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The efficacy of long pools as fire breaks to protect peat swamp forest ecosystems: A case study in Binsuluk Forest Reserve, Sabah, Malaysia

Rebecca Mishallyne[1], Dayang Nur Sakinah Musa[1]*

[1] International Tropical Forestry Program, Faculty of Tropical Forestry, Universiti Malaysia Sabah, 88400, Kota Kinabalu, Sabah, Malaysia.

* Corresponding author's email: dns.m@ums.edu.my

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ABSTRACT

Peat swamp forests are vital carbon sinks but face increasing threats from persistent underground smoldering fires that release massive greenhouse gas emissions. Safeguarding these ecosystems requires effective containment of such threats. One implemented fire management method is the construction of long pools, ranging from 10 m to 20 m wide with strategic crossover points. This study evaluates the effectiveness of long pools as fire breaks by comparing fire distribution and intensity patterns before and after construction, alongside operational perspectives. The methodology combines qualitative interviews with senior Initial Attack Crew (IAC) officers regarding long pool efficacy, and a spatio-temporal analysis using MODIS Active Fire data to compare fire incidents in 2016 (pre-construction) and 2024 (post-construction). Results show a significant reduction in fire frequency, dropping from 91 occurrences in 2016 to 27 in 2024 with $p<0.001$. However, the intensity of fires breaching the boundary remained statistically unchanged with $p=0.90$. This indicates the long pools success is primarily as a preventative shield, providing water sources and access. The findings offer valuable insights into effective fire management and peat swamp forest conservation efforts

Keywords: *Peat swamp forest, Forest fire management, Forest protection, Firebreak, Long pool*

INTRODUCTION

Peat swamp forest ecosystems are critical for

global biodiversity, climate regulation, and carbon storage (Page et al., 2002; Turetsky et al., 2015). In their natural, waterlogged state, these ecosystems store up to one-third of the world's soil carbon (Ballhorn et al., 2009). However, anthropogenic activities, particularly slash and burn agriculture and arson, contribute significantly to fire ignition (SFD, 2019; 2020). As noted by Kamlun and Phua (2024), agriculture remains a dominant anthropogenic factor in fire affected areas. Climate phenomena such as El Niño exacerbate this vulnerability by causing severe droughts that lower the water table, leaving peat highly susceptible to combustion (Sinclair et al., 2020; Goldstein et al., 2020). Unlike typical forest fires, peat fires burn underground and can persist for weeks or months (Rein, 2013). These fires release dense smoke and massive carbon emissions, severely impacting local health and the economy (Hu et al., 2018; Goldstein et al., 2020) and leading to slow forest recovery (Davies et al., 2013). Hence, protecting this ecosystem is crucial.

The Binsuluk Forest Reserve has a recorded history of high fire frequency. Interviews with the Sabah Forestry Department's fire suppression team, the Initial Attack Crew (IAC), revealed that earlier fire breaks lacked strategic crossovers, making it difficult for crews to access burning areas across the reserve. Rapid access to hotspots is critical for effective suppression. In response, an innovative approach was implemented involving the construction of earth bunds to create water holding known as long pools at strategic crossings. Canal style fire breaks were initially constructed in late 2017 following severe fires the previous year (SFD, 2017). These were expanded in 2018 at the Purun and Dungun area, and a 9.15 km fire break at Kampung Takuli was upgraded in 2020 (SFD, 2020). These structures, ranging from 10 m to 20 m wide, were enhanced with earth bunds designed to facilitate access and water retention.

Although the intensity of the 2016 El Niño was like the 1997 to 1998 event, the area burned was far less in 2016 due to improvements in forest fire management. These included effective hotspot monitoring, efficient mobilization of SFD suppression teams, and strong collaboration with the Sabah Fire and Rescue Department (Bomba) (SFD, 2016). Despite these successes, the main challenge faced by crews in 2016 was the lack of accessibility and water resources in affected areas, alongside shortages of equipment (SFD, 2016). Both 2016 and 2024 presented significant fire management challenges for Binsuluk (SFD, 2016; SFD, 2024). Figure 1 illustrates the trend of forest fire occurrences from 2016 to 2024, showing a reduction in fire-affected areas attributed to continuous improvements in training and infrastructure. For instance, in 2024, fire drills included the construction of fire guards, handling water pumps, and testing efficient water delivery systems (SFD, 2024). While the reduction in fire occurrences suggest improved management, however, to quantitatively assess the specific contribution of the upgraded infrastructure remained. Although the operational reports indicate success, a rigorous spatial comparison of fire behaviour between the pre-long pool (2016) and post long pool periods is required to validate this efficacy. Therefore, this study aims to evaluate weather long pools function effectively as fire breaks by comparing fire distribution and intensity patterns before and after their construction, and by examining the operational perspectives of the IAC members. By integrating spatio-temporal analysis with qualitative insights from the IAC members, this research seeks to determine if the long pools have successfully resolved the accessibility and water resource challenges identified in 2016.

METHODOLOGY

Study area

The study was conducted in Binsuluk Forest Reserve (BFR) under Beaufort district,

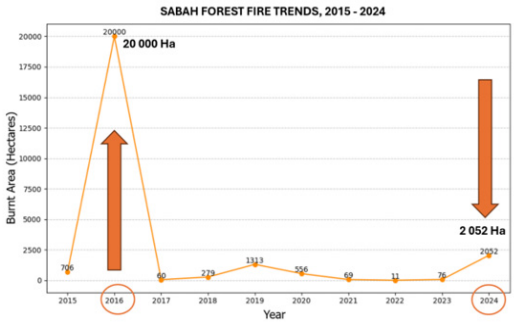

Figure 1: Forest fire trends from 2015 to 2024 (Sources: SFD 2017; 2019; 2020; 2024)

southwest of Kota Kinabalu Sabah. It is a mix-peat swamp forest, a home to endemic species of flora and fauna. This forest is a protected forest reserve under Class 1 category. However, it is threatened by frequent forest fire due to the activities surrounding. Historical logging activities have fragmented the forest structure that increasing the vulnerability to fires in droughts period. It was severely affected by fire in 1997,1998 and 2016 with burnt area covered by small shrubs and less forest (Aziz et al., 2025; Musa et al., 2023).

Data collection.

This study utilized a mixed-methods approach integrating qualitative data with geospatial analysis to evaluate the efficacy of the long pool infrastructure. The data collection and analytical procedures involved are as follows:

The qualitative assessment and field verification were conducted through semi-structured interviews, with informed consent, with two senior forest fire instructors and two senior IAC members. The sampling was purposive, focusing on the function of the long pools and on the ground challenges. These interviews aimed to gather operational insights regarding fire suppression challenges faced prior to the upgrading of fire breaks into long pools. Additionally, field visits were conducted for physical verification.

The geospatial analysis for fire distribution patterns was analysed using Fire Information for Resource Management System (FIRMS) data derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua and Terra satellites. MODIS datasets were selected as they provide global spatial coverage and four times daily imaging, enabling global and local monitoring of combustion processes; hence, they are suitable for studying the impact of fires on ecosystems, the atmosphere, and climate (Mupfiga et al., 2022; Mupfiga et al., 2024). Data were downloaded as shapefiles, filtered for high confidence (>80%) (National Aeronautics and Space Administration [NASA], n.d.), aggregated by year, and overlaid with the forest boundary. This dataset was utilized to conduct a comparative analysis of fire frequency and fire intensity through Fire Radiative Power (FRP) in 2016 and 2024, serving as an indicator for determining the extent of the burnt area and the effectiveness of the intervention. Finally, the fire data for 2016 and 2024 were processed within a Geographic Information System (GIS) to facilitate a visual comparison of the affected areas.

Data analysis.

Thematic analysis was conducted for the semi-structured interviews using Python libraries such as pandas, re, matplotlib. pyplot, and wordcloud within an Interactive Computational Environment, Jupyter Notebook. The qualitative data were defined into three themes that is Prevention, Limitation, and Long Pool, along with specific keywords. To facilitate the text analysis, a domain specific lexicon was constructed using a hybrid inductive deductive approach (Fereday & Muir-Cochrane, 2006). This method ensured that the keyword selection was grounded in both established theoretical frameworks and the empirical data derived from the interviews. The keyword selection process involved three distinct validation criteria, those are;

- Theoretical alignment, deductive: Technical terminology related to peat forest fire suppression, such as check dam, earth bunds, moisture, and smouldering,

was derived from existing Standard Operating Procedures (SOPs) and fire management literature. This ensured technical accuracy within the Prevention and Long Pool themes.

- Empirical frequency, inductive: Words that appeared with high frequency in the interview transcripts were incorporated to capture the respondent's operational reality. This included vernacular terms such as ringgit that is referring to budgetary constraints and tembus which referring to fire breaching containment lines.
- Linguistic code-switching: Reflecting the bilingual nature of the respondents in Malay and English, the lexicon was designed to capture semantic equivalence. Both English technical terms such as fire break and local Malay equivalents of kolam Panjang and pencegahan, were included to ensure no data was lost due to code-switching during the interviews. The resulting lexicon was categorized into three primary conceptual clusters: Prevention which referring to operational protocols, Limitation which referring to environmental and resource constraints, and Long Pool which referring to infrastructure. Data visualization was subsequently used to present these findings.

Following the qualitative phase, spatial analysis using a Geographic Information System (GIS) was conducted to visually compare the burnt areas of 2016 and 2024. Finally, fire frequency and fire intensity analyses were performed using the Python with the following libraries and procedures with Figure 2, summarize the methodology steps in this study.

Data pre-processing: The pandas library was utilized for data cleaning, temporal aggregation, and dataset management. This involved converting acquisition dates into datetime objects and filtering fire incidents by a confidence level of 80% and above for both years. Furthermore, median value from fire intensity from both years were calculated.

Spatial filtering: The geopandas library was employed to perform a Point-in-Polygon (PIP) spatial operation to ensure the analysis focused exclusively on the forest reserve area. This spatially joined the MODIS fire coordinates with the forest reserve boundary shapefile, effectively isolating relevant fire incidents from the surrounding area.

Statistical testing: Two statistical tests were performed using the scipy.stats module to evaluate different aspects of fire behaviours. First, a fire frequency test was conducted using the chisquare function, Chi-Square Goodness of Fit test to determine if the change in the total number of fire incidents the count between both years was statistically significant. Second, a fire intensity test was conducted using the mannwhitneyu function, Mann-Whitney U test to compare the distribution of Fire Radiative

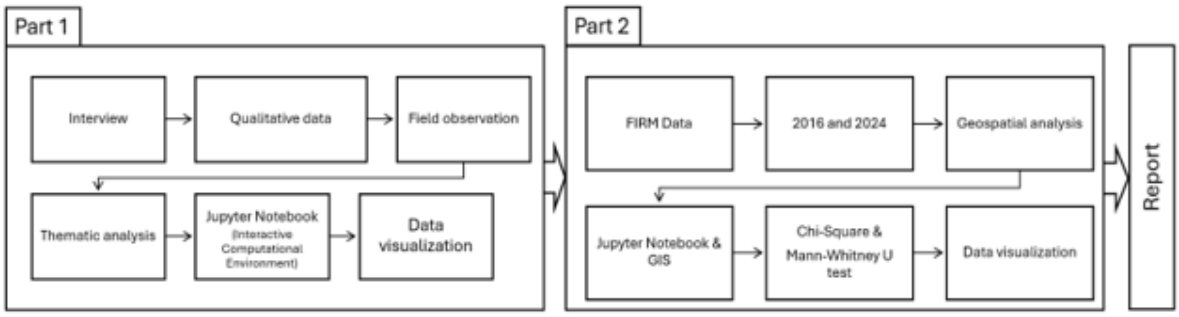

Figure 2: Workflow of long pool as fire breaks to better protect peat swamp forest ecosystems.

Power (FRP) between both years.

RESULTS AND DISCUSSION

Geospatial analysis of burned area.

The geospatial analysis reveals a strong contrast in fire damage between March and April 2016 and 2024, as visualized in Figure 3 and Figure 4. The total burnt area in 2016 was significantly larger than the area affected in 2024. Within the total burnt area, the Binsuluk Forest Reserve experienced severe damage with 5,415 ha burned in 2016, compared to just 1,749 ha in 2024 (SFD 2016; 2024). The burnt area in 2024 appeared as smaller, more localized patches, suggesting that fires were effectively contained within specific zones due to improvements in forest fire management.

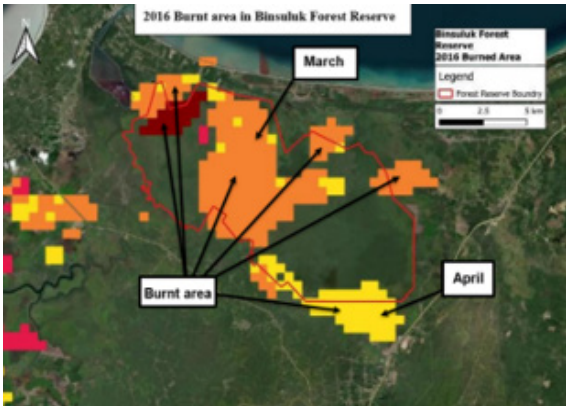

Figure 3: 2016 Burnt area in Binsuluk Forest Reserve, pore long pool (Source: FIRM 2016).

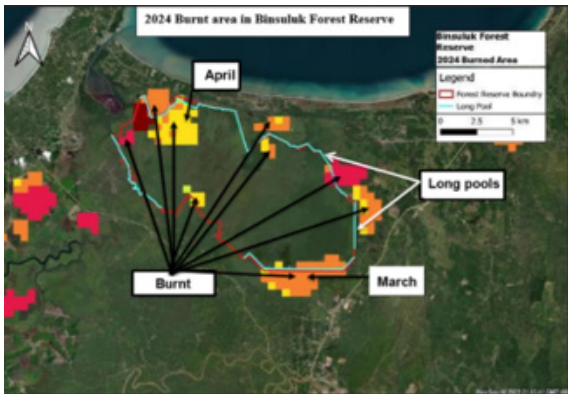

Figure 4: 2024 Burnt area in Binsuluk Forest Reserve, post-long pool (Source: FIRM 2024).

Fire frequency and intensity of the area.

To validate these geospatial observations, statistical testing confirmed a distinct shift in fire behaviours. A Chi-Square test revealed a statistically significant reduction in fire frequency, dropping from 91 recorded incidents in 2016 to 27 in 2024 with $p < 0.001$. The test confirms that the reduction in fire occurrences was not random but a direct result of intervention strategies. However, the Mann-Whitney U test indicated that fires occurred, fire intensity the fire radiative power remained statistically unchanged between the two periods with $p = 0.90$. Figure 5 and Table 1 show the fire frequency and fire intensity in 2016 and 2024. This suggests that while the long pools effectively acted as a preventative measure that drastically reducing the number of fires, the physics of combustion in peat remained consistent once a fire started.

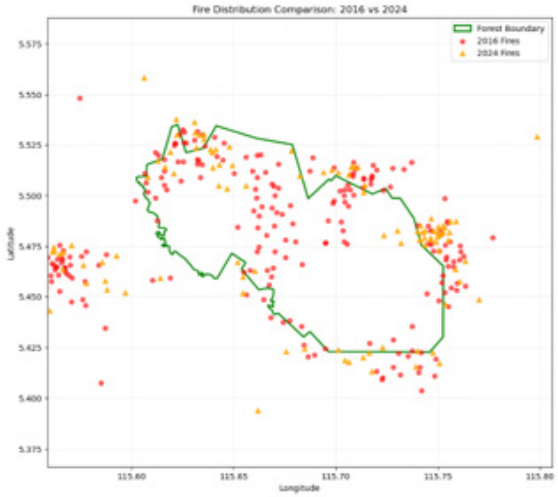

Figure 5: Comparison of fire frequency in 2016 and 2024 in Binsuluk Forest Reserve and nearby

Table 1: Fire frequency and fire intensity within the Binsuluk Forest Reserve area.

Year	Fire Frequency	Fire Intensity, Megawatts (MW)	Result
2016	91	22.10	$p < 0.001$
2024	27	21.10	$p = 0.90$

High fire frequency areas, such as exposed peat forest, are directly vulnerable to sunlight and rapid drying during drought periods (Page et al., 2009; Wösten et al., 2008; Musa et al., 2023). In 2016, this exposure allowed fires to spread uncontrollably across the forest. In

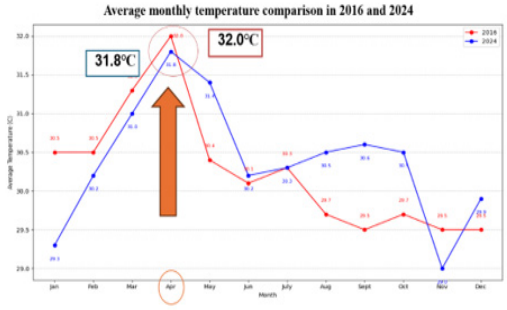

Figure 6: Average monthly temperature comparison in 2016 and 2024 (Sources: SFD 2017; 2019;

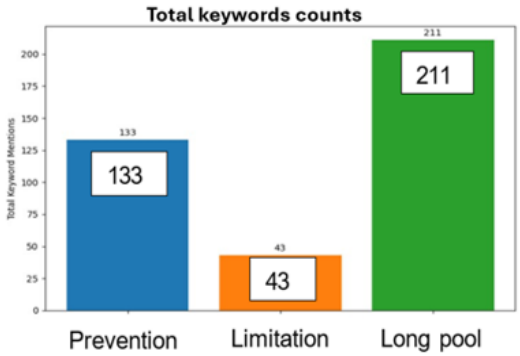

Figure 7: The most prominent theme discussed in the interview; Prevention, Limitation and Long Pool.

contrast, despite the intense heat in 2024, the area exhibited greater resilience. This resilience is attributed to the upgraded fire break canals, which successfully maintained the water table (Musa et al., 2023). As corroborated by IAC members, these long pools retained critical water sources even during drought periods.

Long pool and earth bunds as preventive measures.

The analysis of the interviews revealed that long pool, prevention, and limitation were the most prominent themes. As illustrated in Figure 7, the long pool theme was the most frequently discussed, with a total count of 211 keyword mentions, such as bridge, access, and earth bunds refer directly to the function of the upgraded fire breaks. The insights reveal that the earth bunds serve a critical logistical function. As respondents articulated, these structures provide access like a bridge, thereby enhancing traversability for fire suppression teams across the canals. Figure 8 shows the earth bunds constructed with a 5 m width in strategic locations.

This is followed by prevention, with 133 keyword mentions, indicating importance to the participants. Keywords in this theme included fire break, fire boss, and monitoring. As respondents articulated, long pool is our firebreak, referring to the infrastructure's role in protecting the forest reserve, and command comes from the fire boss, referring to the monitoring protocols. Limitation was the least discussed theme, 43 mentions, with keywords such as ringgit, wind, and safety referring to budget constraints, environmental factors, and crew safety. As respondents articulated, the safety of fire crews is important especially in dangerous weather like windy days.

The drastic reduction in fire damage is not attributed to infrastructure alone but also to the continuous improvement in forest fire management, particularly in training. Following the 2016 fires, the Sabah Forestry Department took drastic steps by conducting intensive training seasons on forest fire prevention and suppression, involving 73 fire crew members and 219 staff and workers of long-term licensees (SFD, 2016). Furthermore, the IAC members explained that the earth bunds allowed them to move quickly and efficiently through the forest to reach hot spots which was a major challenge previously. This ease of access, combined with increased public awareness and strong collaboration with other agencies, was a key success factor in containing fires and preventing them from spreading. Picture 1 shows the earth bunds constructed at a strategic location as a cross over point. Photos were captured from the coordinate 5°31'44.08"N, 115°37'26.50"E.

Limitations and future research.

While this study provides robust evidence for the efficacy of long pools, several limitations must be acknowledged. Firstly, the geospatial analysis relied on MODIS Active Fire data, which, despite its global coverage, it has inherent limitations in

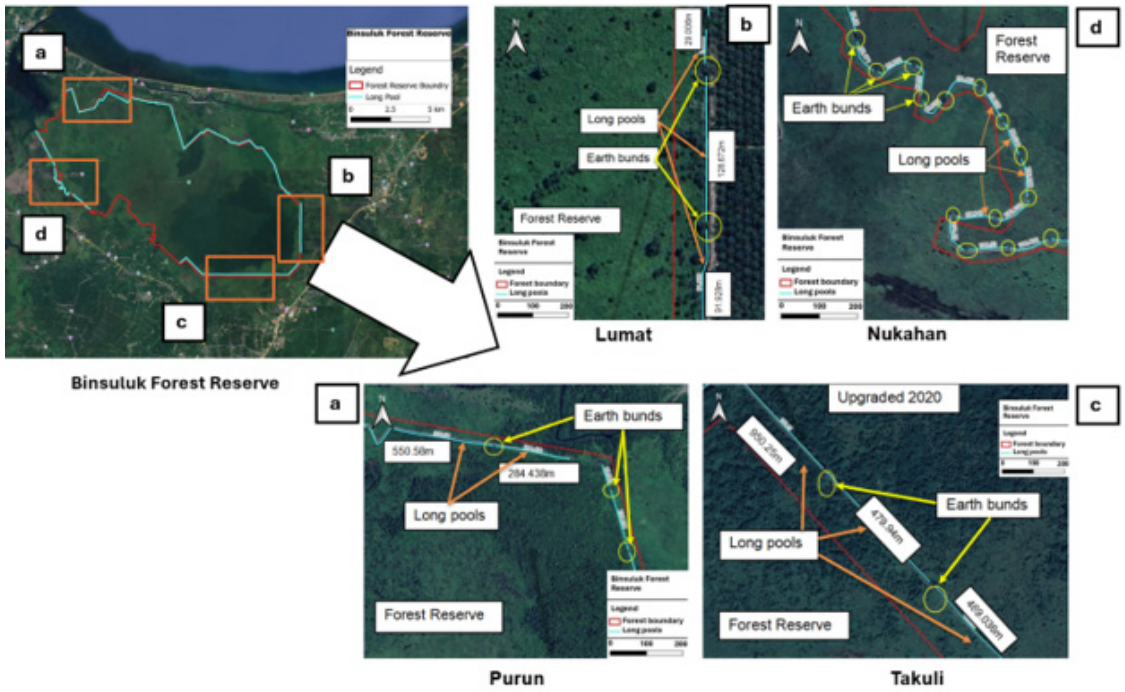

Figure 8: Long pools and earth bunds locations in high-risk area of Binsuluk Forest Reserve: a) Purun; b) Lumat; c) Takuli; d) Nukahan.

Picture 1: Earth bunds in high fire frequency area in Binsuluk Forest Reserve.

peat forest environments where fires often produce thick, dense smoke where these conditions can obscure thermal anomalies from satellite sensors, potentially leading to an underestimation of fire spots during peak burning events. Secondly, the qualitative component relied on self-reported data. While their operational expertise is invaluable but self-reporting carries a potential for bias, larger samples is recommended. Thirdly, while temperature and rainfall data were compared, this study lacked high-resolution temporal data on wind speed and direction at the specific times of fire events. Wind dynamics are a critical driver of fire spread in open peat forest, and their absence limits the ability to fully model the fire behaviours in 2016 versus 2024. Finally, attributing the success solely to the long pools presents a challenge in causal isolation. The post long pool in 2024

period saw simultaneous improvements in training, public awareness, and inter-agency collaboration. Consequently, strictly isolating the long pool effect from these broader management improvements is difficult without a control variable, although the geospatial localization of fires strongly points to the infrastructure's role. To build upon these findings, future research should prioritize long-term hydrological monitoring as monitoring peat moisture content and water table levels adjacent to the long pools would provide quantitative data on the infrastructure. Lastly, developing a hydrological model of the long pools could simulate its effectiveness under various drought scenarios for optimizing their design and placement. It is also recommended to conduct comparative trials in other peat swamp forests to test the replicability of this solution.

CONCLUSION

This study provides compelling evidence that the upgraded fire break canals to long pools in Binsuluk Forest Reserve have been a successful fire management strategy. By comparing fire trends and burnt areas from before and after their construction, the efficacy of long pool in reducing fire affected areas were successfully demonstrated. The findings of these long pools are not just physical barriers, but they are a critical component of an integrated fire management system that addresses key challenges in peat forest fire suppression such as maintaining moisture, water sources and providing access for ground crews. The success of this initiative could have broader implications for fire management and conservation policies in peat forest.

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