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Spatial Model of Fire Vulnerability Distribution Based on Multicriteria in Tropical Forest Areas, Central Sulawesi, Indonesia

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ABSTRACT

The problem of fire always threatens the existence of forests in Indonesia, repeatedly occurring every year, so it becomes one of the national and regional issues, both occurring naturally and caused by human actions. This study aims to develop a spatial analysis model of the multi-criteria-based fire vulnerability distribution in tropical forest areas. Modeling using GIS and spatial correlation analysis. In a tropical forest area of 7,042.29 Ha in the Tepo Asa Aroa KPH area, North Morowali Regency, Central Sulawesi, a spatial model of the distribution of fire vulnerability based on multi-criteria was produced, which could support rapid mapping of fire-prone forest areas. The results of the analysis of variables on land use/vegetation cover, rainfall, slope, distance from roads and settlements, business permits, forest protection, and security simultaneously made it possible to lower the fire vulnerability rating from 'very high' and 'high' to a 'medium' vulnerability rating. ' to 'low' and 'very low'. All parameters tested statistically have a spatial correlation with fire vulnerability.

INTRODUCTION

Indonesia has vast tropical forests, namely 120.6 million hectares within forest areas and 67.40 million hectares outside forest areas (Kementerian LHK 2020), with the benefits of being the lungs of the world, regulating water flow, preventing erosion and flooding, and maintaining soil fertility. In addition, forests also provide economic benefits, so the resources must be preserved to provide optimal benefits. Even so, the problem of fire always threatens the existence of forests, which occurs repeatedly every year so it becomes one of the national and regional issues.

Forest/land fire is an event of forest/land burning, both naturally and by human actions (Kementerian LHK 2016). The forest/land area that burned in Indonesia in 2020 was 296,942 Ha; in 2021 it was 358,867 Ha and up to. July 2022, covering an area of 87,704 Ha. In Central Sulawesi Province, the area of forest/land that burned in 2020 is 2,555 Ha, in 2021 it is 3,133 Ha, and in 2022, until July covering an area of 964 Ha. In 2021, North Morowali Regency has the largest burned forest/land area, namely 1,161 Ha, while up to. July 2022 reached an area of 207 Ha. During 2020-2022, Central Sulawesi Province has 11,051 hotspots (178 high confidence hotspots; 10,051 medium confidence hotspots; 822 low confidence hotspots) (Direktorat PKHL Kementerian LHK 2022)

Forest fires that occur are often only discovered after they have spread over a large area, making controlling and extinguishing fires more difficult, even impossible in some cases (Grari et al. 2022). In forest areas with arid conditions that are periodically affected by global climate change, this can generally trigger forest fires. A higher risk of forest fires can occur due to increased average temperature and decreased rainfall (Busico et al. 2019, Humam et al. 2020). The complexity of the causes of forest fires also includes social, political, and economic problems and weak law enforcement, land conflicts, and community capacities, which can then be categorized as indirect causes of forest fires (Medrilzam et al. 2017). Meanwhile, the direct causes of forest fires are classified as including inappropriate land clearing techniques, poor water management infrastructure, weak fire monitoring, and slow response to fires.

There is a close relationship between fires and changes in land cover. Inappropriate land management systems can increase vulnerability to fire. (Pualilin et al. 2019, Adrianto et al. 2020, Samsuri et al. 2012). Forest land cover conditions such as dry land agriculture, secondary dry land forest, and shrubs have the potential to cause forest fires. Fires will occur more frequently in forest areas that have undergone land cover type conversion than those that have not undergone conversion. The greatest frequency of fires occurs in secondary forest cover that has been converted to shrubs and plantations. This is because the fire that occurs depends on the type of fuel, moisture content, and fuel coating. (Adrianto et al. 2020, Samsuri et al. 2012, Usup et al. 2004).

The unclear boundaries of forest areas and the low social capital of the community in managing land can facilitate the expansion of agricultural land into forest areas, followed by the possibility of cultivating land by burning. The production forest area is one of the forest areas that is easily accessible by the community. This allows land conversion to occur, which causes higher forest fires (Medrilzam et al. 2017, Samsuri et al. 2012). The occurrence of forest fires has a reasonably strong correlation with fire hazard locations. Concession/corporate areas such as permit areas Timber forest product businesses, natural forests, and plantation forests, as well as oil palm plantations, are the most common locations for forest fires to occur, with the spatial distribution of companies and road density having the most decisive influence on fire risk (Medrilzam et al. 2017, Rianawati et al. 2016, Song et al. 2017).

Taking into account the problem of the threat of fire in forest areas as described above, it is deemed essential to carry out a spatial analysis model for the distribution of forest fire vulnerabilities by utilizing Geomatics technology (Remote Sensing and Geographic Information System (GIS)). Remote sensing technology and GIS have been widely used in earth observation activities including spatial mapping, planning, and decision-making involving many criteria (multi-criteria) (Mohammed et al. 2021). Spatial decision-making based on multi-criteria in GIS is a collection of methods and tools for converting and combining geographic data into information. Multi-criteria-based spatial analysis is quite flexible in making decisions (Akhbar et al. 2022, Malczewski & Rinner 2015)

Making a spatial model of forest fire vulnerability level based on multi-criteria, focused on identifying important and salient variables in developing requirements and procedures for assessing forest fire vulnerability level (high, medium, low) using scoring and weighting techniques. The use of spatial knowledge, namely geospatial information systems (GIS) in various fields has been widely applied, especially by using it in spatial modeling (Rosyid et al. 2019). GIS is effectively used in combining several factors that cause forest fires in mapping forest fire risk zones (Mohammed et al 2021, Aronoff 1989, Rikalović et al. 2013, Erten et al. 2004, Guettouche & Derias 2012). Satellite imagery data can be used to look for the effects of fires that occur in an area. Several variables affect fires, such as topography, vegetation, land use, humidity and surface temperature, population, settlements, forest fire monitoring buildings, staff characteristics, and accessibility, which are all integrated into GIS (Erten et al. 2004, Amalina et al. 2016).

The research objective was to develop a spatial analysis model for mapping the distribution of fire vulnerability based on multi-criteria in tropical forest areas. The results of this research are expected to be helpful for the development of forestry science and technology in assessing the level of vulnerability of forest fires and are expected to provide information on forest fire management.

MATERIALS AND METHODS

Study Area

This research was conducted in the Tepo Asa Aroa Forest Management Unit (KPH) area, Mori Atas District, North Morowali Regency, Central Sulawesi Province. The research location is at coordinates 121°7’45.03” E-121°13’15.57” E and 1°55’19.72” S-2°3’55.70” S with an area of 7,042.29 Ha. Data collection and processing were carried out from May to September 2022. Fig. 1 shows a map of the research locations.

Materials and Tools

The materials used in this study include digital data and maps, namely maps of vegetation cover and land use (obtained from satellite imagery data), government administration maps, forest area maps, KPH work area maps, road network maps, forest business permit location maps, climate and population data, forest management data and forest fire management. The tools used in this study included personal computers and the ArcGIS software package version 10.4, compasses, Global Positioning System (GPS), digital cameras, SPOT 7 /Landsat 8 satellite imagery recorded in 2018 – 2021, and writing tools.

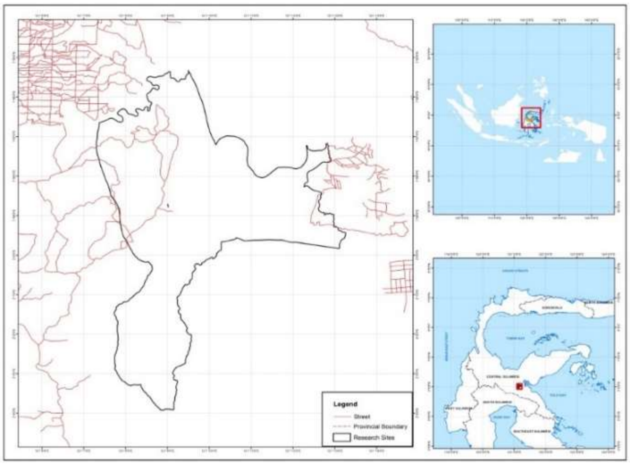

Fig. 1: Map of Research Locations.

Table 1: Variable weighting system in modeling spatial analysis of fire vulnerability distribution in tropical forest areas.

No.	Variable	Weight	Class	Score	Fire Rating Class
1.	Land Use/ Vegetation Cover (LUVC)	7	Grassland/Savanna	5	Very High
			Uncultivated land/shrubs	4	High
			Dryland Agriculture/Seasonal Plants	3	Medium
			Plantation-Forest Plants/Perennial Plants - Timber	2	Low
			Primary Natural Forest – Secondary/ Mixed natural vegetation	1	Very Low
2.	Rainfall (R)	7	Dry (R <60 mm/Bulan)	5	Very High
			Moist (R = 60-100 mm/ bulan)	3	Medium
			Wet (R >100 mm/bulan)	1	Very Low
3.	Land Slope (S)	5	Slope ≥45% (very steep)	5	Very High
			Slope 25-<45% (steep)	4	High
			Slope 15-<25% (rather steep)	3	Medium
			Slope 8-<15% (sloping)	2	Low
			Slope <8% (flat)	1	Very Low
4.	Distance from Road (DSt)	3	<100 m	5	Very High
			100-<200 m	4	High
			200-<300 m	3	Medium
			300-<400 m	2	Low
			≥400 m	1	Very Low
5.	Distance from Settlement (DSe)	3	<1 km	5	Very High
			1-<2 km	4	High
			2-<3 km	3	Medium
			3-<4 km	2	Low
			≥4 km	1	Very Low
6.	Existence of Forest Utilization Permit (FUP)	1	There is no forest utilization permit	5	Very High
			There is a forest utilization business permit, and it is not active	3	Medium
			There is a forest utilization business permit, and it is active.	1	Very Low
7.	Forest Protection and Security (FPS)	1	There are no forest boundaries – no patrols, and no counseling	5	Very High
			There are forest boundary markers – no patrols and counseling	3	Medium
			There are forest boundary markers – there are patrols and counseling	1	Very Low

Source: Erten et al. (2004) modified according to the research needs and conditions of the research location.

Research Methods

The creation of a spatial analysis model for the distribution of vulnerability to forest fires is based on several incidents of forest fires in Indonesia. Forest fires can occur either intentionally or unintentionally. In many cases, forest fires start from the deliberate use of fire, such as activities to clear new land by slashing and burning, burning cattle grazing land, or hunting animals to stimulate the growth of young grass, collecting firewood, and collecting honey by driving bees out of their hives. As for forest fires due to accidents such as the negligence of smokers, tourists, adventurers, workers in the forest, and collectors of forest products.

Development of a spatial analysis model for the distribution of fire vulnerability based on multi-criteria in tropical forest areas using satellite imagery data interpretation and classification techniques, overlays, and map layouts using Geographic Information System (GIS) technology. The application of models using geomatics technology (remote sensing and GIS) makes it possible to create forest fire vulnerability maps by combining several layers of information taken from maps and the field (Guettouche & Derias 2012).

The weighting system and determining the fire vulnerability index refers to the method of determining the level of vulnerability to forest fires by Erten et al. (2004), which was further modified according to research needs. The variable weighting system in modeling the spatial analysis of the multi-criteria-based fire vulnerability distribution in tropical forest areas is shown in Table 1.

In Table 1, it appears that there are as many as 7 (seven) variables that are used as a reference in assessing forest fire vulnerability spatially, namely land use/vegetation cover, rainfall, land slope, distance from roads and settlements, business permits (existence of forest area utilization/use permits).), and forest protection and security. There are several considerations in determining the weight, class, score, and class rating of fire vulnerability for each variable, as follows:

1) Land Use/Vegetation Cover (LUVC): Land use with various types of vegetation or plants covering the land is very vulnerable to fire. The vegetation moisture factor has a significant effect on fires. Very dry vegetation is highly flammable, especially savanna or shrub species, while fresh vegetation is flammable (Erten et al. 2004).
2) Rainfall (R): Monthly rainfall is one of the causes of fires. Low monthly rainfall (dry months) can trigger fires, whereas high rainfall (wet months) can suppress fires (Humam et al. 2020).
3) Land slope (S): The topography of the plains to the mountains has various slope classes, ranging from flat, sloping, rather steep, steep to very steep. Topography is closely related to wind behavior in influencing fire susceptibility. The steeper the slope, the faster the fire spreads (Mukti et al. 2016). Fire travels the fastest up the slope and the least rapidly down the slope (Erten et al. 2004)
4) Distance from Road (DSt): A road network that crosses a forest area will allow humans to move, including animals and vehicles. Forest locations that are close to or crossed by a road network can make these locations vulnerable to fires. The fire risk is high in forest areas near roads (Erten et al. 2004, Mukti et al. 2016).
5) Distance from Settlements (DSe): Forest locations close to settlements can be categorized as fire-prone locations. Likewise, densely populated settlements can become fire-prone locations due to high human activity. High fire risk in forest areas close to settlements (Erten et al. 2004, Mukti et al. 2016, Mukti et al. 2016, Parajuli et al. 2020).
6) Existence of Forest Utilization Permit (FUP): Legal forest utilization following statutory regulations will be implemented by business permit holders to avoid legal sanctions. In the utilization of natural forests or plantation forests, generally, permit holders will apply a silvicultural system without having to burn. Conversely, forest locations not burdened with business permits (illegal forest utilization) are generally vulnerable to fires because there is no forest manager in that location (open access). The cause of the fires comes from uncultivated land use activities (Thoha et al. 2017, Thoha & Ahmad 2018)
7) Forest Protection and Security (FPS): Forest protection and security are closely related to forest management, including forest fire management. Outer boundaries of forest areas that are not clear boundaries or have no fixed boundaries, without patrols and forest counseling, will trigger conflicts over forest use, and it is easy for these forest areas to be used by people illegally, which is usually followed by land clearing by slashing and burning. Conversely, forest area boundaries with clear forest boundary markers, followed by good forest patrols and counseling, will reduce and control forest fires. Routine forest patrols and counseling are the main means of controlling forest fires (Zulkifli & Kamarubayana 2017).

To find out whether or not there is a link between the seven variables with fire vulnerability in tropical forest areas, spatial covariation is analyzed which is the study of two or more different spatial distributions in an area or region. In several previous studies, it was reported that the theoretical basis had been tested so it confirmed that the statistical correlation test could be applied in this spatial covariation analysis.

Furthermore, by using the contingency table, a statistical correlation test is carried out for each variable related to fire vulnerability. Hypothesis testing using Chi-Square Testing (χ^2). With *k* observation frequencies, namely $o_1, o_2, o_3, \ldots, o_k$ and expected frequency (*expectation*), namely $e_1, e_2, e_3, \ldots, e_k$, then the chi-square formula is written (Sudjana, 2005):

$$\chi^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i} \quad \text{...(1)}$$

If $\chi^2 = 0$, then there is a perfect fit between the observed results and the expected value. If $\chi^2 > 0$, then there is no match between the observation results and the expected value. The bigger the value χ^2, the discrepancy between the observed results and the expected value is also getting bigger. In this analysis, we used the hypothesis: H_0 accepted if the occurrence of forest fires is not related to the variable being tested ($\chi^2 hit < \chi^2 tab$), while H_0 is rejected if the occurrence of forest fires is related to the parameter being tested ($\chi^2 hit \geq \chi^2 tab$). The significant degree is used $\alpha = 5\%$.

Compilation of a range of levels of vulnerability to forest fires:

Class width = (Biggest Data Value - Smallest Data Value)/(Number of Classes) ...(2)

To calculate the value *Forest Fire Vulnerability Index* (FFVI) equation is used:

FFVI = 7x(LUVC) + 7x(R) + 5x(S) + 3x(DSt) + 3x(DSe) + 1x(FUP) + 1x(FPS) …(3)

The FFVI level values are shown in Table 2.

RESULTS AND DISCUSSION

Presence of Hotspots

The determination of the research location for the spatial model of the distribution of fire vulnerability in tropical forest areas in the function of protection forest and production forest covering an area of 7,042.29 Ha in the Tepo Asa Aroa Forest Management Unit (KPH) of Tepo Asa Aroa, Mori Atas District, North Morowali Regency, Central Sulawesi Province referred to the hotspot distribution map "SiPongi PKHL Directorate of the Ministry of Environment and Forestry in 2022. In 2021, in this tropical forest area, there will be 2 (two) high confidence hotspots and 7 (seven) medium confidence hotspots, all of which will be in savanna and shrub land cover, while in 2022, Around the tropical forest area, there are 6 (six) medium confidence hotspots in dryland agriculture. Hotspots that have relatively higher temperatures compared to the surrounding temperature can be indicators of forest fires. Denser temporal hotspots will provide a high vulnerability to fire, while the occurrence of the highest number of hotspots in Indonesia is generally in June, July, August, September, and October (Humam et al. 2020, IDGA et al. 2018).

Table 2: FFVI Value.

No.	FFVI Value	Information
1	≥ 113	Very High (SH)
2	91 - < 113	High (H)
3	70 - < 91	Medium (M)
4	48 - < 70	Low (L)
5	< 48	Very Low (VR)

The survey results show that the hotspot location has a very high fire potential because it is generally forest land covered with flammable savanna/grass and shrubs. Considering the behavior of monthly rainfall during the 2015-2021 period from the Kasiguncu Meteorology and Geophysics Station, Poso Regency, Central Sulawesi Province, the dry months are January, August, September, October, November, and December. The existence of these dry months can trigger forest fires due to increasing air temperatures and decreasing monthly rainfall. High surface temperatures and low rainfall in forest areas contribute to forest fires (Parajuli et al. 2020).

Land Use/Vegetation Cover

From the results of the interpretation of Landsat 8 and SPOT 7 satellite imagery and the results of field checks in 2022, in this forest area, there are types of land use/vegetation cover, namely, grazing land in the form of savanna covering an area of 842.83 Ha, uncultivated land in the form of shrubs 42.53 Ha, dry land agriculture in the form of annual crops covering an area of 664 Ha, plantations in the form of oil palm plantations covering an area of 48.55 Ha, secondary natural forest in the form of mixed natural vegetation covering an area of 5,444.38 Ha. The condition of land use/vegetation cover illustrates that this forest area has five fire vulnerability classes, namely: 'very high' area of 11.97%, 'high' area of 0.60%, 'medium' area of 9.43%, 'low' area of 0.69% and 'very low' area of 77.31% of the total forest area of 7,042.29 Ha. The amount of fuel accumulated in forest areas contributes to forest fires, while very dry vegetation cover is highly sensitive to fire (Erten et al. 2004, Parajuli et al. 2020). Savanna is a land cover with high fire vulnerability (Mukti et al. 2016).

Rainfall

Rainfall data obtained from the Kasiguncu Meteorology and Geophysics Station, Poso District, Central Sulawesi Province for 2015-2021 with an annual average of 2,210.17 mm and a monthly average of 184.18 mm (in the wet month category, R>100 mm/month). This condition illustrates that in a forest area of 7,042.29 Ha, there is only one fire vulnerability class, namely 'very low' because it has high rainfall, while the average surface air temperature is 27.1 -27.8 °C and average humidity -average 84.4 - 87.6%. The higher the rainfall, the lower the fire vulnerability (Humam et al. 2020)

Slope Class

There are five classes of slopes in this forest area consisting of a very steep slope class of 356.93 Ha, a steep slope class of 588.69 Ha, a rather steep class of 1,958.80 Ha, a gentle slope class of 2,709.76 Ha, and flat slope class covering an area of 1,428.10 Ha. The condition of the slope class indicates that this forest area has five fire vulnerability classes, namely: 'very high' area of 5.07%, 'high' area of 8.36%, 'medium' area of 27.81%, 'low' area of 38.48%, and 'very low' area of 20.28% of the total forest area of 7,042.29 Ha. Class Slopes with a slope of >35% (steep - very steep) are very sensitive to forest fires (Erten et al. 2004).

In this forest area, there is a road network of 28,334.48 m (28.33 km). The road network connects the locations of agricultural land, plantations, grazing land, and land that is still forested. The length of the local road network is 17,204.17 m (17.20 km), other roads are 9,546.82 m (9.55 km), and footpaths are 1,583.49 m (1.58 km). The road network is concentrated in the northern and eastern parts of the location within Peonea Village, Mori Atas District, and Tiu Village, Petasia Barat District, North Morowali Regency.

The distance of the forest area from the road network in this forest area is: distance <100 m covering an area of 511.90 Ha, distance 100-<200 m covering an area of 419.40 Ha, distance 200-<300 m covering an area of 344.03 Ha, distance 300-< 400 m covering an area of 305.47 Ha, and a distance of ≥ 400 m covering an area of 5,461.49 Ha.

The condition of the forest area's distance from the road indicates that this forest area has five fire vulnerability classes, namely: 'very high' area of 7.27%, 'high' area of 5.96%, 'moderate' area of 4.89%, 'low' of 4.34%, and 'very low' of 77.55% of the total forest area of 7,042.29 Ha. Distance of forest areas from roads that are less than 200 m is very sensitive to forest fires (Erten et al. 2004).

Distance from Settlements

The locations of the settlements analyzed were all settlement locations around this forest area. So, the existence of residential areas largely determines the distance between settlement locations and forest areas. Around the forest area are 10 (10) settlement locations in Peonea Village, Kolaka, Lanumor, Ensa, Mori Atas District, Era Village, North Mori District, Togomulya Village, Petasia Barat District, North Morowali Regency. Of the 10 settlement locations, there is one settlement location in Peonea Village with a distance of 1-<2 km, two settlement locations in Kolaka Village and one location in Togomulya Village with a distance of 2-<3 km each, one location settlements in Era Village, one location in Ensa Village, and one location in Kolaka Village with a distance of 3->4 km each; one settlement location in Ensa Village and one location in Lanumor Village with a distance of ≥4 km each.

The distance of the forest area from the location of settlements in this forest area is: Distance <1 km covering an area of 0 Ha, distance 1-<2 km covering an area of 19.09 Ha, distance 2-<3 km covering an area of 421.30 Ha, distance 3-<4 km covering an area of 1,211.89 Ha, and a distance of ≥4 km covering an area of 5,390.01 Ha. The condition of the distance of the forest area from the settlement location shows that there are four classes of vulnerability in this forest area: 'high' of 0.27%, 'moderate' of 5.98%, 'low' of 17.21%, and 'very high'. Low' area of 76.54% of the total forest area of 7,042.29 Ha. Distance of forest areas from settlements that are less than 1,000 m (<1 km) has a high risk of forest fires (Erten et al. 2004; Parajuli et al. 2020).

The Existence of Business Permits for Forest Utilization

In this forest area, there are 3 (three) permits for forest utilization: a business permit for PT. Wana Rindang Lestari for forest utilization covering an area of 302.52 Ha and for harvesting natural rattan covering an area of 316.59 Ha, the business permit for the use of forest area by PT. Raya Utama Synergy for constructing a hydroelectric power plant covering an area of 33.08 Ha. In addition, there is also an area reserved for agrarian reform objects (TORA) covering an area of 2,305.76 Ha and an indicative map of social forestry areas (PIAPS) covering an area of 614.64 Ha.

Thus, the area that still needs to get a forest utilization permit is 3,469.95 Ha. Thus, the total area that already has business permits reaches 50.73%, and those that do not yet have business permits is 49.27% of the total forest area of 7,042.29 Ha. Forest utilization business permits are permits given to business actors to start and run their businesses and activities (Government of Indonesia 2021).

Of the forest area covering 50.73%, which already has a business license, 46.23% has a business license but has yet to be active, while only 4.50% has a business license and is active. The conditions for the existence of these business permits indicate that this forest area has three classes of fire vulnerability, namely: ‘very high’ covering 49.27%, ‘medium’ covering 46.23% and ‘very low’ covering 4.50% of the entire forest area and covering an area of 7,042.29 ha.

Forest Protection and Security

Forest protection and security in this forest area are quite good because this area is part of the Tepo Asa Aroa KPH management area. The entire outer boundary of the forest area has been demarcated by setting up boundary stakes to provide clear boundaries between the boundaries of forest areas and non-forest areas. Forest area patrol activities and counseling to communities around forest areas are also carried out by the FMU manager every year. These conditions indicate that there is only one fire vulnerability class in a forest area of 7,042.29 Ha, namely ‘very low’.

Forest protection is an effort to prevent and limit damage to forests and forest products caused by human actions, livestock, fires, natural forces, pests, and diseases, as well as defending and safeguarding the rights of the state, communities, and individuals over forests, areas forests, forest products, investments, and tools related to forest management (Government of Indonesia 2021).

Spatial Model of Fire Vulnerability Distribution Based on Multi-Criteria

Spatial modeling of the multi-criteria-based fire vulnerability distribution in tropical forest areas using geographic information systems (GIS) produced only three of the five available fire vulnerability classes. In the protection forest area and production forest area of 7,042.29 Ha which were analyzed using seven parameters of fire vulnerability assessment simultaneously in tropical forest areas, the three classes of fire vulnerability are referred to, namely: (a) ‘medium’ fire vulnerability class with an area of 287.93 Ha (4.09%), (b) ‘low’ fire vulnerability class with an area of 1,815.16 Ha (25.78%), and (c) ‘very low’ fire vulnerability class with an area of 4,939.20 Ha (70.14 %).

The results of spatial analysis of fire susceptibility to types of land use/vegetation cover in tropical forest areas show that for the three resulting fire vulnerability classes, the distribution of ‘moderate’ fire vulnerability classes is for savanna type 3.90% and dryland agriculture with annual crops 0.19 %, while the ‘low’ fire vulnerability class included savanna 8.07%, shrubs 0.60%, dryland agriculture with annual crops 7.92%, oil palm plantations 0.69%, and secondary dryland forest with mixed natural vegetation types 8.50%. The distribution of ‘very low’ fire susceptibility classes to dryland farming with seasonal crops was 1.32%, oil palm plantations 0.004%, and secondary dryland forest with mixed natural vegetation 68.81%.

According to the partial analysis results, ideally, the fire vulnerability classes are distributed from the ‘very high’ to ‘very low’ class. In the results of this multi-criteria-based simultaneous analysis, it is possible that the level of fire vulnerability in tropical forest areas can be derived from the ‘very high’ class and ‘high’ being a ‘moderate’ to ‘very low’ level of vulnerability. The statistical test in the spatial covariation analysis shows that there is a correlation between fire vulnerability and the type of land use/vegetation cover because H0 is rejected at the 0.05 confidence level ($\chi^2 hit = 5.233,24 > \chi^2 tab = 15,51$). Land use/vegetation cover affects fires (Parente et al. 2023), while in this tropical forest area, grazing land/savanna or open land is prone to fire, where hotspots are most common in this type of vegetation cover (hotspot). The open land cover class is the most vulnerable to fire (Kelompok Advokasi Riau 2018, Thoha & Triani 2021).

Furthermore, the area (hectares) of each class of fire vulnerability in tropical forest areas is based on the type of land use/vegetation cover as shown in Fig. 2.

The results of the spatial analysis of fire vulnerability based on rainfall in tropical forest areas show that for the three classes of fire vulnerability resulting in the ‘wet month, R>100 mm/month’ class, the distribution of ‘medium’ fire vulnerability classes is 4.09%, in the ‘wet month’ class ‘low’ fires 25.78%, and in the ‘very low’ fire vulnerability class of 70.14% of all tropical forest areas covering an area of 7,042.29 Ha. This simultaneous analysis shows that the fire vulnerability class spreads into three fire vulnerability classes.

By the results of the partial analysis, which ideally is distributed only in the ‘very low’ class, in the results of the simultaneous analysis based on this multi-criteria, the level of forest fire vulnerability can be distributed into the ‘very low’ class (dominant), followed by the ‘low’ class and the ‘moderate’ class’. A forest area may be in a different class of fire vulnerability even though the climatic conditions

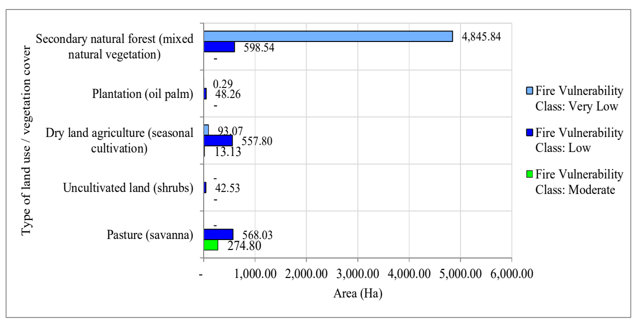

Fig. 2: Graph of fire vulnerability based on type of land use/vegetation cover.

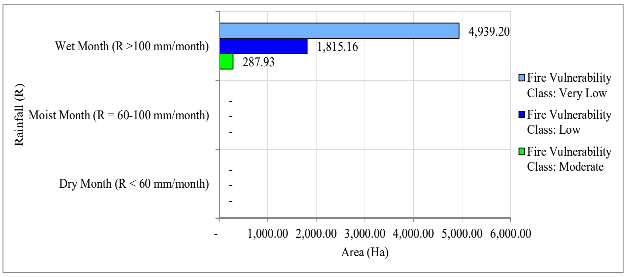

Fig 3: Graph of Fire Vulnerability Based on Rainfall.

(rainfall) are in the wet month category due to the different types of surface fuel and dryness conditions. Statistical tests in spatial covariation analysis show a correlation between fire vulnerability and climate (rainfall) because H0 is rejected at the 0.05 confidence level ($\chi^2 hit$ = 4.789,13 > $\chi^2 tab$ = 5,99). Climate can cause forest fires because it can affect the dryness of surface fuels, the amount of available oxygen, and the speed at which fire spreads (Syaufina & Hafni 2018).

Furthermore, the area (hectares) of each class of fire vulnerability in tropical forest areas based on rainfall is shown in Fig. 3.

The results of the spatial analysis of fire vulnerability based on the slope of land in tropical forest areas show that for the three resulting fire vulnerability classes, the distribution of 'medium' fire vulnerability classes on flat slopes is 1.74%, sloping slopes are 0.46%, rather steep slopes are 1.70 %, steep slopes 0.12%, very steep slopes 0.06%, while in the 'low' fire vulnerability class on flat slopes 11.61%, gentle slopes 3.18%, rather steep slopes 3.67%, steep slopes 2.31%, very steep slope 5.01%. The distribution of 'very low' fire vulnerability classes on flat slopes is 6.93%, sloping slopes are 34.84%, rather steep slopes are 22.45%, and steep slopes are 5.92%.

By the results of the partial analysis, ideally, the vulnerability of fires is distributed from the 'very high' to the 'very low' class; in the results of this multi-criteria-based simultaneous analysis, the level of vulnerability to forest fires can be reduced from 'medium' to 'very low' class. A forest area may be in a lower fire vulnerability class due to the influence of other factors, such as slope aspect, wind direction, surface temperature, and humidity. The statistical test in the spatial covariation analysis shows that there is a correlation between fire vulnerability and the slope of the land because H0 is rejected at the 0.05 level of confidence ($\chi^2 hit$= 2.599,19 > $\chi^2 tab$ = 15,51). Land slope affects forest fires (Erten et al. 2004).

Furthermore, the area (hectares) of each fire vulnerability class in tropical forest areas is based on the slope of the land, as shown in Fig. 4.

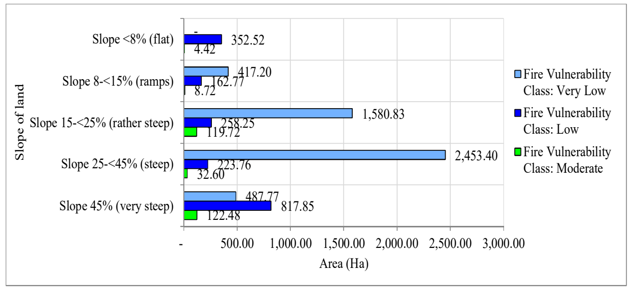

Fig. 4: Graph of fire vulnerability based on land slope.

The results of the spatial analysis of fire vulnerability based on the distance from the road in tropical forest areas show that in the three resulting fire vulnerability classes, the distribution of 'moderate' fire vulnerability classes at a distance of <100 m is 2.42%, a distance of 100 - <200 m is 1.23%, distance 200 - <300 m 0.25%, distance 300 - <400 m 0.13%, distance ≥400 m 0.05%, while in the 'low' fire vulnerability class at a distance of <100 m 3.82%, distance 100 - <200 m 3.51%, distance 200 - <300 m 3.00%, distance 300 - <400 m 2.20%, distance ≥400 m 13.25%. The distribution of 'very low' fire vulnerability classes at a distance of <100 m 1.02%, a distance of 100 - <200 m 1.21%, a distance of 200 - <300 m 1.64%, a distance of 300 - <400 m 2.00 %, distance ≥400 m 64,26%.

By the results of the partial analysis, ideally, the vulnerability of fires is distributed from the 'very high' to the 'very low' class; in the results of this multi-criteria-based simultaneous analysis, the level of vulnerability to forest fires can be reduced from 'medium' to 'very low' class. '. A forest area may be in a lower fire vulnerability class due to adequate forest protection and security and the presence of a legal area manager so that human activities in utilizing existing roads are safer and more controlled from causal sources. Fire. Statistical tests in spatial covariation analysis show that there is a correlation between fire vulnerability and distance from the road because H0 is rejected at the 0.05 level of confidence ($\chi^2 hit$ = 2.892,95 > $\chi^2 tab$ = 15,51). A road network influences forest fires (Erten et al. 2004, Thoha & Triani 2021).

Furthermore, the area (hectares) of each fire vulnerability class in tropical forest areas is based on the distance from the road, as shown in Fig. 5.

The results of spatial analysis of fire vulnerability based on distance from settlements in tropical forest areas show that for the three resulting fire vulnerability classes, the distribution of 'medium' fire vulnerability classes at distances of 2 - <3 Km is 0.10%, distances of 3 - <4 km 1, 13%, distance ≥4 km 2.85%, while in the 'low' fire vulnerability class at distance 1 - <2 km 0.21%, distance

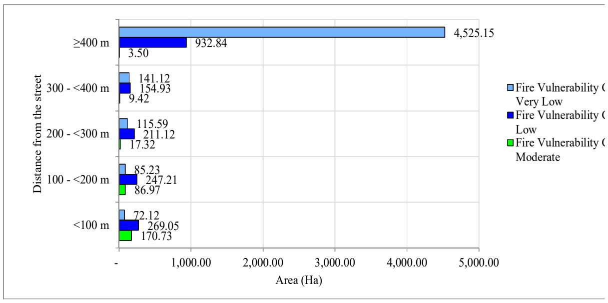

Fig. 5: Graph of fire vulnerability based on distance from the road.

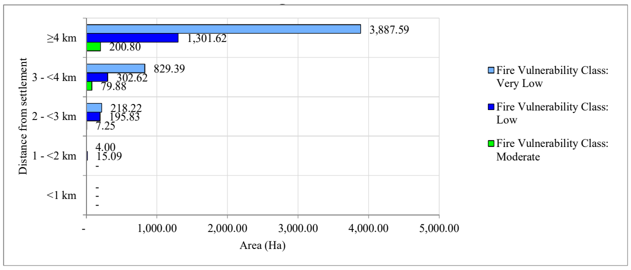

Fig. 6: Graph of fire vulnerability based on distance from settlements.

2 - <3 km 2.78%, distance 3 - <4 km 4 .30%, distance ≥4 km 14.48%. The distribution of 'very low' fire vulnerability classes at a distance 1 - <2 km 0.06%, distance 2 - <3 km 3.10%, distance 3 - <4 km 11.78%, distance ≥4 km 55.20 %.

By the results of the partial analysis, ideally the vulnerability of fires is distributed from the 'high' class to the 'very low' class. In the results of this multi-criteria-based simultaneous analysis, forest fires' vulnerability level can be reduced from a 'medium' class to a 'very low' class. The 'moderate' statistical tests in spatial covariation analysis show that there is a correlation between fire vulnerability and distance from settlements because H0 is rejected at the 0.05 level of confidence ($\chi^2 hit = 154{,}12 > \chi^2 tab = 12{,}59$). The existence of settlements is at risk of forest fires (Erten et al. 2004, Parajuli et al. 2020, Thoha & Triani 2021).

Furthermore, the area (hectares) of each class of fire vulnerability in tropical forest areas is based on distance from settlements, as shown in Fig. 6.

The results of a spatial analysis of fire vulnerability based on forest utilization permits in tropical forest areas show that in the three resulting fire vulnerability classes, the distribution of 'moderate' fire vulnerability classes with no permits is 2.97%, there are permits and inactive 1.12%. In contrast, in the 'low' fire vulnerability class with no permits 10.13%, there are permits, and they are not active 15.58%, there are permits, and they are active 0.07%. The distribution of 'very low' fire vulnerability classes with no permits is 36.17%; there are permits and they are not active, 29.54%; there are permits, and they are active, 4.43%.

According to the results of the partial analysis, which ideally is distributed only in the 'very high' to 'very low' class, in the results of this multi-criteria-based simultaneous analysis, the vulnerability level of forest fires can be lowered from the 'very high' class to the 'moderate' to 'very low' class. Low' with a decreasing area distribution. It appears that the 'moderate' fire vulnerability class on forest land that does not have a permit or is not cultivated is wider than the area that has a permit and is not active. In statistical tests in spatial covariation analysis, it shows that there is a correlation between fire vulnerability and the existence of forest utilization permits because H0 is rejected at the 0.05 level of confidence ($\chi^2 hit = 315{,}72 > \chi^2 tab = 9{,}49$). The cause of the fires comes from land use activities that are not cultivated or open access (Thoha et al. 2017, Thoha & Ahmad 2018).

Furthermore, the area (hectares) of each class of fire vulnerability in tropical forest areas is based on the existence of forest utilization permits, as shown in Fig. 7.

The results of spatial analysis of fire vulnerability based on forest protection and safety in tropical forest areas show that in the three classes of fire, vulnerability resulting in the class 'there are forest boundary markers – there are patrols and counseling', the distribution of fire vulnerability classes is 'medium' 4.09%, in the 'low' fire vulnerability class was 25.78%, and the 'very low' fire vulnerability class was 70.14% of the entire tropical forest area of 7,042.29 Ha. This simultaneous analysis shows that fire vulnerability classes based on forest protection and security (in the class 'there are forest boundary markers, there are patrols and counseling') spread into three fire vulnerability classes.

By the results of the partial analysis, which ideally is distributed only in the 'very low' class, in the results of the simultaneous analysis based on this multicriteria, the level of forest fire vulnerability can be distributed into the 'very

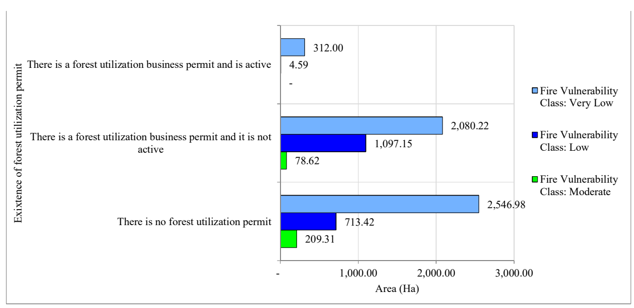

Fig. 7: Graph of fire vulnerability based on existence of forest utilization permits.

low' class (dominant), followed by the 'low' class and the 'moderate' class. A forest area may be in a different class of fire vulnerability even though the forest protection and security conditions are quite good. In statistical tests in spatial covariation analysis, it shows that there is a correlation between fire vulnerability and forest protection and security because H0 is rejected at the 0.05 level of confidence $\chi^2 hit = 4.789,13 > \chi^2 tab = 5,99$). Efforts to prevent forest fires can be carried out by carrying out preventive activities in the form of forest patrols, especially during fire-prone months or long dry seasons, putting up warning boards and prohibiting forest burning, and holding forest fire education to the community (Zulkifli & Kamarubayana 2017)

Furthermore, the area (hectares) of each class of fire vulnerability in tropical forest areas based on forest protection and security is shown in Fig. 8.

A spatial model map of the multi-criteria-based fire vulnerability distribution in tropical forest areas is shown in Fig. 9.

In the map of Fig. 9, it appears that the locations of the 'medium and low' fire vulnerability classes correspond to the existence of hotspot locations. Thus, a multi-criteria-based spatial model of fire vulnerability distribution in tropical forest areas can be used for rapid mapping of forest fire vulnerability levels. Fire risk models are a good approach to fire prevention and forest protection. Integrating remote sensing data and GIS concepts can help determine fire risk areas and forest management planning (Adab et al. 2019).

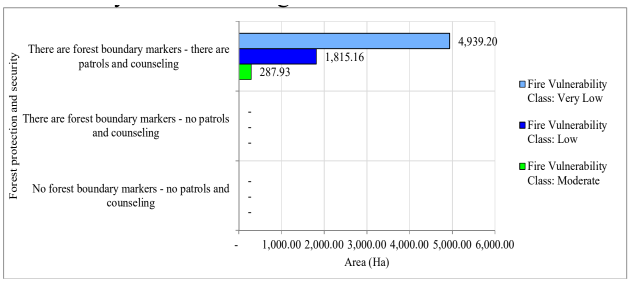

Fig 8: Graph of fire vulnerability based on forest protection and safety.

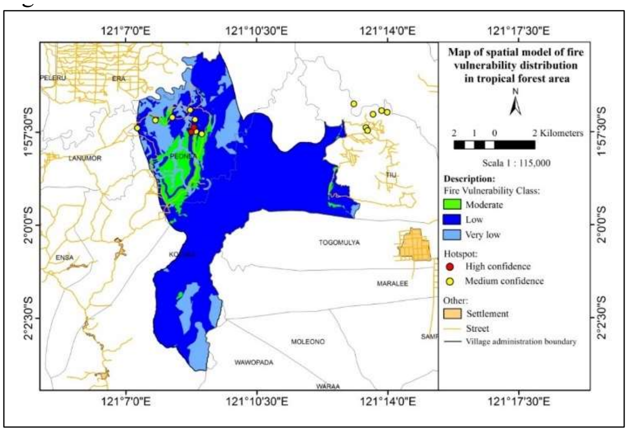

Fig. 9: Spatial model map of fire vulnerability distribution based on multicriteria in tropical forest areas.

Spatial analysis based on multi-criteria mapping the distribution of fire vulnerability in this tropical forest area allows the level of fire vulnerability to be lowered from 'very high' and 'high' classes to 'moderate' to 'very low' levels of vulnerability. These results indicate that the multi-criteria-based spatial analysis approach allows each variable of land use/vegetation cover, rainfall, accessibility (distance from roads and settlements), business permits, forest protection, and security to support each other in reducing the level of fire vulnerability in a forest area.

It can be explained that the active holders of business permits in a forest area, good forest protection and security, and land use in tropical forest areas are easily controlled and controlled by various efforts to burn forests and land. On the other hand, in forest areas with open access, forest encroachers will be free to carry out their activities (Utomo & Arifianto 2019). multi-criteria decision-making is a decision-making method for determining the best alternative based on certain criteria.

CONCLUSIONS

This research produced a spatial model of the distribution of fire vulnerability based on multi-criteria in tropical forest areas that can support rapid mapping of fire-prone forest areas. The results of the analysis of variables on land use/vegetation cover, rainfall, distance from roads and settlements, business permits, forest protection, and security simultaneously using a Geographic Information System (GIS) make it possible to rank fire vulnerability from 'very high' and 'high' classes. To 'moderate' to 'low' and 'very low' vulnerability ratings. All variables tested statistically have a spatial correlation with fire vulnerability. The results of this study can be used as a reference in the development of technology and forest management based on fire prevention and control in tropical forest areas.

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