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REGULAR RESEARCH ARTICLE

# Peatland fire regime across Riau peat hydrological unit, Indonesia

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**ABSTRACT**

Peatland stretches across approximately 8% of Indonesia's land area. Peat fire disturbance, which affects the carbon dynamics of the ecosystem, will determine the country's vision for a long-term strategy for low carbon development. While the impact of excessive draining on peatland fire is well-known to the scientific community, much less is known about peatland fire regimes in distinctive land management systems. We examined the effect of land use, land management, and climatic factors in peatland fires. The examination was performed at the Peat Hydrological Unit at Gaung–Batang Tuaka, Riau, Indonesia. We used a semi-automatic approach to determine the area of burned peatland and used a spatial analysis tool to analyze the spatio-temporal pattern of peatland fire in the region. Our results demonstrate an increasing trend of peatland fires between 2001 and 2020, with 33% of the burned peatland undergoing multiple fires. The bulk of the burned land was covered by either wet shrubs or estate crops, with the area of burned wet shrub-land cover was two times higher than the burned estate crop-land cover. Concerning peatland draining, this study found a positive correlation between draining intensity, as represented by canal density, and burned area in peatland forests. In managed and unmanaged land, canal density had no apparent correlation with the area of peatland burned; however, we found that the weighted area of burned peatland was, on average, seven times higher in the unmanaged area compared to the managed area. These findings urgently demand an increase in community participation in the utilization of unmanaged land and prompt execution of peatland rewetting in drained peat forests. While the government of Indonesia has developed a social forestry and agrarian reform scheme to enable the legal utilization of unproductive land in forest areas, we argue that greater impacts can only be achieved if environmental services incentive schemes escalate non-party actors' participation.

**KEYWORDS**
Fire regime; KHG-based; Peatland fire; Peatland management; Spatio-temporal pattern.

## 1. INTRODUCTION

Peatland is one of the most valuable ecosystems, providing multiple ecosystem services which enhance human welfare. The most fundamental of these services is carbon regulation. By storing 88.6 Gt of soil carbon (S. E. Page et al., 2011), tropical peatland plays a very significant role in the global climate (Leifeld et al., 2019). The statement in the IPCC 6$^{th}$ Assessment Report that human activities unequivocally cause the "increase in GHG emissions" (IPCC, 2021), is relevant to the case of peatland. Nearly 80% of Southeast Asian peatland has been artificially modified to support dryland cultivation (Mishra et al., 2021), which transforming peatland from a carbon sink to a carbon source (Gunawan et al., 2016; Hirano et al., 2016; Hooijer et al., 2010).

To date, the objective of mitigating global temperature increase has led to more than 50 countries, including Indonesia, declaring their net-zero emission (NZE) ambitions. Many studies have noted that achieving the targets defined in the Paris Agreement of 2015 will require massive land-based carbon dioxide removal (Roe et al., 2019; Rogelj et al., 2018). In this context, the conservation of peatland ecosystems can be considered part of nature-based solutions to the climate crisis (Mishra et al., 2021). In Indonesia, where peatland stretches across approximately 8% of the country's land area, any disturbance affecting the ecosystem's carbon dynamics will determine the success of NZE strategies (Republic of Indonesia, 2016, 2021).

Peat fires are among the most concerning forms of peatland disturbance, as they vary temporally and are complicated by their connection to biophysics and socioeconomic conditions. Before 2000, peatland fires triggered by rapid development were considered the major cause of deforestation in Indonesian peatlands. In recent years, fire occurrence has shifted to areas of non-forest land cover (Field et al., 2009; Hoscilo et al., 2008). Furthermore, there is much evidence indicating the role of peatland drainage in generating a vicious cycle of continuous ecosystem degradation, producing an ecosystem less resistant to hydrological change and more vulnerable to fire (Taufik et al., 2019; Wösten et al., 2006).

While excessive drainage's role in peatland fires have now been accepted as scientific consensus, much less is known about peatland fire regimes, which are characteristic of fire occurrence in landscapes where anthropogenic forces play a distinctive role. Indonesia's peatland is currently dominated by unmanaged and degraded areas (Miettinen et al., 2011); hence, a scientific basis for managing peatland fires according to land management types is necessary. This study seeks to fill this gap by making the best use of currently available spatial information to properly analyze the peatland fire regime in a peatland ecosystem boundary and its association with land management. We conducted three separate assessments: an examination of the distribution of peatland fires across different land cover types, an identification of peatland fire patterns across varying densities of drainage canals, and the generation of a statistical model that captures the dynamics of annual peatland burning driven by climatic factors (e.g., anomalous rainfall events) and land use.

## 2. METHODOLOGY

The research objective will be addressed at the Peat Hydrological Unit (KHG) assessment level at Gaung–Batang Tuaka KHG (Figure 1), one of the prioritized KHGs in Riau, the province with the largest peatland area in Indonesia and one of the most fire-prone provinces (Albar et al., 2018). Our interest in conducting the study at the KHG level was prompted by the release of Government Regulation No.57/2016, which states that the KHG level and the boundaries of peat ecosystems are the main scales for peatland management. The study area extends for 315,326 ha, and 87.2% of this area is peatland (275,099 ha). The peatland area is dominated by very deep peat (>3 m), with half of the peatland at the fibric maturity level (i.e., mainly containing fibre).

The study was conducted from January to December 2022. We examined the peatland fire regime by initially determining the annual area of peatland burned, followed by a spatio-temporal analysis of peatland fires. The data used in this study comprise point and spatial data covering the study area (Table 1). We refer to 2001-2020 as our analysis timeframe for peatland fire detection and 2003, 2006, 2009, and 2011-2019 as our timeframe for spatial analysis of the area of burned peatland. Data processing and visualization were performed using Microsoft Office and ArcMap 10.3.

In addition to primary data, we used supplementary indicative maps of social forestry[1], agrarian reform objectives and TORA[2] participation to garner supporting information on existing land policies.

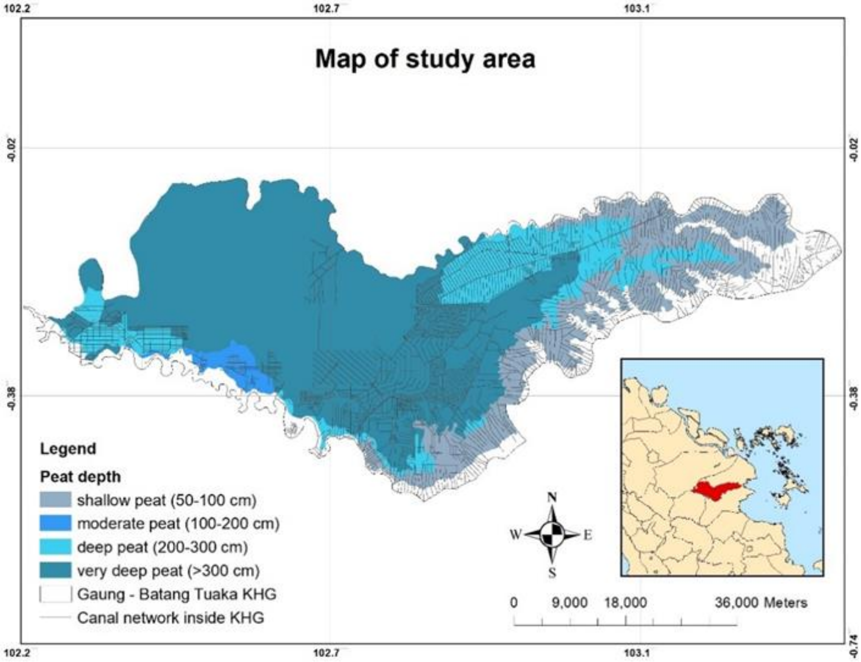


Figure 1. Map of the study area showing the spatial distribution of peat depth and canal networks

Visual analysis of burned areas was conducted using on- and off-screen manual digitization of a composite of the red, green, and blue (RGB) bands of satellite data from LANDSAT TM 8 and LANDSAT TM 5 (LAPAN, 2015) at 30 m resolution. The analysis was initiated by determining the annual burned area. Then, information on burned areas was estimated using semi-automatic classification conducted via a visual identification process that considered spatial hotspot information. Each path/row of the LANDSAT data was derived from two periods of the acquisition dates, which were determined based on the periods preceding and following hotspot peaks. This approach provided a more accurate depiction of the burned area than the intuitive approach using only hotpots (Rossita et al., 2019).

Table 1. Data sources and description of the variables.

| No | Variable | Date (spatial resolution or scale) | Source | The variance of data collected |
|---|---|---|---|---|
| 1 | Historical hotspot | 2001-2020 (N.A.) | MODIS | 3 to 398 |
| 2 | Remote sensing imagery | 2001-2020 (30 m) | LANDSAT Thematic Mapper 8 and 5 | N.A. |
| 3 | Historical | 2001-2020 (5 km) | https://chc.ucsb.edu/data/ | 1,834 mm to |

1 The government of Indonesia grants communities' access to utilize forest areas under the social forestry scheme, regulated by the Ministerial Law of Environment and Forestry No. 83/2016.

2 The TORA scheme aims to evaluate the structure of land ownership in the country by retroactively legalizing the community cultivation of state land that the community has long occupied. This scheme is regulated under Presidential Decree No. 86/2018.

| No | Variable | Date (spatial resolution or scale) | Source | The variance of data collected |
|---|---|---|---|---|
| | rainfall reanalysis data | | chirps | 3,279 mm |
| 4 | Land cover | 2003, 2006, 2009, 2011-2019 (30 m) | Ministry of Environment and Forestry | 14 land cover classes |
| 5 | Canal density map | 2017 | Processed from canal network data published by Rupa Bumi Indonesia | 0.82 to > 2.45 |
| 6 | Peat depth | 2010 (1:50,000) | Ministry of Agriculture | 50-100 m to >300 m |

To overcome the limited temporal availability of LANDSAT data, it was assumed that peatland fires only occur during peak hotspot periods (Albar et al., 2018; Hayasaka et al., 2016). Hence, this study does not capture peatland fires recurring in the same year. Furthermore, as remote sensing could only detect surface burning, our results do not reflect subsurface peatland fires (Ballhorn et al., 2009). Therefore, the metric obtained by this approach is the total area of peatland burned in a year. For more technical details on the semi-automatic approach used in this study, readers are advised to refer to our previous study (Rossita et al., 2019).

We used supplementary maps to clip relevant areas for the first part of the land management analysis. These included land cover maps and canal density maps. These maps are official data released by the Indonesian Ministry of Agriculture (MoA) and the Ministry of Environment and Forestry (MoEF). Historical land cover maps from MoEF were only available for the years 2003, 2006, 2009, and 2011-2019; hence, for the spatial analysis, we only assessed the area of peatland burned during the specific period for which land cover maps were available. The land cover classification employed in the study uses the definitions in the national land use monitoring system (Agus et al., 2013; Direktorat IPSDH, 2015). Overlaying the land cover and annual area of peatland burned generated the distribution of each land cover type's annual area of peatland burned.

In the second assessment, we endeavored to generate information on the total burned area detected in managed land, unmanaged land, and forest land and compare this to different classes of canal density. Initially, we developed three main land classifications (forest, managed, and unmanaged areas) by classifying primary and secondary peat forests as forest areas; timber plantations, estate crops, dryland agriculture, and paddy fields as managed areas; and bare ground, wet shrubs, and mixed dryland agriculture as unmanaged areas. We separated forest area from the unmanaged classification due to a distinctive pattern we found when interpreting the peatland fire data for unproductive land and peat forest areas.

We obtained information on canal density via line density analysis of the map of the canal network. As we are unable to obtain the width information of the canal, canal density was only defined as the ratio of the total length of the canals in an area to the total area observed (km/km$^2$). In this case, we perceive further studies are needed to capture different draining impacts under various canal types (e.g., primary, secondary, and tertiary). We reclassified the contour map of canal density into five main classes: <0.82, 0.82 – 1.64, 1.64 – 2.45, and >2.45 km/km$^2$. The higher the canal density, the more drainage occurs in the area. To enable a direct comparison of the three land classifications, we applied the ratio of the burned area to the total land area in a given year, then aggregated the burned area for each canal density class and the three land classifications. This process generated information on the total burned area detected in managed, unmanaged, and forest areas that could be cross-referenced to the different classes of canal density.

In addition to land management analysis, we also assessed the contributions of fire drivers, namely rainfall anomalies and the extent of unmanaged land, to peatland fire occurrence by conducting a statistical analysis of the relationship between these drivers and the area of peatland burned. The multilinear regression process used in this process is described in Eq. 1. The decision to include unmanaged land in the equation was taken based on studies that have found that peatland fires mostly occur in unproductive and degraded peatland (E. I. Putra et al., 2016; Thoha et al., 2017). We used the annual Standardized Precipitation Anomaly Index (SPAI), a normalized measurement of rainfall anomalies, to reflect rainfall factor. The SPAI is commonly employed to capture extreme rainfall events (Chanda & Maity, 2015) in which rainfall far exceeds or falls far below its average value for a climatological time window of 30 years. The SPAI is estimated using as described in Eq. 2.

$$\boldsymbol{Peatlandburnedarea(ha) = a + bA_{SPAI} + cUL} \quad (1)$$

where *peatland burned area (ha)* refers to the total burned area per year, *a* is the intercept of the equation, $A_{SPAI}$ is the standardized annual rainfall anomaly index, *UL* is the area of unproductive land, consisting of bare ground and shrub (ha), and *b* and *c* are the coefficients for annual SPAI and unproductive land, respectively.

$$\boldsymbol{A_{SPAI} = \frac{R(t) - Rave}{Rstd}} \quad (2)$$

where *R(t)* is annual rainfall (mm), *t* refers to the year, *Rave* is the 30-year average value of annual rainfall from 1987 to 2017 (mm), and *Rstd* is the standard deviation of 30 years of annual rainfall from 1987 to 2017 (mm).

For the multi-regression analysis, we used annual information on the extent of unproductive land by disaggregating the land cover maps for the periods 2000–2003, 2003–2006, 2006–2009, and 2009–2011 into annual land cover information using the deforestation rate. The disaggregation was performed using an approach similar to that employed for national greenhouse gas (GHG) monitoring (Ministry of Environment and Forestry, 2017). In this case, we obtained annual information for all variables in Eq. 1 from 2001 to 2019.

To maintain data variability in the multi-regression process, we excluded outliers in the data on the area of peatland burned by setting agreeable residuals at a 95% confidence level. We repeatedly generated the multi-regression model while assessing the residual value for each annual datapoint and completed this process when all residual values fell under the 95% confidence level. The final equation obtained by this process was then used in the study. The outlier analysis for the multi-regression excluded the data for the years 2001, 2010, 2016, 2017, and 2019.

## 3. RESULTS

Between 2001 and 2020, the total burned area varied from 1 ha to 10,034 ha with an annual average of 1,666.7 ha (see Figure 2). The severe El Niño events in 2015 and 2019 resulted in the two largest annual areas of burned peatland (Figure 2). The results shown in Figure 2 reveal that large areas of peatland also burned during La Niña years (2008, 2011, and 2012) and normal years (2013 and 2014). Except for declines in 2010, 2016-2017, and 2020 due to the combined effect of an extremely strong La Niña (measured as low NIÑO 3.4 SST anomaly) and the negative phase of the Indian Ocean Dipole (IOD), the results indicate an increase in the area of burned peatland from 2001 to 2020. However, if the study period was extended back to 1980, it would include a noticeable 10–15 year recurrence pattern: there were massive fires in 1982/83 and again in 1997/98 (Sloan et al., 2017).

In terms of frequency, our study has detected multiple fires in as much as 33% of the area of burned peatland, with a maximum frequency of seven. Spatially, recurrent peatland fires occurred more frequently in the southwestern region of the study area (Figure 3). According to the results, most of the fires in the study area (67%) did not recur, and these one-time fires were detected in each year of the period from 2001 to 2020. The total burned area was 21,690 ha and the total unburned area was 253,409 ha by 2020.

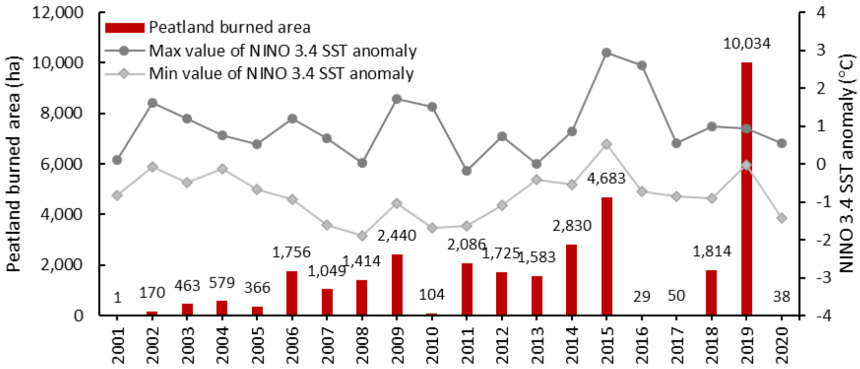


**Figure 2.** The total area of peatland burned in Gaung–Batang Tuaka KHG and the maximum and minimum NIÑO 3.4 sea surface temperature (SST) anomaly values according to the El Niño Southern Oscillation (ENSO) index.

An intersection of the map of burned peatland with the land cover map of the respective year demonstrates that before 2010 most peatland fires occurred in secondary peat swamp forests and wet shrub areas (Table 2). However, since 2010 peatland fires have shifted mainly to unproductive land (wet shrub and bare ground areas). This finding aligns with recent studies which have underscored that shrubland dominated by fern species (e.g., *Pteridium sp.*), is the most fire-prone land cover type in Indonesia, particularly during dry periods (Prayoto et al., 2017; Shiodera et al., 2016; Thoha et al., 2017).

Most burned land was covered by wet shrubs and estate crops. For a better understanding of the influence of anthropogenic factors on peatland fire regimes in managed and unmanaged areas, we disaggregated the burned peatland information into four main classes of canal density. We also classified forest plantations, estate crops, dryland agriculture, and paddy fields as managed areas, primary and secondary forests as forest areas, and the remaining land as unmanaged. As shown in Figure 4, the impact of drainage on the area of burned peatland is most apparent in forest areas. The drainage intensity on managed and unmanaged land does not have a significant impact on the area of burned peatland. Unmanaged land has the highest ratio of burned area relative to the land area. In this case, anthropogenic factors such as land supervision and management might reduce the occurrence of peatland fires. However, this would be highly dependent on the effectiveness of land management.

As Table 2 shows, the three largest areas of burned peatland all burned during periods of reduced rainfall, as illustrated by their negative SPAI indices. The effect of land use patterns and rainfall anomalies on the temporal variation of burned peatland area was measured by fitting the actual area of burned peatland to the annual SPAI and the extent of unproductive land. The inclusion of unproductive land originated from results provided in Table 2, which revealed that peatland fires occur in these areas most often.

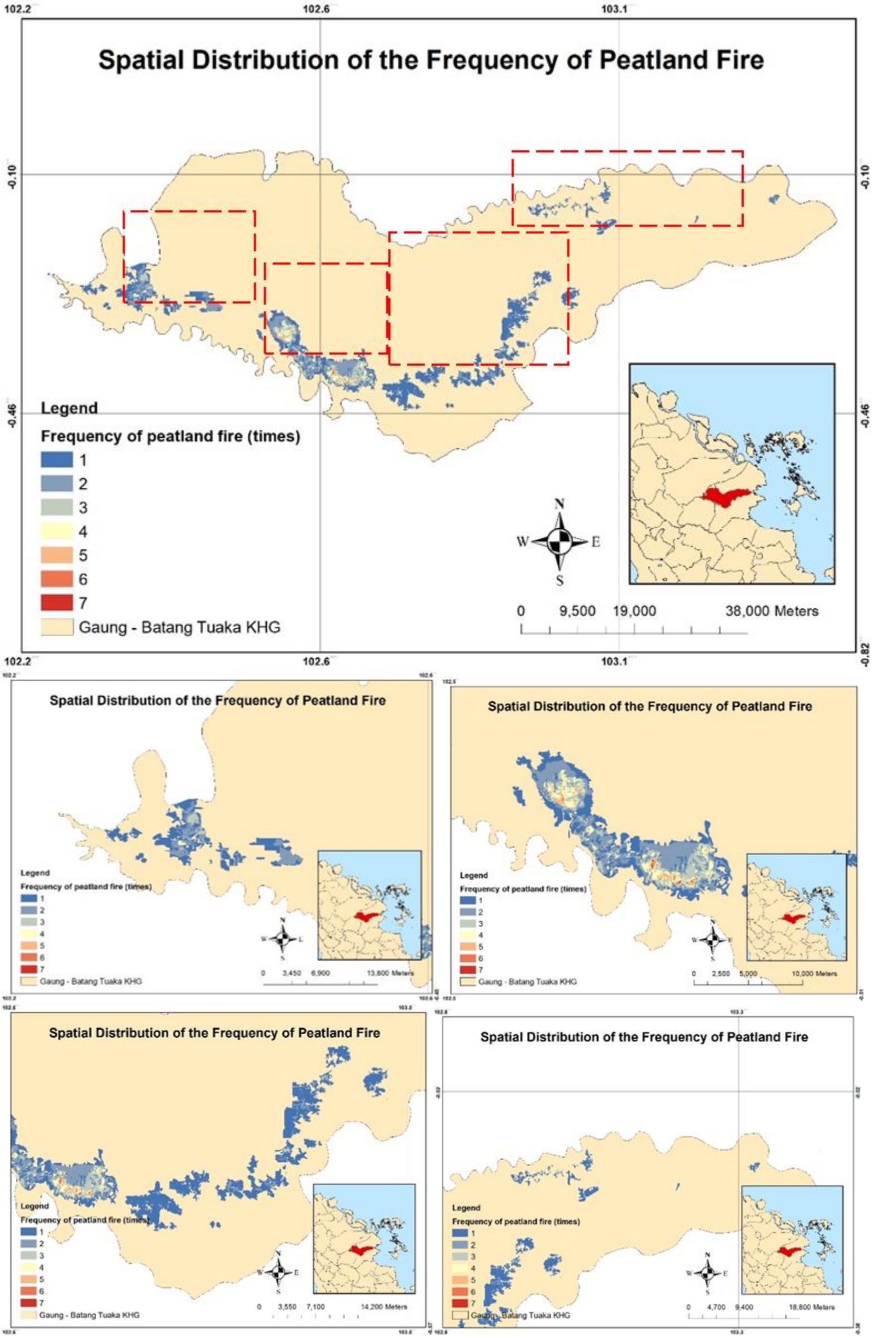


**Figure 3.** Spatial distribution of the frequency of fire occurrence from 2001 to 2020 in the study area.

**Table 2.** Area of burned peatland (2003–2019) by land cover type, annual rainfall, and SPAI index per year.

| Land use type | Burned area (ha) | | | | | | | | | | | | Total burned area (ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2003 | 2006 | 2009 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | |
| **Forest area** | **453** | **699** | **391** | **63** | **12** | **126** | **334** | **201** | | | **59** | **975** | **3,313** |
| Primary swamp forest | | | | | | | | 25 | | | | 11 | 35 |
| Secondary swamp forest | 453 | 699 | 391 | 63 | 12 | 126 | 334 | 176 | | | 59 | 965 | 3,277 |
| **Managed area** | | **36** | | **860** | **163** | **546** | **419** | **834** | **29** | **1** | **874** | **3,674** | **7,435** |
| Forest plantation | | | | 812 | 163 | 38 | 17 | 55 | | | 2 | 285 | 1,373 |
| Estate crop | | | | | | 508 | 401 | 779 | 29 | 1 | 871 | 3,319 | 5,907 |
| Dryland agriculture | | 20 | | | | | 1 | | | | | 45 | 65 |
| Paddy field | | 17 | | 47 | | | 1 | | | | | 25 | 90 |
| **Unmanaged area** | **10** | **1,021** | **2,048** | **1,163** | **1,549** | **912** | **2,077** | **3,649** | | **49** | **881** | **5,384** | **18,744** |
| Bare ground | | 457 | 162 | 34 | 30 | 53 | 965 | 2,147 | | 4 | 1 | 476 | 4,330 |
| Wet shrub | 10 | 504 | 1,886 | 1,128 | 1,520 | 859 | 1,100 | 1,471 | | 40 | 863 | 4,018 | 13,401 |
| Mixed dryland agriculture | | 60 | | | | | 13 | 30 | | 5 | 17 | 889 | 1,013 |
| Total burned area (ha) | 463 | 1,756 | 2,440 | 2,086 | 1,725 | 1,583 | 2,830 | 4,683 | 29 | 50 | 1,814 | 10,033 | 29,492 |
| Annual rainfall (mm) | 2,637 | 2,696 | 2,605 | 2,886 | 2,702 | 2,595 | 2,416 | 2,094 | 2,675 | 2,734 | 2,599 | 2,245 | |
| SPAI[1] | 0.49 | 0.79 | 0.33 | 1.76 | 0.82 | 0.27 | -0.64 | -2.27 | 0.68 | 0.98 | 0.30 | -1.50 | |

[1]SPAI = standardized annual precipitation anomaly index

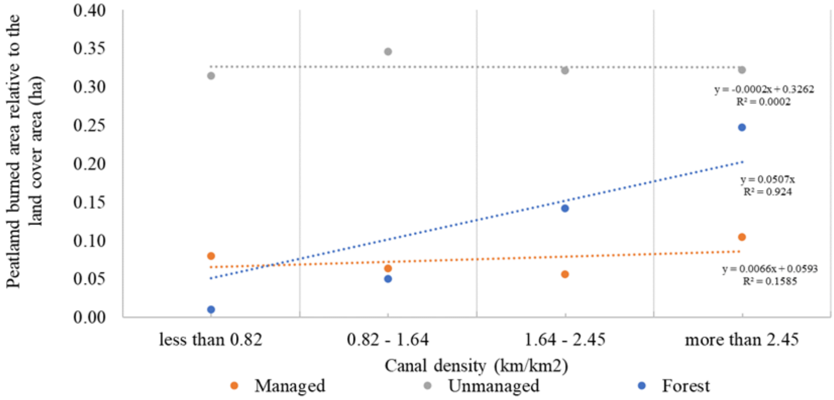


**Figure 4.** Burned area and canal density in managed and unmanaged land. The managed land category comprises timber plantations, estate crops, dryland agriculture, and paddy fields; the unmanaged land category comprises bare ground, wet shrubs, and mixed dryland agriculture; and the forest area comprises primary and secondary swamp forests.

After excluding outliers, a multi-regression analysis was performed (Table 3). The coefficient of the parameters indicates that the logarithmic form of the area of burned peatland increases by 1% as annual SPAI decreases by 0.1134 units (or when a rainfall deficit occurs), and the logarithmic form of the area of the unproductive land increases by 2.88%. The effect is significant (p-value < 0.1) with an $R^2$ of 72.8%. The extent of the unproductive area significantly affects the area of burned peatland (p-value < 0.1). The multi-regression results support the conclusion that the expansion of unmanaged lands will increase the fire risk in the area.

**Table 3.** Multi-regression of logarithmic natural form of area of burned peatland as response with SPAI and logarithmic natural form of area of unproductive land (bare ground and wet shrub) as predictors. Significance level at alpha ($\alpha$) of 5% ($R^2$=72.8%, ρ=0.001)

| Parameter | | Coefficient | S.E. | p |
|---|---|---|---|---|
| - | $\beta_0$ | -23.768 | 5.712 | 0.002 |
| SPAI | $\beta_1$ | -0.1134 | 0.1432 | 0.445 |
| Ln UA[1] | $\beta_2$ | 2.8827 | 0.5330 | 0.000 |

[1]logarithmic natural form of unproductive area (bare ground and shrubs)

## 4. DISCUSSION

Many studies of tropical countries have recognized an increasing trend of fires, despite the humid nature of the climate in the regions (Turetsky et al., 2015; Vadrevu et al., 2019; Van Der Werf et al., 2008). The increasing trend has also led to concerns about the status of peatland ecosystems in the coming decades, along with the incompatibility of current ecosystem restoration pace with global targets and commitments to the Paris agreement. In the national context of Indonesia, historical peatland fire patterns indicate that reaching NZE will require transformative policy action and a massive paradigm change in the utilization of peatland to prevent as much disturbance as possible.

As presented in Table 2, peatland fires in unmanaged land occurred nearly every year in the study area. Most peatland fires took place in the non-forest area, including areas of wet shrubs, which aligns with a study performed in Kalimantan (Cattau et al., 2016). Furthermore, in South Sumatra, although hotspot density is highest in industrial plantations, hotspot emergence consistently appears in unmanaged land (R. Putra et al., 2019). This evidence strongly indicates that unmanaged land should be prioritized as the main target for peatland fire prevention measures.

Many studies have emphasized the primary role of extensive drainage in increasing the vulnerability of peatland to fire (Taufik et al., 2019; Wösten et al., 2006). As peatland is generally perceived as marginal land, draining these areas was necessary to allow the cultivation of dryland commodities. This study found a strong correlation between intensive peatland drainage, measured as canal density, with increased burning in peatland forests (Figure 4). This finding confirms the urgent need to rewet drained peat forests, as the combination of drainage and fire is the main cause of total ecosystem destruction in these areas (S. Page et al., 2009).

In the non-forest area (cultivated and unmanaged land), increased canal density was less correlated with peatland burning (Figure 4). Another notable finding of this study is that unmanaged land was the most vulnerable fire at all canal density classes. This finding also suggests that draining would trigger ecosystem degradation and vulnerability to burning in areas without water management at any level of draining intensity or canal density.

The area of burned peatland was considerably lower in managed areas, but its socioeconomic impact was still significant. For instance, a previous study has found that the monetary value of ecosystem capacity-generating provisioning services declined after the massive peatland fire in 2015 (Rossita et al., 2021). In addition, the environmental impact of peatland fires has been addressed by many studies, highlighting reduced air quality and increased GHG emissions in a densely populated peatland area (Jayarathne et al., 2018; Marlier et al., 2015).

A study by Miettineen et al. (2017) highlighted the influence of poor water management on peatland fires in managed areas, which indicates that non-government actors could play a significant role in improving peatland water management and conducting peatland restoration. On a national scale, plantation companies have installed 17,292 canal blocks and restored 4,438 ha of peatland, contributing to a 190 $MtCO_2e$ reduction in emissions (Ministry of Environment and Forestry, 2018). Canal blocks with spillways are installed in planting areas, helping to avoid overflooding during the wet season and overflowing during the dry season. Canals are also backfilled purposively to promote permanent rewetting in non-planting areas. While spatial data on canal blocking in concession areas is not currently accessible, in future work these should be taken into account in the quantitative analysis, as they could eliminate the draining effect of dense canal systems, particularly during the dry season (Hirano et al., 2012; Hooijer et al., 2010; Wösten et al., 2006).

Additional data on canals consisting of canal width (for primary, secondary and tertiary canals) and canal structure types are required to improve the analysis of the relationship between peatland drainage and fire occurrence. The analysis should also consider intervention measures from peatland rewetting through canal blocking. Canal blocking does not always permanently eliminate canals, although backfilling or composite dams always close canals through soil filling and vegetation planting (Suryadiputra et al., 2005). Hence, canal networks might still be detectable using remote sensing data and therefore could result in bias when interpreting canal density. Therefore, we strongly suggest that the number of canal blocks installed in an area should be included as a new variable in future work to better explain the relationship between peatland fires and canal networks. Further study is necessary to explore this new variable, as the effectiveness of canal blocking in reducing the capacity of a canal for peat drainage varies by region due to socioeconomic conditions, including community acceptance (Ward et al., 2021).

When examining temporal variability, studies have identified the role of climatological conditions in peatland fires (Putra & Hayasaka, 2011; Van Der Werf et al., 2008). By comparing the annual area of peatland burned with annual SPAI values in the study area, we found greater fires in years with relatively low annual rainfall and SPAI values (Table 2). Nevertheless, large peatland fires have occurred during years with normal or good climatological conditions. The non-significant effect of SPAI on the area of burned peatland (Table 3) indicates the artificially modified peatland ecosystems' inability to store water, particularly during the dry season.

As shown in Figure 2, El Niño Southern Oscillation (ENSO) variance has a weaker influence on the area of burned peatland in our study area than in Kalimantan (Miettinen et al., 2017; Taufik et al., 2017). Many studies have noted that the combination of ENSO and IOD in the same period increases the impact of rainfall deficit (Nur'utami & Hidayat, 2016; Nurdiati et al., 2022). As IOD mode also drove the climate dynamic on Sumatra Island (Gaveau et al., 2014; Nurdiati et al., 2021); Sumatran peatland is therefore at greater risk of fire during drought periods.

This study shows that more fires take place in unproductive area due to a lack of land management. The multi-regression analysis performed in our study suggests that an increase in unproductive land of 2.88% leads to a 1% increase in the area of burned peatland. Although other studies have suggested that cultivated land (especially land used for smallholder "slash-and-burn" agriculture and oil palm plantations) generally has more primary ignition sources (Cattau et al., 2016; Sloan et al., 2017), it is also possible for human activity (e.g., hunting) to lead to fires being ignited in unproductive land. Many studies have shown that anthropogenic activities like land clearance or accidental fires are often identified as the main drivers of wide-scale fires (Goldstein et al., 2020; Harrison et al., 2009).

Beyond this study, it is noteworthy that land cover does not necessarily reflect the nature of fires. Studies have revealed the influence of relative distance from anthropogenic disturbance, vegetation condition, topography, population density, and livelihood options on fire regimes (Medrilzam et al., 2014; Sloan et al., 2017), and also the likelihood of peat fires spreading horizontally across different land covers and vertically from underground to overground (Goldstein et al., 2020; Widyastuti et al., 2021). The evidence indicates a potentially more complex relationship between land cover and peatland fires at the local level.

As a preventive measure, unmanaged land could be supervised according to a sustainable land management strategy under the social forestry and agrarian reform (TORA) program to reduce the possibility of repeated peatland fires in the future. Initially, the MoEF instituted the social forestry scheme to resolve tenurial issues between local communities and the private sector. The instrument grants communities' access to forest land (except for conservation forests) to combine agricultural activity and the extraction of non-timber forest products and environmental services. The total area targeted for the social forestry program was 12.7 million ha at country level, spatially distributed according to the indicative map of social forestry (Ministerial Decree of MoEF No. 2111/2020), which was determined according to the potential for land conflict in different areas and different communities' dependence on forest resources.

In contrast to social forestry, TORA aims to reform the current structure of land ownership in the country by granting legally binding land permits to communities that have long utilized government lands. The scheme aims to maximize the benefit gained from the land by communities located near forests. The indicative area for TORA falls mostly in ex-concession areas for oil palm plantations (HGU), which are already largely occupied by the community. The total area targeted by the TORA program at country level was 4.1 million ha (Ministerial Decree of MoEF No. 7434/2019).

According to overlaid maps of fire frequency from 2001 to 2020, 2,391 ha and 896 ha of peatland burned within the indicative areas of social forestry and TORA, respectively. Social forestry in the peat ecosystem remains in the initial regulation development phase. In contrast, the TORA program for the peat ecosystem has been well-implemented in the Siak Regency (approximately 4,000 ha). It has been intertwined with sustainable management strategies that consider the peat characteristics in the region (e.g., class of peat depth, drainage conditions, soil acidity, and soil fertility) when utilizing the land (Priyono et al., 2019).

As the vulnerability of degraded peatlands to fire has been scientifically proven, many studies have suggested that converting unmanaged land to managed land is necessary (Gunawan, 2018; Mishra et al., 2021). However, this idea has been debated in the literature, as converting these areas into agricultural lands will not necessarily hinder the occurrence of fire hotspots (Miettinen et al., 2017). The results presented in this study highlight that leaving land to be unmanaged results in higher fire risk, irrespective of the drainage level. As scientific evidence has revealed a high subsidence rate during the initial years of drainage in commercial plantations (Anshari et al., 2021; Khasanah & van Noordwijk, 2019), we suggest that existing policies on the utilization and management of peatland according to its ecological functions (e.g., its production and protection functions), should be referred to when utilizing unmanaged peatland (Ministerial Law of MoEF No.10/2019).

Peatland rewetting is an alternative to the conversion of peatland to cultivated land. Many studies have confirmed rewetting's positive impact on water levels and that it positively affects microbial peat oxidation (Jauhiainen et al., 2013; Könönen et al., 2018; Lestari et al., 2022). Peatland rewetting can eliminate drainage in an area and increase the ecosystem's capacity to maintain the water level during the dry season; hence, reducing the area's vulnerability to fire (Lestari et al., 2022; Ritzema et al., 2014; Taufik et al., 2019). Our results show that reduced drainage in the forest areas may result in less peatland being burned yearly. Nonetheless, the efficiency of dams will eventually regulate changes in the water level regime of the rewetted area (Jauhiainen et al., 2008).

Government Regulation No. 57/2016 defines permissible water-table depth for peatland use. However, to maintain the peat's ecological function, the commodity chosen from the list of alternatives in the Ministerial Law of the MoEF No.16/2017 should be adapted to the actual land conditions (e.g., post-fire, sparsely vegetated, or ex-selective logging). Several studies have identified peat-adapted commodities derived from paludiculture, including timber, edible food plants and medicinal plants (Giesen, 2013; Lisnawati et al., 2019). However, low economic value, limited market scalability, and farmers' unwillingness to accept the new system have posed obstacles to expanding paludiculture planting (Tata, 2019; Uda et al., 2020).

Until 2020, the extent of the land covered by the national social forestry and TORA programs was only 4.2 million ha and 2.7 million ha, respectively. An adjustment in the administration of these programs is required to increase local communities' interest in implementing the social forestry and TORA agendas. For example, the village cooperation system, known as *Koperasi Unit Desa* (KUD), could facilitate a financing scheme to support the community in implementing TORA. Another alternative would be to combine TORA with the Peat Restoration Agency (BRGM)'s Peat Care Village (DPG) program to provide farmers with training and resources on sustainable peatland management.

In light of the impact of drainage on peatland fires, specifically in intact ecosystems and unproductive land, biophysical intervention with rewetting is necessary. Rewetting is likely more efficient in an intact ecosystem than in cultivated land. In cultivated land, and especially where commercial trees like oil palm have already been planted, the increased water level will affect the production of the commodity, which is better suited to drained conditions and low water levels. In cultivated land, a rewetting program will be most effective if a concomitant shift toward paludiculture accompanies it. However, this option may be less attractive to farmers who must wait a few years to see any returns from this change, even as they increase their investment in the first two years of planting. To address this issue, a study in Jambi Province evaluated a mixed cropping pattern involving native species and plantation crops (Yuniati et al., 2018). Under this cultivation system, existing commercial trees can be harvested while waiting for the native species to reach their productive age.

While drainage levels seem to have less impact on burning in managed areas, we do not suggest that land be converted from peat forests to plantations. The conversion of intact peatland to commercial plantations has been found to affect the fire regime in many regions of Indonesian peatland. In South Sumatra, the industrial plantation has the highest hotspot density, with consistent appearance of hotspots (R. Putra et al., 2019). Conservation and protected forests appear to undergo fewer active fires (Albar et al., 2018), which indicates that the ideal intervention in these areas is to merely conserve peatland rather than converting it.

As the extent of the indicative area for social forestry and TORA is just a small part of the KHG area and is mainly located in areas with shallow-to-moderate peat depth, we argue that these programs could act as the main vehicle for peatland restoration. Currently, Indonesia's land-based mitigation policies still lack an implementation scheme. To encourage further peatland restoration and revegetation, increased participation of NPAs (e.g., local government, communities, and the private sector) is needed, as approximately 40% of the study area is dominated by the concession area. One way to achieve this would be to develop an innovative financing and incentive scheme to support sustainable business mechanisms. Currently, Indonesia is still developing the domestic carbon trade after the release of a presidential regulation on carbon's economic value. Furthermore, during the full implementation of domestic carbon trade, NPAs need to be equipped with knowledge about the Monitoring, Reporting, and Verifying (MRV) system in order to acquire domestic certification for emission reductions.

## 5. CONCLUSION

There was an increasing trend in the area of burned peatland from 2001 to 2020, with a temporary decrease in 2010. Around 33% of the study area experienced more than one peatland fire occurrence between 2001 and 2020, with a maximum frequency of seven fires. This study found that the drainage level determined the frequency of peatland fires in forest areas. However, the impact of draining intensity was insignificant in non-forest areas (i.e., managed and unmanaged areas). The significant impact of extensive peat drainage in the forest area underscores the need for peatland rewetting to reduce the possibility of repeated fires in areas with dense canal networks. Despite the low ratio of the burned area to the total area for all canal density classes, peatland fires in the managed area highlight the need to increase the effectiveness of land supervision and water management systems.

While the impact of drainage level on the area of burned peatland was not significant for the non-forest land category, unmanaged land had a higher ratio of the burned area to total area extent compared to the forest and managed land. In this case, the utilization of this land for productive purposes or land management—particularly when combined with rewetting and paludiculture—could considerably reduce its vulnerability to fire. The government's social forestry and TORA programs present one possibility for increasing the utilization of unmanaged land; however, the programs must be conducted carefully to prevent more drainage in the area. Due to the limited indicative area for social forestry and TORA, it is necessary to involve NPAs in peatland rewetting and revegetation. The presence of an incentive scheme that makes the environmental benefits economically apparent, primarily for the private sector, is key to increasing NPAs' participation in peat restoration and peat fire prevention.

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