, and second and third experiment with heat pipe application. A 50 g was burnt until it turned to embers and placed on the surface

⁸ The measurement is not according to scale; it is used to better describe the experimental rig used in Experiment 3.

of the dried peat for 5 minutes. Then, about 100 g of dried peat was placed on top of the ember. The second experiment with heat pipe application was successful in using this method. It was continuously used in the third experiment with heat pipe application. The description of the ember placement is illustrated in **Figure 57**.

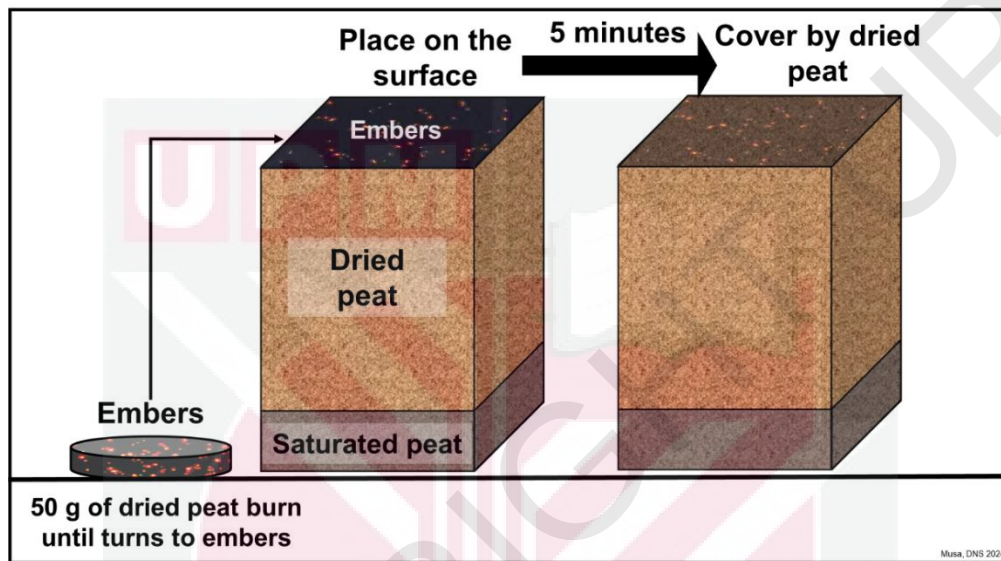


Figure 57: Illustration of burning using the ember method on dried peat as ignition sources.

6.4 Results and Discussion

6.4.1 Peat fire phenomena and role of heat pipe as suppression tool

The susceptibility of peat soil to fire is due to the presence of dry peat near the surface during the drought season. Understanding smouldering fire conditions within the dry peat layer and its self-suppression in the presence of saturated peat is limited. This section presents smouldering fire conditions in the dry peat layer (initial moisture content = $10 \pm 5\%$ for oven-dried peat) above the saturated peat layer (Moisture = 900%) using various sizes of experimental rigs. The safe region in this context is referred to as the unburnt layer between dry

peat and saturated peat, which remains safe from fire due to moisture increases in this layer up to 400%. The application of a heat pipe enhanced the elaboration of the formation of this safe region, is provided.

6.4.2 Discovery of Safe Region Formation

To achieve the third objective of the thesis, a proof-of-concept experiment on safe region formation was conducted. First, this chapter assesses the role of saturated peat in a smouldering fire situation to imitate the condition of peatland with a high water table in a small-scale experiment. This work shows the tendency of the 'safe region' formation development below the ashes and above the saturated peat in the preliminary and addition experiment as described in 6.4.1 i) safe region discovery. In this experiment, we found out that the safe region was not affected by the smouldering fire, yet the initial moisture of $15 \pm 5\%$ MC was increased to 250% - 400% MC at the end of the experiment.

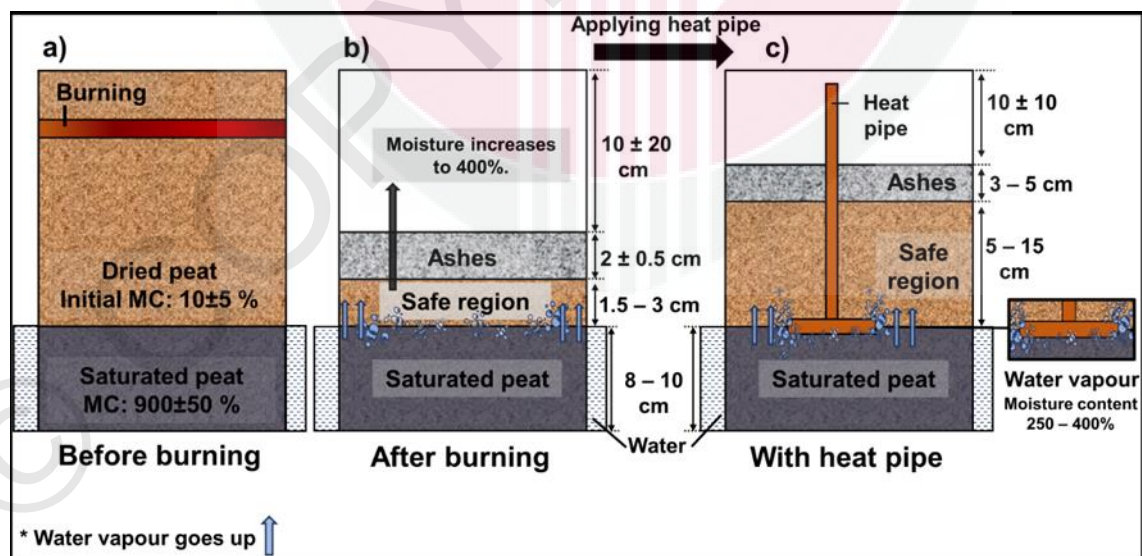


Figure 58: a) Burning process; b) A layer referred to as a safe region was found between saturated peat and dried peat; c) The heat pipe application enhanced the safe region layer.

The safe region, which was previously dried, had absorbed the moisture from the saturated peat as water vapour accumulated in the safe region, as illustrated in **Figure 58**. The observation from this experiment is that the saturated peat influences the protection of the peat in a small-scale experiment (**Figure 58a**). The authors observe the 'safe region' formation trend below ashes and upper the saturated peat at the end of the experiment (**Figure 58b**).

The preliminary experiment to discover the safe region formation resulted in forming 1.5 cm to 2 cm of safe region formation. Meanwhile, for the addition experiment to find the safe region formation, the safe region formed about the same as the preliminary experiment, which was 3 cm (**Figure 59**). However, it still initiated the concept of saturated peat to protect the dry peat without the heat pipe application.

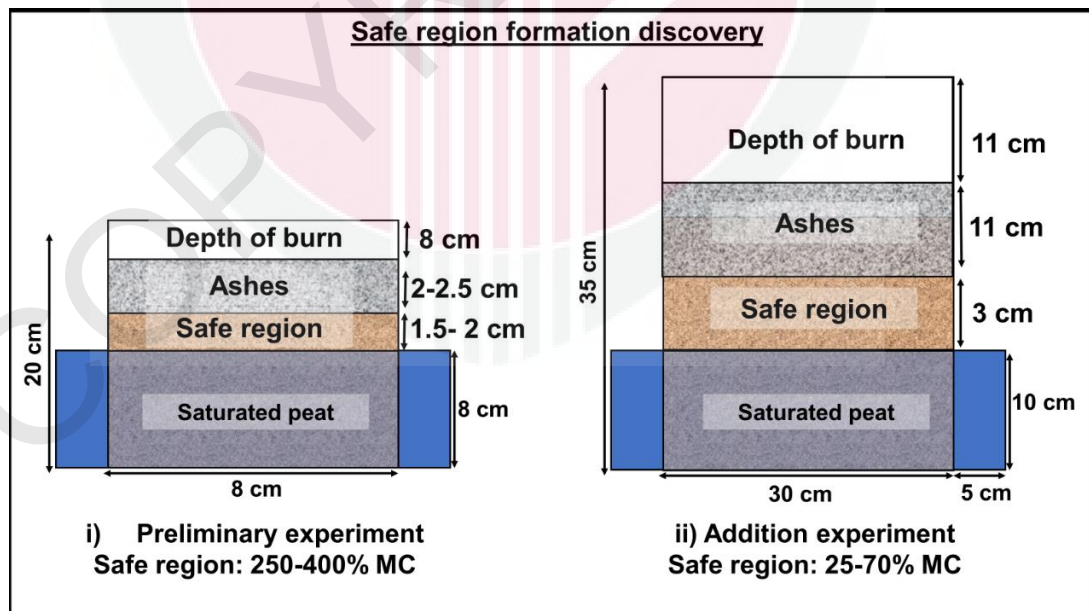


Figure 59: Safe region formation discovery without heat pipe application for both i) preliminary (mesh) and ii) addition experiments (sealed rig) to observe the safe region formation under different experimental rig conditions.

Therefore, to increase the role of the saturated peat, the heat pipe application with different designs was used in the first, second, and third experiments with heat application. The experimental rig condition and saturated peat maintenance might affect the result. In this work, the preliminary experiment was soaked in water and the water level was made sure to be maintained at 8 cm. Meanwhile, for the addition experiment, the water level was not maintained, and it was found that the water level dropped about -2.5 cm to -3 cm. From this observation, the findings will be compared with heat pipe application in the following discussion in 6.4.2, 6.4.3, and 6.4.4.

6.4.3 Experiment 1: 10 cm heat pipe (L-shape vs T-shape)

The study developed and tested a proof-of-concept smouldering fire prevention theory with the potential to prove the comprehensive heat pipe application underground through experimental research. With the application of a heat pipe in the experiment, the formation of the safe region increased from 1.5 ± 0.5 cm to 8 cm (**Figure 58**). With the heat pipe application, the safe region area was increased during burning because the heat evaporates the water from the saturated peat upwards and condenses in the safe region was improved. Technically, the heat pipe acts like a pump installed underground when heat is present near the surface.

A further experiment was conducted using different quantities and designs of the heat pipe, and it has proven to increase the moisture from $15\% \pm 5\%$ MC to $300 \pm 50\%$ MC to prove the concept. Through the experiment, we noticed that by applying one heat pipe of either L or T shapes will increase the safe region

formation. By increasing the quantity of the heat pipe, the safe region formation also increases in height as illustrated in **Figure 60** and **Figure 61**. In this experiment, the maximum amount of heat pipe use is three (3) to observe the heat pipe's effectiveness in efficiently enhancing the safe region formation.

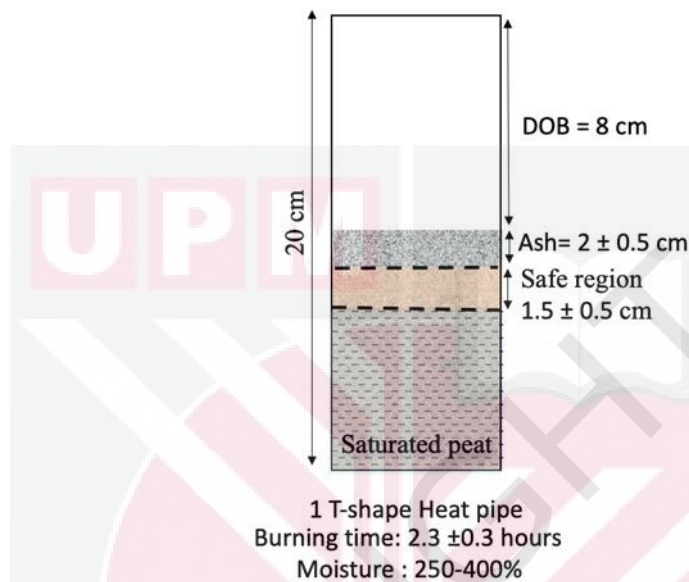


Figure 60: Without heat pipe application, using mesh as an experimental rig is compared to using a heat pipe application.

The differences between safe region formation between the L-shape and T-shape were graphed in **Figure 62**. Both designs show increasing safe region formation by increasing the quantity of heat pipe. The L-shape indicates that two (2) quantity of heat pipe is needed for this shape to form an 8 cm safe region and protect the dry peat. However, to achieve a similar result as L-shape, T-shape required three (3) heat pipe quantities to create an 8 cm safe region. Thus far, the L-shape is the most suitable design for controlling the peat fire and protecting the dry peat.

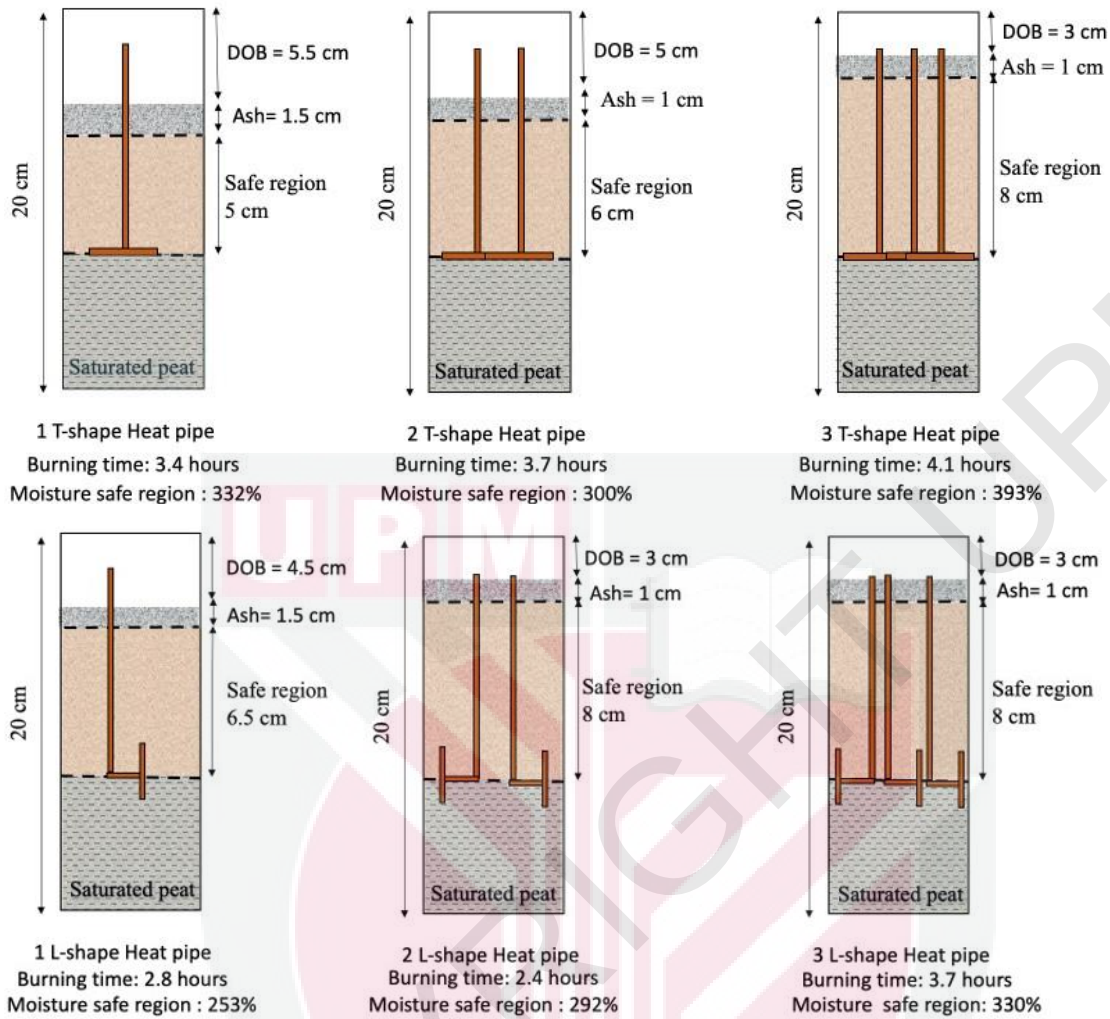


Figure 61: Assessment of the depth of burning and safe region area at the end of the experiment for without-heat pipe, with heat pipe of different designs and quantity, and copper tube.

Moreover, we also monitor the heat pipe's temperature to figure out how the heat pipe controls the smouldering temperature. The results of the temperature neat heat pipe for presented in **Figure 63**. The observation suggests that the temperature near the heat pipe is lower for the L-shape, implying that the L-shape heat pipe will lower the temperature in the heat pipe and increase the safe region formation to protect the dry peat. Therefore, it demonstrated that L-shape is the best design for this experiment. Further research in the second experiment will observe the temperature neat heat pipe and the surroundings to prove that the

heat pipe is lowering the temperature and eventually stopping the smouldering fire.

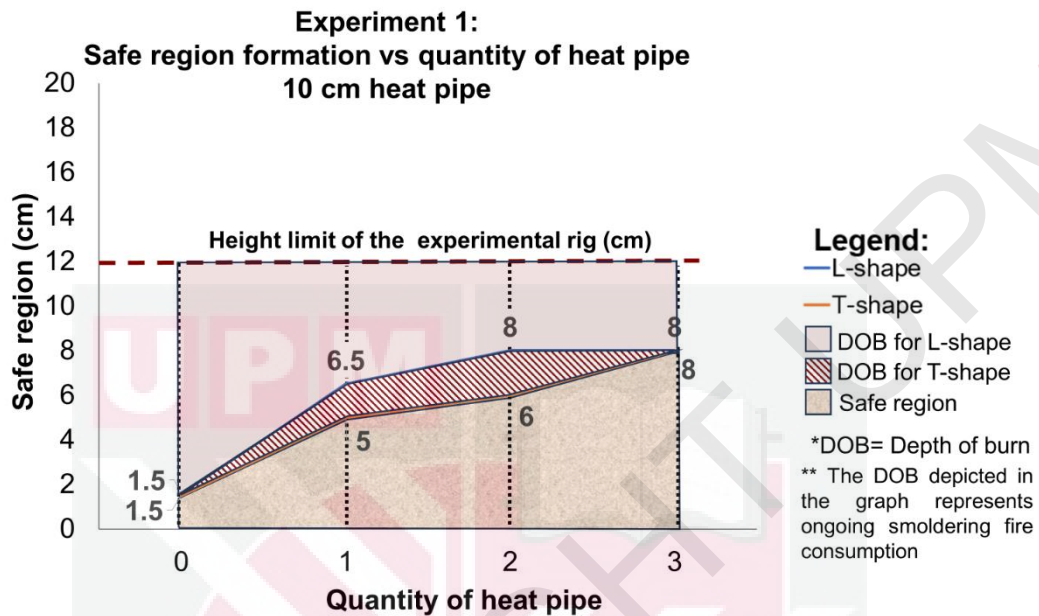


Figure 62: Safe region formation by applying a heat pipe (10 cm) in a small experimental rig.

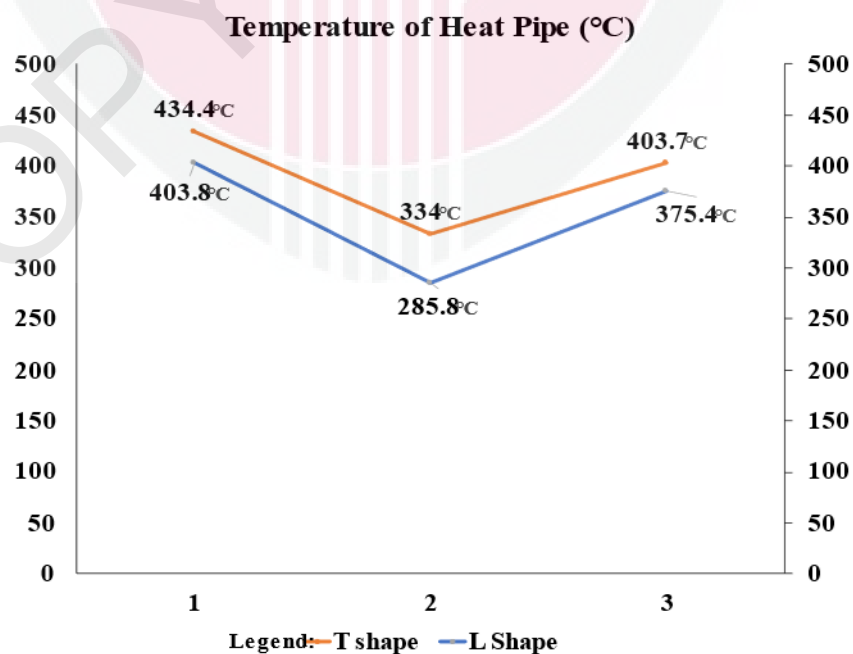


Figure 63: Temperature near the 10 cm heat pipe for 20 cm height experimental rig.

6.4.4 Experiment 2: 20 cm heat pipe (L-shape vs T-shape)

Based on the previous experiment in 6.4.3 Experiment 1: 10 cm heat pipe (L-shape vs T-shape), we understood that the quantity of the heat pipe is performing well at two (2) units for L-shape. Therefore, based on the effectiveness shown by the L-shape heat pipe, the experiment was conducted with only two (2) units of heat pipe for both shapes in this experiment. Furthermore, we wanted to address this chapter's concern based on the different diameter effectiveness towards the safe region formation to stop the fire. To do that, this experiment will be conducted using a 10 mm and 5 mm heat pipe, and the results of the observation were illustrated in **Figure 64**. The observations of the experiments are shown in **Figure 65**, **Figure 66**, and **Figure 67**.

The moisture content of the dry peat for the 10 mm diameter of the heat pipe ranges from 383% to 457% MC, and 5 mm ranges from 404% to 446% MC. From the experiment, the moisture does not have significant differences between the quantity of heat pipe and heat pipe design. The findings indicate that the heat pipe design does not significantly influence the after-moisture availability in the dry peat after the smouldering fire stops. By increasing the moisture of the dry peat up to 457% MC with the application of the heat pipe despite the diameter, the dry peat will be challenging to consume by the smouldering fire, which signified the role of the heat pipe in increasing the moisture and stopped the smouldering fire despite of the diameter and designs. However, the design and the diameter of the heat pipe used in the experiment influenced the safe region formation.

From **Figure 65**, by increasing the number of heat pipes, the temperature will be lower near the heat pipe. This situation validates the theory of heat pipe to evaporate the water from below and condense in the dried peat. This experiment suggested that L-shape best protected the dry peat by proving the higher safe region creation. The figure below shows a comparison between the surrounding temperature and around the heat pipe (**Figure 66**). The surrounding temperature is higher, with the highest temperature of 507°C compared to the temperature near the heat pipe, with the highest temperature of 457°C. As a result, we understood the importance of a heat pipe to control the temperature near its surrounding to control the smouldering fire until it stopped. From the current experiment, we also understood that increasing the diameter of the heat pipe can increase the formation of the safe region. Thus, the following experiment should focus on a bigger diameter in a sealed experimental rig to confirm the heat pipe concept as an early suppression tool to mitigate peat fire.

Further experiments with larger diameters in different experimental rigs will be conducted to answer the question we have in this experiment about how a larger diameter will provide more protection. And how the sealed experimental rig will specify similar results? An ongoing experiment in 6.4.5 Experiment 3: 30 cm heat pipe (L-shape vs H-shape) will provide the information on the increment of the safe region by increasing the diameter to 2.2 cm of the heat pipe and change the experimental rig into sealed rig instead of mesh to widen the information on the heat pipe performances similar to the real peatland in the laboratory.

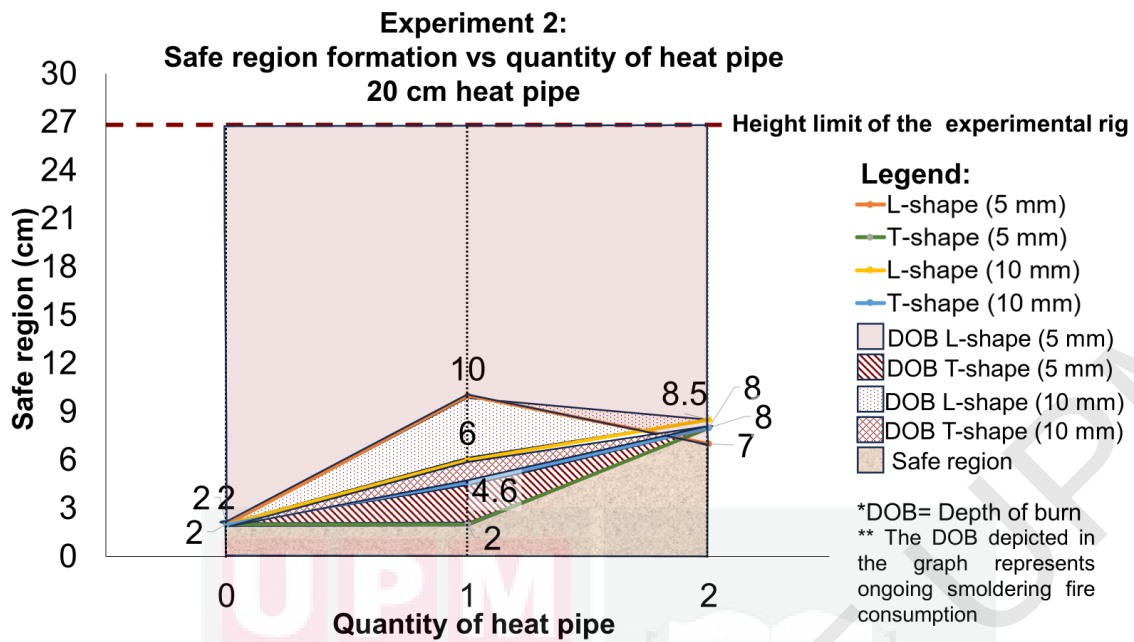


Figure 64: Safe region formation by applying heat pipe (20 cm) in a small experimental rig.

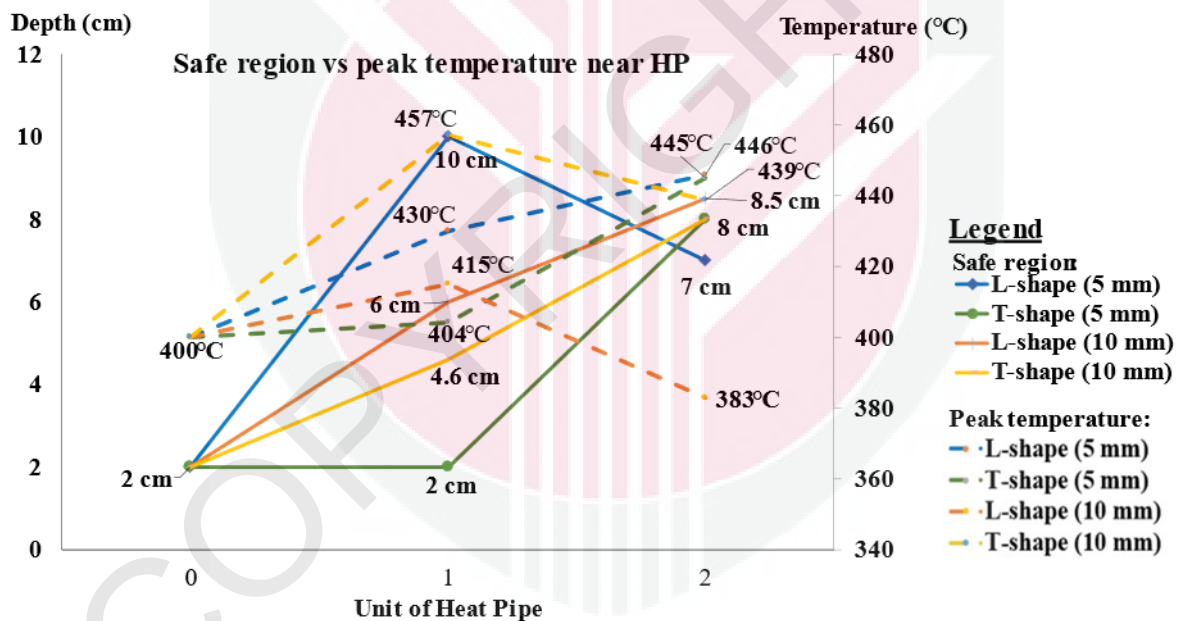


Figure 65: summary of the heat pipe vs the safe region formation based on the heat pipe quantity. The temperature was measured in the dry peat region.

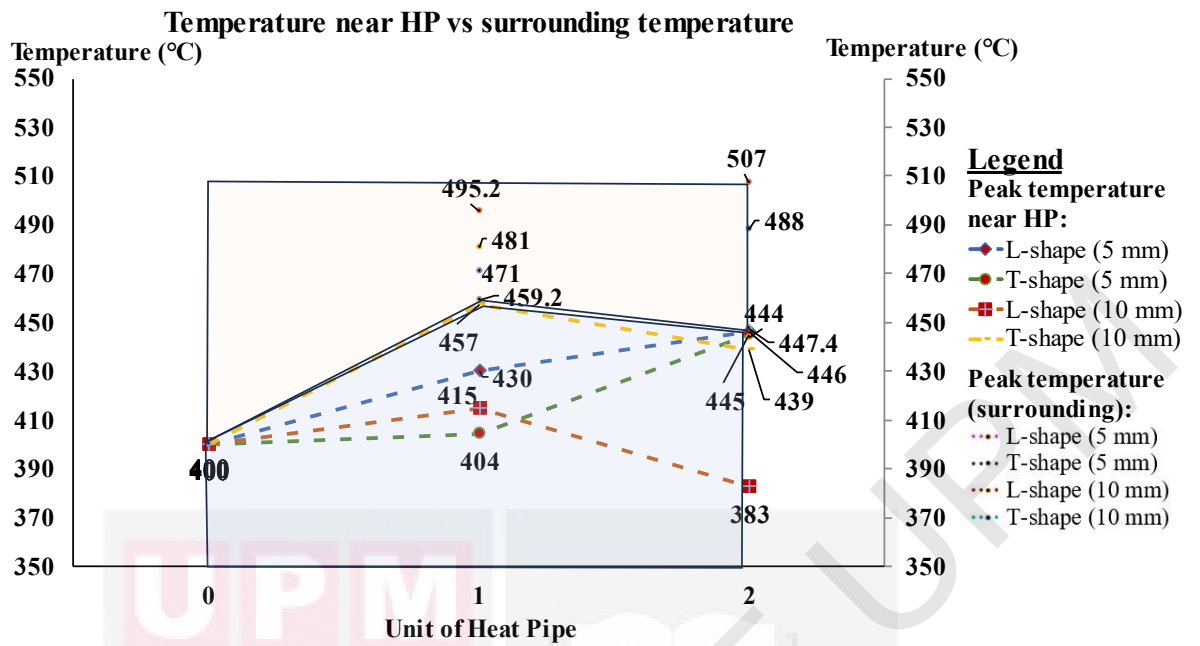


Figure 66: temperature surrounding vs near heat pipe (HP) in the experimental rig.

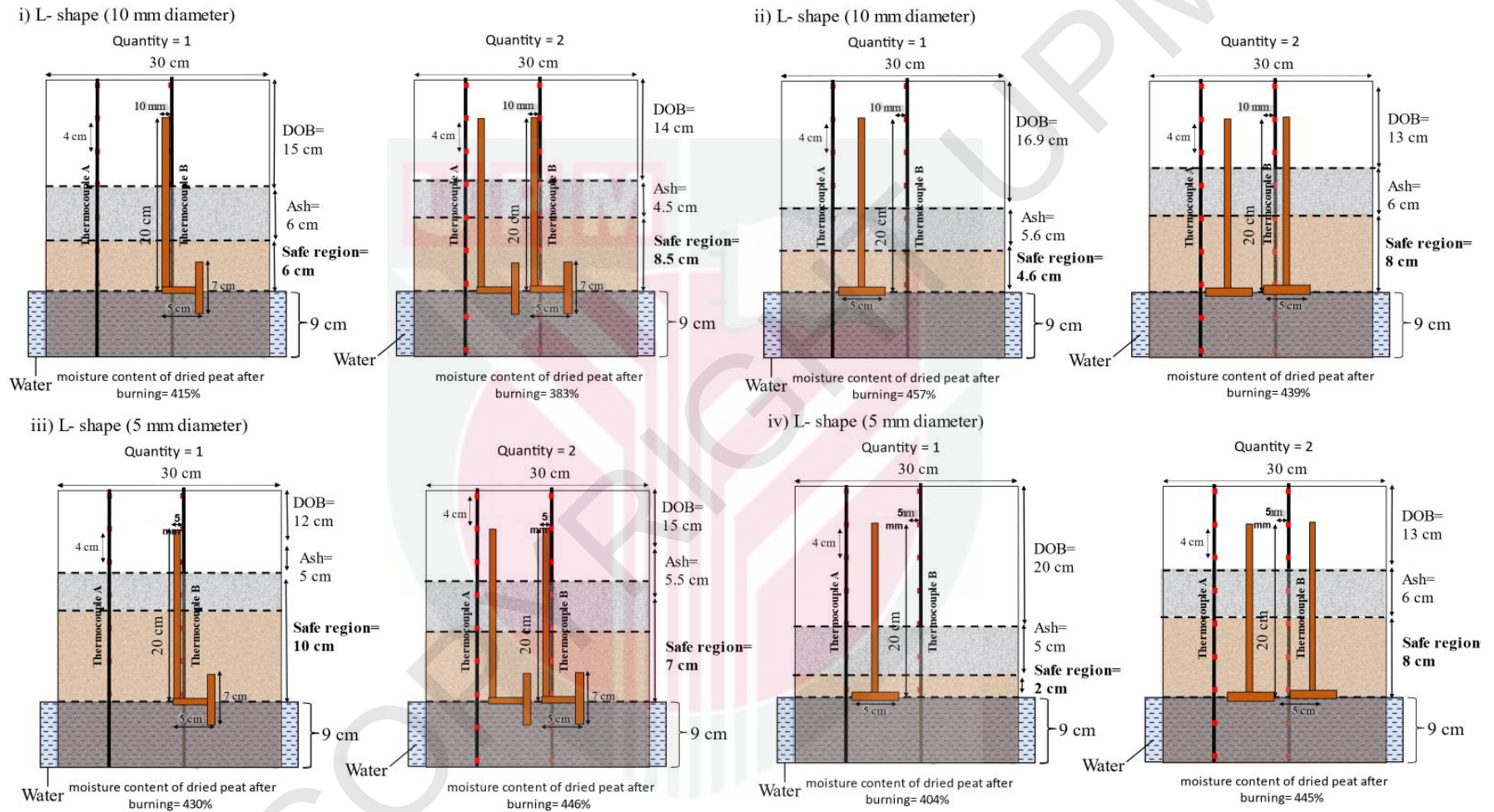


Figure 67: Assessment of the depth of burning and safe region area at the end of the heat pipe of different designs (20 cm), diameter and quantity; i) 1 quantity L-shape, 10 mm, ii) 1 quantity T-shape, 10 mm, iii) 2 quantity L-shape, 5 mm, iv) 2 quantity T-shape, 5 mm.

6.4.5 Experiment 3: 30 cm heat pipe (L-shape vs H-shape)

Based on the previous experiment in 6.4.2 and 6.4.3, the heat pipe design of an L shape is the best to increase the safe region formation and lower the temperature near the heat pipe to protect the dried peat. Therefore, further investigation was conducted to enhance the function of the L shape design by constructing the H-shape design, as shown in **Figure 53**. The H-shape design is a mirror design of the L-shape that this chapter hypothesis to increase the safe region formation compared to the L-shape. Based on our concern in the previous section of 6.4.3, the experimental rig created for the third experiment was more extensive than in the previous 6.4.3 experiment, as shown in **Figure 56**. Moreover, the rig was sealed and not made up of mesh not to allow the supply of oxygen from different directions. We hypothesised that the experiment would stay longer, referring to a previous study by Qin et al., (2022) for their findings in deep peat fire smouldering for weeks in a laboratory experiment (Qin et al., 2022). In addition to filling in the study's gap, we will measure the additional water reduction from the WTD section to understand the water drop from the fire break canal during the fire outbreak near the fire break canal.

In this chapter, we have found that without heat pipe application, the maximum of the safe region formation will be 3 cm, as shown in **Figure 68**. Moreover, the burn depth is 11 cm and 11 cm ash burns for four (4) days which is more than the previous experiment in 6.4.3 and 6.4.4. Previously in 6.4.3 and 6.4.4 experiments, the moisture can increase up to 400%, which is very high to prevent the fire from smouldering in the dry peat. Contrarily, the moisture content found in the sealed rig experiment is that the moisture is lower than

68% MC which is significantly lower compared to the minimum moisture content of 253% MC in 6.4.3 and 353% MC in 6.4.4. The lower moisture content in this experiment resulted in a longer burning time lasting four (4) days. Since the burning is longer and the moisture is lower, we figured out that the weight loss of the peat should be measured to determine how much the dry peat was consumed during the experiment. Without the heat pipe application, the findings indicate that 52% of the peat was lost during the experiment with the safe region formation of 3 cm (**Figure 68**). Although the burning is more prolonged than previous experiment, the safe region is still formed and protected.

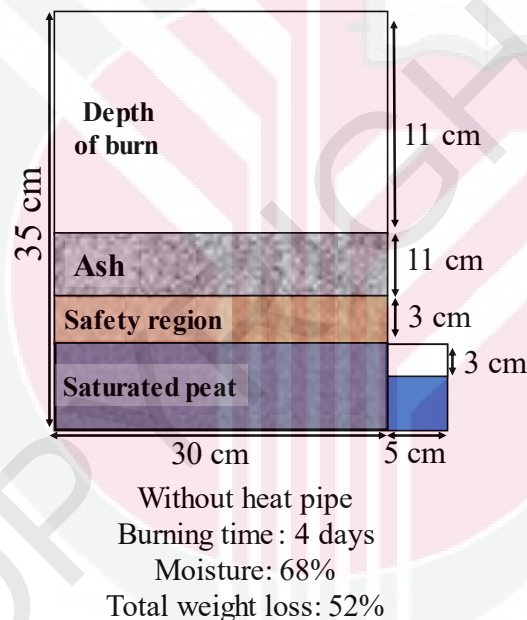


Figure 68: Experiment of safe region formation without heat pipe application on a larger scale and sealed rig.

By applying a 2.2 cm diameter L-shape heat pipe and a new H-shape design, the safe region formation was observed for its safe region formation, different quantity, and mass loss. The summary of the safe region formation based on the quantity and shape of the heat pipe is illustrated in **Figure 69**, and the safe region formation is shown in **Figure 70**. The experiment suggests that the newly

designed H-shape increases the safe region formation more than the L-shape heat pipe. The result of the investigation supports the hypothesis that the mirror shape of the H-shape design will increase the safe region formation more than the L-shape heat pipe. Although the previous experiment showed the L-shape to be better in protecting the dry peat, the experiment can achieve a higher increment of safe region formation by improving the heat pipe design.

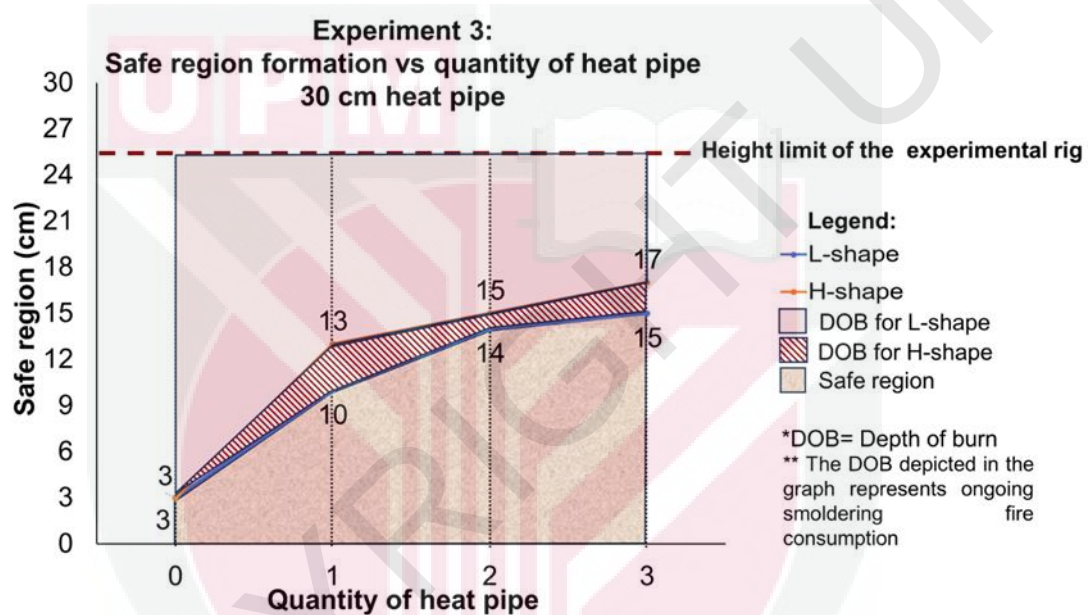


Figure 69: Safe region formed influenced by L-shape and H-shape heat pipe designs at different quantities.

Further description of the safe region formation, moisture after the burning and total weight loss was illustrated in **Figure 70**. From the illustration, the longest burning time is for one (1) L-shape in a 6 kg dry peat that took ten (10) days and consumed 33% of the dry peat. Although the period is more extended than without the heat pipe application, the weight loss is lower than without the heat pipe application. The findings indicates that the heat pipe in a sealed rig increase the temperature and the moisture are condensed into the dry peat which took longer period to reach temperature below 30°C.

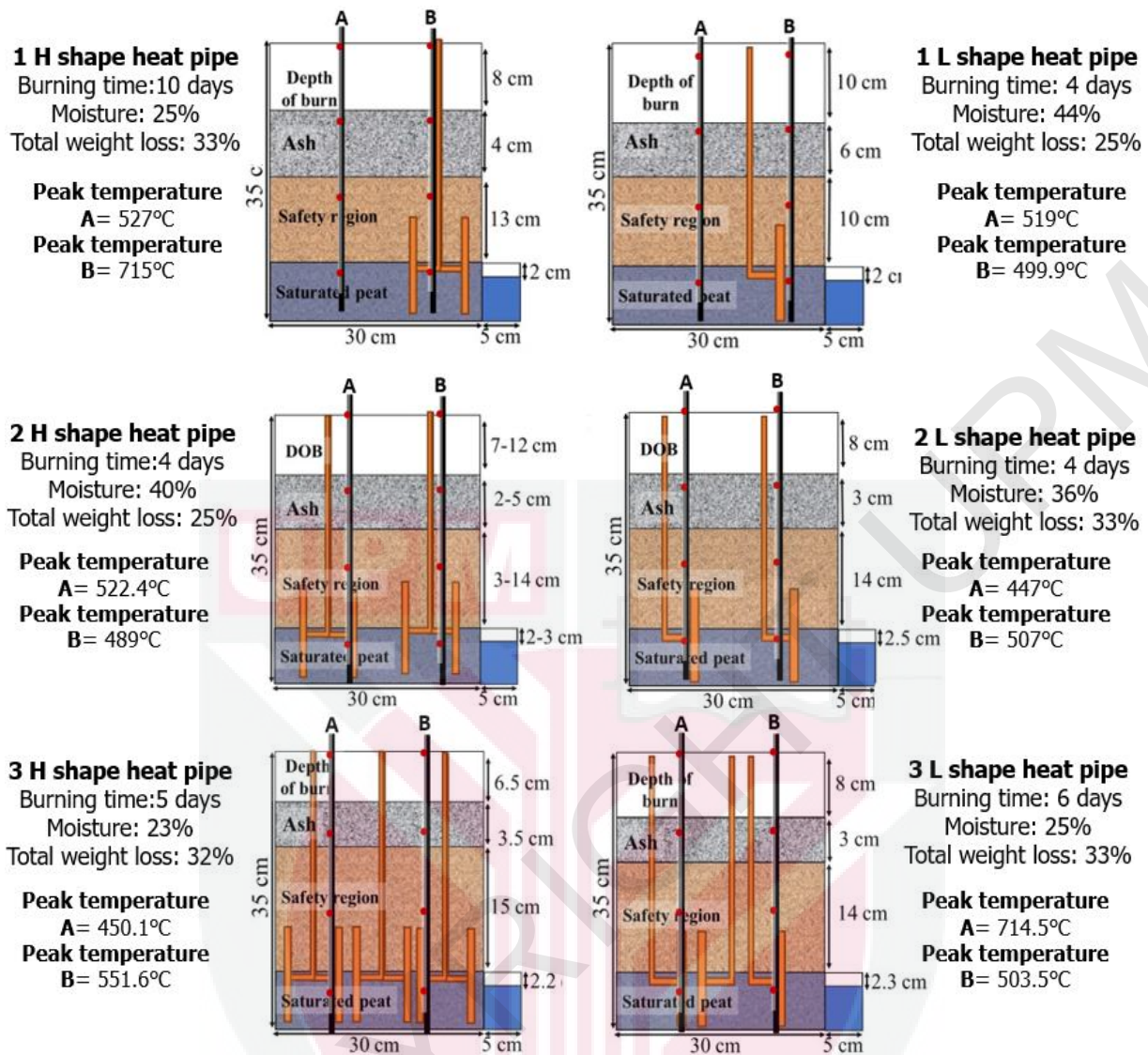


Figure 70: Application of 30 cm heat pipe with 22 mm diameter in a sealed experimental rig.

Moreover, this experiment was conducted in Malaysia during an El-Niño season and temperature can reach 40°C with the lowest of 34°C during the day and 26°C at the night, which might contribute to the extended period of the smouldering due to hot environment. However, further experiment regarding the influence of the surrounding temperature towards the peat burning should be investigated in future research. Regarding the presence of the canal imitation, we have figured out that without heat pipe application, the water in the canal imitation partition was lowered to -3 cm. Nevertheless, the fluctuation is not significant

compared to the heat pipe presence with water lower down -2 cm to -2.5 cm. Nevertheless, the water evaporated from the saturated peat was condensed in the dry peat and protect the dry peat layer with the presence of the heat pipe. Thus, the study on this chapter also figures out that the moisture in sealed-rig is lower than 50% and it can last for more than four (4) days, yet still effective to control the smouldering peat fire since the weight loss are 23%-44% which indicate the peat fire consumption of the dry peat in the experiment.

6.4.6 Future directions for application of heat pipe

The study focused on highlighting the importance of maintaining peat in a saturated condition to prevent underground smouldering fires. Additionally, it aimed to emphasize the significance of maintaining consistent water table depths in peat, as fluctuations can enable subterranean smouldering fires. The experiments conducted in this chapter offer insight into potential applications of heat pipes in real-world scenarios, aiding our understanding of their effectiveness as early mitigation measures for controlling and suppressing smouldering peat fires. However, the feasibility of implementation is subject to water table fluctuations, which could impact field research.

This chapter specifically examined and validated the efficiency of three (3) types of heat pipes in preventing smouldering fires within mesh and sealed experimental rigs. Methodologically, a crucial discovery in this chapter lays the groundwork for future research applications in practical settings. Given that the research centres on using saturated peat to control smouldering peat fires, an area for future experiments could involve studying the relative water table in

fire-affected peatlands to apply heat pipes as a method for preventing peat fires. Questions arise regarding the interpretation of initial results concerning the formation of safe regions protected from smouldering fires. Currently, the indication is that dry peat up to 8 cm below the surface can be safeguarded, and in a 25 cm sealed experimental rig, peat up to -17 cm below the surface can be protected. Further exploration of protection range and heat pipe placement in more extensive laboratory-scale experimental rigs will provide valuable insights for implementing fire prevention strategies in the field.

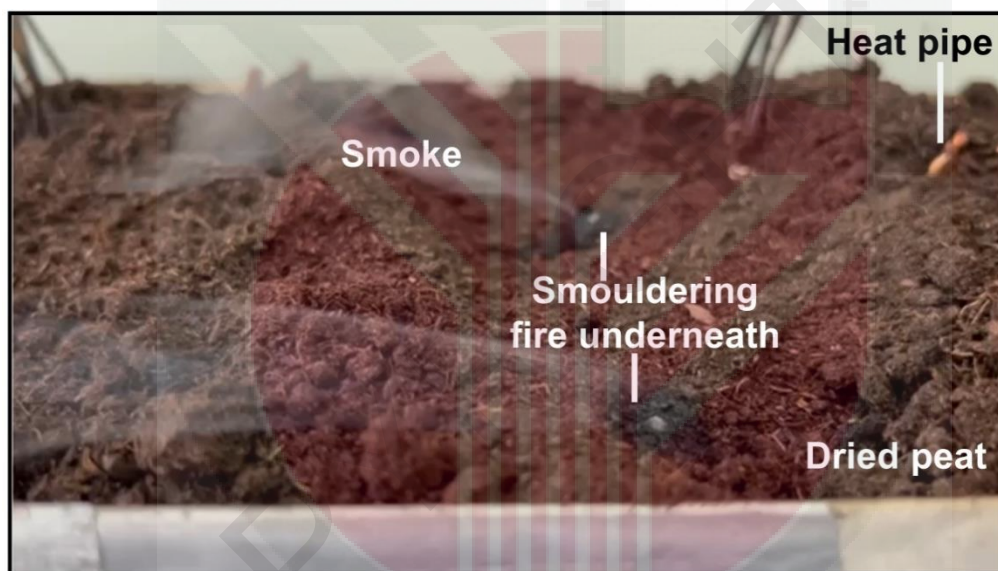


Figure 71: Smouldering fire below the surface during the experiment produces smoke in the presence of a heat pipe in a laboratory.

Figure 71 depicts a potential future application of the heat pipe in natural peat swamp forests. In drained peatlands with intense water deficits, substantial water table drawdown and severe burning can occur (Granath et al., 2016). This concept suggests that the lowered water table during dry seasons may be less concerning when facing smouldering fires, given the implementation of heat pipes underground that can reach the water table. Without heat pipe application, fires would consume the organic layer, leading to prolonged suppression efforts

involving flooding or water bombing by firefighters.

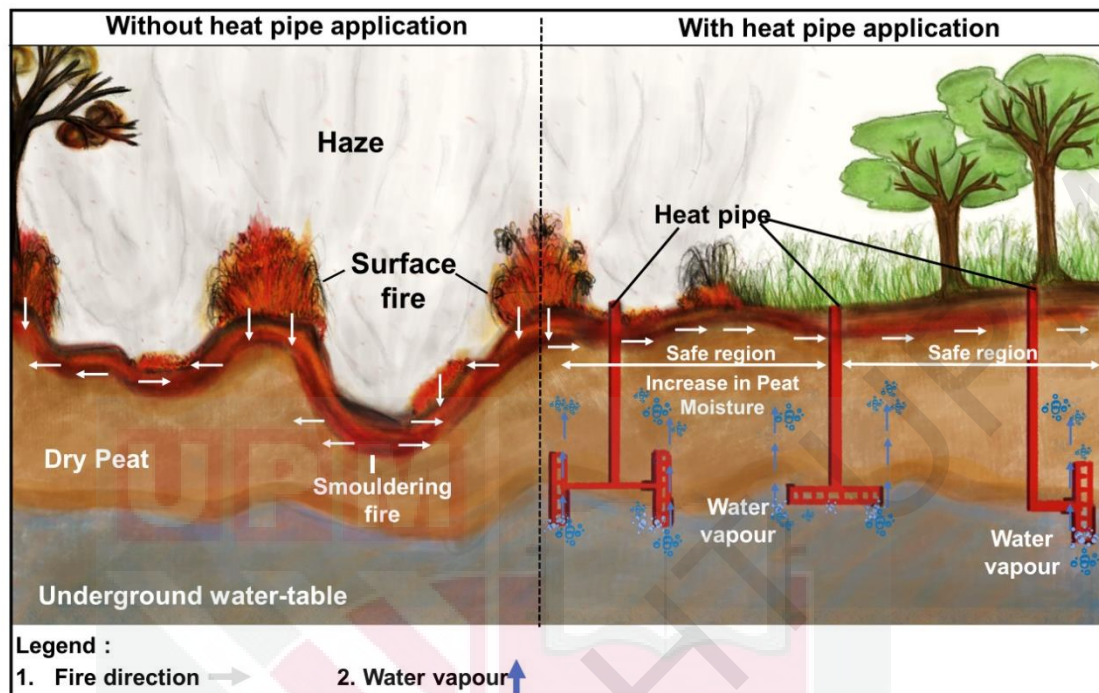


Figure 72: Illustration of heat pipe application on natural peat swamps as part of early fire prevention during the dry season.

The envisioned approach with heat pipes involves them functioning as water pumps, triggered by heat from smouldering fires. This would enable water vapour to condense in dry areas. Consequently, the organic layers of peat would remain unharmed, limiting consumption by smouldering fires and reducing smoke pollution. Additionally, the smoke coming from underground contribute to climate change by releasing greenhouse gases such as CO_2 and CH_4 (Stockwell et al., 2016). In the future, comprehensive monitoring efforts in peatlands will be essential to quantify the emissions of greenhouse gases and other pollutants released during peatland fires. This process would elevate moisture content in dry regions, facilitating early fire prevention that supports suppression procedures, as illustrated in **Figure 72**.

Further investigation into the presence of the water table below the surface, particularly in burnt areas of peatlands, warrants a more comprehensive study. The proof-of-concept approach undertaken in this chapter was confined to a small-scale laboratory setting. To further advance this concept, a broader study encompassing larger areas and employing diverse heat pipe designs becomes imperative. The successful prevention of smouldering fires through heat pipe applications, as demonstrated in this chapter, sets the stage for implementation in more expansive study areas, particularly within field studies. Essential insights can be gleaned from field studies focusing on underground water tables during both dry and wet seasons in areas subjected to repeated burning. Such studies are crucial for a thorough comprehension of the applicable concept.

6.5 Conclusion of chapter

The safe region discovered in this chapter signifies an unburnt layer of dry peat, with moisture increasing from $15\% \pm 5$ MC to 200-400% MC in the mesh rig and significantly lower, at 68% MC, in the sealed rig experiment, resulting in the cessation of smouldering fire. However, the moisture in the sealed rig experiment lowers to 25% to 33% MC in the presence of a heat pipe. The role of the water table in establishing a safe region that curbs further fire propagation is illuminated in this chapter. The water table's influence manifests in the creation of a small safe region, expanding from 1.5 ± 0.5 cm without a heat pipe application to 5 cm to 8 cm with a heat pipe application in the mesh rig, and up to 17 cm in a sealed rig experiment involving 25 cm dry peat. Furthermore, the augmentation of the safe region's height through the application of heat pipes of various designs to suppress smouldering fire is also elucidated. This chapter

can be extended to comprehend the heat pipe's role in peat protection through further experimentation across a wider scope of experimental rig areas, employing diverse heat pipe designs and diameters.

The number of heat pipes also plays a pivotal role in expanding the safe region, as demonstrated in this chapter. Notably, the use of T-shaped, L-shaped, and H-shaped heat pipes showcased the capacity to transport moisture from saturated peat, which subsequently evaporates in the safe region—a previously dry peat with an initial moisture level of 10% MC. If this method is adapted to the field, it could shield dry peat from imperceptible smouldering fires during droughts. This work introduces the concept of smouldering fire prevention in peatlands through a simple heat pipe application. The insights from this chapter stand to benefit future researchers and peatland managers in augmenting peatland protection against fires.

The study reveals that peat fire occurrences, regardless of fire frequency, significantly impact peat layers and lead to substantial alterations in properties extensively discussed in **Chapter 4** and **Chapter 5**, detailing their effects on physical and chemical attributes. Therefore, safeguarding peat becomes crucial to maintaining its properties and functionality—carbon storage, flood mitigation, and air pollution reduction. The study highlights that smouldering plays a pivotal role in persistent and prolonged fires that consume subterranean peat like a ghost or zombie-like fire, which can resurface and cause surface fires even after suppression efforts, as elucidated in **Chapter 3**. The research underscores the significance of peat fire mitigation in reducing the fire's impact. The proposed application of heat pipes as early mitigation measures aim to minimise peat's

effects and enhance on-field protection in the future.

The cumulative findings in this chapter demonstrate an enlargement of the safe region, making it valuable for on-site implementation. The key strength of the heat pipe application lies in its ability to establish a safe region, providing firefighters with time to suppress and mitigate impacts on peat in real-world scenarios. By delaying peat consumption due to smouldering fires, the management approach for on-the-groundwork by forest managers or oil palm plantation owners becomes more targeted and efficient. Moreover, the heat pipe application complements existing government prevention measures, enhancing their efficacy without disrupting other strategies and intensifying fire prevention efforts in peatland areas.

CHAPTER 7

CONCLUSION AND RECOMMENDATION FOR FUTURE RESEARCH

7.1 Conclusion

This thesis has examined various aspects of peat swamp forest fire management, summarizing the connections between chapters here. To outline the work, this thesis is organized into the following chapters: **Chapter 1** Introduction, **Chapter 2** Literature Review, **Chapter 3** Peat Swamp Forest Fire Management, **Chapter 4** Pre-Fire and Post-Fire Areas, **Chapter 5** Low and High Fire Frequencies, Chapter 6 Heat Pipe as Suppression Tools. In this **Chapter 7** Conclusion summarising the research works discussed in in **Chapter 3, 4, 5, and 6.**

To achieve **Objective 1**, **Chapter 3** were conducted which focuses on peat swamp forest fire management from a ground perspective. In the interview study, the interviewee highlighted the challenges in effectively combating peat fires, the community involvement and awareness are identified as crucial factors in fire prevention. Respondents have justified the interviewee statement on the current policy prevent the peat fire occurrences, pandemic proves human is main contributor to peat fire, local villagers help preventing peat fire, high fire intensity is the main challenge during firefighting, and rotation hour can reduce the firefighter's stress. Total of 77% from the total respondents trained for peat fire suppression and more than 50% of the respondents' experience in firefighting for more than 10 years. They justified that most influence factors are open burning, and strong wind, high temperature are the most important factors

to worsen the situation in which increase the impact on the peat.

To achieve **Objective 2**, **Chapter 4** and **5** were conducted in which **Chapter 4** investigates the impact of peatland fires on ecosystems, comparing peat properties between pre-fire and post-fire areas. This chapter's findings indicate that the pH, CEC, P, and K differs significantly between the pre-fire and post-fire area. The N, Mg and Ca content is significantly lower in post-fire than in pre-fire area. Moreover, properties like N, P, K, dry bulk density, wet bulk density, and moisture content exhibit significant values within the depth. **Chapter 5** examining the effects of fire frequency on peat properties. When comparing HFF and LFF areas, no significant differences are noted in physical and chemical properties ($p > 0.05$), except for porosity ($p < 0.05$). The mean porosity in the HFF area is 9% higher than in LFF peat, contributing to higher moisture by 434% in the HFF area, lower bulk density and OMC by 0.05 g cm⁻³ and 8%, respectively. Lower OMC in HFF leads to statistically lower C_{org} by 5% compared to LFF area. Ash content is significantly higher in the HFF area by 8%, indicating carbon loss. This chapter also suggest that the distance from the fire-break canal does not impact moisture content, but peat depth up to -150 cm from the surface at varying fire frequencies affects moisture availability. Laboratory analysis provides scientific evidence of these effects, emphasizing the importance of effective fire management in preserving peat and highlights the need for effective fire suppression to mitigate such impacts.

Chapter 6 exploring the use of heat pipes as potential tools for suppression to aid in mitigation approach to achieve **Objective 3**. This chapter paves the way for refining heat pipe technology through controlled field trials and simulations

for enhanced peat fire suppression. The safe region discovered in this chapter indicates that a dry peat with initial moisture about 15% can increase to approximately 400% in the mesh rig, and 68% in a sealed experimental rig. The safe region is unaffected dry peat between the ash and saturated peat. This safe region can be increase through the heat pipe application that act as peat fire suppression that will aid in mitigation approach. Before applying the heat pipe, the safe region is about 1.5 cm height, then was increase to 8 cm in a mesh rig and 17 cm in a sealed rig. This chapter emphasise the significance of peat fire suppression to reduce the impact on peat properties and also can be proposed as early mitigation measures to safeguard the peat in the future.

A ground-level perspective on fire management is crucial for complementing fire researcher perspectives on smouldering peat fires. The multidimensional research methods have provided a comprehensive understanding of peat fire dynamics, fire effects on peat properties, and potential innovative suppression techniques. Overall, this thesis seeks to deepen the understanding of peat swamp forest fire management, emphasizing the significance of integrated and sustainable approaches. The relationship between fire management practices, impact assessments, innovative suppression techniques, and effective preservation strategies for valuable ecosystems is central to this thesis's contribution.

7.2 Summary of Chapter

Recommendations for future research have been outlined, identifying key areas that warrant further investigation to address existing knowledge gaps and

enhance fire management strategies. Building upon the research conducted in this thesis on peat swamp forest fire management, there are several critical domains that merit further exploration. Future research efforts should concentrate on filling gaps in our understanding and exploring novel approaches to bolster fire management, comprehend peat's responses to fire, and develop more effective tools for suppression and mitigation. Here are some suggestions for future research:

1. Extend investigation into Peatland Fire Management: Long-term monitoring and impact assessment are essential to track the ecological changes within peat swamp forests following fire incidents. Sustained monitoring of recovery processes offers invaluable insights for adaptive management.
2. Study on Peat Recovery and Restoration: Extended research periods should be devoted to examining peat recovery and restoration processes, particularly in proximity to fire break canals. Understanding the peat rehabilitation process over time is crucial.
3. Determine the Diverse Fire Intensity Impacts: Research should delve into the varying impacts of different fire intensities, encompassing scenarios ranging from infrequent to frequent fire occurrences.
4. Investigate the Socio-Economic Impacts and Community Involvement: Investigate the socio-economic implications involving local communities in post-fire rehabilitation efforts. Assess the long-term economic value of peat swamp forests as a sustainable resource.
5. Evaluate the Adaptive Fire Management Strategies: Regularly updating fire management strategies based on emerging research findings and

technological advancements will strengthen the resilience and effectiveness of fire suppression initiatives.

By addressing these research recommendations, we can advance our comprehension of peat swamp forest fire management and devise more potent strategies for combatting peat fires. Safeguarding and conserving peat as an invaluable treasure within unique ecosystems is vital for the benefit of generations to come. Effective collaboration among researchers, policymakers, local communities, and non-governmental organizations is essential to drive meaningful progress in mitigating the devastating impacts of peat and forest fires within protected peat swamp forests.

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APPENDICES

Appendix A

Interview session with Fire Managers

Table 1: The analysis of the interview.

Theme	Code	Summary
Peat Fire	Forest fire occurrences	Representatives A: Fire occurrences during drought and worsen by El-Niño cases. Representative B: Peat fire occurrences in Klias and Binsuluk Forest Reserves. Representative C: Smoke was used to indicate whether a peat fire is fully suppressed but the fire will come out again after some time (after suppression) in Sarawak. Representative C: Experience with peat fire in Kalimantan Barat, Indonesia.
	Peat fire effects	Representatives A: Peat fire affect people, the ecosystem, and the economy Representative C: Had personally experienced the worst haze event in 1997/98 Kalimantan, Indonesia peatland fire when Malaysia helped Indonesia at that time to reduce the impact. This haze event, also known as transboundary haze pollution, urged the ASEAN county to sign a Transboundary Haze Pollution in 2001. Representative C: Heavy smoke will increase breathing difficulty, and the heat during the peat firefighting will also contribute to breathing problems and movement constraints.
	Fire Causes	Representative B: Human activities such as arson, land development, open burning, hunting, and recreational activities Representative B: The Pandemic Covid-19 reduced the fire to 550 ha from thousands of ha in previous years. In 2021, the area burn is 100ha Representatives C: The human factor is believed to be the main reason for the peat fire, which is proven during the Movement Controlled Order (MCO) by the government of Malaysia as the number of fires has been reduced since the pandemic in the past 2 years. The slash-and-burn activity cannot be

		completely prevented and should exit as it relates to the economy.
Current approaches	Prevention/ mitigation	Representatives A & B: Prevention/control- a fire break or fireguard to prevent fire spreading. For example canal as fire break that has been implemented in Klias and Binsuluk Forest Reserves (peat swamp forest). Representatives A & B: In addition to the prevention measures by the Sabah Forestry Department, they also implemented an awareness issue, especially for the people near the forest reserve, to increase awareness of the peat fire. Representative B: The regular awareness campaign with the local communities includes flyers and signboards (placed in a strategic area). Representative C: To control the peat fire, collaboration with the Forestry Department also helps monitor the forest area. Cooperation is necessary in this matter to prevent peat fire. For example, in 2017, there was an opening of the agricultural proposes that contributed to the high number of fires cumulatively. Therefore, if we can control the activities, we can control the fire and eventually increase awareness and create more champions to help control the fire. Representative C: The prevention measure that was introduced by the Fire & Rescue Department is a Standard Operational Procedure that must be followed by the companies or local people when doing the slash and burn. This method has reduced fire events, especially the peat fires in Sarawak. Representative C: A tube well with 247 units will be installed for flooding when the water table depth is lower. This ensures the water table depth is always maintained to prevent peat fire. Further research on this matter is highly recommended. Other engagements with the Institute of Peat in Sarawak to do research related to peat soil also gave information to increase the knowledge in this matter. He also mentioned that Sabah has a similar approach where 283 tube wells were installed with the same purpose (Representative B). A check dam was used

		to measure the water table depth. Additionally, irrigation can help in supplying the water from the nearby river to help prevent the peat from drying. Also, collaborating with the Meteorological Department to monitor the weather and potential fire area is essential. Representative C: Technology is very important nowadays; another method that has been implemented is patrolling using a drone. Representative C also encourages engagement with the local community, which is known as the Champion, to assist with fire-related issues. When discussing cross-border fire, it does not occur as the State of Sarawak creates a resilient community that understands its responsibility to protect the environment. As far as the Representative C is concerned, the current approach by President Jokowi of Indonesia to move the capital city from Jakarta to Kalimantan has made the community love nature, which eventually reduced the fire cases. So, it is a positive sign of reducing the fire through this method despite huge agricultural activities.
	Suppression	Representative B: The department uses water bombing, flooding techniques, and water pumps. Representative B: After applying the suppression technique, we do mopping-up to ensure the fire is fully suppressed. Representative A: The suitable time for suppression is 10:00 am. At 12:00 pm in Sabah, it is too hot and difficult to do suppression. Representative C: Regarding suppression, the fire and rescue department will use various methods, such as water bombing by using a helicopter, hand tools and a water pump. Representative C: As the peat fire can last from weeks to months, the firefighters only have 12 hours (6:00 am to 6:00 pm) to suppress it. It can be difficult especially when water shortage happens during the prolonged dry season. Representative C: Fast enforcement in the area and to make sure the peat fire is fully

		extinguished is significant. Representative A, B, C: Rain is helpful to suppress the peat fire. Peat fire can re-appear after suppression/rain.
	Monitoring	Representatives A: Monitoring through a Fire Danger Rating System (FDRS) was used and is currently being improved by developing a new mobile application technology. This new technology is known as the FDRS data collector, which uses a daily input of weather (humidity, rain, wind speed and temperature) for 27 districts in Sabah. Representative C: In the case of a hidden fire that is coming up in the dry season, the department will use a drone and thermal image to monitor the in-depth peat condition. Representative C: Currently, they use thermal image technology to detect and do total flooding to ensure the fire is fully suppressed. The thermal image will be available within 1-2 hours, which can be checked underground by the National Disaster Management Agency (NADMA), and we do not have to make any requests from the fire department as this matter is crucial. As the team marked the potential area and do the total flooding for the past 2 years, the fire cases have extremely reduced.
Management/operation	Others	Representative A: In Sabah, the Forest Fire Management Unit was established under the SFM division, SFD; it was reported in the 1980s. Representative C: Limiting the oil palm plantation suggested by the EU is also part of the challenge to Malaysia, as the oil palm production is strongly related to the economy of Malaysia. The palm oil industries have been monitored by the Malaysian Timber Board (MTOB) to make sure that the oil palm company follows the standard on cutting trees for opening new plantations monitored by the National Resources and Environment Board Sarawak (NREB) and, some extent by Sarawak Forest Department. They are responsible for creating the policy related to oil palm plantation
	Suggestion to	Representative A: As a way forward to work with researchers, collaboration in research

	researcher	with the objective to improve fire suppression techniques effectiveness and invent an advanced tool to put out fires, especially in the peat swamp forests as it is very difficult to mobilize the heavy equipment in the swamp area. Representative C: If researcher can analyze the effectiveness of the approach is much appreciated. During the suppression, firefighters will also face a few challenges. For example, heavy machinery is one of the challenges, as the peatland area is hard to access.
	Crews experience	Representatives A: Strengthening: i) monitoring, ii) crew, iii) equipment, and iv) suppression techniques. Representative B: Sabah Forestry Department was the first in Malaysia to have its firefighters fight forest fires. We were informed that this crew was divided into Initial Attack Crew (IAC) and Forest Fire Crew (FFC). The IAC is an elite group with a total of 80 personnel. These crews are well-trained in controlling and suppressing forest fires and will be deployed as the first group to fight them. During the firefighting, these crews will be grouped into 4 people groups and follow the Incident Command System (ICS) as part of the safety measure. The ICS allows a group rotation and better logistics (4x4 vehicle) during the service. They are also very well equipped and knowledgeable on forest fire, including peatland fire, which is also part of their training. As for the equipment, the crew will have their protective equipment as PPE, gloves, and boots. Another crew that is attached to each district's offices will support the IAC when the fire is huge and hard to control, which is known as Forest Fire Crew (FFC). The FFC is a general crew with basic fire control and suppression training. All crews will always be ready for any forest fire alarm, especially during the dry season. As the person mentioned during the session, they will also make sure all crews are in high spirits and in a good mood during the firefighting, and they will be treated with good food after each service to boost their energy and spirits. Representative A: Another precaution they

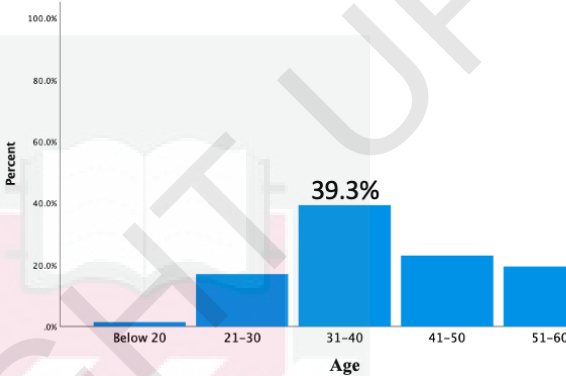
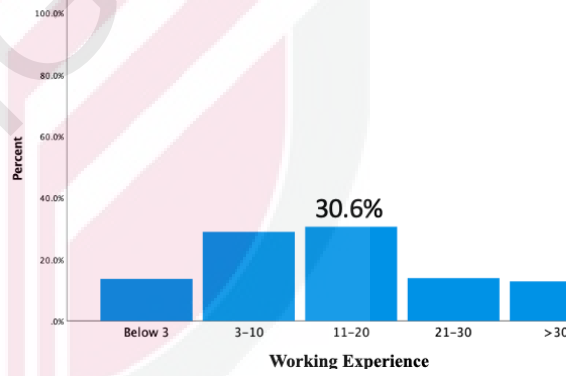
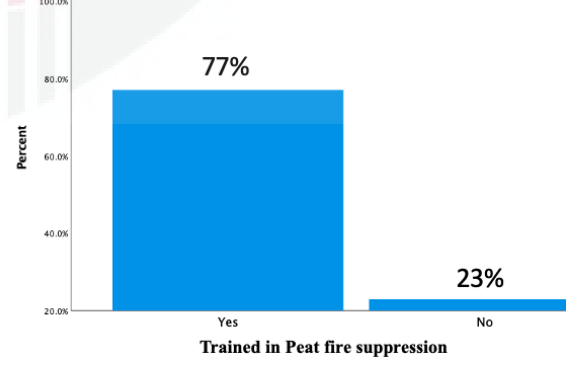
		will take during thick smoke and huge fires, especially the peat fire, is waiting for the rain to pour down. Representative C: As the peatland is not stable land and is hard to predict, the situation can be stressful for the firefighters. Other than that, peat fire can reduce visibility by about 70%. When water is at stake, it will make the peat suppression super challenging, and they also need a lot of water to keep them hydrated. Representative C: Even though the firefighters are physically healthy, the situation cannot be predicted when it comes to forest fires, especially peat fires. As the Director said, "I like to fight building fire. When it comes to forest fire, especially the peat fire, the situation is stressful". For firefighters, a jungle or a forest is a real challenge as they must also deal with wildlife, such as snakes, and they must be mentally ready.
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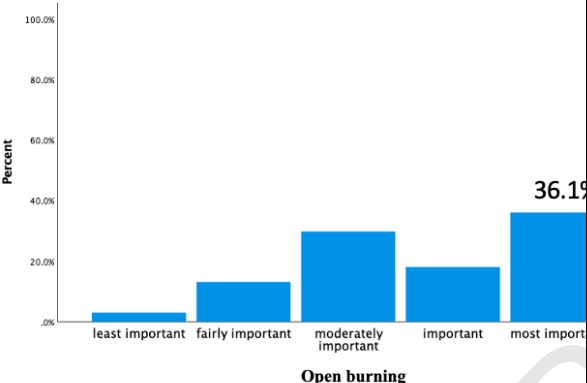
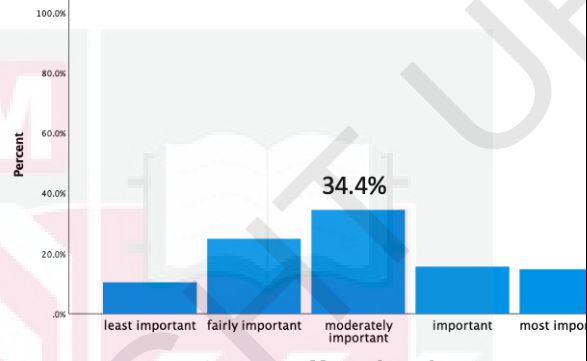
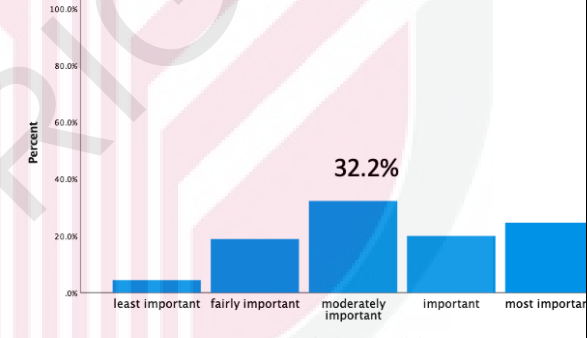
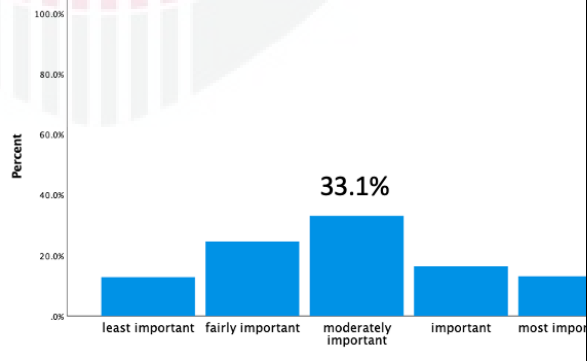
Appendix B

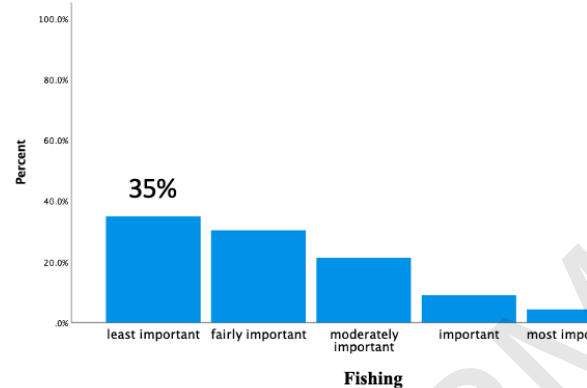
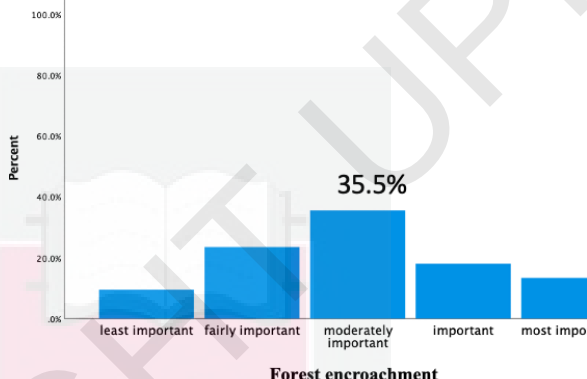
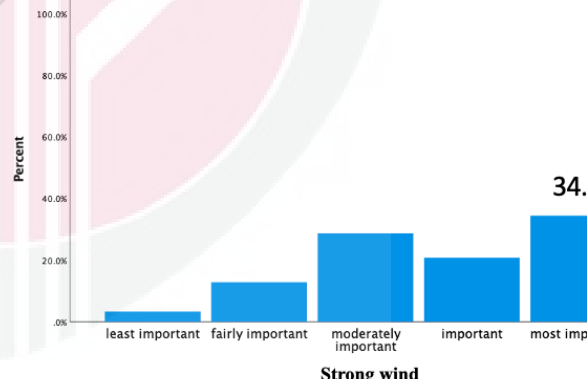
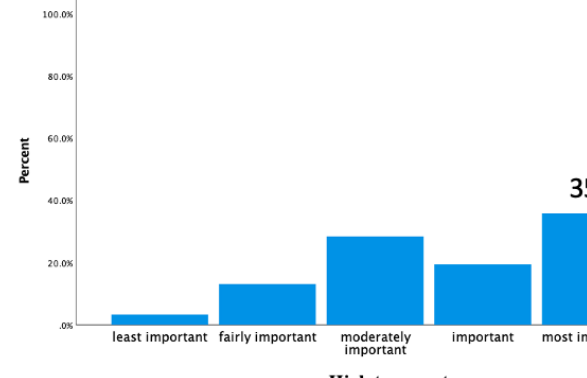
Survey study on Peatland Fire Management (questionnaire)

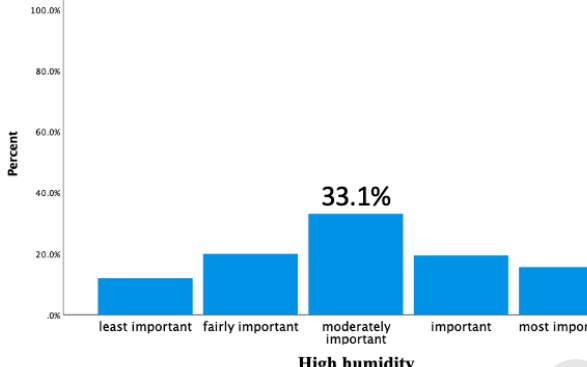
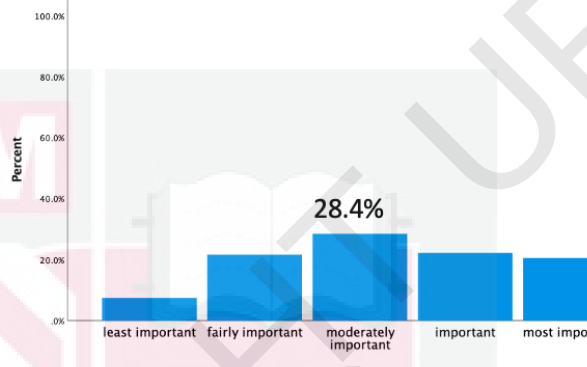
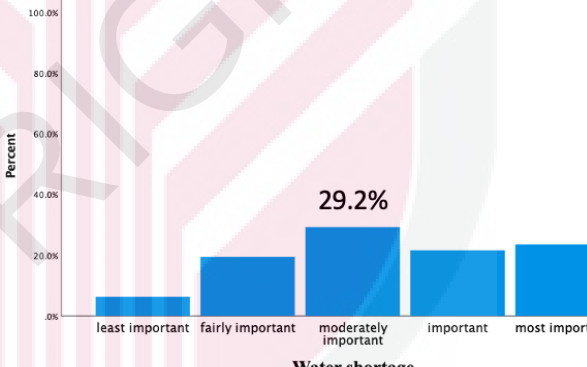
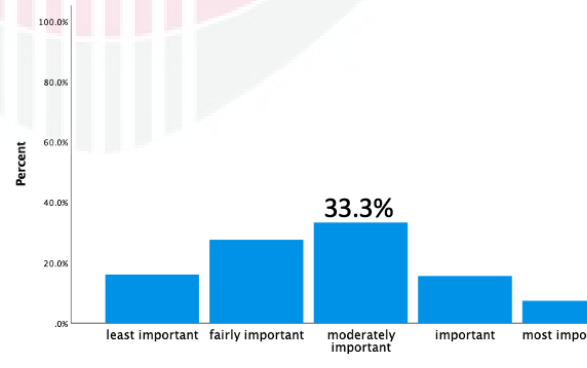
The analysis of the questionnaire was presented in Table 2, Table 3, and Table 4.

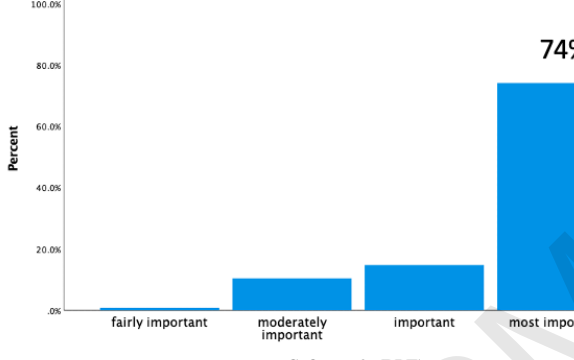
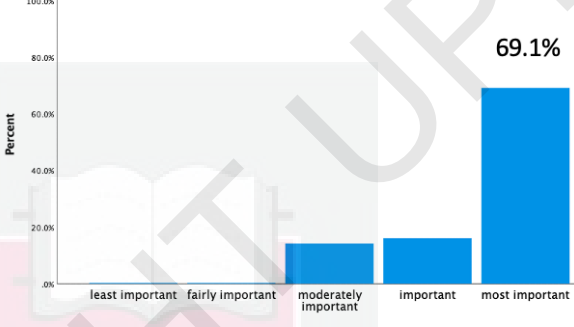
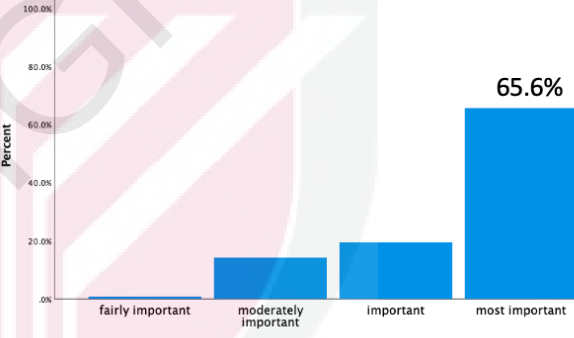
Table 2: Description of the survey study from the questionnaire

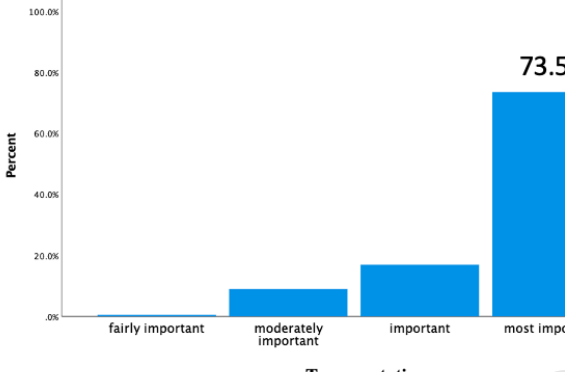
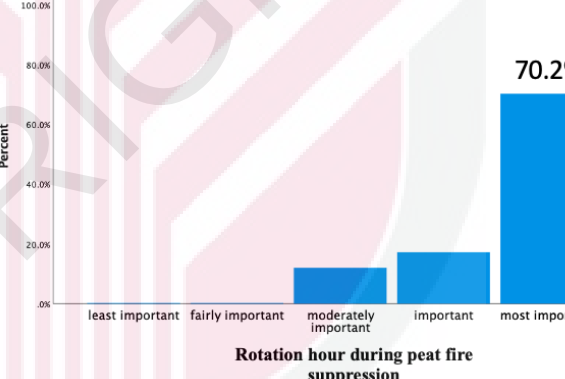
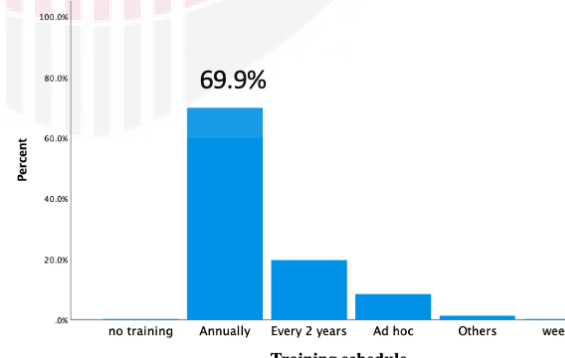
Description	Graph												
Respondents profile													
Number of respondents	366												
Age 39.3% of the firefighters age between 31 – 40 years old.	 <table border="1"> <caption>Age Distribution Data</caption> <thead> <tr> <th>Age Group</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>Below 20</td> <td>~1.0%</td> </tr> <tr> <td>21-30</td> <td>~18.0%</td> </tr> <tr> <td>31-40</td> <td>39.3%</td> </tr> <tr> <td>41-50</td> <td>~25.0%</td> </tr> <tr> <td>51-60</td> <td>~16.7%</td> </tr> </tbody> </table>	Age Group	Percent	Below 20	~1.0%	21-30	~18.0%	31-40	39.3%	41-50	~25.0%	51-60	~16.7%
Age Group	Percent												
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Working experience in peatland fire suppression 30.6% of the firefighters have experienced more than between 11 – 20 years.	 <table border="1"> <caption>Working Experience Distribution Data</caption> <thead> <tr> <th>Working Experience</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>Below 3</td> <td>~15.0%</td> </tr> <tr> <td>3-10</td> <td>~28.0%</td> </tr> <tr> <td>11-20</td> <td>30.6%</td> </tr> <tr> <td>21-30</td> <td>~15.0%</td> </tr> <tr> <td>>30</td> <td>~11.4%</td> </tr> </tbody> </table>	Working Experience	Percent	Below 3	~15.0%	3-10	~28.0%	11-20	30.6%	21-30	~15.0%	>30	~11.4%
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>30	~11.4%												
Trained in peat fire suppression 77% of the respondents were trained in peatland fire suppression, meanwhile 23% were not specifically trained for peat fire suppression.	 <table border="1"> <caption>Training Status Data</caption> <thead> <tr> <th>Trained in Peat fire suppression</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>Yes</td> <td>77%</td> </tr> <tr> <td>No</td> <td>23%</td> </tr> </tbody> </table>	Trained in Peat fire suppression	Percent	Yes	77%	No	23%						
Trained in Peat fire suppression	Percent												
Yes	77%												
No	23%												
Most important contributing factor to peat fire occurrences													
Likert scale 1= least important, 2= fairly important, 3=moderately important, 4=important, and 5=mostly important													

a) Open burning Respondents with majority 36.1% agreed that open burning is one of the most important factors that contributing to fire in peatland area.	 Open burning <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~2.0%</td> </tr> <tr> <td>fairly important</td> <td>~15.0%</td> </tr> <tr> <td>moderately important</td> <td>~30.0%</td> </tr> <tr> <td>important</td> <td>~18.0%</td> </tr> <tr> <td>most important</td> <td>36.1%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~2.0%	fairly important	~15.0%	moderately important	~30.0%	important	~18.0%	most important	36.1%
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most important	36.1%												
b) man-made canal in the nearby peatland area In the case of the existence of man-made canal in the peatland area, a majority 34.4% of the respondents corresponded that it is a moderate factor that increase potential to peat fire occurrences.	 Man-made canal <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~10.0%</td> </tr> <tr> <td>fairly important</td> <td>~25.0%</td> </tr> <tr> <td>moderately important</td> <td>34.4%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>~10.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~10.0%	fairly important	~25.0%	moderately important	34.4%	important	~15.0%	most important	~10.0%
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most important	~10.0%												
c) Agricultural activities nearby The respondents rank agricultural activity as moderate factor that contribute to peat fire occurrence with 32.2%.	 Agricultural activity <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~5.0%</td> </tr> <tr> <td>fairly important</td> <td>~20.0%</td> </tr> <tr> <td>moderately important</td> <td>32.2%</td> </tr> <tr> <td>important</td> <td>~20.0%</td> </tr> <tr> <td>most important</td> <td>~25.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~5.0%	fairly important	~20.0%	moderately important	32.2%	important	~20.0%	most important	~25.0%
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d) Arson 33.1% of the total respondents chosen arson as moderate important factor that will contribute to peat fire events.	 Arson <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~12.0%</td> </tr> <tr> <td>fairly important</td> <td>~25.0%</td> </tr> <tr> <td>moderately important</td> <td>33.1%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>~10.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~12.0%	fairly important	~25.0%	moderately important	33.1%	important	~15.0%	most important	~10.0%
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e) Fishing Fishing activity in the peatland area indicated as least important factor contributing to peat fire by 35% of the respondents.	 Bar chart showing the percentage of respondents rating Fishing activity as a factor contributing to peat fire. The y-axis represents Percent (0.0% to 100.0%). The x-axis shows importance levels: least important, fairly important, moderately important, important, and most important. The bar for 'least important' is labeled 35%. <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>35.0%</td> </tr> <tr> <td>fairly important</td> <td>~28.0%</td> </tr> <tr> <td>moderately important</td> <td>~22.0%</td> </tr> <tr> <td>important</td> <td>~10.0%</td> </tr> <tr> <td>most important</td> <td>~5.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	35.0%	fairly important	~28.0%	moderately important	~22.0%	important	~10.0%	most important	~5.0%
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f) Forest encroachment 35.5% of the respondents point out that the forest encroachment will moderately contribute to peat fire occurrences.	 Bar chart showing the percentage of respondents rating Forest encroachment as a factor contributing to peat fire. The y-axis represents Percent (0.0% to 100.0%). The x-axis shows importance levels: least important, fairly important, moderately important, important, and most important. The bar for 'moderately important' is labeled 35.5%. <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~10.0%</td> </tr> <tr> <td>fairly important</td> <td>~25.0%</td> </tr> <tr> <td>moderately important</td> <td>35.5%</td> </tr> <tr> <td>important</td> <td>~18.0%</td> </tr> <tr> <td>most important</td> <td>~12.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~10.0%	fairly important	~25.0%	moderately important	35.5%	important	~18.0%	most important	~12.0%
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Most factor that will worsen the peat fire condition in peatland Likert scale 1= least important, 2= fairly important, 3=moderately important, 4=important, and 5=mostly important													
a) Strong wind 34.4% of the respondents agreed that strong wind is one of the most important factors that will worsen the peat fire condition	 Bar chart showing the percentage of respondents rating Strong wind as a factor that will worsen the peat fire condition. The y-axis represents Percent (0.0% to 100.0%). The x-axis shows importance levels: least important, fairly important, moderately important, important, and most important. The bar for 'most important' is labeled 34.4%. <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~5.0%</td> </tr> <tr> <td>fairly important</td> <td>~15.0%</td> </tr> <tr> <td>moderately important</td> <td>~30.0%</td> </tr> <tr> <td>important</td> <td>~20.0%</td> </tr> <tr> <td>most important</td> <td>34.4%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~5.0%	fairly important	~15.0%	moderately important	~30.0%	important	~20.0%	most important	34.4%
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b) High temperature High temperature also one of the most important factor according to the respondents with majority of 35.8%.	 Bar chart showing the percentage of respondents rating High temperature as a factor that will worsen the peat fire condition. The y-axis represents Percent (0.0% to 100.0%). The x-axis shows importance levels: least important, fairly important, moderately important, important, and most important. The bar for 'most important' is labeled 35.8%. <table border="1"> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~5.0%</td> </tr> <tr> <td>fairly important</td> <td>~15.0%</td> </tr> <tr> <td>moderately important</td> <td>~30.0%</td> </tr> <tr> <td>important</td> <td>~20.0%</td> </tr> <tr> <td>most important</td> <td>35.8%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~5.0%	fairly important	~15.0%	moderately important	~30.0%	important	~20.0%	most important	35.8%
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most important	35.8%												

c) High humidity Other factors such as high humidity, haze, water shortage, and smaller population in the peatland area were considered as moderate important factors by the respondents.	 <table border="1"> <caption>High humidity</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>10.0%</td> </tr> <tr> <td>fairly important</td> <td>20.0%</td> </tr> <tr> <td>moderately important</td> <td>33.1%</td> </tr> <tr> <td>important</td> <td>20.0%</td> </tr> <tr> <td>most important</td> <td>17.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	10.0%	fairly important	20.0%	moderately important	33.1%	important	20.0%	most important	17.0%
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d) Haze	 <table border="1"> <caption>Haze</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>10.0%</td> </tr> <tr> <td>fairly important</td> <td>20.0%</td> </tr> <tr> <td>moderately important</td> <td>28.4%</td> </tr> <tr> <td>important</td> <td>20.0%</td> </tr> <tr> <td>most important</td> <td>21.6%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	10.0%	fairly important	20.0%	moderately important	28.4%	important	20.0%	most important	21.6%
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e) Water shortage	 <table border="1"> <caption>Water shortage</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>10.0%</td> </tr> <tr> <td>fairly important</td> <td>20.0%</td> </tr> <tr> <td>moderately important</td> <td>29.2%</td> </tr> <tr> <td>important</td> <td>20.0%</td> </tr> <tr> <td>most important</td> <td>21.0%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	10.0%	fairly important	20.0%	moderately important	29.2%	important	20.0%	most important	21.0%
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f) smaller population in the area	 <table border="1"> <caption>Smaller population in the area</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>15.0%</td> </tr> <tr> <td>fairly important</td> <td>25.0%</td> </tr> <tr> <td>moderately important</td> <td>33.3%</td> </tr> <tr> <td>important</td> <td>15.0%</td> </tr> <tr> <td>most important</td> <td>11.7%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	15.0%	fairly important	25.0%	moderately important	33.3%	important	15.0%	most important	11.7%
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Most important safety precautions Likert scale 1= least important, 2= fairly important, 3=moderately important, 4=important, and 5=mostly important													

a) Safety suit (PPE) Safety precautions such as proper safety suit (PPE) is considered most important safety precaution (74%). In Table 3, some respondents corresponds that not enough PPE is one of the issue during the firefighting.	 <table border="1"> <caption>Safety suit (PPE)</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>fairly important</td> <td>~1.0%</td> </tr> <tr> <td>moderately important</td> <td>~12.0%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>74%</td> </tr> </tbody> </table>	Importance Level	Percent	fairly important	~1.0%	moderately important	~12.0%	important	~15.0%	most important	74%		
Importance Level	Percent												
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important	~15.0%												
most important	74%												
b) Hand tools Hand tools is important to help the firefighters in peat fire suppression such as seesaw and rake, thus, 69.1% respondents agrees that hand tools can be one of the safety precaution measures.	 <table border="1"> <caption>Hand tools</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>0.0%</td> </tr> <tr> <td>fairly important</td> <td>0.0%</td> </tr> <tr> <td>moderately important</td> <td>~15.0%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>69.1%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	0.0%	fairly important	0.0%	moderately important	~15.0%	important	~15.0%	most important	69.1%
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c) Water back-pump Water-back pump is mainly used in mopping-up process after the major peat fire suppression and also considered as most important safety measures for the firefighters (65.6%).	 <table border="1"> <caption>Water- back pump</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>fairly important</td> <td>~1.0%</td> </tr> <tr> <td>moderately important</td> <td>~15.0%</td> </tr> <tr> <td>important</td> <td>~20.0%</td> </tr> <tr> <td>most important</td> <td>65.6%</td> </tr> </tbody> </table>	Importance Level	Percent	fairly important	~1.0%	moderately important	~15.0%	important	~20.0%	most important	65.6%		
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important	~20.0%												
most important	65.6%												
d) Communication gear Communication is important to send order or received order. Any updates regarding the suppression procedure is very important, thus, 68% respondents point out communication gear as one of the safety measures.	 <table border="1"> <caption>Communication gear</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>fairly important</td> <td>~1.0%</td> </tr> <tr> <td>moderately important</td> <td>~12.0%</td> </tr> <tr> <td>important</td> <td>~20.0%</td> </tr> <tr> <td>most important</td> <td>68%</td> </tr> </tbody> </table>	Importance Level	Percent	fairly important	~1.0%	moderately important	~12.0%	important	~20.0%	most important	68%		
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e) Transportation 73.5% of respondents correspond that transportation also important safety measures.	 <table border="1"> <caption>Transportation</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>fairly important</td> <td>~1.0%</td> </tr> <tr> <td>moderately important</td> <td>~10.0%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>73.5%</td> </tr> </tbody> </table>	Importance Level	Percent	fairly important	~1.0%	moderately important	~10.0%	important	~15.0%	most important	73.5%				
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f) Training for peat fire suppression Training is important safety measure as the peat fire is unpredictable. Thus, 71.9% of the respondents response that training is most important factor that support the safety measures.	 <table border="1"> <caption>Training for peat fire suppression</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~1.0%</td> </tr> <tr> <td>moderately important</td> <td>~10.0%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>71.9%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~1.0%	moderately important	~10.0%	important	~15.0%	most important	71.9%				
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g) Rotation hour during peat fire suppression 70.2% of the respondents agree that rotation hour during peat fire suppression as one of the safety measure during firefighting.	 <table border="1"> <caption>Rotation hour during peat fire suppression</caption> <thead> <tr> <th>Importance Level</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>least important</td> <td>~1.0%</td> </tr> <tr> <td>fairly important</td> <td>~10.0%</td> </tr> <tr> <td>moderately important</td> <td>~15.0%</td> </tr> <tr> <td>important</td> <td>~15.0%</td> </tr> <tr> <td>most important</td> <td>70.2%</td> </tr> </tbody> </table>	Importance Level	Percent	least important	~1.0%	fairly important	~10.0%	moderately important	~15.0%	important	~15.0%	most important	70.2%		
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important	~15.0%														
most important	70.2%														
h) Training schedule Corresponding to (f), 69.9% of the respondents actually stated that they were trained annually.	 <table border="1"> <caption>Training schedule</caption> <thead> <tr> <th>Training Schedule</th> <th>Percent</th> </tr> </thead> <tbody> <tr> <td>no training</td> <td>~1.0%</td> </tr> <tr> <td>Annually</td> <td>69.9%</td> </tr> <tr> <td>Every 2 years</td> <td>~15.0%</td> </tr> <tr> <td>Ad hoc</td> <td>~5.0%</td> </tr> <tr> <td>Others</td> <td>~1.0%</td> </tr> <tr> <td>weekly</td> <td>~0.0%</td> </tr> </tbody> </table>	Training Schedule	Percent	no training	~1.0%	Annually	69.9%	Every 2 years	~15.0%	Ad hoc	~5.0%	Others	~1.0%	weekly	~0.0%
Training Schedule	Percent														
no training	~1.0%														
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Ad hoc	~5.0%														
Others	~1.0%														
weekly	~0.0%														

e) Indicator the peat fire underground is fully suppressed by respondents

The respondents considered the peat fire underground is fully suppressed when there's no smoke from underground, followed by no visible flame and no sight of ember. Additionally, the respondents also respond that they will make sure to wet the area to make sure that the fire underground is fully suppressed.

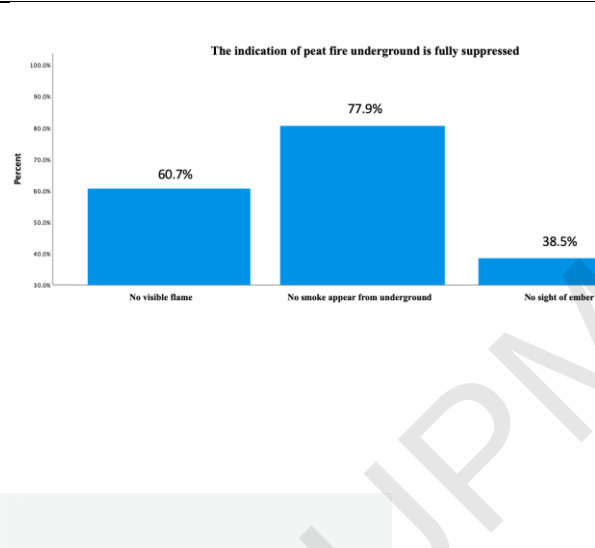


Table 3: Statement from the peat fire managers according to respondents.

STATEMENTS	PERCENTAGE (%)				
	Totally disagree	disagree	Neutral	agree	Strongly Agree
1 Current policy can prevent the peat fire occurrences	5.7	3.6	15.6	26.5	48.6
2 The pandemic situation in Malaysia proves that human is the main contributor to peat fire	3.3	1.9	14.5	20.5	59.8
3 Local villagers can help prevent peat fire on their own by proper training	2.2	1.6	9.6	19.1	67.5
4 High fire intensity is the major challenge during the firefighting	1.1	0.5	8.5	19.9	69.9
5 Rotation during firefighting can reduce the stress	2.2	1.1	11.7	12.3	72.7

Table 4: Unforgettable moments respondents experienced during peat fire suppression.

Code	Summary
Water shortage	Related to water shortage during peat fire suppression. It worsens when there's no water supply to extinguish peat fire
Past events	Most firefighters mentioned the places they do peat fire suppression. They work at night and sleep in forest.
Physical and	Inhale smoke, fatigue, thirsty, hard to breathe, stress,

mental issue	heavy equipment. Small group to extinguish large area, losing a friend
Long operation hour	Long operation where they don't shower and stand-by up to 2 months
Trapped in fire	Almost trapped during service because of huge fire and thick smoke. They share how they were surrounded by fire.
Collaboration with Indonesia	Help in peat fire suppression in Indonesia. Most of them mentioned 'Operation KALBAR 1997 Indonesia'
Equipment issue	Not enough PPE for firefighters during suppression, but some firefighters think their PPE are good. Equipment to help in suppression is not enough. Some firefighters burnt their hose during suppression
Other issues related to peat fire suppression	Come across venomous animals and insects not enough manpower; friendship; fire in oil palm plantation; tree fall in front of them; lost communication etc.

Appendix C

Weather observation in Selangor in 2014

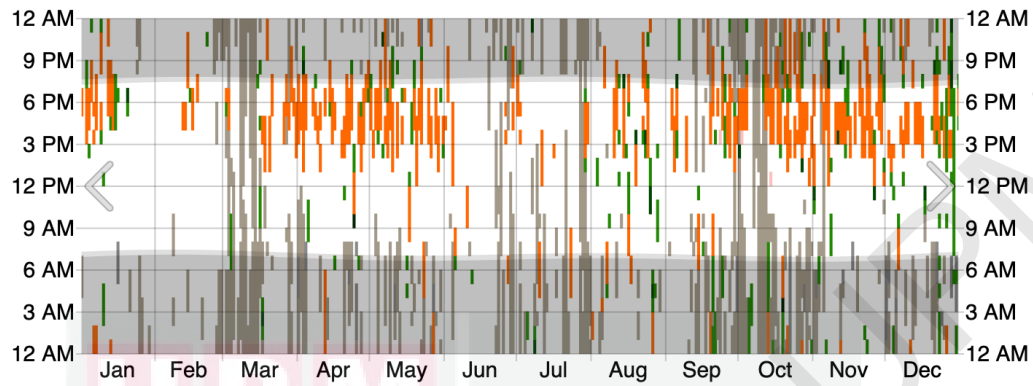


Figure 1: Observed weather of Selangor as overall in 2014.

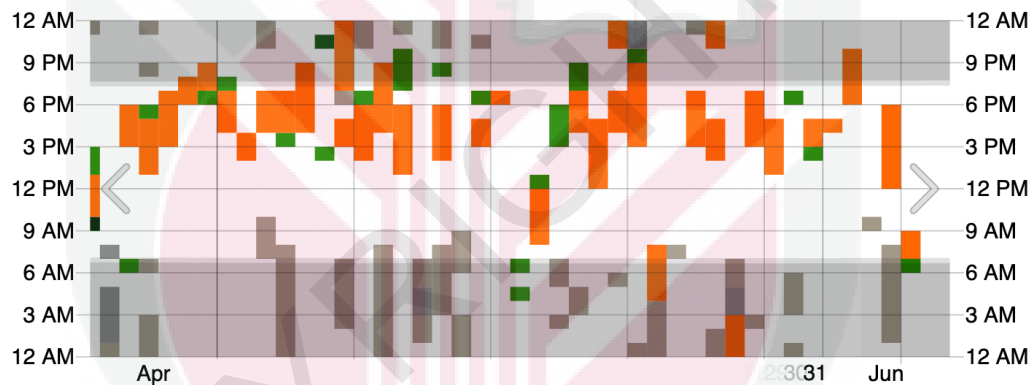


Figure 2: Observed weather in May, 2014 were mostly light rain to thunderstorm.

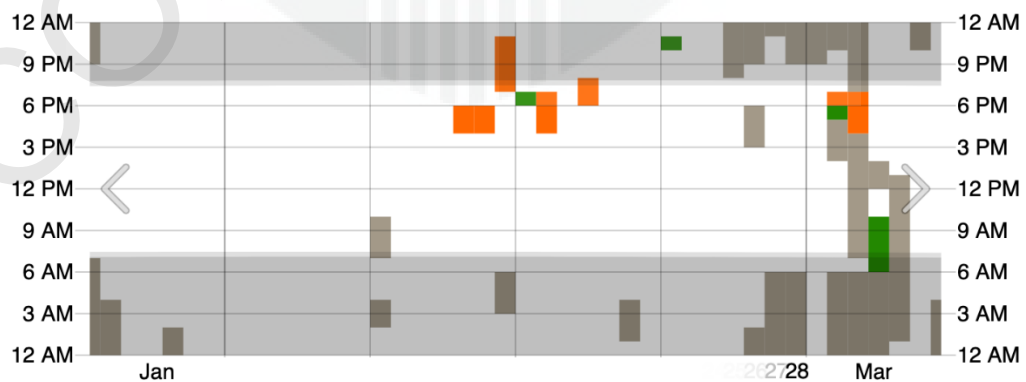
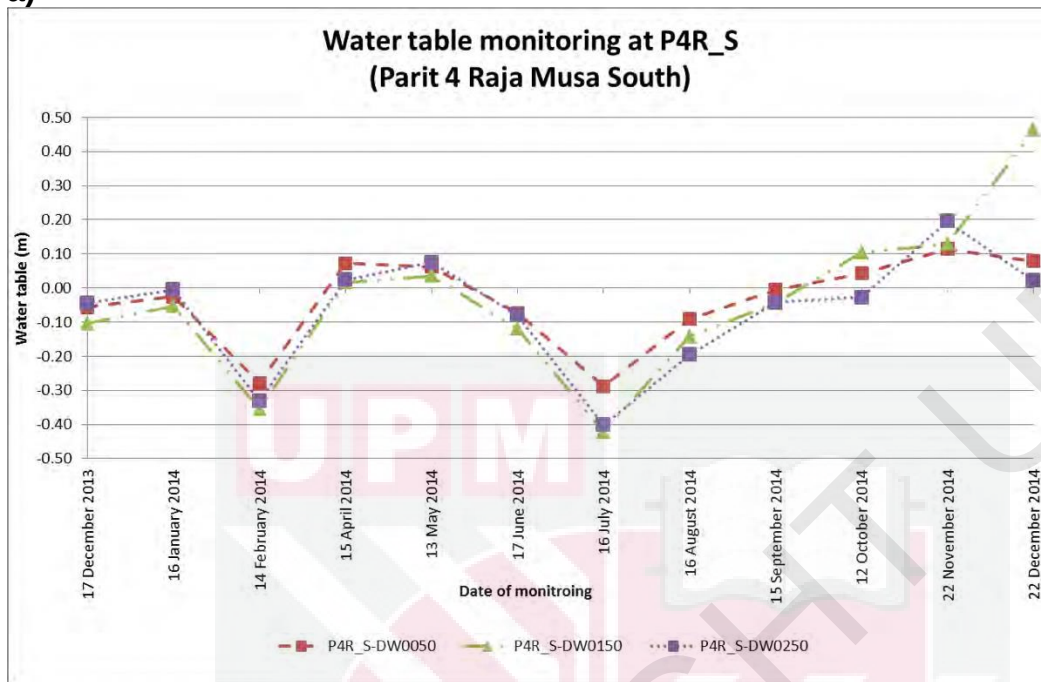


Figure 3: Observed Weather in February 2014 where most of the time haze is occurred.

Appendix D

Water table observation in RMFR

a)



b)

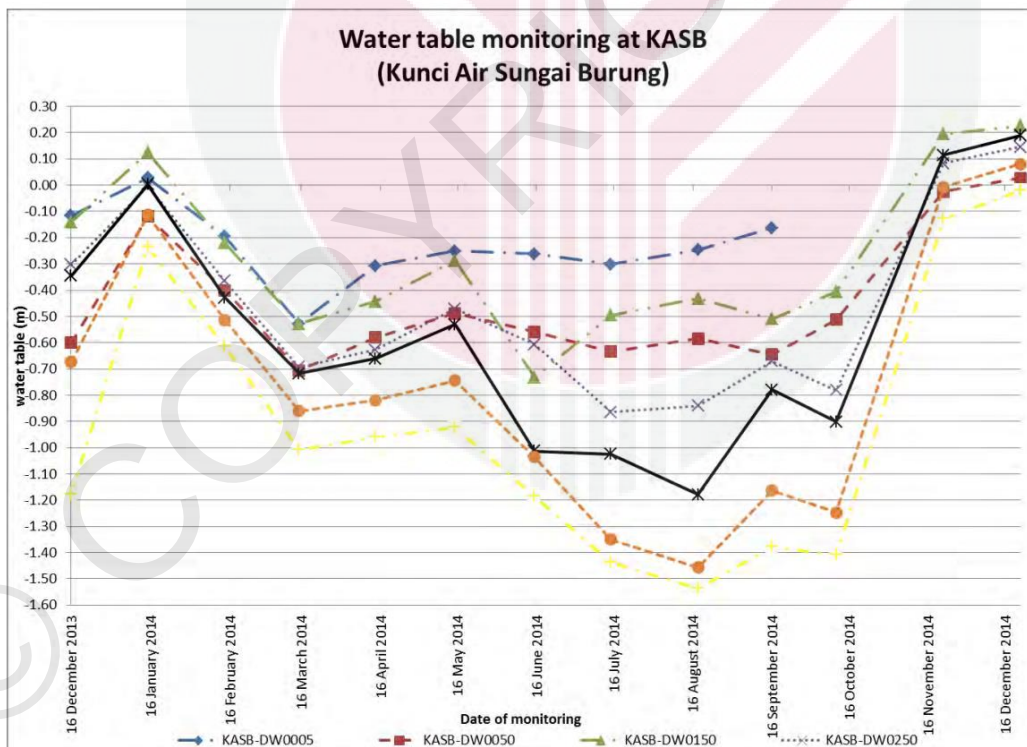


Figure 4: Water-table from December 2013 to December 2014 in Raja Musa Forest Reserve; a) Parit 4 near compartment 99, b) KASB near compartment 1

Table 5: Water table depth in RMFR.

Transect	Number of observation	Mean water table (m)	St deviation (m)	Lowest (m)	Highest (m)
Transect 1/ JSP	65	-0.39	0.27	-1.06	0.00
Transect 2/ TSD	64	-0.28	0.22	-0.71	0.16
Transect 3/ P4R_S	36	-0.05	0.18	-0.42	0.46
Transect 4/ TC_W	65	-0.33	0.32	-0.85	0.75
Transect 4/ TC_E	52	-0.29	0.27	-0.68	0.65
Transect 5/ KASB	88	-0.54	0.43	-1.54	0.23
Transect 6/ JHD	64	-1.22	0.54	-2.27	-0.07

Referring to Table 5 in this appendix, mean water table for three transects (JSP, TSD and TC_W) located inside forested transect is KASB near compartment 1 that recorded lower mean water table at 54cm below peat surface. The lowering of water table in this transect could very well be the effect from a small canal running parallel to the piezometers. On the other hand, the transect P4R_S which are located in grassland/ fern recorded highest mean value, this may have related to the loss of surface peat due to fire and subsidence, which gave the wrong impression of higher water table. Historically, this area had subjected to repeated burning in the past, and fire usually associated with low water table. Based on these information, it help to understand the higher moisture content ($p < 0.05$) in the burnt peat samples area compared to unburnt peat samples.

Appendix E

Map of Raja Musa Forest Reserve part of North Selangor Peat Swamp Forest

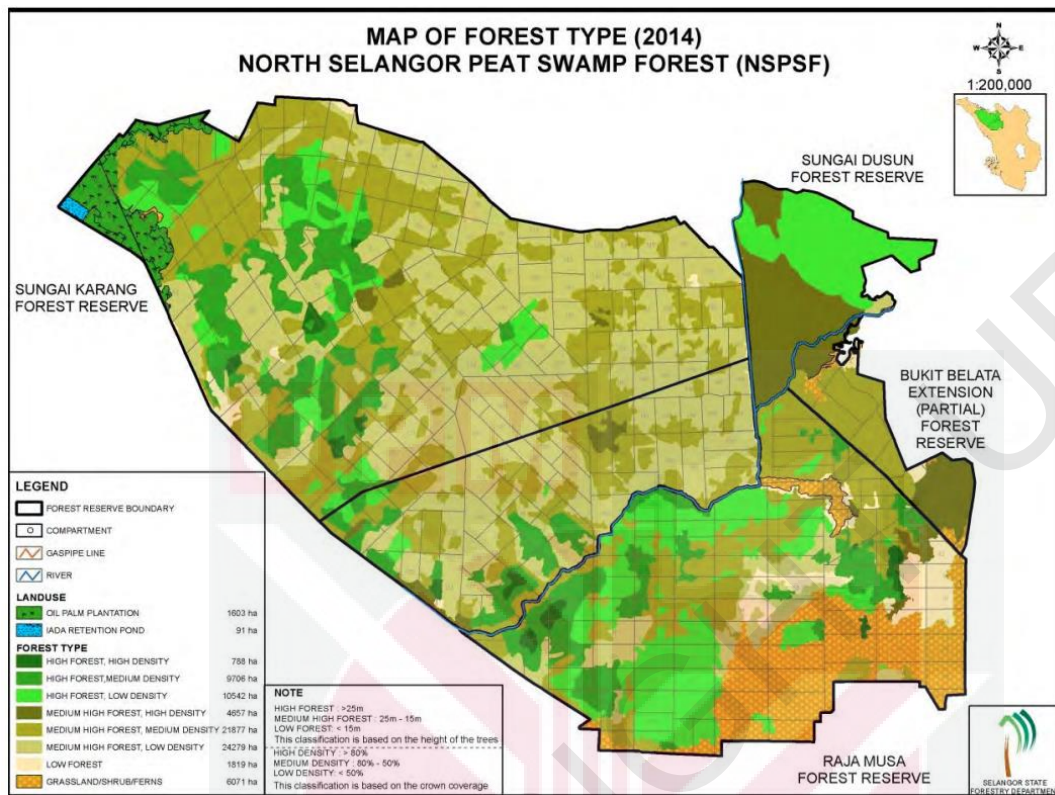


Figure 5: Type of forest map in RMFR

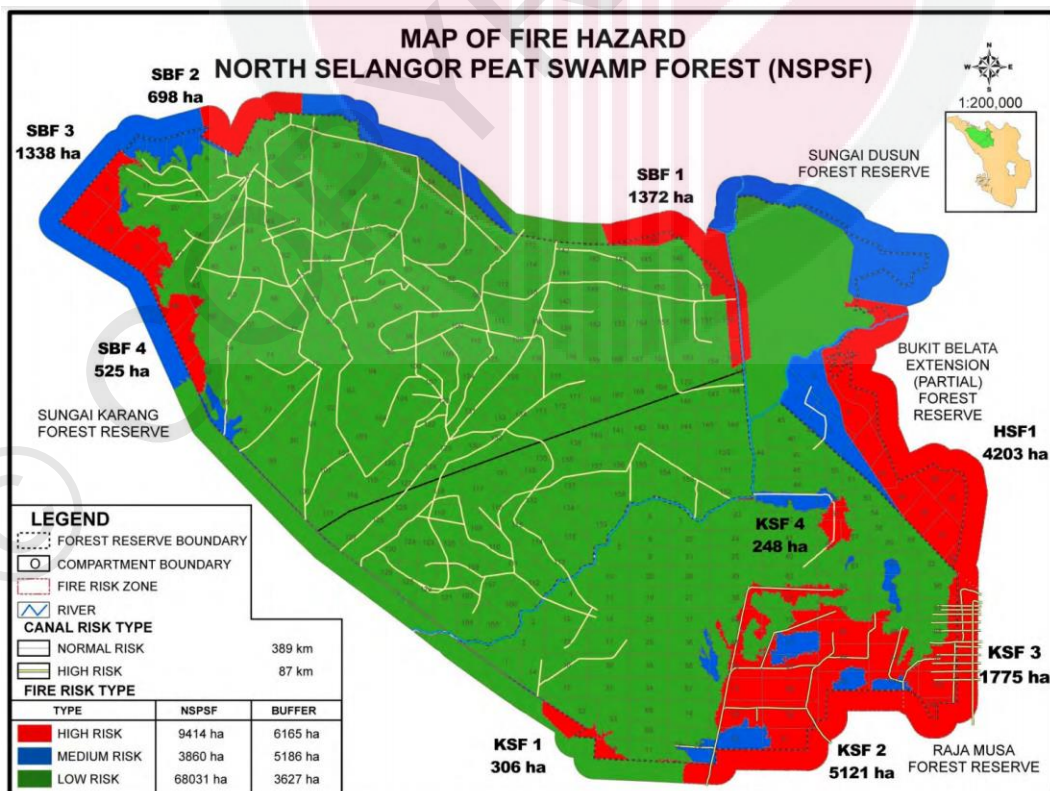
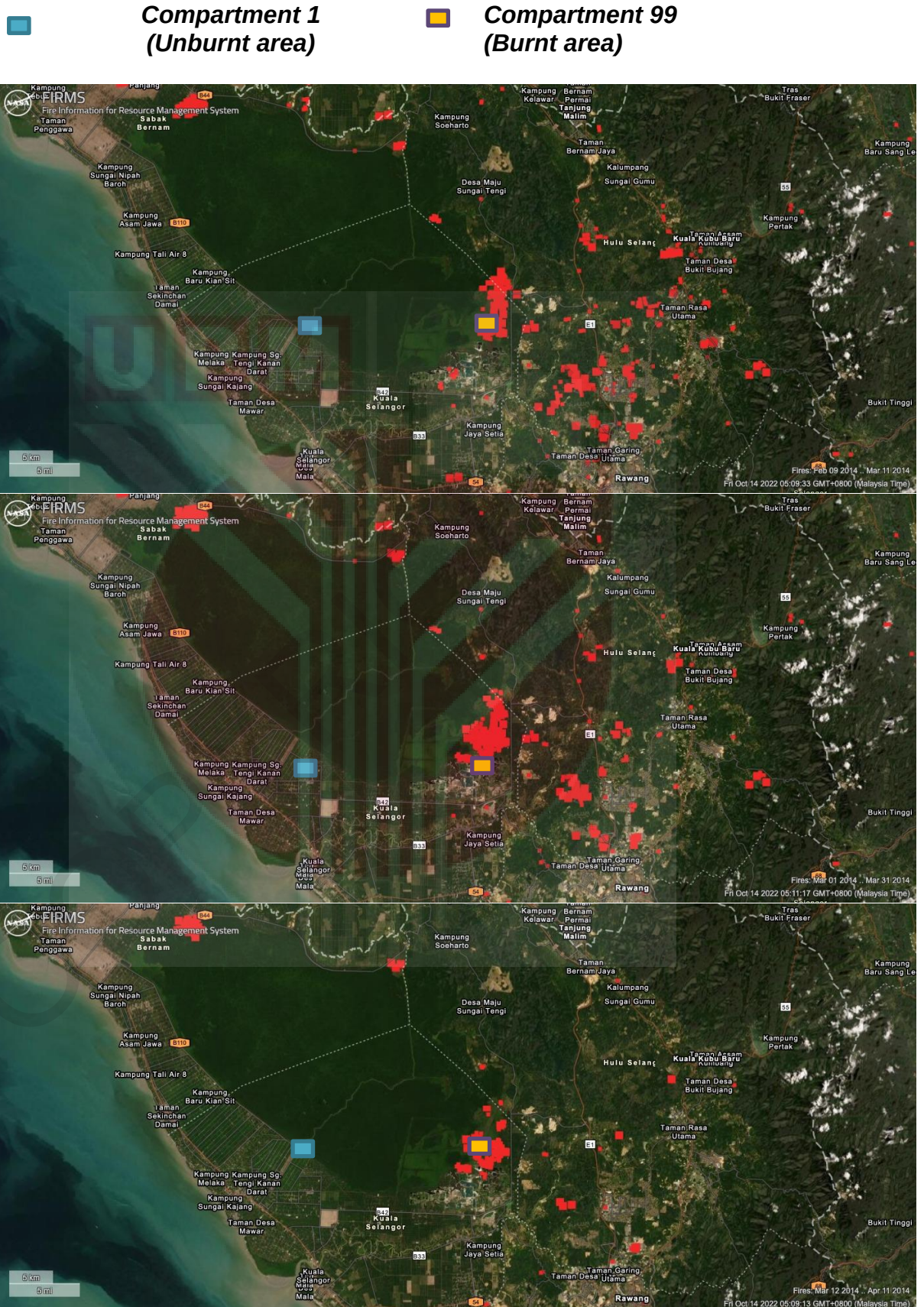
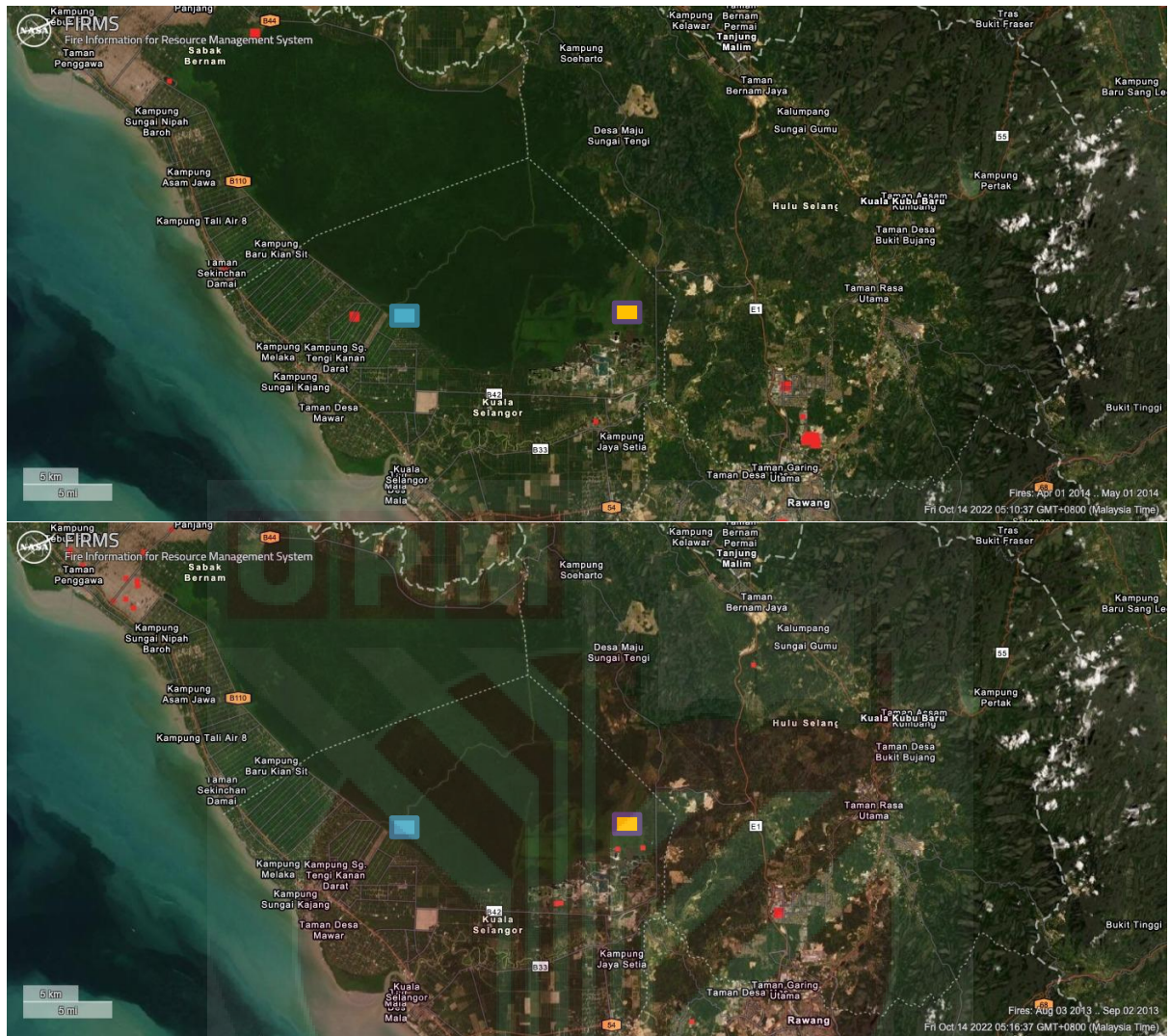


Figure 6: Fire Hazard in RMFR

Appendix F

Hotspot of Compartment 1 and 99 from February to September 2014





Compartment 1 from 2004-2006 hotspots history (no fire history in this area)





Appendix G

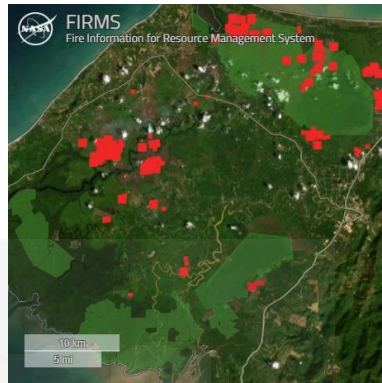
Year 2020:

Hotspots detected in Binsuluk FR in February to April, while hotspots in Klias FR was detected near the border of the FR in March.

February 2020



March 2020



April 2020



Year 2019:

Hotspots detected in Binsuluk FR and Klias FR in April to May.

April 2019



May 2019



Year 2018:

A hotspot was recorded in April in Binsuluk FR. Adjacent fire was detected in Klias FR in July and August

April 2018



July 2018



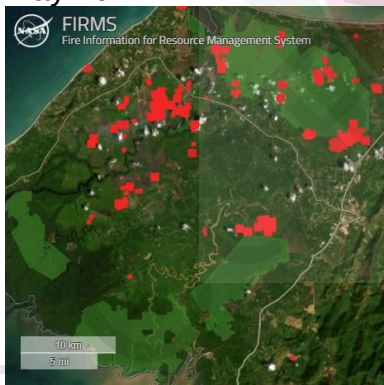
August 2018



Year 2017:

Fire hotspots were detected adjacent to Klias FR that spread to the border of the FR in May. Several area was marked with fire hotspots in Binsuluk FR.

May 2017



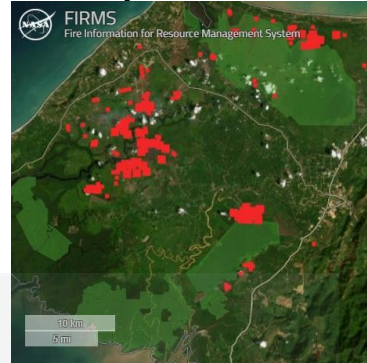
Year 2016:

2016 is the year with El-Niño phenomenon that worsen the fire cases. Therefore, hotspots were detected January until April mainly in Binsuluk FR. Meanwhile, the Klias FR was affected in northern border in February to March.

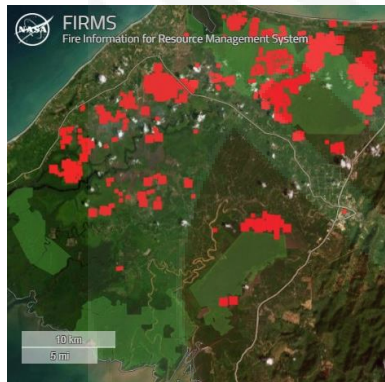
January 2016



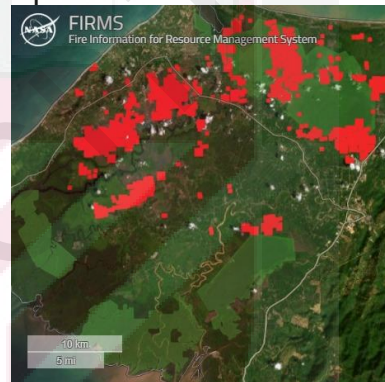
February 2016



March 2016



April 2016



Year 2015:

Fire hotspots were detected in Binsuluk FR in February and March.

February 2015



March 2015



Year 2014:

Hotspots were detected in Binsuluk FR from March to May.

March 2014



April 2014



May 2014



Year 2013:

Hotspots were detected in February, March, August, and September for Binsuluk FR. Klias FR shows adjacent fire occur but did not spread to the FR in October, but spread to border of FR in February and March.

February 2013



March 2013



August 2013



September 2013



October 2013



LIST OF PUBLICATIONS

Journal

Musa, D.N.S., Mohd Tohir, M.Z., Syafie, S., Yahaya, R. (2024) Thermal decomposition and combustion analysis of Malaysian Peat Soil Samples using Coats Redfern model free method. *Pertanika Journal of Science and Technology* 32 (2).

Musa, D.N.S., Mohd Tohir, M.Z., Xinyan, H., Luqman, C.A., Md Said, M.S., Sulaiman, M.F. (2024). Tropical Forest Reserve's Peat Properties Adjacent to Fire-break Canal, *Journal of Forestry Research* 35(1).

Qin, Y., **Musa, D.N.S.**, Lin, S., Huang, X. (2022). Deep peat fire persistently smouldering for weeks: a laboratory demonstration. *International Journal of Wildland Fire* 32, 86–98. doi:10.1071/wf22143.

Book

Musa, D.N.S., Mohd Tohir, M.Z., Xinyan, H., Luqman, C.A., Md Said, M.S., Sulaiman, M.F. (2022). Canal Influence on Peat Properties at Different Fire Frequency Area. *Advances in Forest Fire Research 2022* (DOI: [10.14195/978-989-26-2298-9_155](https://doi.org/10.14195/978-989-26-2298-9_155)).

Qin, Y., **Musa, D.N.S.**, Lin, S., Huang, X. (2022). Persistent Underground Smouldering Fire in Deep Peat Layer. *Advances in Forest Fire Research 2022*.

International Magazine

Mohd Tohir, M.Z and **Musa, D.N.S.** (2023). Getting the Root of the Peat Fires- Researchers Propose Increased Collaboration. *International Association of Wildland Fire*. *International Association of Wildland Fire*. <https://www.iawfonline.org/article/situation-report-malaysia/>.

Musa, D.N.S and Huang X. (2022). Challenges and Hopes Peat Fire Management in Borneo Island. *International Association of Wildland Fire*. <https://www.iawfonline.org/article/challenges-and-hopes-peat-fire-management-in-borneo-island/>.

Conference Proceeding

Musa, D.N.S., Mohd Tohir, M.Z., Xinyan, H., Luqman, C.A., Md Said, M.S., Sulaiman, M.F. (2022). Canal Influence on Peat Properties at Different Fire Frequency Area. *IX International Conference on Forest Fire Research & 17th International Wildland Fire Safety Summit*.

Musa, D.N.S., Mohd Tohir, M.Z., Xinyan, H., Luqman, C.A., Md Said, M.S., Sulaiman, M.F. (2024). Fibre Content and Moisture Availability of Different Different Fire Severity Areas in Tropical Peat Swamp Forest. *Tropical Forestry Conference 2024*.

