Fire vulnerability level model for land fire and forest management in Labuhanbatu, North Sumatera, Indonesia

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Abstract. The effect of forest degradation had been apparent increasing disaster level risk, including land fire and forests. The real impact of land fire and forests, particularly in Labuhanbatu District, North Sumatera Province, was physical, socio-economic, and environmental losses that had the potential to cause further disasters. The research objective was to determine the vulnerability grade from forest level and fire lands in Labuhanbatu District, North Sumatera Province. The determination of vulnerability level model of land fire and forests used spatial modelling with the Composite Mapping Analysis method. The dependent variable of this model was the fire hotspot density. The driving factor for land fire and forests from the model of vulnerability for land fires and forest was the accessibility of the community, which was the distance from the road with a weighting of 63% in determining the fire vulnerability level. About 20% of Labuhanbatu District, North Sumatera Province, was in the high-very high vulnerability levels. Areas that had high-very high vulnerability levels were quite wide, including Aek Natas, Kualuh Hulu, and Na IX - X Districts. These areas were generally on a hilly-steep slope. The government and the community needed to improve monitoring and evaluation on lands.

1. Introduction
Massive fires throughout Indonesia in 2015 produced 700-800 million tonnes of CO2 [1,2], causing a loss of 221 IDR T [3] and affected 69 million people due to hazardous air quality [4]. The air pollution exposure was estimated to cause 11,880 deaths in the short term and 100,300 premature deaths in the long term [5]. Peatland areas experienced rapid land cover change and frequent fires in Sumatera and Kalimantan contributed most to regional air quality problems [6].

North Sumatera Province is one of the areas that are more vulnerable to disasters, include land fire and forest. Steep topography and the wide area of critical and abandoned lands that dominate several regencies in North Sumatera are natural conditions that hold the potential for land fire and forest hazards. The areas with a high vulnerability level to the land fire and forests in North Sumatera are peatlands and steep-sloped lands covered with shrubs and grasslands [7]. Critical and abandoned land in the form of shrubs and grassland is the trigger for the initial fires in the land fire and forests in Kapuas District [8,9] and North Sumatera Province [7].

In the long term, the impact of fire will result in further disasters, such as loss of biodiversity, global warming, and desertification [10]. Follow-up disasters after land fire and forests will also occur if the burned lands are left without a restoration.

In the past, land fire and forests often occurred in Labuhanbatu Utara District. According to [11], one of high frequency area of disasters in North Sumatera is Labuhanbatu Utara District. This has also
been studied in [7] where there are locations with a high and very high vulnerability grade of land fire and forest level, analyzed from the history of hotspots ten years ago.

2. Methods

2.1. Study area

This study was taken place in the Labuhanbatu Utara District, North Sumatera Province. The study was implemented for five months starting from April to August 2020. Previous studies that had been carried out had examined the disaster vulnerability map model for land fire and forests in North Sumatera Province scale [7] and spatial-temporal analysis of land fire and forests in Labuhanbatu Utara District [12].

2.2. Data analysis

Materials used in this study were fire hotspot maps were derived from the Moderate-resolution Imaging Spectroradiometer (MODIS) from the Fire Information for Resource Management System (FIRMS) in 2012-2019, land cover maps of 2017, river network distance maps, road network maps, village distribution map, and population density map. The field data collection tools included the Global Positioning System, tally sheets, digital camera and stationery. The data analysis tools used Microsoft Excel and ArcGIS 10.5. The method of determine the vulnerability grade of land fire and forest level used Composite Mapping Analysis (CMA) that had been developed by [7] and [8].

Each factor used in the formulation of the model was divided into several classes as listed at Table 1

| Variable | Factor                        | Class                                                                 |
|----------|-------------------------------|----------------------------------------------------------------------|
| X1       | Land Cover                    | Based on the class on the land cover map Republic Indonesia Minister of Environment and Forestry 2017 |
| X2       | Distance from the road        | Buffer at intervals of 1,000 m (eq 1 km)                              |
| X3       | Distance from the river       | Buffer at intervals of 1,000 m (eq 1 km)                              |
| X4       | Distance from the settlement  | Buffer at intervals of 1,000 m (eq 1 km)                              |
| X5       | Population density           | Divided into 5 classes (number of people/Km²):                        |
|          |                               | 1 = 0.08 - 0.96                                                       |
|          |                               | 2 = 0.97 - 2.34                                                       |
|          |                               | 3 = 2.35 - 5.00                                                       |
|          |                               | 4 = 5.01 - 12.00                                                      |
|          |                               | 5 = 12.01 - 25.21                                                     |

Determination of the weight of a spatial which was carried out empirically used the Composite Mapping Analysis (CMA) method. The steps for determining the weight of the constituent variables for vulnerability to land fire and forest in Labuhanbatu Utara District are as follows:

The score of each sub-factor can be calculated using formulas (1) and (2)

\[
X_i = \left[ \frac{a_i}{e_i} \right] x \frac{100}{\sum \left( \frac{a_i}{e_i} \right)} \quad (1)
\]

\[
E_i = \left[ \frac{T_x F}{100} \right] \quad (2)
\]

where:
Xi = class (sub-factor) score on each factor, Oi = the number of hotspots in each class (observed hotspots), Ei = number of hotspots expected in each class (expected hotspot), T = the total number of hotspot, F = area percentage in each class

To gain the same standard score among all the factors to be used in making the model, the score was calculated again to obtain a scale score using the formula by Jaya et al. [13] in equation 3 below:

\[
\text{Score Rout} = \left[ \frac{\text{Score Einput} - \text{Score Emin}}{\text{Score Emax} - \text{Score Emin}} \right] \times \text{Score Rmax} - \text{Score Rmin} + \text{Score Rmin}
\]

where:
Score Rout = rescaling result score, Score Einput = the estimated score of the input, Score Emin = the minimum of estimated score, Score Emax = the maximum of estimated score, Score Rmax = the highest score of rescaling results, Score Rmin = the lowest score of rescaling results

The composite score was obtained from the sum of the multiplication of each variable class score with its weight as can be seen in equation 4 below:

\[
y = w1x1 + w2x2 + \ldots + wixi
\]

where:
Y : Composite Score from Model, wi : Variable weight… -I, xi : Variable scaled score… -i

Based on the pixel size used and the radius between the hotspots, the fire vulnerability class, the composite score values were divided into five classes with a quantile classification with class divisions from lowest, low, medium, high, highest.

In spatial modeling of the vulnerability level to land fire and forests, two activities were carried out; creating a vulnerability map of the land fire and forest formulated from statistical equations.

3. Results and discussion

The determination of the score each variable class was based on the relationship between the hotspot density made in the form of the actual score and the class on each variable. The actual score relationship identified included the relationship between the actual score and land cover type, distance from the road, distance from the river, distance from the settlement, and population density.

![Graph](image)

Remark : 1 = Water Body, 3 = Primary Dry Land Forest, 6 = Dry Land Forest Secondary 7 = Pond, 10 = Mangrove Forest Secondary, 11 = Mixed Dry Land Agriculture, 12 = Settlement, 14 = Shrubs, 15 = Dry land agriculture, 16 = Plantation forest, 18 = Plantation, 21 = Swamp, 22 = Paddy field, 23 = Open land.

Figure 1. The pattern of relationship between the land cover classes and the actual scores in Labuhanbatu Utara District.
The estimated score generated from the regression equation between the land cover classes and the actual scores followed a polynomial pattern (order 2) with a coefficient of determination ($R^2$) of 30.9%. The highest score (100) was found in open land, while the lowest score was in mixed dry land agriculture. The relationship between the actual scores and the land cover classes can be seen in Figure 1.

The land cover type play a role in determining land fire and forests. The rarely vegetated land cover type generally provide combustible materials, such as shrubs and grasslands. The open land includes unmanaged land and burned land overgrown with shrubs and grasslands. In general, unmanaged land is vulnerable to burning based on several studies, such as those found by [8] and [14].

The estimated score generated from the regression equation between the distance from the road and the actual score followed a polynomial pattern (order 3) with a coefficient of determination ($R^2$) of 93.2% which showed that the farther from the road, the greater the estimated score (Figure 2). The distance from the road have an important role in driving land fire and forests. The relationship between the distance from the road and the actual scores in Figure 2 showed that the farther from the road, the higher the fire activity. The results of a study conducted by [14] in Central Kalimantan stated that roads have a major role in determining the vulnerability of land fire and forests, although it showed the opposite results. The study conducted [15] stated that degraded forests leave unmanaged land which can increase fire vulnerability. Study [16] found that roads are access to land for easy management and supervision. Other study by [17] also found that fire activity occurred increasingly at far away from road.

The estimated score that is generated from the regression equation between the distance from the river and the actual scores followed the exponential pattern with a coefficient of determination ($R^2$) of 33% which showed that the farther from the river, the greater the estimated score (Figure 3).
The river is a means of access or transportation route to land for the community. Rivers can also play a role in fire control efforts because they are a source of water for extinguishing. The pattern of relationship between the distance from the river and the scores in Figure 3 showed that the farther from the river, the higher the potential for increased fire activity. The study by [7] in the North Sumatera region found the same findings that the farther from the river, the higher the fire activity.

The estimated score generated from the regression equation between the distance from the settlement and the actual scores followed the power pattern with a coefficient of determination ($R^2$) of 15.2%, which showed that the farther from the settlement, the greater the estimated score (Figure 4). Basically, settlements in Indonesia are the center of villages or sub-districts where many human activities are taken place. In practice, burning land avoids the negative impact of fires on settlements. The study by [7] found the same finding where the farther from the settlement, the greater the possibility of fire activity.

**Figure 4.** The pattern of relationship between the distance from the settlement and the actual scores in Labuhanbatu Utara District.

The estimated score generated from the regression equation between the population density and the actual scores followed a polynomial pattern (order 2) with a coefficient of determination ($R^2$) of 98.1% (Figure 5). This pattern showed that the lower the population density, the greater the estimated score. This is consistent with the pattern of the relationship between the distance from the settlement and the actual scores in Figure 4.

**Figure 5.** The pattern of relationship between the population density classes and the actual scores in Labuhanbatu Utara District.

Remark: 1 = 0.08 - 0.96 people/Km$^2$, 2 = 0.97 - 2.34 people/Km$^2$, 3 = 2.35 - 5.00 people/Km$^2$, 4 = 5.01 - 12.00 people/Km$^2$, 5 = 12.01 - 25.21 people/Km$^2$. 
In general, densely populated areas have very little chance of high fire activity. This was also found in a study conducted by [9] in Central Kalimantan that the chance of fire activity decreases as the distance is further from the center of a densely populated village. Study [18] found that population density not significant to contribute to fire activity. This is in accordance with the results of the weighting of the variable model presented in Table 2.

The results of the regression analysis obtained the coefficient and weight of each variable as shown in Table 2. The highest to lowest weights of the five variables composing the land fire and forest vulnerability model in Labuhanbatu Utara District are the distance from the road, distance from the settlement, distance from the river, land cover, and population density.

Table 2. Coefficients and weights composing composite score of vulnerability level model for land fire and forests in Labuhanbatu Utara District.

| Variable               | Coefficient | Weight |
|------------------------|-------------|--------|
| Land Cover             | 0.000331    | 0.03   |
| Distance from the road  | 0.006825    | 0.63   |
| Distance from the river | 0.001631    | 0.15   |
| Distance from the settlement | 0.002044 | 0.19   |
| Population density     | 0.000086    | 0.01   |

The largest area based on the results of the vulnerability model for land fire and forest is at a very low level (Table 3 and Figure 6). Meanwhile, at the high-very high levels, it covers an area of more than 36,000 hectares, about 20% of the total area of Labuhanbatu Utara District.

Table 3. The distribution of fire areas with classes of vulnerability model for land and forest fire in Labuhanbatu Utara District.

| Vulnerability Level | Model Composite Score | Area (Ha) | Percentage |
|---------------------|-----------------------|-----------|------------|
| Very Low            | 10.03 - 13.70         | 190,153.87| 52.16%     |
| Low                 | 13.71 - 15.65         | 63,824.27 | 17.51%     |
| Moderate            | 15.66 - 17.66         | 37,258.92 | 10.22%     |
| High                | 17.67 - 20.53         | 32,103.98 | 8.80%      |
| Very High           | 20.54 - 84.89         | 41,186.8  | 11.29%     |

Areas classified as having level of high-very high are distributed in the south of Labuhanbatu Utara District. This area mostly borders Toba Samosir and North Tapanuli District (Figure 6). The areas of vulnerability levels of high-very high are distributed over the flat-steep slopes. The high-very high vulnerability levels are in the peatland area, especially in Kualuh Ledong District.

The driving factor for land fire and forests in Labuhanbatu Utara District is related to the accessibility of the community to manage the land, which is the distance from the road. This means that road access plays a very important role in the occurrence of land fire and forests. This is also in line with the studies conducted by [7] and [9] that human activity in terms of road access is a very significant variable in determining the vulnerability level to land fire and forests.

Spatially, based on the administrative area of the sub-district, the areas that have the high-very high vulnerability levels are in Kualuh Hulu, Na IX-X, and Aek Natas Districts (Table 4). In general, these three sub-districts are located in areas with hilly topography and are very steep. Studies by [7] and [12] stated that forest fires in North Sumatera and Labuhanbatu Utara are often found in sloping areas with community activities in terms of clearing land for rubber and coffee plantations.
Figure 6. Land fire and forests vulnerability level map in Labuhanbatu Utara District.

Table 4. The distribution of areas of vulnerability level of land fire and forest with high and very high classes of based on the sub-districts.

| No | Sub-district | High | Very High |
|----|--------------|------|-----------|
|    |              | Area | Percentage | Area | Percentage |
| 1  | Aekuo        | 2,524.42 | 7.86 | 2,373.47 | 5.76 |
| 2  | Aeknatas     | 4,475.52 | 13.94 | 24,573.82 | 59.66 |
| 3  | Kualuh Hilir | 3,002.67 | 9.35 | 2,291.81 | 5.56 |
| 4  | Kualuh Hulu  | 10,142.11 | 31.59 | 8,338.28 | 20.25 |
| 5  | Kualuh Selatan | 2,642.98 | 8.23 | 25.23 | 0.06 |
| 6  | Kualuh Leidong | 3,792.16 | 11.81 | 1,062.66 | 2.58 |
| 7  | Marbau       | 464.71 | 1.45 | 24.01 | 0.06 |
| 8  | Na IX - X    | 5,059.41 | 15.76 | 2,497.53 | 6.06 |

The implementation of the vulnerability level of management land fire and forests can be utilized in several aspects. First, it can be used to understand the relationship between the various driving factors of land fire and forests so that the characteristics of the causes of fires can be determined in more detail. Second, key factors causing land fire and forests can also be known so that the relevant program to reduce land fire and forests and the potential for further disasters can be formulated. Third, priority areas can be determined for handling land fire and forests on land with the high-very high vulnerability levels.
based on sub-district to village areas. Fourth, it can be used as input for the preparation of development programs that minimize disaster risk to the village level.

4. Conclusions
The important factor to land fire and forest from the vulnerability model for land and forest fire is the accessibility of the community, which is the distance from the road. About 20% of Labuhanbatu Utara District is in the high-very high vulnerability levels. Areas that have the high-very high vulnerability levels are quite wide, including Aek Natas, Kualuh Hulu, and Na IX - X Districts. These areas are generally on a hilly-steep slope. The government and the community need to improve monitoring and evaluation on lands with the high-very high vulnerability levels to anticipate the potential for further disasters.

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