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# Forest Fire Dynamics Over a Decade in Mappi District, South Papua: Hotspot Trends and Burned Areas Estimation Using MODIS Data

Ati Dwi Nurhayati, Handi Satriawan, Citra Septriantri Putri

Department of Silviculture, Faculty of Forest and Environment, IPB University, IPB Dramaga Campus, Bogor, 16680, Indonesia

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**ABSTRACT**

Forest and land fires have become an annual occurrence in South Papua Province over the past decade, with Mappi District identified as a fire-prone hotspot. This study analyzes hotspot trends and dynamics from 2012 to 2021 and estimates burned areas using Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data and ArcMap 10.8. The highest number of hotspots was recorded in 2015 (3,879), with 36.5% occurring on peatland and 63.5% on mineral soils. A historical hotspot analysis pinpoints the prevalence of fire incidents between July and October, highlighting the necessity for intensified prevention measures before July. Furthermore, a significant linear regression is established between annual hotspot numbers and rainfall in Mappi District (p-value = 0.006), signifying the impact of climatic factors on fire occurrences. The largest burned area, estimated at 134,051.74 hectares, also occurred in 2015, coinciding with a strong El Niño event. More importantly, these fires occurred not only on mineral soil but also on peatland areas. Hence, this study highlights the critical need to prioritize comprehensive forest and land fire management in Mappi District, South Papua Province.

## Introduction

The issue is the alarmingly high rate of annual deforestation. Indonesia has experienced one of the most rapid rates of deforestation globally, resulting in a total forest loss of approximately 1.1 million hectares, equivalent to approximately 2% of the total area of 130 million hectares per year [1]. This rate of deforestation is not comparable to the acceleration in the implementation of forest and land rehabilitation. One of the causes of deforestation, a crucial issue of both local and global concern, is forest and land fires. Previous studies have indicated that various factors influence fires, including climatic conditions, land cover characteristics, soil type, socioeconomic factors, and government policies. The leading cause of the high number of forest fires in Indonesia is land conversion for various socioeconomic purposes and conditions in the community. The consequences of these fires extend beyond mere financial losses and cause a wide array of ecological, environmental, and public health impacts. These include the degradation of natural ecosystems, destruction of forested landscapes and vegetation, biodiversity loss, reduced availability of clean air, habitat loss for wildlife, and health-related issues experienced by communities residing near fire-affected areas.

Forest and land fires are recurring in Indonesia, primarily affecting Kalimantan and Sumatra. However, Eastern Indonesia, particularly Southern Papua, has increasingly witnessed frequent forest and land fires. Papua are classified as prone to such incidents [2]. Within South Papua Province, Mappi District stands out as one of the areas with the highest hotspot number over the last decade (2012–2021), second only to Merauke. Indonesia experienced a catastrophic fire season in 2015, the previous decade, resulting in 2.6 million hectares of burned land [3]. This event caused financial losses estimated at approximately IDR 221 trillion. This is equivalent to US$ 16.1 billion [4]. Another significant fire event occurred in 2019 and 2023, with 1.6 million and 1.1 million hectares of land affected, respectively. The scale of the impacts and losses from forest and land fires requires serious effort for effective control. Hence, continuous monitoring of

**Corresponding Author:** Ati Dwi Nurhayati awinur@apps.ipb.ac.id Department of Silviculture, Faculty of Forestry and Environment, IPB University, IPB Dramaga Campus, Bogor, Indonesia.

hotspots is an effort to prevent forest and land fires. Hotspot monitoring can be conducted by analyzing hotspots in specific years using remote sensing technology, providing data with comprehensive coverage, near-real-time information, consistent data acquisition, and relatively cost-effective implementation in Indonesia. Given the potential occurrence of forest and land fires in Mappi District and their resulting impacts, gathering information regarding hotspot distribution and its relationship with rainfall in areas prone to forest fires is imperative.

However, there is a lack of comprehensive data regarding the historical patterns of forest and land fires in South Papua Province, specifically within the Mappi District. To address this gap, this study aimed to (1) analyze the trends and dynamics of hotspots throughout the 2012–2021 period, (2) examine the relationship between rainfall and hotspots, and (3) estimate the extent of burned areas in the Mappi District, South Papua Province. Following this study, the findings can act as essential information, aiding in formulating improved forest and land fire prevention approaches in the Mappi District.

## Materials and Methods

### Study Area

Hotspot and burned area analyses were conducted in Mappi District, South Papua Province (see Figure 1). According to Law No. 26 of 2002 in Indonesia, Mappi District emerged as an expansion of Merauke District and is situated between 137°29' and 139°52’ east longitude, and between 4°4' and 9°2' south latitude, covering an area of 24,182.22 $km^2$ [5]. The Mappi District is subdivided into 15 sub-districts, with Kepi as the district’s administrative center. Geographically, the Mappi District consists of 70% lowlands and swamps and 30% upland areas, which tend to be rocky and located to the north. In addition, Mappi District has the largest peatland within South Papua Province, covering approximately 479,848 ha, or 19% of the total area [6].

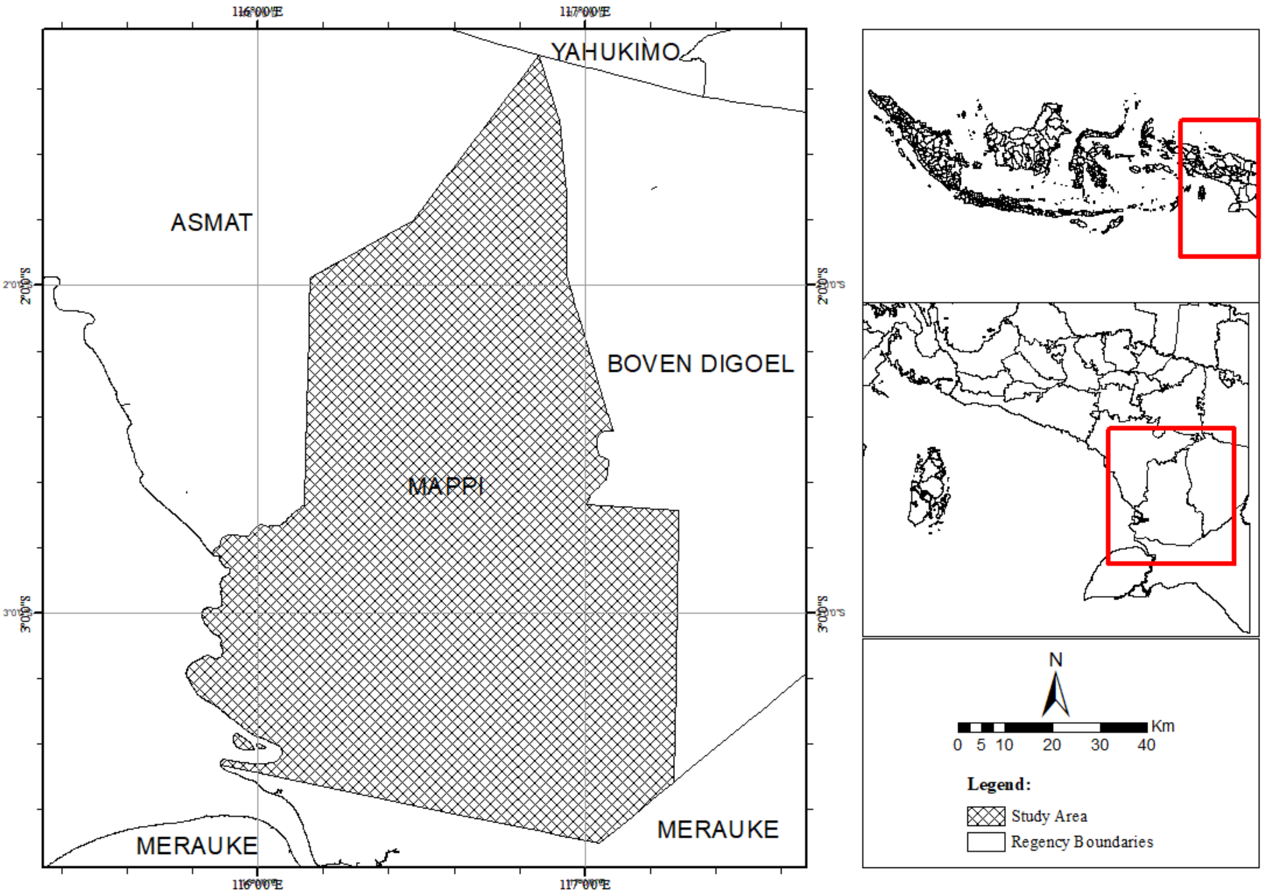


**Figure 1.** Mappi District, South Papua Province.

**Data and Source**

The map of the administrative boundary was acquired from the *Badan Informasi Geospasial* (BIG) (https://tanahair.indonesia.go.id accessed on 8 December 2022), and peat distribution data were obtained from *Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian* (BBSDLP) (http://bbsdlp.litbang.pertanian.go.id/ accessed on 12 December 2022). Hotspot data were acquired from Satellite Imagery Terra/Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) and downloaded from the official website NASA Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov accessed on 9 December 2022). Data are available at all confidence levels. Hotspot distribution data with a confidence level of ≥ 80% were used to estimate burned areas within the Mappi District, and data processing was conducted using QGIS 3.26. Data on daily rainfall in the Mappi District from 2012 to 2021 were utilized to investigate the relationship between rainfall and hotspots. It was acquired from the NASA Langley Research Centre's (LaRC) (https://power.larc.nasa.gov/data-accessviewer/ accessed on 12 December 2022).

**Data Analysis**

The annual hotspot distribution in Mappi District from 2012 to 2021 was analyzed to identify fire occurrence trends over time. For each sub-district, the estimated burned area was used to assess the spatial extent of annual fires during the same period. In addition, linear regression analysis was conducted to examine the relationship between annual rainfall and the number of hotspots. The overall workflow of this study is illustrated in Figure 2.

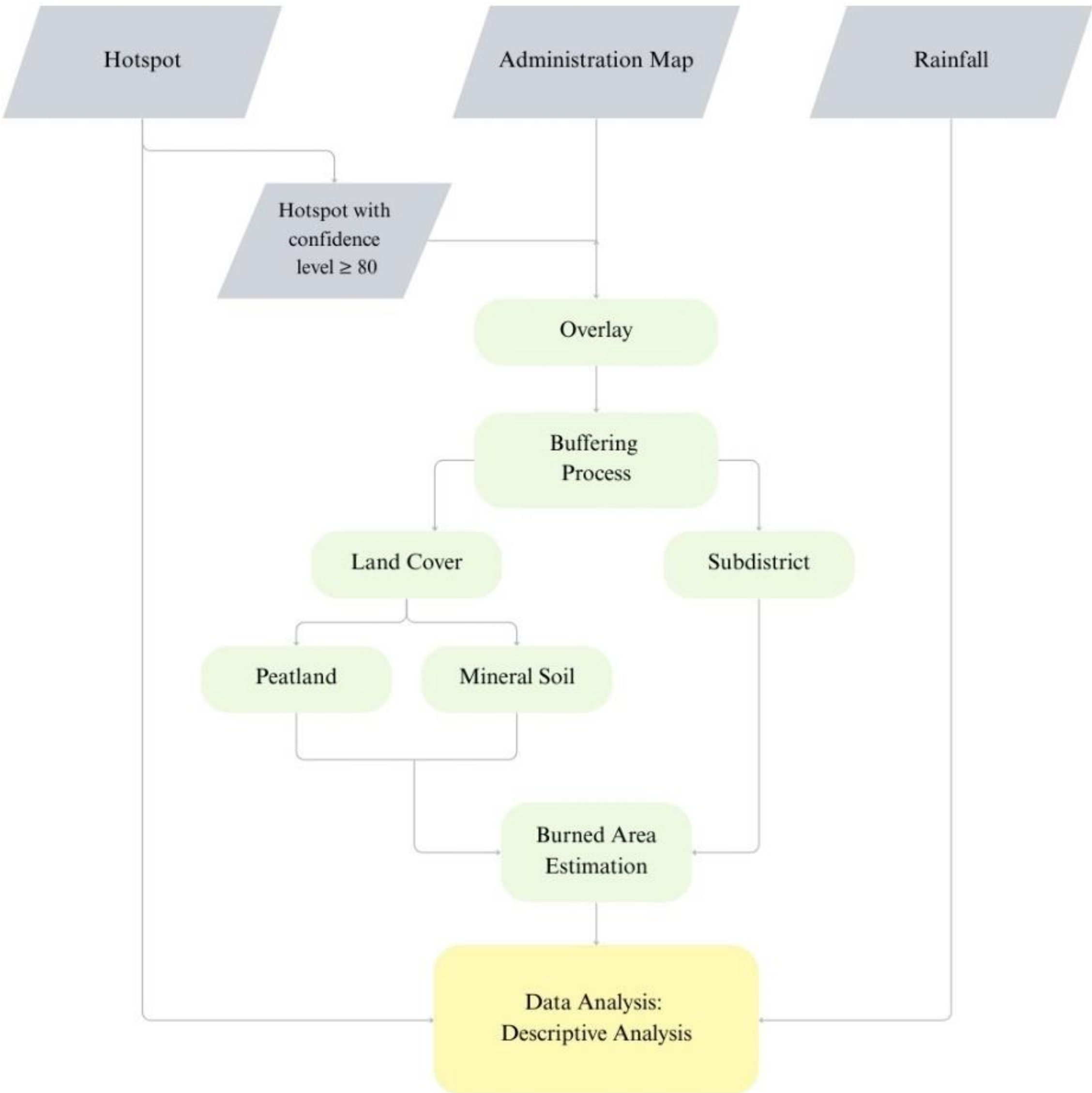


**Figure 2.** The flowchart illustrates the study's implementation in the Mappi District, South Papua.

## Results and Discussion

### Results

#### *Hotspot Number and Rainfall in the Period of 2012–2021*

Figure 3 illustrates the annual fluctuations in the number of hotspots in the study area. In 2015, the Terra/Aqua Satellites data showed the highest hotspot number (2,844), with 1,931 hotspots located on mineral soil and 913 hotspots on peatland. The lowest hotspot numbers during this period were in 2020 and 2021. In 2020, there were 55 hotspots, of which approximately 29 were located on peatlands. In 2021, the lowest hotspot number was 41, of which approximately 24 were identified on peatlands.

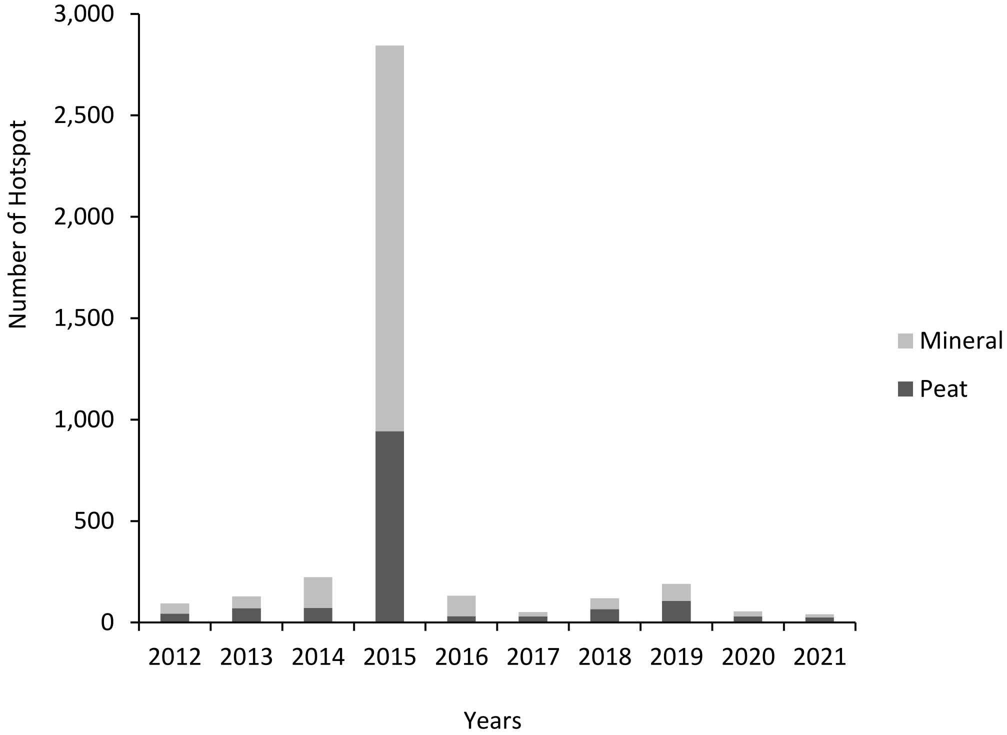


**Figure 3**. Trend in the number of hotspots from 2012 to 2021 on mineral soils and peatlands in Mappi District.

The study was conducted in Mappi District, South Papua Province, for hotspot and burned area analyses. Figure 4 illustrates that 2015 experienced the highest density of hotspot distributions, whereas other years had considerably lower counts. However, throughout 2012–2021, the Mappi District had yearly hotspot occurrences. Figure 5 shows the fluctuation in hotspot numbers from 2012 to 2021 in the Mappi district. The notable increase started in July and intensified significantly in September, reaching a peak in October. A subsequent decline in the number of hotspots was observed in November. September and October were the most susceptible months to fires in the Mappi District.

The hotspot numbers and amount of rainfall in Mappi District exhibited year-to-year fluctuation throughout 2012–2021. Over a decade, the average monthly rainfall in Mappi District stood at 338.71 mm. Subsequently, during 2020–2021, Mappi District experienced relatively wet months. The onset of the dry season in the Mappi District typically starts in August (61.41 mm) and reaches its peak conditions in September (23.2 mm), as observed in 2015. The number of hotspots in 2015 increased significantly to 1,023 in September and reached 1,491 in October. Remarkably, even as October saw an increase in rainfall, totalling 105.8 mm, it experienced the highest number of hotspots.

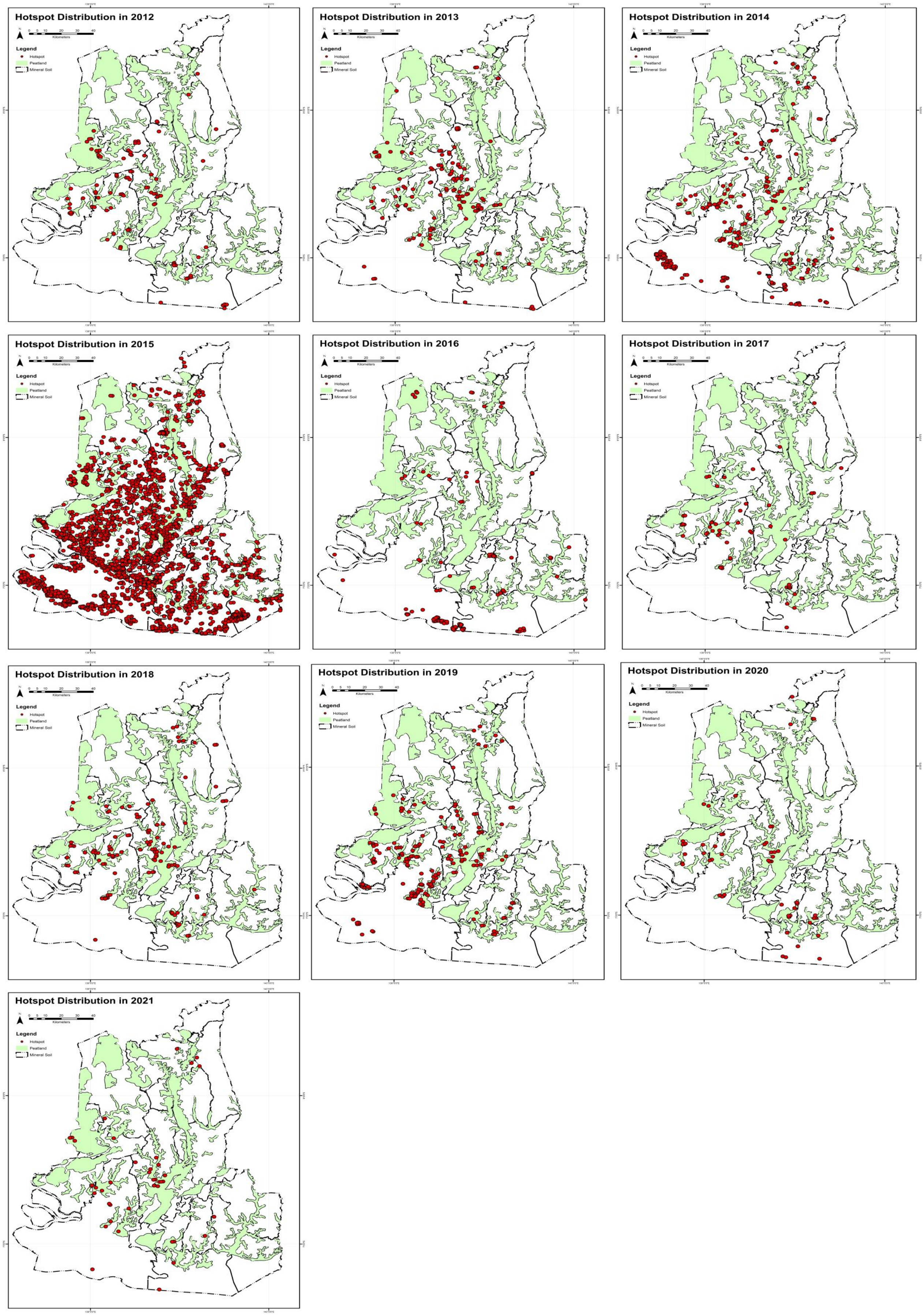


**Figure 4**. Distribution of hotspots in Mappi District during 2012–2021.

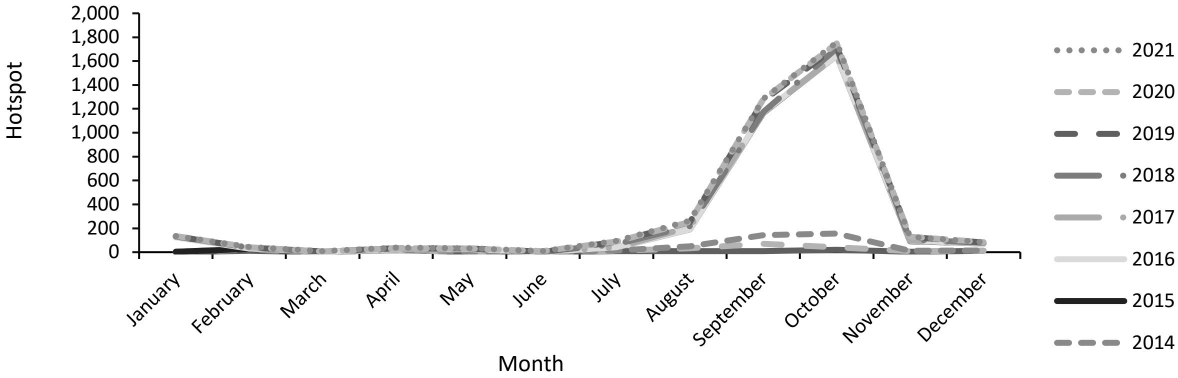


**Figure 5.** Monthly distribution of hotspots in Mappi District from 2012 to 2021.

Figure 6 shows the distribution of hotspots and monthly rainfall in Mappi District. Over the past decade (2012–2021), there has been a clear trend: as rainfall decreases, the number of hotspots tends to increase. The lowest rainfall during this period occurred in 2015, when Mappi District experienced a prolonged dry season beginning in August and peaking in September, with rainfall dropping to below 50 mm. Correspondingly, the number of hotspots began rising in July and peaked in September.

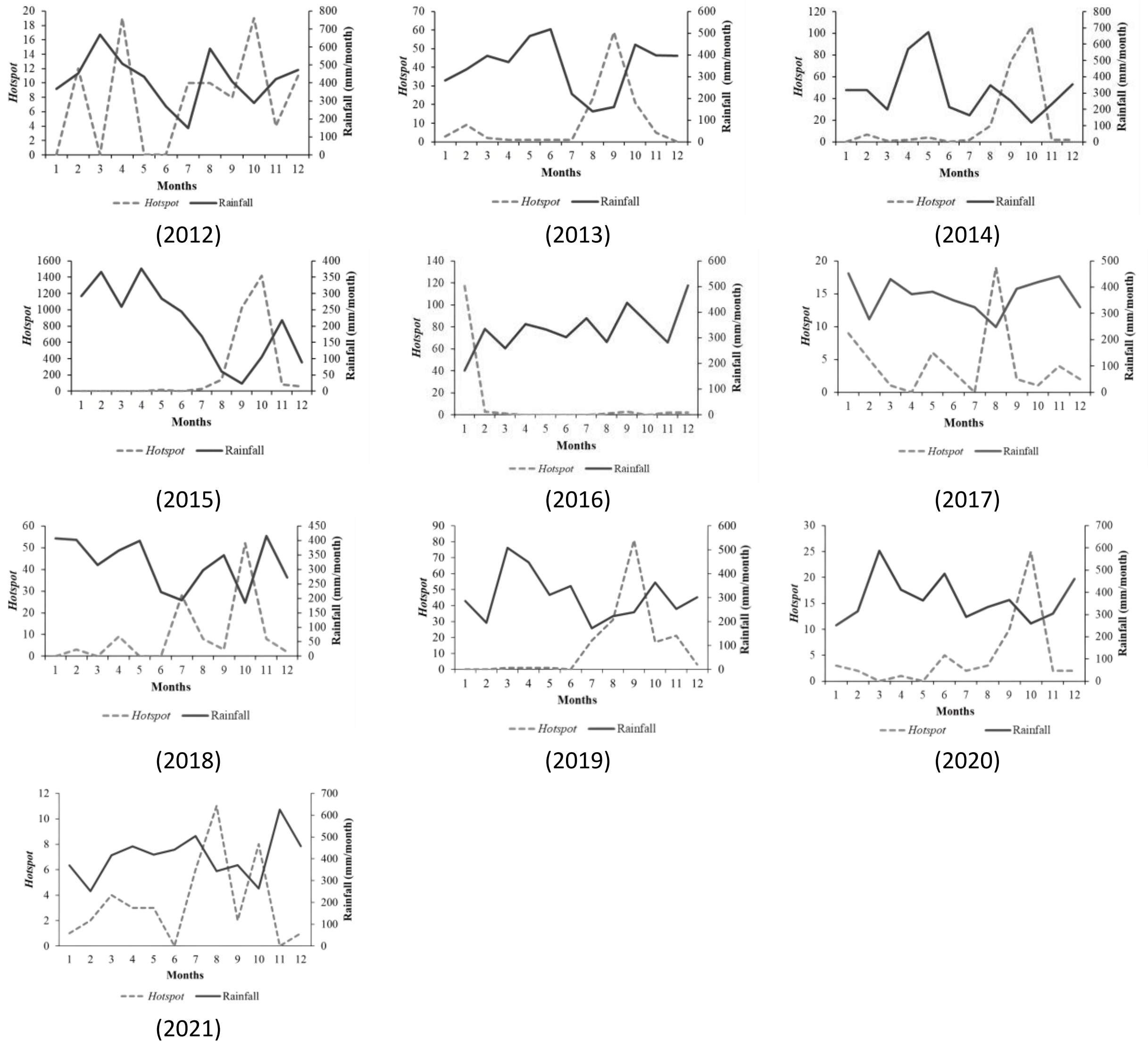


**Figure 6**. Trends in hotspots and monthly rainfall from 2012 to 2021 in the Mappi District.

***Relationship between Annual Hotspot Numbers and Annual Rainfall in Mappi District***

Linear regression analysis of hotspot numbers and annual rainfall was significant (p-value = 0.006). The regression coefficient for hotspots was negative (–0.9468), suggesting an inverse relationship between rainfall and the number of hotspots. In Figure 7, the displayed R-squared value is 0.6311. The R-squared ($R^2$), or the coefficient of determination, measures how effectively the resulting regression model accounts for the data. This value indicates that, from 2012 to 2021, rainfall in Mappi District only affected 63.11% of the hotspots, while approximately 36.89% of the hotspots were affected by other factors.

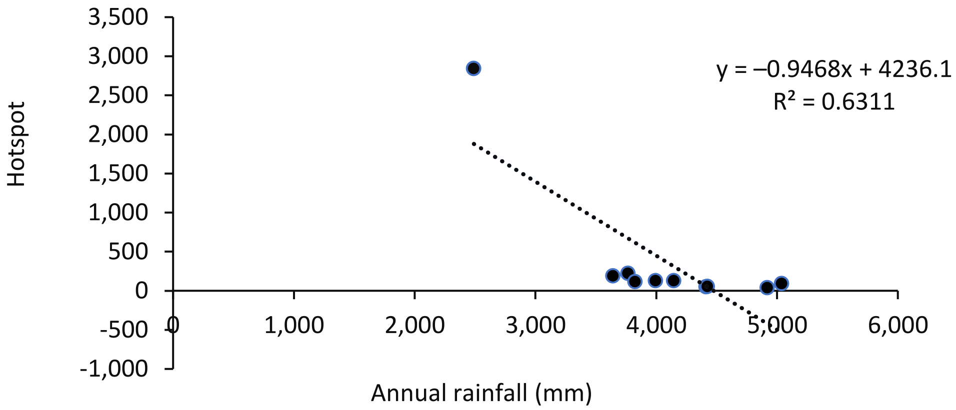


**Figure 7**. Relationship between the number of hotspots and annual rainfall from 2012 to 2021 in Mappi District.

The Mappi District consists of 15 sub-districts, and Kepi serves as the district capital. Figure 8 shows that the Mambioman Bapai Sub-District registered the highest hotspot numbers from 2012 through 2021 in the Mappi District, with a total of 1,316 hotspots. The second-highest hotspot number was observed in Obaa Sub-District, totalling 696 hotspots, followed by Edera Sub-District with 362 hotspots, Minyamur Sub-District with 329 hotspots, and Bamgi Sub-District with 240 hotspots.

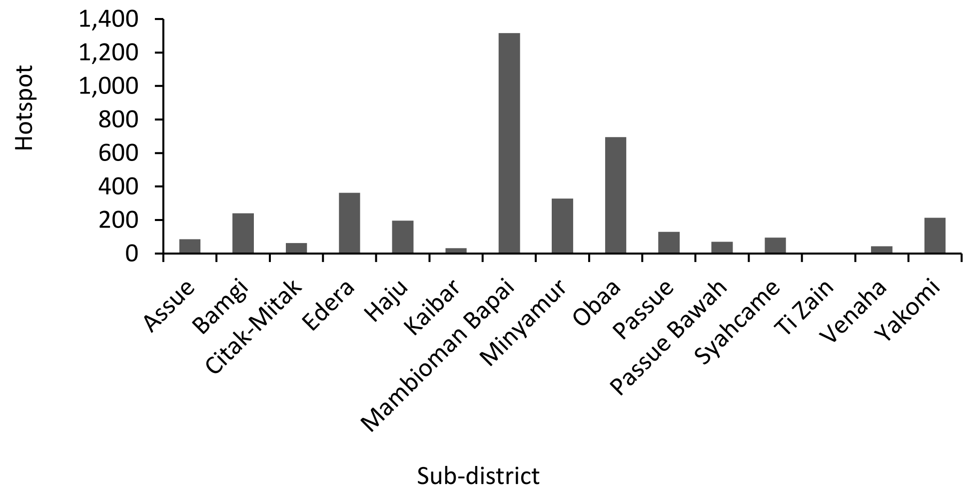


**Figure 8**. Number of hotspots in each sub-district of Mappi District from 2012 to 2021.

***Estimated Burned Areas in Mappi District (2012–2021)***

Based on the estimated burned areas in the Mappi District (Figure 9), the highest burned area occurred in 2015. The estimated burned area reached 134,052 ha, comprising 90,653 ha of mineral soils and 43,399 ha of peatland. The estimated burned area in Mappi District in 2016 was approximately 5,508 ha, comprising 3,957 ha of mineral soils and 1,551 ha of peatland. In comparison to the extensive fires in 2015, there was a 96% reduction in the incidence of forest and land fires. Furthermore, the estimated burned area increased significantly in 2019, reaching approximately 9,594 ha, with 4,776 ha on mineral soil and 4,817 ha on peatland.

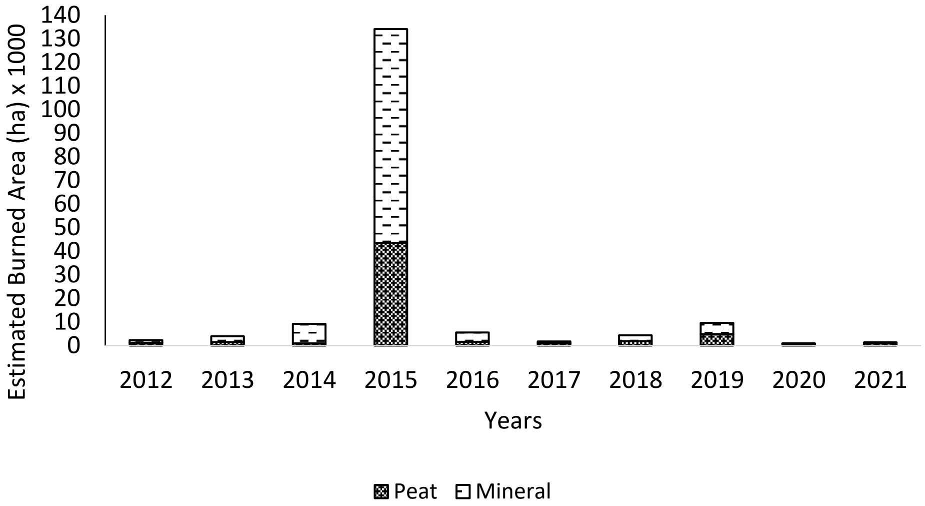


**Figure 9**. Annual estimation of burned areas in the Mappi District from 2012 to 2021.

In the recapitulation of the estimated burned area per sub-district (Figure 10), it is evident that four sub-districts accounted for the highest burned areas during the 2012–2021 period. These sub-districts are Mambioman Bapai Sub-District, Obaa Sub-District, Edera Sub-District, and Bamgi Sub-District. Mambioman Bapai Sub-District recorded the highest burned area of approximately 67,570 hectares, while Obaa Sub-District closely followed the second-highest burned area of approximately 33,099 hectares. Minyamur Sub-District reported a burned area of roughly 15,592 hectares; Edera Sub-District reported around 10,590 hectares; and Bamgi Sub-District reported around 10,498 hectares.

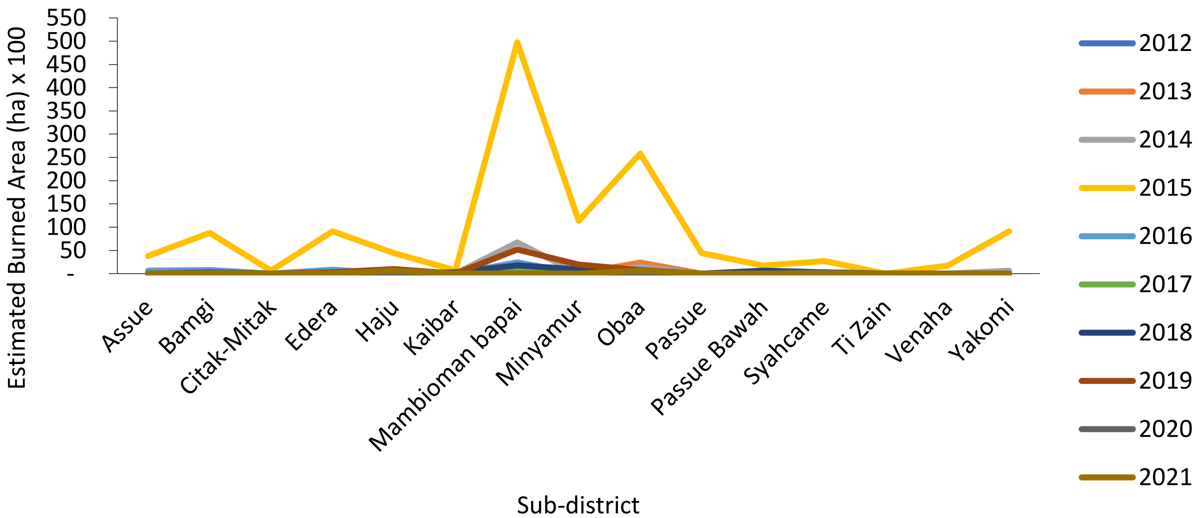


**Figure 10.** Estimation of burned area in each sub-district of Mappi District from 2012 to 2021.

## Discussion

### *Hotspot Trends in Mappi district*

Hotspots indicate forest and land fire occurrences, characterized by a relatively higher temperature in the surrounding area, as detected by satellites through specific temperature thresholds. This represents potential fire locations; their presence does not necessarily signify active fires. In this study, hotspots of all confidence levels were used. While low-confidence hotspots are not always indicative of actual fires, they can suggest that a fire has occurred, and their inclusion can enhance the accuracy of the overall burned area estimates [7]. Hotspots are frequently used for the early detection of forest and land fires.

In the Mappi District, 3,879 hotspots were recorded during 2012–2021, with 2,464 identified on mineral soil and 1,415 on peatland. Although the hotspot numbers on peatlands are comparatively lower than those on mineral soils, the impact of fires on peatlands on the environment is notably severe. When peatlands are degraded by forest clearing or drainage, water is lost from the system, causing near-surface peat to dry out [8]. Dry peatland conditions render the environment vulnerable to forest fires.

Peatlands are wetland ecosystems that store significant amounts of carbon [9–11]. Peatlands have a high water-absorbing capacity, and in the event of a peat fire, the resulting smoke becomes mixed with water vapor, forming what is known as haze. Peat fires present more challenges than fires on mineral soil because they are ground fires. These fires burn organic materials beneath the litter surface and remain unaffected by wind, making them difficult to detect and control [12]. Peat fires are typified by smoldering combustion burning underground organic matter, with fire spread very low from a few decimeters to tens of meters per day [13].

The number of hotspots in the Mappi district fluctuated yearly during 2012–2021. The highest number of hotspots was in 2015, with 2,844 hotspots (Figure 3). Moreover, the area affected by fires in Indonesia in 2015 reached approximately 2,611,411 hectares, with approximately 350,005 hectares (13.40%) burned in Papua Province [14]. This is in line with data from the Southern Oscillation Index and NINO 3.4 SST Index, which indicates a strong El Niño event in that year [15]. In this area, the occurrence of El Niño was linked to periods of drought, which noticeably influenced the increased concentration of hotspots in 2015. The El Niño event aggravated forest and land fires in 2015, which reduced rainfall in several regions, making fires increasingly difficult to extinguish.

Otherwise, 2020 and 2021 had the lowest hotspot number compared with other years during the 2012–2021. Based on the Terra/Aqua MODIS analysis, the number of hotspots in 2022 is only 21, with a confidence level below 80%. The decline in the number of hotspots from 2020 to 2021 can be largely attributed to the La Niña phenomenon, which persisted from late 2020 through early 2023. This prolonged event, commonly referred to as a “triple-dip La Niña,” is relatively rare and significantly influences regional and global climate patterns. La Niña conditions typically result in increased rainfall across much of Indonesia, including the Papua region. This increase in precipitation leads to higher soil and vegetation moisture levels, which in turn reduces the likelihood of fire ignition and spread. Consequently, the number of hotspots—often used as indicators of fire activity—decreased during this period. This situation underscores the substantial influence of large-scale climate variability on forest and land fire dynamics. In particular, La Niña contributes to wetter environmental conditions that suppress fire potential by limiting the availability of dry fuel and reducing fire-prone conditions during the dry season.

The hotspot numbers in the Mappi district generally started in July and intensified significantly in September, reaching a peak in October. Subsequently, from 2020 to 2021, Mappi District experienced relatively wet months. The onset of the dry season in the Mappi District typically starts in August (61.41 mm) and reaches its peak conditions in September (23.2 mm), as observed in 2015. This can be attributed to the relatively strong El Niño event 2015 that led to drought conditions [16].

***Relationship Between Rainfall and Hotspot in Mappi District***

This study also calculated the relationship between the number of annual hotspots and annual rainfall in the Mappi district. Linear regression analysis of hotspot numbers and annual rainfall was significant. As shown in Figure 7, the annual rainfall affected hotspot numbers in Mappi District during 2012–2021, where approximately 63.11% and 36.89% of the hotspot numbers were affected by other factors.

Rainfall is not the only factor that causes fires; there are other contributing factors, primarily human activity. Although rainfall may not directly cause fires, it indirectly impacts forest and land fires. An essential aspect is the influence of rainfall on fuel moisture conditions. Rainfall in a given area directly affects the fuel dryness, oxygen availability, and fire spread. Low rainfall causes a decrease in the groundwater level in peatlands, resulting in dryness at the upper surface of peat, making it more susceptible to fire ignition. Regarding the number of hotspots based on sub-district areas in Mappi District, Mambioman Bapai Sub-district had the highest hotspot numbers from 2012 through 2021. The substantial hotspot numbers in Mambioman Bapai Sub-District can be attributed to its extensive area, covering 4,368.98 $km^2$, which accounts for 18.07% of the total area [10]. Therefore, it is reasonable to categorize the Mambioman Bapai Sub-District as a high-risk area for forest and land fires within the Mappi District. Subsequently, prioritizing fire prevention efforts in the Mambioman Bapai Sub-District is crucial to minimize the losses incurred due to fire.

***Trends in Burned Area Estimation Over a Decade in Mappi District***

In this study, the estimated burned area was calculated for the 2012–2021 period. Based on Figure 9, The highest estimated burned area was observed in 2015. The El Niño phenomenon in Indonesia during July 2015 triggered drought conditions and worsened forest and land fires [16]. However, this estimation decreased in 2016. One contributing factor to this decline can be attributed to the weak La Niña phenomenon in 2016, which led to increased rainfall during the dry season. In addition, based on the 2015 forest fires, which caused significant damage in the past decade, the focus should now be on prioritizing efforts to control forest and land fires, rather than merely fire prevention.

Furthermore, the estimated burned area increased significantly in 2019. The El Niño phenomenon from mid-2018 to 2019 exacerbated the fire incidents. The El Niño phenomenon occurred in 2019, during which the estimated burned area in Mappi District reached 9.59 million hectares, with around 4.8 million hectares on mineral land and 4.8 million on peatland, based on analysis.

The El Niño Southern Oscillation greatly influences fuel dynamics by first promoting fuel load growth during the wet season and later affecting fuel dryness and availability in the dry fire season [17]. The abundant biomass from the wet season turns into substantial fuel loads, increasing fire risk during the dry season.

However, in 2020, there was a sharp decline of 90–942 ha. This decrease in 2020 is believed to be associated with the COVID-19 pandemic and the La Niña phenomenon, which significantly reduced forest and land fires. Based on hotspot analysis and estimates of burned areas in Mappi District, fires have consistently occurred over the past decade, even in the absence of the El Niño phenomenon. Over the last 10 years, approximately 58,412 hectares have comprised peatland or about 33.8% of the total burned area. Papua accounts for approximately 24.76% of Indonesia's total peatland, covering an extensive area of 14,905,575 ha [6].

***Human Activities and Policy Implications***

Human activities on peatlands play a major role in increasing the risk of forest and peatland fires. The majority of these fires are driven by anthropogenic factors [18,19]. Inadequate management of drainage systems can lead to significant declines in groundwater levels, causing the peat to dry out and become highly flammable during the dry season. According to Government Regulation No. 57 of 2016 on the Protection and Management of Peat Ecosystems, a groundwater level (GWL) exceeding 0.4 meters below the peat surface is the threshold used to classify peat as degraded in cultivation zones. However, degraded forests and peatlands are more vulnerable to fires and must be maintained in wetter conditions, with a critical groundwater level of 10 cm below the surface [20].

The impact of peat fires on the environment and human health is severe, emphasizing the urgent need for significant government attention and preventive measures to address forest and land fires in eastern Indonesia. In previous studies, an analysis of smoke from peat fires in Central Kalimantan Province identified over 90 different gases, including greenhouse gases and those toxic to human health [21]. Comparative studies in Central Kalimantan and Riau similarly found anthropogenic factors and peat degradation to be major drivers of forest fires. Based on the estimated burned area analysis, the Mambioman Bapai and Obaa Sub-Districts need to be prioritized by the local government in controlling forest and land fires, particularly with greater emphasis on prevention efforts. This prioritization should result in a heightened focus on preventive measures to minimize the damage and impacts caused by these fires. Effective prevention strategies include educational campaigns discouraging open burning, empowering *Masyarakat Peduli Api* (MPA), implementing early warning systems, promoting sustainable, non-burning land preparation, and coordinated actions among local institutions by adopting these strategies, local governments can significantly reduce the risk and impact of forest and peatland fires in eastern Indonesia.

## Conclusions

From 2012 to 2021, the Mappi District recorded 3,879 hotspots, with 2,464 in mineral soils and 1,415 in peatlands. The highest hotspots occurred in 2015, totaling 1,931 in the mineral soils and 913 in the peatlands. The number of hotspots started to increase in July, reaching a peak in September and October. Regression analysis between annual rainfall and hotspot numbers showed a statistically significant correlation (p-value = 0.006). Over the decade, the total estimated burned area was 172,752 hectares, with 58,412 hectares (33.8%) of peatlands. As one of the most fire-prone districts in South Papua, Mappi District requires increased fire prevention efforts, especially as the dry season approaches in July.

## Author Contributions

**ADN:** Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing, Supervision; **HS:** Conceptualization, Methodology, Software, Investigation & Writing; **CSP:** Writing - Review & Editing.

## Conflicts of Interest

There are no conflicts to declare.

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