Analysis of Areas at Risk of Fire in Khuan Kreng Peat Swamp Forest in South Thailand

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Abstract

Khuan Kreng Peat Swamp Forest is Thailand's second-largest peat swamp forest. It serves as the primary source of income for villagers in this area. In this study, we 1) created three-dimensional (3D) images with Mathematica using Digital Elevation Model (DEM), 2) analyzed the displacement of wildfire risk of this research with Google Earth Pro with the wildfire data of Thale Noi Forest Fire Control Station from 2010 to 2022, and 3) analyzed the duration of forest fire risk to monitor and open platform field trips with villagers. We found that the forest fires in the Khuan Kreng Peat Swamp Forest had an average displacement of 93.88 ± 6.61m from the road line and an average displacement of 92.28 ± 7.33 m from the canal line, with an area of 339.158 km^2 under special surveillance. The forest fire risk area was dense in the UTM range of 617000 - 629000 E and 870000 - 890000 N. The cases of wildfire peaked between May and August annually. In the Kreng sub-district, the topography of a lowland alternating with Phangan (low hill) is covered with Krajood (Lepironia articulata (Retz.) Domin) and Samed (Melaleuca quinquenervia (Cav.) S.T. Blake). The fire-prone areas are located near the roaming path around the Krajood forest. The best method to prevent forest fires is to maintain water in the Khuan Kreng Peat Swamp Forest from drying up. Avoid deepening the main canal around the swamp area and provide oil palm plantation limits, and sustainable land use management. In addition, awareness should be raised about the loss incurred from forest fires and a network should be created to monitor forest fires for villagers in risky areas and long-term monitoring.

Keywords: karjood forest, Khuan Kreng Peat Swamp Forest, risk of wildfire, topographic model

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Introduction

Khuan Kreng Peat Swamp Forest is the second-largest swamp forest in Thailand. Khuan Kreng swamp forest is a swamp forest with a total area of approximately 357.312 km^2 [1]. The Khuan Kreng Peat Swamp Forest is located in the area of the Royal-initiated Pak Phanang River Basin Development Project in Southern Thailand. With an approximate area of 165,825.50 square kilometers, it covers Hua Sai, Chian Yai, Cha-uat, Chaloem Phrakiat, Ronphiboon, and Chulabhorn districts of the Nakhon Si Thammarat province. Furthermore, it covers certain parts of the Ranot district in the Songkhla Province and a part of the Khuan Khanun district in the Phatthalung Province. Khuan Kreng Peat Swamp Forest serves as the primary source of income for villagers in the communities around the peat swamp forests such as fish products, forest products, honey, herbs, and Krajood, essential raw materials for handicrafts produced by the Kreng sub-district and Thale Noi communities. In addition, hardwood trees are dense, containing several streams, creeks, a drainage canal across the area, and a reservoir for rainwater and runoff. The ecological condition of the water source is a substantial stagnant basin [1]. The Khuan Kreng Peat Swamp Forest is plain on the northern side of Songkhla Lake. The peatlands receive water from upstream and collect overflow from the lakes. Moreover, the area serves as an essential source of carbon dioxide absorption and filters sediments and minerals from natural water sources and agricultural areas before releasing water into the Songkhla Lake [2]. However, the area has increasingly become prone to wildfires. Wildfires in developing countries or underdeveloped countries are often caused by forest burning. According to the 2016 statistics, 103 wildfires were reported in the Khuan Kreng Peat Swamp Forest, covering an area of approximately 320 acres of land with strong winds and gray smoke from the subsequent fire flying into the communities, forcing the villagers to evacuate [3].

Peat swamp forests are wetland ecosystems characterized by the accumulation of peat, an organic soil formed from decayed plant matter. The forest is unique biodiversity and ecological importance. Peat fires can smolder for extended periods, releasing large amounts of smoke, and greenhouse gases, and contributing to air pollution. The smoke caused carbon and other environmental emissions, and it is one of the leading causes of extreme weather events which negatively impact the production systems and cause shifts in species composition [4, 5, 6]. Wildfires often cause dramatic changes in forest vegetation structure and soil conditions and alter the watershed processes that control streamflow, soil erosion, nutrient export, and downstream water chemistry [7, 8, 9]. A study on the peat swamp wildfires in the Indonesian island of Sumatra reported forest burning of approximately 30 cm in depth due to reduced oxygen content and soil moisture as they approached the water layer [10, 11, 12]. December 2018 - February 2019, an abnormal drought (the El Niño phenomenon) occurred that resulted in a severe forest fire situation as compared to previous years [13]. Peat fires are difficult to extinguish both horizontally and vertically. In addition, it is challenging to identify the true extent of the fire due to the enormous smoke. No flame is seen, and the fire continues to spread continuously, giving the impression that it has been extinguished; however, it may later start again. A small swamp forest fire that covers only a few areas can be extinguished. If allowed to spread, the fire covering a large area of thousands of acres will be out of control. For example, a fire in the Pa Pru To Daeng Peat Swamp Forest in 1998 was almost impossible to extinguish. It took months for the government to control it, resulting in severe economic losses as well.

(a)

(b)

Figure 1. Forest fire situation on September 11, 2019 [7]
(a) Forest fire with massive smoke clouds
(b) Samed forest condition after the forest fire

Two-dimensional (2D) and three-dimensional (3D) modeling could be generated primarily using the Digital Elevation Model (DEM), which is derived from remote sensing. Survey data can be used for spatial analysis. The accuracy of DEM-based computing is related to its resolution. DEM can explain elevation-related topographic variations in the study area with 2D and 3D topography maps [14]. It digitizes the topographic characteristics of surfaces and elevations as a raster of a square grid, representing the elevation. The smaller grid yields reliable results for hydrological parameters, which are effective in separating the drainage network. DEM is widely used to simulate and study hydrological properties such as slopes, catchment areas, and topographic analysis [15]. High-resolution DEM requires high-performance computing as well. It is currently in the order of gigabytes, which is on the increase with continuously enhanced computer processing and memory performance [16]. DEM can be arranged as a list, allowing data manipulation using functional programming algorithms [17]

Mathematica is a high-level symbolic and high-performance numerical program. It is user-friendly and is a potent computing aid. It is primarily operated in the areas of education and research [18]. The functional programming model in Mathematica uses symbolic 2D and 3D graphics. Scripts written in a functional language in Mathematica are concise and similar to traditional mathematical notations [19]. Google Earth Pro can be used to generate simulated images from the DEM data through Arc GIS, while creating an aerial map, by combining aerial imagery and high-resolution satellite imagery with the streaming technology and linking the data from the base information of Google to create a digital map generated by blending images from different sources from several satellites brought together as if they were the same piece. Thus, it can process images, giving the impression that they are the same image, and can position itself on the surface of the earth. In this research, we 1) used DEM to create 3D images using Mathematica, 2) studied the forest fire statistics of the past 10 years from the Thale Noi Forest Fire Control Station to analyze the displacement of wildfire risk with Google Earth Pro, and 3) analyzed the extent of the risk area, duration of the Khuan Kreng Peat Swamp Forest fire to monitor using the Arc GIS program analyzes.

Study Area, Materials, and Methods

1. Study Area

The research area included the Khuan Kreng Peat Swamp Forest, Kreng sub-district, Cha-uat district, Nakhon Si Thammarat province, Southern Thailand (Figure 2). It covers an area of 64 square kilometers. The UTM grid shows the coordinates of the square simulation area as 618000–626000 E and 882000–874000 N.

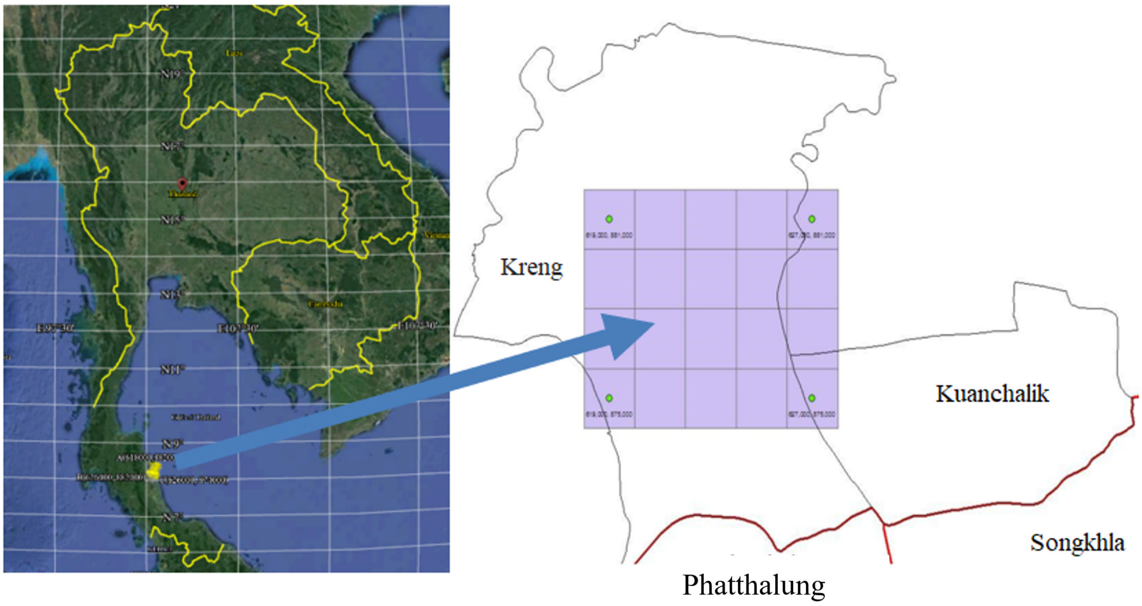


Figure 2. The study area observed using Google Earth Pro 2017 [20]

2. Materials and Equipment

We acquired the DEM data from the Department of Land Development, Ministry of Agriculture and Cooperatives (Thailand), and the historical forest fire statistics of the past 10 years by the Thale Noi Forest Fire Control Station, Nakhon Si Thammarat province (2010–2020). The hardware comprised a computer notebook, Intel Core i9 [8-core], 2.3 GHz, Turbo Boost 4.8 GHz, DDR4 2400 MHz-16 GB SSD PCle 512 GB, and installed memory [RAM] 64.0 GB. Windows XP Profession was the operating system. The simulation and analysis result programs were written in Mathematica 12, Microsoft Excel, ArcGIS 10.6, and Google Earth Pro.

3. Methods

The steps to produce the forest fire risk map and analyze fire risks in the Khuan Kreng Peat Swamp Forest are shown in Figure 3.

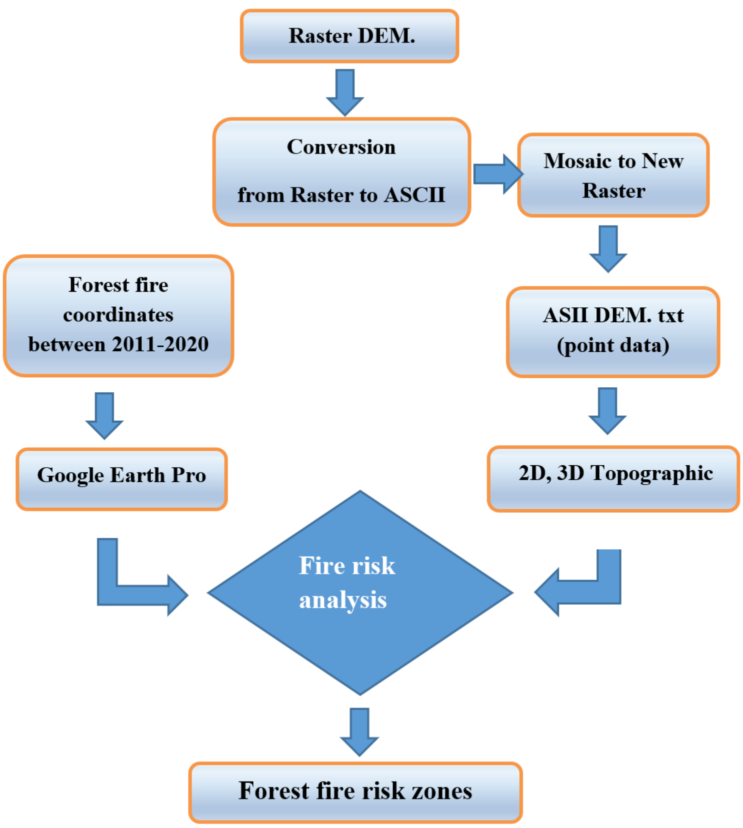


Figure 3. Flow chart showing the study operation.

We used 1) the DEM with a scale of 1:4,000, size 2 × 2 square kilometers per section, and a resolution of 5 m pixel size stored in the raster format (Filename .img). Each section had 400 cells, with a single cell divided into 5 × 5 square meters. All areas were composed of 16 sections, the total of which was composed of 2,560,000 cells. The data were stored as rows and columns in the matrix and analyzed for 2D and 3D topography using Mathematica.

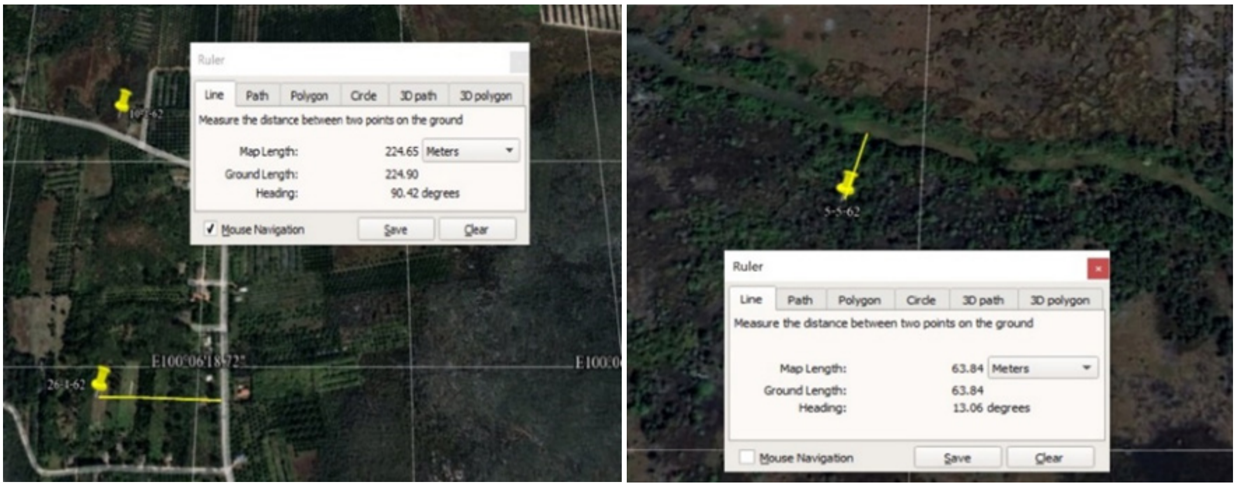
We used 2) the data of the historical forest fire statistics of the past 10 years derived from the Thale Noi Forest Fire Control Station, Nakhon Si Thammarat province between 2010 and 2020 were used to identify the risk area boundaries from the coordinates of the wildfires with Microsoft Excel and ArcGIS. The forest fire locations were studied using Google Earth Pro to locate the centers of each forest fire. In addition, we analyzed the boundaries of risk area displacement from the villagers' transportation routes within the study areas (canals and roads), as shown in Figures 4 and 5. The data were analyzed by dividing the data into two sets, namely the hotspots near the roads and those near the canals and the waterways. These were analyzed to generate normal curves to calculate and monitor the risk of forest fires. The average displacement of the firing was measured to identify the monitoring range of fire location between forest fires and the road and between forest fires and the canals or ditches. The standard deviation (σ) is shown in Equation (1)

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (1)$$

where n is the sample's size and $\bar{X}$ is the sample's mean. We analyzed the range of the highest forest fire risk and regulated the scope of the alert areas to identify the solutions to prevent forest fires within the community.

standard error in the mean $$\sigma_m = \frac{\sigma}{\sqrt{n}} \quad (2)$$

surveillance displacement $$S = \bar{X} \pm \sigma_m \quad (3)$$



(a) (b)

Figure 4. Measurement of the displacement
(a) between forest fire and road (b) between forest fire and canals or ditches

The data were divided into two sets, namely, the hotspot near the road and the one near the canals or ditches. Afterward, the data were analyzed to identify the normal curve and calculate the range of fire risk to monitor the fires.

Results and Discussion

1. 2D and 3D topography

The 2D and 3D topographic map of the study area were created from the point data obtained from the Department of Land Development, Ministry of Agriculture and Cooperatives (Thailand). As shown the 2D topographic in Figure 5.

Figures 6, 7, 8, and 9 display the 3D topography generated from the study area, which was divided into four parts for simulation using the Mathematica program.

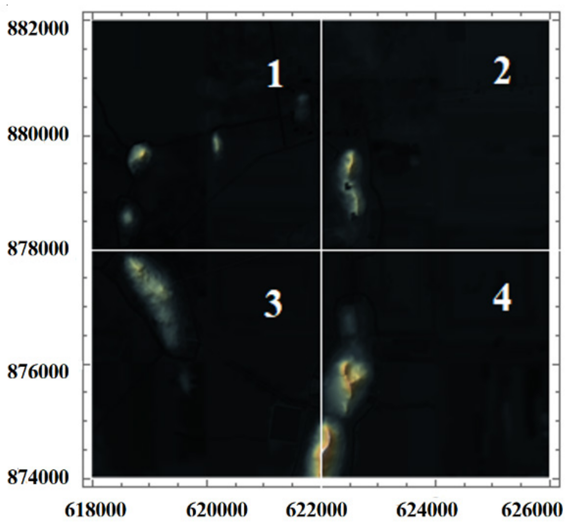
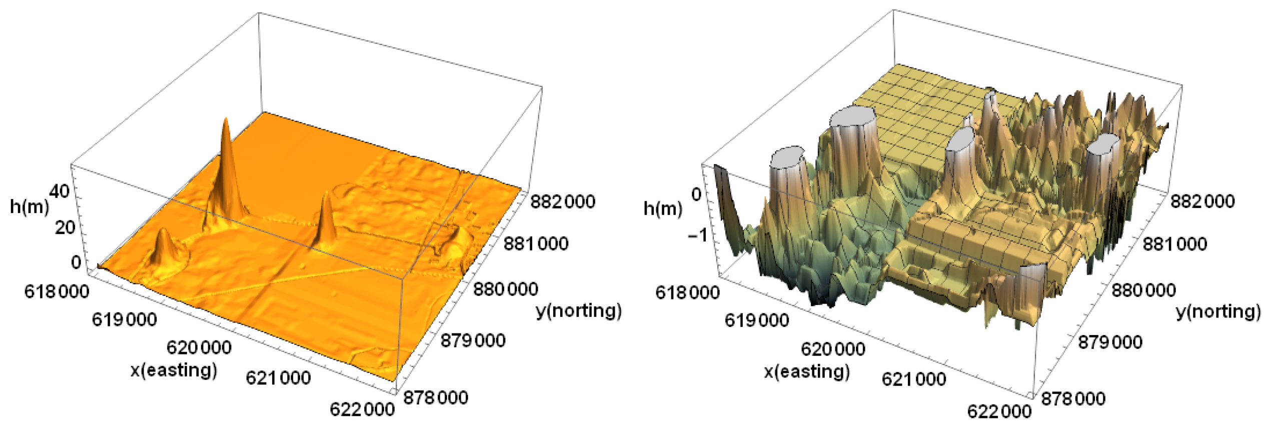


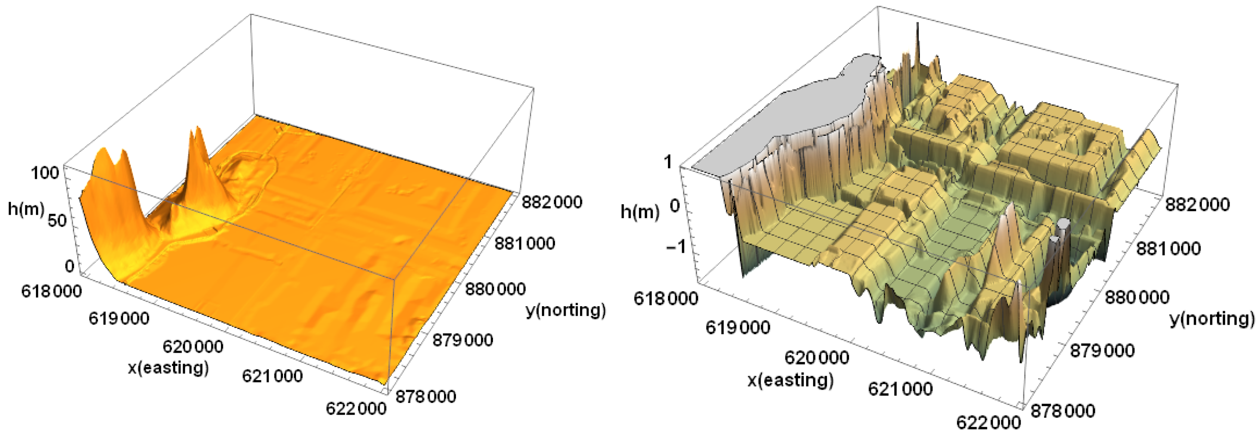
Figure 5. The 2D and 3D topographic maps of the study area from UTM coordinates 618000–626000 N and 874000–882000 E (including areas 1–4)



(a) (b)

Figure 6. Three-dimensional topographic map of Area 1(878000-822000 E, 618000-622000 N)

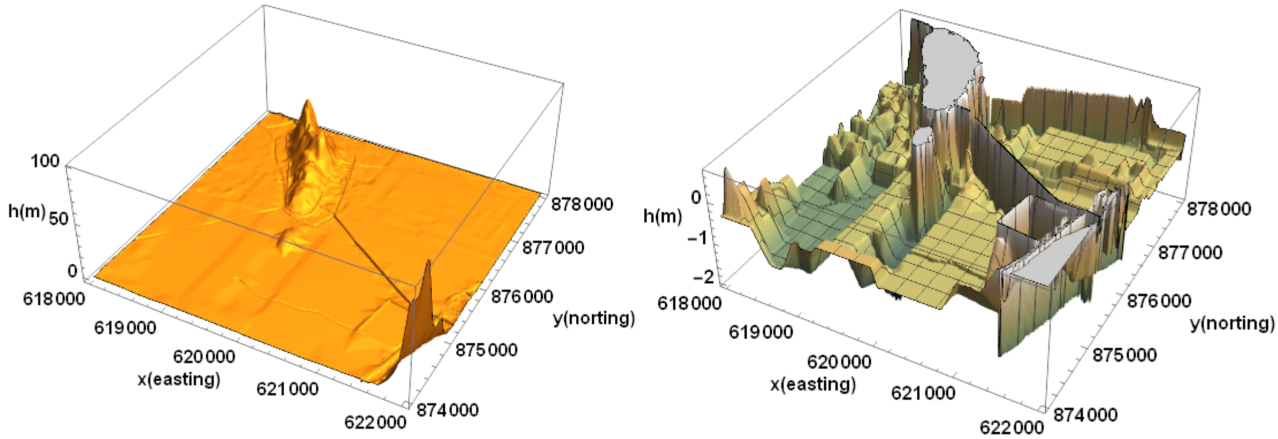
(a) Area 1 by bird's eye view (b) Area 1 by Close-up view



(a) (b)

Figure 7. Three-dimensional topographic map of Area 2(878000-882000 E, 618000-622000 N)

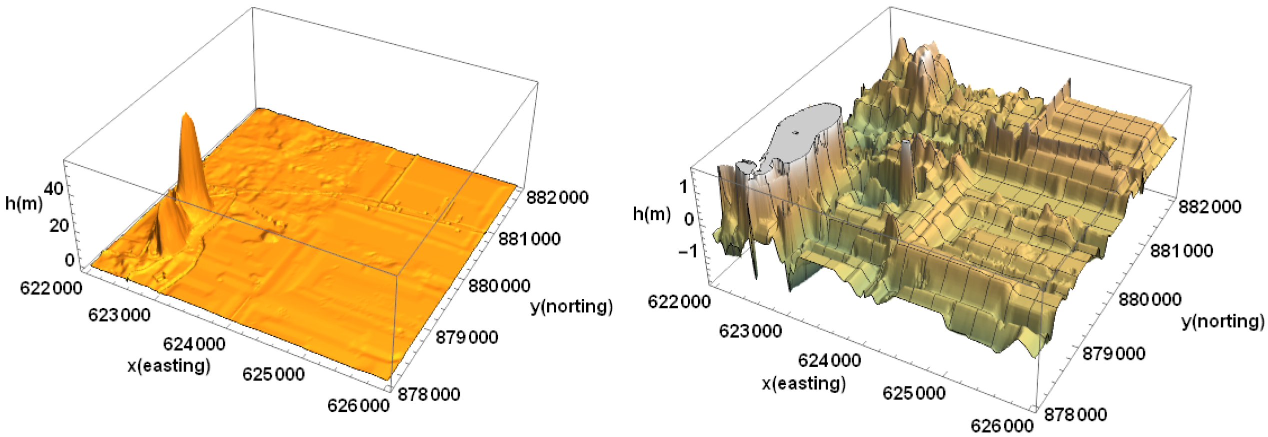
(a) Area 2 by bird's eye view (b) Area 2 by Close-up view



(a) (b)

Figure 8. Three-dimensional topographic map of Area 3(874000-878000 E, 618000-622000 N)

(a) Area 3 by bird's eye view (b) Area 3 by Close-up view



(a) (b)

Figure 9. Three-dimensional topographic map of Area 4(874000-878000 E, 622000-626000 N)

(a) Area 4 by bird's eye view (b) Area 4 by Close-up view

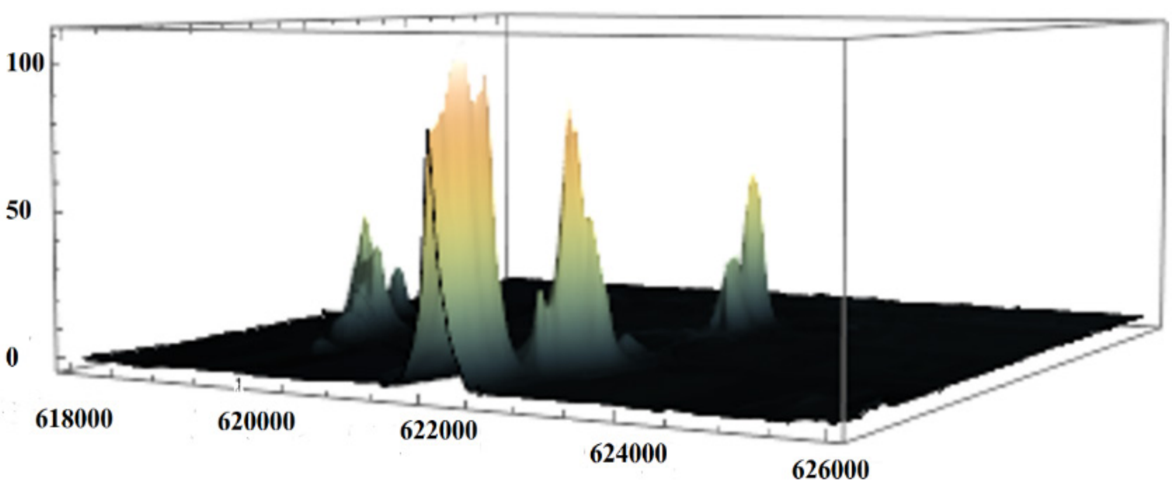


Figure 10. The 3D topographic maps of the study area from UTM coordinates 618000–626000 N and 874000–882000 E (including areas 1–4)

The geography of the Khuan Kreng Swamp Forest, Kreng sub-district, Cha-uat district, and Nakhon Si Thammarat province is plain. The elevation of the area is lower than the sea level and has an alternating channel line used as a thoroughfare. Figures 6 and 7, areas 1 and 2 have an elevation of –1 m, whereas areas 3 and 4 in figure 8 and 9 have an elevation of –1 to –2 m. Area 1 has three alternating low hills. Area 2 is a hill with a height of approximately 40 m and is called Khuan Ching. Area 3 has a long hill called Khuan Yao and is approximately 40 m high. Area 4 has a long hill called Khuan Kreng, with a length of 100 m, as shown in Figure 10.

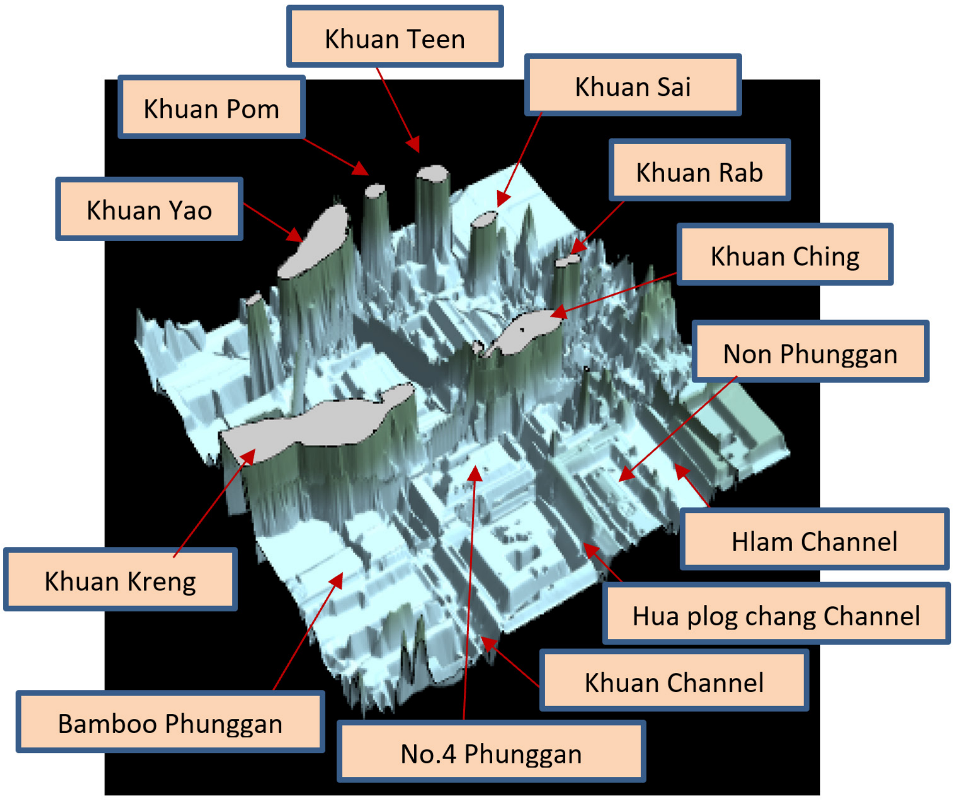


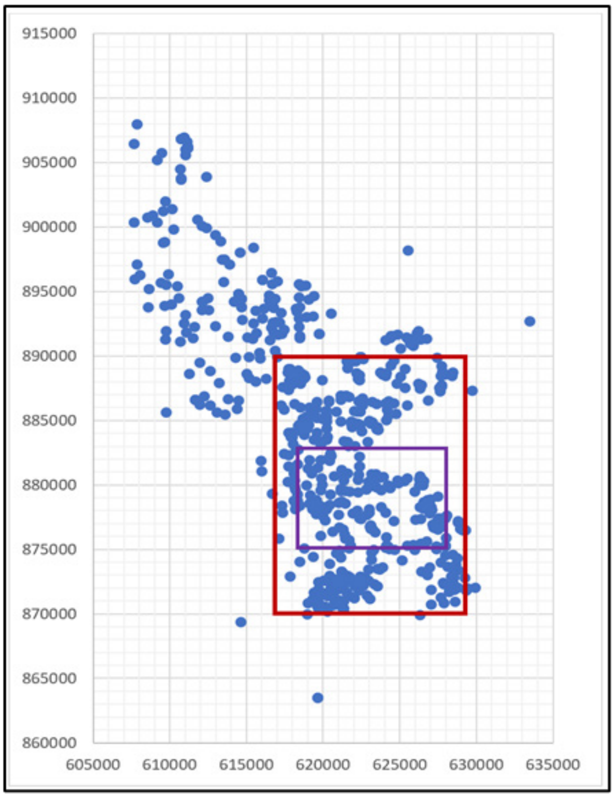
Figure 11. The 3D remote topographic map of the study from UTM coordinates 618000–626000 N and 874000–882000 E

Figure 5 and Figure 11, The 2D and 3D topography models showed three types of areas, namely flooded areas, plain areas without flooding, and hills or khuan. The survey of the Khuan Kreng Peat Swamp Forest area revealed that most of the area is around 1 to 2 m below sea level and is a flooded plain. The above area is the Krajood forest area, as shown in Figure 5, in black, blue, and red frames, with the red frame being the largest plot. Figure 8 shows a canal line as a thoroughfare within the Krajood forest. It is interspersed with hills called non-Phangan, No. 4 Phangan, and bamboo Phangan, which alternates between low hills and low land. These areas are grazing fields for water buffaloes raised by the villagers. The height of the seven hills is around 30 to 100 m (Khuan Yao, Khuan Pom, Khuan Teen, Khuan Sai, Khuan Rab and Khuan Ching, and Khuan Kreng). Khuan Kreng is the largest hill and has three parallelly dug canals, namely Khlong Laem, Khlong Hua Pluak Chang, and Khlong Khuan. Khuan Kreng swamp forest is the source of the Pak Phanang River and Thale Noi, which are parts of the Songkhla Lake. It was originally a sea, which eventually became a lagoon area as a barrier beach was blocked. Sediments from the hill west of the Pak Phanang watershed flow down and deposit the area to form a filled lagoon area. Originally, the Khuan Kreng Peat Swamp Forest was a large watershed area that was connected to surface water ecosystems and the Thale Noi Phatthalung province, which is linked to the Songkhla Lake, Songkhla province.

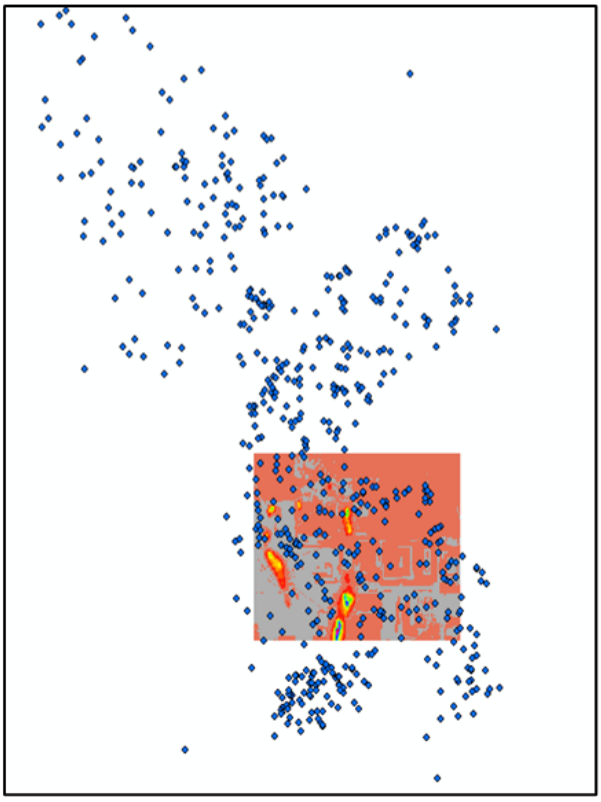
The 2D and 3D topography models showed three types of areas, namely flooded areas, plain areas without flooding, and hills or khuan. In Krajood forests, the Kreng sub-district is flooded throughout the year because it is 1 to 2 m below sea level. A natural river flows through the Khuan Kreng Peat Swamp Forest. The Google Earth Pro showed that this Cha-uat river flows into the sea in the Pak Phanang district. Fluctuations in the peat water table largely depend on rainfall because of relatively constant evaporation and outflow of groundwater [21]. The water table decreases by around 1 cm per month before summer. If the water table is controlled between 0.30 and 0.50 m, it will last for 2 to 3 months in the peat swamp forest. If it dries up to −0.20 m, it reduces the risk of forest fires [1].

2. Forest fire location in the past 10 years

The graph in Figures 12 and 13 showed the location of wildfires in the Khuan Kreng Peat Swamp Forest in 10 years between 2010 and 2020. Wildfires were calculated to occur 639 times. The scope of the forest fire risk area was dense in the UTM range of 617000–629000 E and 870000–890000 N



(a)



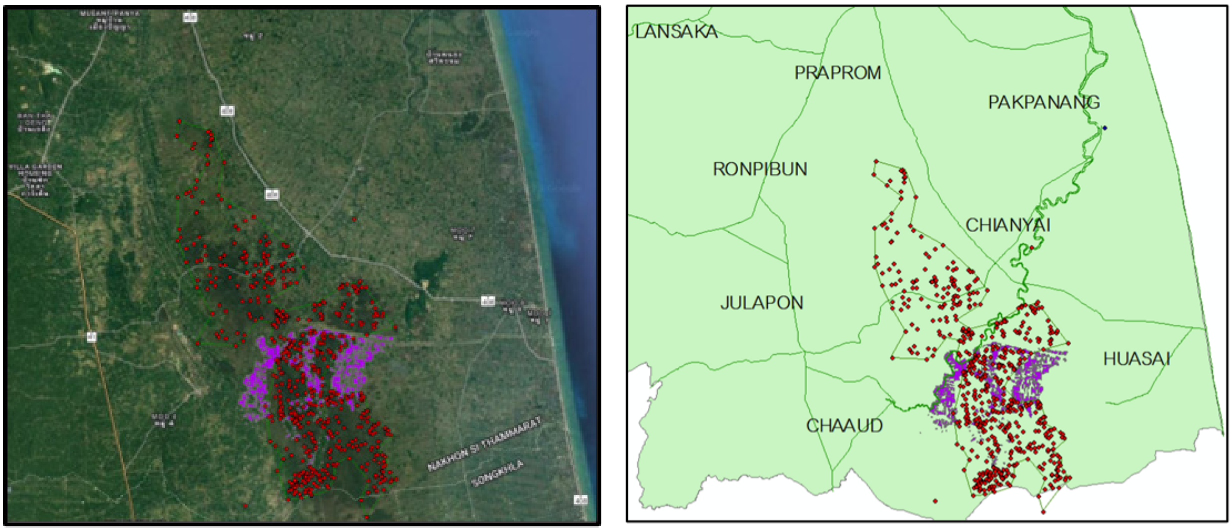
(b)

Figure 12. Wildfires (blue dots) in the Khuan Kreng Peat Swamp Forest, Southern Thailand.
(a) Coordinates corresponding to wildfire using Excel, and (b) coordinates corresponding to wildfire using Arc GIS

Represent the boundaries of the study area

Represent the extent of the area where wildfires frequently occur

Figure 12 shows the wildfires (red dots) in the Khuan Kreng Peat Swamp Forest, Southern Thailand. The map displays the locations of wildfires from 2010 to 2020 (occurred 639 times, fires represented by red dots). The fires spread continuously from the Chaloem Phrakiat district down to the Cha-uat district, Nakhon Si Thammarat province, and the end of the forest fire lying over Thale Noi, Khuan Khanun district, Phatthalung province.

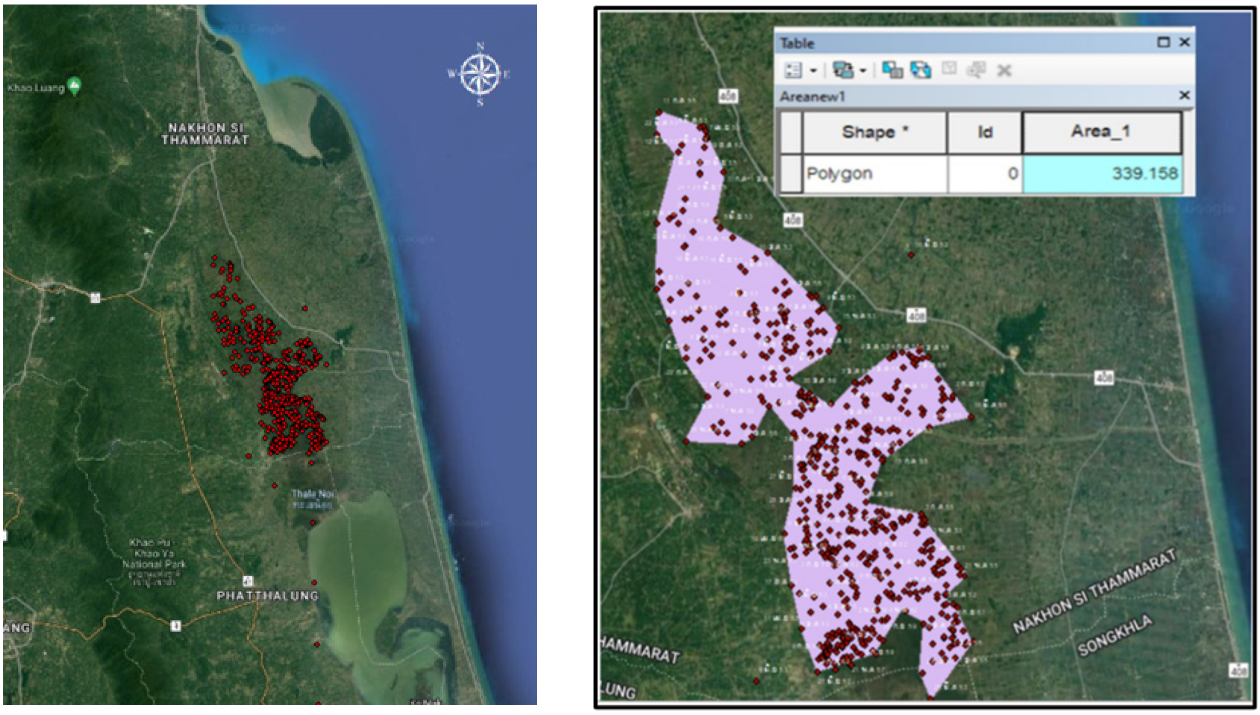


(a) (b)

Figure 13. The fire risk map of the Khuan Kreng Peat Swamp Forest, Nakhon Si Thammarat Province, Kreng sub-district, Cha-uat district, Nakhon Si Thammarat province.

Figure 13(a) and Figure 13(b) show the wildfires (red dots) in the Khuan Kreng Peat Swamp Forest, Southern Thailand, and show palm plantation (white area). Forest fires in Thailand are primarily caused by human activities. The total oil palm plantation area around has increased, because of a Thai government policy promoting the use of biodiesel and increasing capacity of palm oil production in 2005 [22, 23]. The Cha-uat Canal across through the swamp forest and connect the Cha-uat Phraek Mueang Canal, passes through the swamp forest. When the Cha-uat Phraek Mueang Canal is dug more depth for agriculture, drained the water faster, and the peat swamp forest is dried which increases the likelihood of wildfires. The main canal adjacent to the reserved forest area drained the water from the swamp forest. The drainage networks created within the entire area do not have a functional water control structure. Water gets drained from the peat to the digging pond near the peat, especially the major canal between the forest reserve. However, the drainage and subsidence of water in the peat subside due to the sunlight, as evident from the reduced water table and burning depth of up to 60 cm. Peat materials are highly dry and ignite easily [24]. Avoid deep digging of main canals around peat areas, such as the Cha-uat Phraek Mueang Canal. The excessive depth of the Cha-uat Phraek Mueang Canal causes the water level within the swamp to decrease. In addition, the increasing amount of water in the canal resulted in the expansion of palm plantations around the forest and the encroachment of conserved forest areas for agriculture. Provide oil palm plantation limits and sustainable land use management and long-term monitoring.

Figure 14 shows that the Cha-uat canal line crosses the forest fire. Water is drained from the peat to the Cha-uat canal between the Khuan Kreng Swamp Forest reserves. The yellow and purple areas are the Kreng sub-district, Cha-uat district, and Nakhon Si Thammarat province. The yellow area is inhabited by villagers, whereas the purple area is a protected forest area where Krajood is intermingled with sand and other types of trees. The locations of wildfires were more concentrated in the conservation area and around the boundary between the community and the protected forest areas, with an extremely high density around Khuan Kreng, Khuan Ching, and Khuan Yao, which are Krajood forest areas and white Samed forests. The 2011–2022 statistics revealed that out of 306 times, forest fires occurred in the Krajood Forest area 46 times, representing 15.03%, 43 times of which occurred in the Kreng sub-district, representing 93.47% of the forest fires up in the Kreng sub-district. Figure 14(a), is shown the Locations of wildfires from 2010 to 2020, 639 times. Figure 14(b), the forest fire risk map by Arc GIS showed fires covering an area of 339.158 square kilometers. Based on the proposed factors for multi-criteria overlay tech-



(a) (b)

Figure 14. Khuan Kreng peat swamp forest using Arc GIS
(a) Locations of wildfires from 2010 to 2020, 639 times
(b) distribution of fires and burned areas

niques, the high-risk area was found to be around 218 square kilometers, whereas medium and low-risk areas were found to be about 378 square kilometers and 65 square kilometers, respectively [25].

Humidity and organic matter in the peat swamp area depend on different annual periods. A wildfire is a semi-surface fire that burns in two dimensions; one part of it occurs in the plain along the forest surface, whereas the other part occurs vertically deep in the peat layer. Humidity produces excessive smoke, and the fire source is difficult to identify. The wildfires rapidly destroy forests and cut off access to several natural renewables, thereby resulting in a loss of workforce and a heavy budget to repair. Therefore, the most appropriate approach is to look for wildfires. If early summer fires are low, late summer fires will be intense because of the accumulation of fuel. In case of the accumulated fuel accidentally ignites, fires can spread widely and rapidly and are difficult to control when fires burn to the peat layer.

3. Displacement between locations of wildfires and villagers' transportation routes

The data were divided into two groups, namely, hotspots near the canals and those near the roads. Table 1 shows the displacements of hotspots to the canal or the canal using square root transformation for normalizing a skewed distribution. The displacement data of hotspots to the canal was around 225 times. The forest fire risk displacement from the road was around 93.88 ± 6.61m (standard error in the mean before transform). In the processing summary, , as shown in the descriptives in Table 1.

Table 1. Displacements of hotspots to roads

			Statistic	Std. Error
Road	***Mean***		9.6891	0.31286
	95% Confidence Interval	Lower Bound	9.0726	
	For Mean	Upper Bound	10.3056	
	5% Trimmed Mean		9.5938	
	Median		9.7581	
	Variance		22.023	
	Std. Deviation		4.69291	
	Minimum		1.18	
	Maximum		22.92	
	Range		21.74	

Table 2. The displacements of hotspots to canals or ditches

			Statistic	Std. Error
Canals	***Mean***		9.6062	0.25426
	95% Confidence Interval	Lower Bound	9.1062	
	For Mean	Upper Bound	10.1061	
	5% Trimmed Mean		9.4437	
	Median		9.1634	
	Variance		24.825	
	Std. Deviation		4.98251	
	Minimum		1.18	
	Maximum		22.81	
	Range		21.63	

Table 2 shows the square root transformation for normalizing a skewed distribution and ignoring six data sets because the displacement of the hotspot was far from the transportation routes. However, certain wildfires could start on their own. The displacement.

4. Periods and areas damaged by wildfire

Figure 15 shows that May to August is the peak period for wildfire in the Khuan Kreng Peat Swamp Forest. The occurrence of a few early-season wildfires in May and June will result in more fires during the dry season in late August. However, the number of wildfires in July decreased because those in May and June destroyed a large amount of fuel in the peatlands and created a natural fire barrier in certain areas. However, the weather is still hot and dry, with the water table being less than 30 cm. Therefore, the drought and dry leaves can cause more wildfires a month later. No wildfires occurred from 2021 to 2022 because the La Niña phenomenon caused more annual rainfall. A wildfire is a natural process in several parts of Khuan Kreng Peat Swamp Forest. Our data showed the increasing possibility of recurring fires in the same area. An open platform was used to identify solutions with the community. In this context, villagers built a disaster prevention network in the form of a Disaster Management Center in the Kreng sub-district and a disaster management center in the Koh Khan sub-district (Koh Khan is self-managed). It comprises a group of volunteers to prevent forest fires. During summer, they take turns riding motorcycles around the areas where wildfires frequently occur. There exists a small check dam in the Khuan Kreng Peat Swamp Forest that stores water, which is used to generate products as the main sources of income for the people in the community. The most recent (2019) peatland fires were caused by human incineration without any intention to spread the wildfires to such a wide area. It was highly challenging to extinguish the fires because, during the dry season, dry grass and leaf fragments pile up as fuel as well. In 2019, the El Niño phenomenon, or unusual drought, caused more severe wildfire situations than the previous years. Climate changes are dominant factors affecting the occurrence of forest fires during different periods. When the temperature increases by 2 °C, >15% of the global land area becomes exposed to levels of heat stress that affect human health. The response of fire number (NF) and burned area (BA) to climate trends, disentangling the drivers responsible for long-term increasing temperatures promotes a positive trend in NF. We found that it is highly crucial to study relevant indicators of the autumn fire prevention period (average surface temperature and sunshine hours) [26, 27].

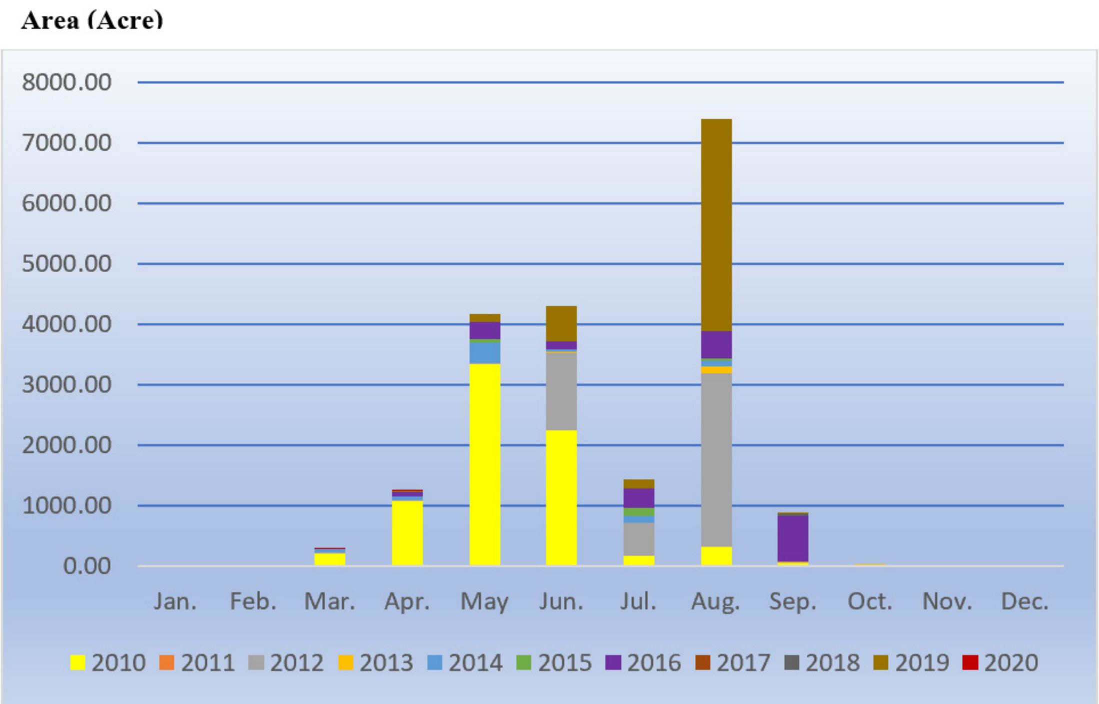


Figure 15. Areas damaged by wildfires in each month from 2010 to 2020.

The correlation graph between the timing of wildfires and the area revealed that the highest intensity of forest fires was recorded in August, followed by June and May. During July, wildfires noticeably decreased because of the low amount of fuel. The peat was completely dry, resulting in the accumulation of fuel fractions, and the fires occurred again in August. August is the end of the summer when the environment has accumulated the most heat and drought. Higher temperatures and drought increase the potential for wildfires. Climate changes exacerbate the factors that create perfect conditions for fire. Decreasing rainfall and warmer temperatures can enhance the drying of forests and other vegetation. The time to look for peatland fires is from June to August. The study results demonstrated that the majority of the Khuan Kreng peat swamp, estimated to be 375.31 square kilometers, during the drought was at a high risk of fires. Critical areas included Hua Sai district, Cha-uat district, and Chian Yai district, with 107.73, 77.64, and 74.68 square kilometers, respectively [28]. According to Anan Kamphira, the majority of the areas are composed of lowlands, degraded peat swamp forests, grassland, forest, etc., some of which were later changed to oil palm and rubber plantations.

Krajood forests are located in the conservation areas, near the villages where people inhabit. The wildfire spreads heavily in the Khreng sub-district, Cha-uat district, Nakhon Si Thammarat province, spreading to Thale Noi in the Phatthalung province. The wildfires mostly occur under the Cha-uat canal. The layer of peat was significantly smaller due to the drainage and subsidence affected by sunlight. Extremely dry peat material can ignite easily. The drainage networks created within the entire area do not have a functional water control structure. Water is drained from the peat to the digging pond near the peat, especially the major canal between the forest reserve [29]. For example, the Cha-uat Phraek Mueang Canal was excavated considerably deeper to transport water from the Cha-uat Canal to the Cha-uat Phraek Mueang Canal for agriculture, such as palm plantations that are popular among the people around the Khuan Kreng Peat Swamp Forest. Agriculture results in plant residues and waste burning to prepare the area for planting. Debris from the samed trees, together with the hot weather, can initiate forest fires. Peat swamp forest fires have a unique characteristic; it is a semi-ground fire that burns in two dimensions. One part burns along the surface of the forest floor as well as the ground surface fire, whereas the other part burns vertically deep. The depth of fire in the peat swamp forest on Sumatra Island, Indonesia, is approximately 20 to 30 cm [30].

The majority of these areas are peat swamp forests connected to agricultural areas, which are constantly undergoing development for agricultural preparation. Furthermore, these areas are often grasslands, with a certain overlapping between agricultural areas and areas dedicated to preservation. This map can be used as a guideline for planning, monitoring, and preventing fires in the Khuan Kreng peat swamp forest preservation [31]. The primary reason for the Khuan Kreng Peat Swamp Forest dryness is the dredging of the Cha-uat Phraek Mueang canal to increase its capacity. The higher availability of water results in more areas turning into plantations, which causes the drying of the Khuan Kreng Peat Swamp Forest. Forest fires will occur more often with increased intensity. Therefore, we should implement water management approaches in the peat area by maintaining the water table in the peat swamp forest near the surface throughout the year to prevent the spread of forest fires. The degraded swamp forest was the most vulnerable area to forest fires. The most important factor for the forest fires of Khuan Kreng was land use.

Conclusion

Three-dimensional images and statistics of wildfire were analyzed to identify the displacement of wildfire risk. From 2010 to 2022, the forest fires were located near the roaming path around the Krajood forests, with UTM coordinates of 617000–629000 E and 870000–890000 N. Krajood forests, the most densely forested fires in Nakhon Si Thammarat, are in the conservation areas and near the villages where people inhabit. The wildfire spreads heavily in the Khreng sub-district, Cha-uat district, and Nakhon Si Thammarat province, thereby spreading to Thale Noi in the Phatthalung province. The risk was consistent with 10-year hotspot data. Khuan Kreng Peat Swamp Forest has an average displacement of 93.88 ±6.61 m from the road and an average displacement of 92.28 ±7.33 m in canal lines, with an area of 339.158 km^2 covering special surveillance. The study will help us understand the fire risk distribution of forest fires based on history and will help decision-makers optimize fire management strategies to reduce potential fire risks. The best method to prevent forest fires is to create a water check dam and dredge small canals scattered within the area to maintain water in the Khuan Kreng Peat Swamp Forest from drying up. In addition, awareness should be raised about the loss incurred from forest fires and a network should be created to monitor forest fires for villagers in risky areas. Avoid deep digging of the Cha-uat Phraek Mueang Canal and provide oil palm plantation limits, sustainable land use management, and long-term monitoring.

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