Eastern European
Journal of Regional Studies
ISSN: 1857-436X / ISSN: 2537-6179

Volume 9 / Issue 2/ December 2023
https://doi.org/10.53486/2537-6179.9-2.12

FOREST FIRES IN A CHANGING CLIMATE: RISK ASSESSMENT AND MANAGEMENT IN LEIRIA NATIONAL FOREST, PORTUGAL

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Abstract: *Forest ecosystems are vital for sustainable development and human well-being globally and in Europe. Sustainably managed forests are fundamental in combating natural disasters and providing multiple important goods and services for humans and the environment. However, with increasing climate change and its associated effects, forests have become severely and regularly prone to fires. This is seriously threatening forest protection, human safety, the economy, and biodiversity. In this context, understanding future forest fire risks, susceptibility, hazards, and fire prevention is essentially needed. This study thus examines the forest fire risks and hazards in Leiria National Forest (Mata Nacional de Leiria), Portugal using the 2017 forest fire as a benchmark. With the adoption of GIS and remote sensing techniques and data, vegetation type (NDMI), human factors (roads and settlement proximity), and terrain characteristics (slope and aspect) were assessed to map fire risk. Through multi-criteria analysis, these data were integrated to generate a forest fire risk index. Results demonstrate that about 46% of the study area is within high-risk and risky zones, 50% is considered moderate-risk fire zones and 3% is classified as low and risk-free zones. Sensitivity analysis indicated that high-risk areas are mostly low moisture coniferous fuel types while risk-free areas are high moisture deciduous fuel types. Further, it was established that the observed high-risk and risky zones are attributed mostly to proximity to settlements and roads and little topographical influence. The study thus suggests an increased future forest fire risk under the prevailing conditions and a hiking potential of increased burnt areas. We thus proposed effective proactive measures and adaptive management approaches to prevent and mitigate the devastating impacts of forest fires within the study location.*

Keywords: *Forest Fires, Climate Change, Fire Risk Assessment, Spatial Framework, Fire Hazards, Leiria National Forest, Mediterranean Europe*

UDC*: 005.931.11:614.841.42(469)*

JEL Code: *Q51, Q54, Q57*

Introduction

Forest fires are becoming considerably common in Europe as a result of climate change and its potential consequences (Pausas, 2009; San-Miguel-Ayanz, et al. 2018; EFFIS, 2021). While fire prevention efforts in the Mediterranean region have increased, high warming scenarios, frequency of drought, and low precipitation levels coupled with land use conditions are anticipated to result in an increased risk of forest fires, expanded burn areas, and longer fire seasons in most European regions (Buhk et al. 2006; Oliveras et al., 2011; Casau et al. 2022; Parente et al. 2022). Better information and more knowledge

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Received: 03.09.2023 Accepted: 12.10.2023

are consequently needed to understand future forest fire risks and develop innovative preventive measures. Large-scale forest fires have negative consequences on forest ecosystems, services, and functions such as affecting air and water quality, biodiversity, species riches, soil, and landscape aesthetics (San-Miguel-Ayanz, et al. 2018; Rodrigues et al. 2020; Pacheco et al. 2021). Additionally, they contribute to climate change as they emit high amounts of greenhouse gas emissions and particles into the atmosphere that disturb air quality and lead to health problems and economic losses (Eskandari, 2017; Nuthammachot et al., 2019; EFFIS, 2021).

In Portugal, wildfire accounts for a majority of the country's burned surface area mostly driven by climate and weather conditions (heat, wind) (Pausas, 2004; Aguiar et al., 2021; Parente et al., 2022). During the last few decades, Portugal has experienced a significant number of wildfires usually as a result of a combination of drought, heat, wind, as well as socio-economic and land-use factors (Pausas, 2004; Rodrigues et al., 2020; Farinha et al., 2022). Climate change and land-use activities have led to increased growth of woody vegetation, rising flammable fuel load, and changes in moisture content that are critical to fire ignition and spread (Ruffault et al., 2016; Castro et al. 2020; Casau et al., 2022). In 2003 summer, Portugal accounted for the worst-hit country in the EU burned forest area estimation (Eisenreich, 2005; Clerici et al., 2014; San-Miguel-Ayanz, et al., 2018; Júnior et al., 2022). This led to severe financial loss (1 billion euros loss), social cost (loss of lives), and ecological impacts (PM_{10} emissions, forest loss) (UNEP, 2004; Pereira et al., 2005; Oliveira et al., 2017; Casau et al., 2022). Portugal has been described as a hotspot of forest fires in Europe (Pereira et al., 2005; Júnior et al. 2022; Parente et al., 2022).

In 2017, wildfires in Portugal made the country the highest in terms of forest fires and burnt areas (60%) in Europe (EFFIS, 2021; Casau et al., 2022; Júnior et al. 2022). A wildfire that burnt 86 percent (94000 ha) of the largest Portuguese public forest, Leiria National Forest (Mata Nacional de Leiria (MNL), in the central west of the country, was the major contributor (Botequim et al., 2017; Aguiar et al., 2021). This forest fire was directly responsible for multiple disturbances such as loss of biodiversity and lives, and a decline in forest cover (Botequim et al., 2017; ICNF, 2017; Castro et al., 2020). About 84% of Maritime pine trees (Pinus pinaster Aiton) which covers most areas of the land were affected by the fire (Rodrigues, et al., 2021). MNL forest is known for its crucial functions such as timber production, recreational activities, and cultural significance (AFN, 2010 cited in Aguiar et al., 2021). The forest has a history of wildfires dating back to the 19th century that pose a significant threat to the biodiversity, and social, and economic functions of the forest (Pinto, 1938; Botequim et al., 2017). Climate change (heatwaves and drought), human activities, and ineffective management practices have been described as the main drivers responsible for the fires (Nunes et al., 2016; Parente et al. 2017; Castro et al., 2020). This has made the forest receive considerable attention in environmental discourse over the years. Forest fire incidence continues to increase because of existing natural and human pressures on the forest Botequim et al., 2017; ICNF, 2017; Castro et al., 2020). With an expected increase in climate change and its related hazards and risks

Received: 03.09.2023 Accepted: 12.10.2023

(social, economic, environmental, health, etc.) coupled with the evolution of human influence on the environment in some years to come (IPCC, 2014), it is essential to understand forest fire risk levels and the likelihood and magnitude of future forest fire events to enable the development of plans to identify and prioritize fire-prone zones.

So far, forest fires in Portugal have been widely documented by numerous studies (see Meira-Castro et al. 2015; Nunes et al. 2016; Parente et al. 2017; Nunes et al. 2019; Pacho et al. 2021; Casau et al. 2022). However, most of these studies have focused on drivers (Castro et al., 2020), spatial patterns (Nunes et al. 2016; Parente et al. 2017), vulnerability (Nunes & Lourenço, 2017), danger rating (Júnior et al. 2022) spread (Sá et al., 2022), fire soil risk (Parente et al. 2020), or risk reduction (Casau et al., 2022) among others. Precise data in terms of understanding fire detection, sensitivity, risks, and management remain in their infancy (Maia et al. 2012; Monteiro-Henriques & Fernandes, 2018; Aguiar et al., 202; Casau et al., 2022). Assessment of forest fire risk mapping with respect to the 2017 forest fires and taking into account the major risk factors to forest fires to assess current and future fire risk within the study locality could barely be found in the literature. The research gap is even more evident with the case forest under study and in the methodology i.e. the adoption of a multi-criteria decision analysis (Analytic hierarchy process (AHP)) for forest fire risk assessment.

Hence, there is a need to fill this gap and generate more valuable information to understand future forest fire risks to help mitigate potential threats and institute proactive and innovative management strategies by paying significant attention to existing management strategies to minimize or prevent future occurrences. With the availability of geospatial techniques and data, it is imperative to model forest fire risks in the area to deliver robust information and knowledge for planning decision support. Using the 2017 forest fire as a benchmark and the adoption of AHP approach and GIS (see Ajin et al., 2016; Eugenio et al., 2016; Gigović et al., 2018; Nuthammachot & Stratoulias, 2021), the study aims to examine forest fire hazards and risks in the study region, taking into account the prevailing factors of fires (vegetation type, proximity to settlements and roads, and topography (slope, aspect)) and ultimately propose sustainable management plans to prevent fire incidents and sustainably manage the area.

1. Study Area

The Mata Nacional de Leiria is located on the coast of Portugal, approximately 140 kilometers north of Lisbon (39°46’18.30’’N; 8°58’05.35’’ W). It is bounded to the North by the river Liz, to the south by the municipality of Nazare, to the west by the Atlantic Ocean, and to the east by the city of Marinha Grande. It covers an area of around 11,080 ha, which corresponds to about 60% of the area of the municipality of Marinha Grande (Alcarva, 2011). The site is covered mainly by pure stands of maritime pine with different age classes and divided into 342 rectangular management units with, approximately, 35 ha each. It has a maximum width of 8,394 m and a maximum length of 18,549 m (Aguiar et al., 2021).

The area is part of the Mediterranean temperate climate, characterized by the influence of the proximity to the sea. The fundamental characteristics of this type of climate are hot and dry summer, winter of mild temperatures, and usually rainy (AFN, 2010). Temperature and precipitation show strong seasonal variation. Temperature records its maximum values in the months of June, July, August, and September, while the highest amounts of rainfall are concentrated between the months of October and April. Regarding average temperatures, there are no major differences, only in the average maximum of the hottest month (August) which ranges from 21.5°C to 25°C.

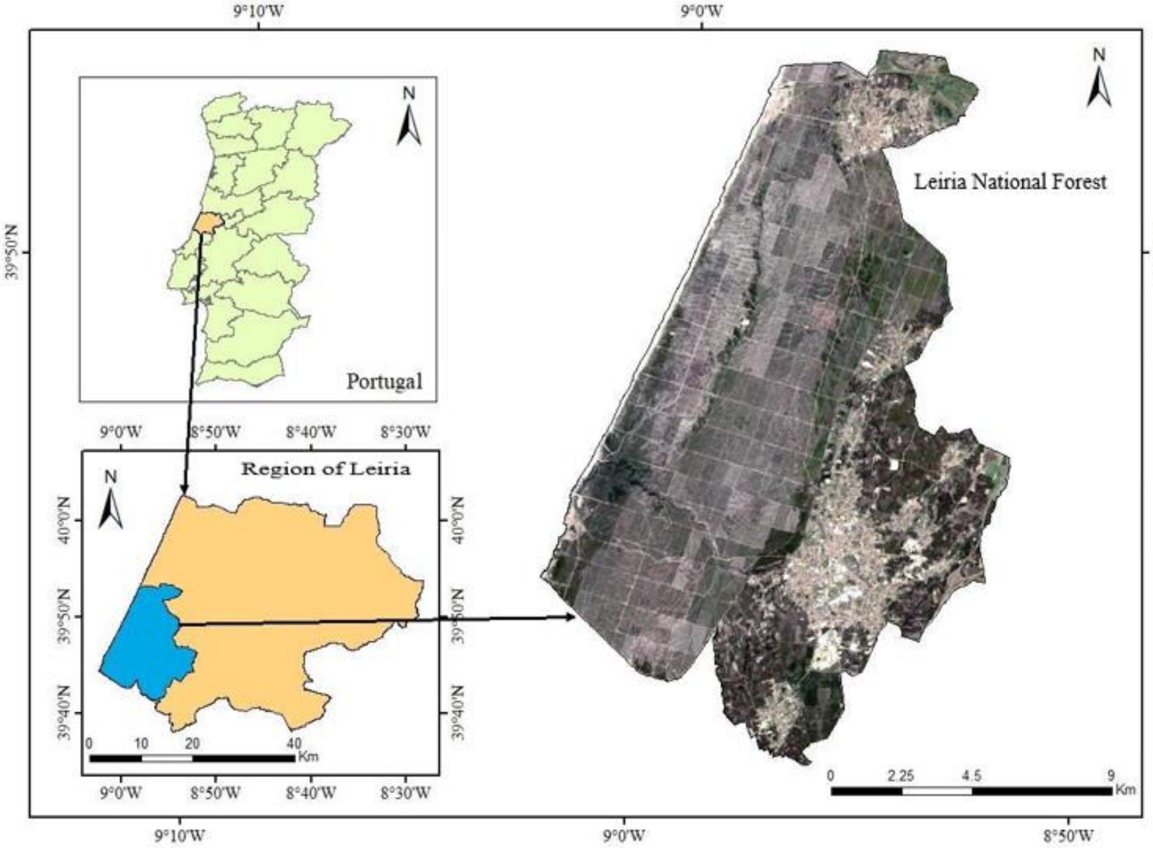

Figure 2. Study Area Map: (a) Portugal (b) Region of Leiria (c) Leiria National Forest

Source: author's research

1.1 October 2017 Fire Incidence

On October 15, 2017, the Leiria National Forest (Mata National de Leiria) was heavily affected by 2 fires, both caused by re-ignitions, in the parish of Pataias in Praia da Légua and Burinhosa about 9km and 1km to the National Forest of Leiria, with a total of 19,975.2 ha burning, of which 9,475.15 ha are in the National Forest of Leiria, representing about 85% of its surface (CTI Report, 2017). The relatively uniform vegetation in some places, flat terrain, and wind contributed to the severity of the fire. The fires were predominantly on the surface (but with total blight of the crowns) in the pine forests with heights greater than 10-12 m and of crowns in the remaining ones (CTI Report, 2017).

Received: 03.09.2023 Accepted: 12.10.2023

According to San-Miguel-Ayanz (2020), this situation resulted from exposure to hot, dry air from the south intensified by Hurricane Ophelia combined with the severity of seasonal drought. In fact, on October 15th the potential for the development of large fires was high and the moisture content of all forest fuels (dead and live fine) was very low (ICNF, 2021).

Given the number of occurrences of rural fire on October 15th associated with the extreme weather conditions that were felt that day, the ignitions quickly gave rise to large areas covered by fires in Mata Nacional de Leiria, therefore, the difficulty of suppression in the face of the extreme behavior of the fire combined with the difficulty of mobilizing fire-fighting means (San-Miguel-Ayanz, 2020). Regarding the fire suppression conditions, they were carried out on a day with extremely strong winds, high temperatures, and low atmospheric humidity (no night recovery), which exceptionally aggravated the risk and extreme behavior of the fire, with very high propagation speeds, high consumption of materials and high resilience (ICNF, 2020).

The fires of October 2017 were the largest that occurred here, radically altering the ecosystems and landscape of the forest. The recurrence indirectly reflects all the variables involved in the process, from the natural conditions (weather, fuel, relief, etc.), to the direct and indirect causes of fire, essentially of human origin, including efficiency, or not, of prevention and combat, constituting a relevant indicator in forest fire risk assessment (Oliveira et al., 2017). The depiction of the vegetation before and after the fire can be seen in the NDVI figure below.

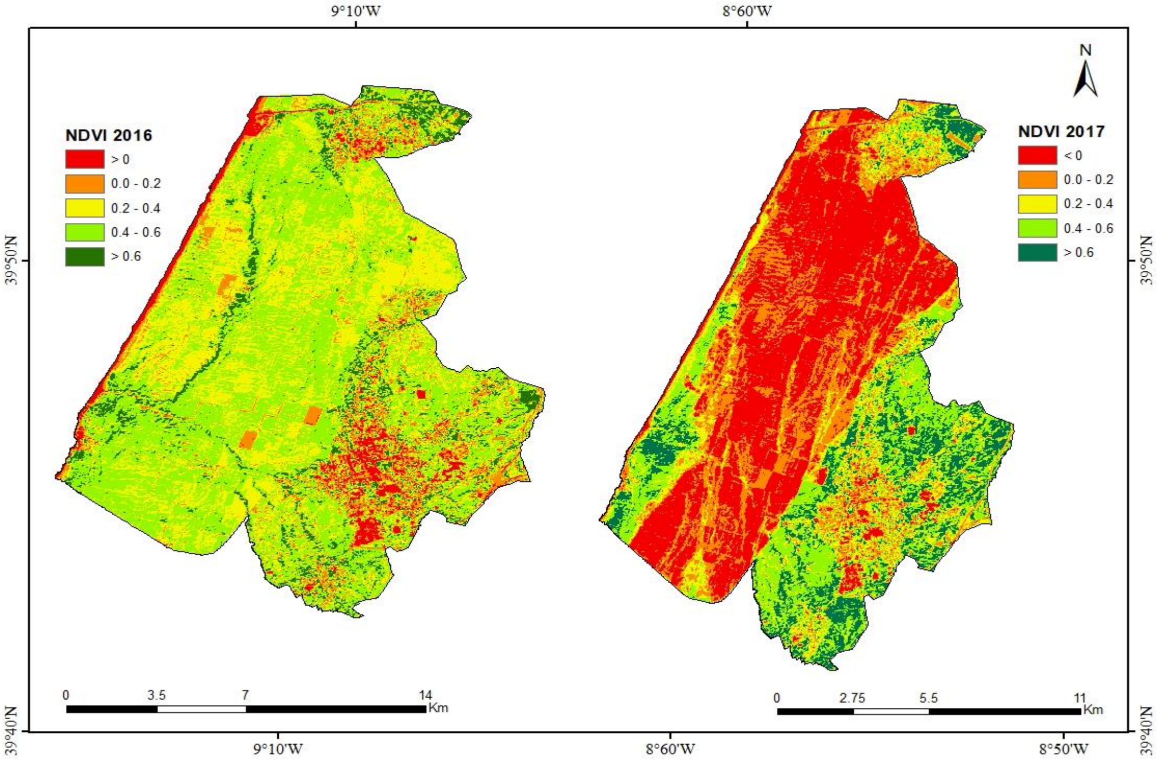

Figure 3. NDVI Maps of Study Area (Left, 2016 before the fire; Right, 2017 After the Fire)

Source: author's research

1.2. Fire Risk Factors

Climatic conditions, fuel, topography, and anthropogenic elements are the most significant drivers of the ignition of forest fires in the Mediterranean regions (Ganteaume, 2013). Climatic factors and the availability of fuel decide the conditions beneath which fires happen and spread once ignition has occurred. The extraordinary fire scenes and obliterating fire seasons in Europe are, in most cases, driven by extreme fire weather conditions. In this way, climate change is expected to have a strong impact on forest fire regimes in Europe (De Rigo, 2017). Fire as the main threat to forests in the Mediterranean basin is especially high in forest areas characterized by summer droughts, high plant productivity, and the presence of shrubs which substantially increase the severity of fire damages (Cruz & Viegas, 2001). Currently, Maritime pine (Pinus Pinaster Ait.) is the most important timber species in Portugal, its area extending over 710600 ha (DGRF, 2006). Maritime pine stands are mainly even-aged plantations frequently affected by forest fires. The current management is mainly done without considering explicitly the risk of fires. Thus, the need to address fire risk in forest management planning is evident. Modern forest planning tools are needed to advise managers to adopt practices that reduce the losses due to fires (Garcia-Gonzolo, 2014)**.**

Portugal is by far the Mediterranean country that has suffered the most due to forest fires: in the last 30 years, it has faced more fire incidents with more hectares burned. About 35% of the region's fire incidents and 39% of the area affected each year occur in Portugal. An average of 3% of Portugal's forests burn each year (WWF, 2019). The year 2017 presented extreme meteorological conditions, with a severe heatwave and extreme atmospheric instability in June, the influence of Hurricane Ophelia, and a record drought in October. These extreme conditions led to a multiplicity of wildfires, many active fire fronts, and explosive fire behavior, contributing to the catastrophic fires in the central and northern regions of the country, with heavy impacts on human lives and assets. These critical fire episodes often referred to as mega-fires or extreme wildfire events (EWEs) have been documented in several scientific publications (see San-Miguel-Ayanz et al., 2013; Costa et al., 2020)

Studies in Portugal have addressed the behavior and effects of fire on maritime pine stands, especially about prescribed burning (Fernandes, & Botelho, 2004; Fernandes & Rigolot 2007; Fernandes et al., 2009). The MNL is mainly made up of pure stands of maritime pine (Pinus pinaster subsp. Atlantica) exploited to produce quality wood in rotations of 75 years with 3,154 ha of extension (AFN, 2010). Pinus pinaster stands have characteristics inherent to the species that favor the progression of fires - flammability of the species associated with the presence of volatile compounds, the existence of a thick dead blanket in the abundant soil, and undercover, often allowing the vertical continuity of the stands. However, maritime pine also has characteristics that give it resistance to fire – thick bark in the adult stage and serotine cones that allow the release of seeds after the fire, provided that the fire has not destroyed the cones (Collins et al., 2013; Pinto-Correia et al., 2011).

2. Data and Methodology

In order to minimize and manage forest fire impacts on forest ecosystem services and functions, analyzing the geospatial patterns of forest fire risk zones is imperative (Gigović et al., 2018; Naderpour et al. 2021; Nuthammachot & Stratoulias, 2021). This will help understand and demarcate forest fire risk areas and come up with conservation plans (Naderpour et al., 2019; 2021). To do this forest fire risk zones and maps were produced by employing fire risk factors data layers discovered as the main factors responsible for forest fires within the study area (Catry et al., 2010; Castro et al., 2020). GIS techniques and data are known to have a vital potential for assessing forest fire risks (Leblon et al., 2012).

2.1. Data

In this study, GIS and Remote sensing data sets and techniques were employed. The data sets adopted were acquired from different sources. The remotely sensed data were freely acquired from the USGS Earth Explorer website *(https://earthexplorer.usgs.gov/)*. Two Landsat 8 satellite data were utilized in this study (path 204, row 32: December 05, 2016; path 204, row 32. November 06, 2017). The acquisition date of these data was chosen based on the 2017 fire occurrence date and cloud-free conditions (20% cloud cover). These images were used to derive spectral indices. In addition, ASTER Digital Elevation Model data was obtained from *https://earthdata.nasa.gov* whereas land use and land cover data (settlement, water, forest cover, etc.) were retrieved from the CORINE map obtained from the European Environment (100m resolution grid). Roads and settlement data were obtained from OpenStreetMap (OSM). Information such as date, location, and fire-damaged area about the forest fire in the area was obtained from the EFI site. These retrieved data were stored in a GIS database and integrated into ArcGIS for analysis to be carried out.

2.2 Methods

The initial method entails gathering, extracting, and producing the required study area data sets. To generate the forest fire risk, data layers like vegetation type, slope, aspect, and land features (roads and settlement proximity) were individually evaluated. A weighting criteria system (Analytic hierarchy process (APH)) was assigned to each of the variables (layers) as done by various forest fire risk analyses (see Akay, 2019; Gulcin & Deniz, 2020). Parameters with the greatest effect on forest fire sensitivity were given the highest weight score. All parameters are given a risk score based on their level of sensitivity to fire. The most sensitive to fire is expressed with the number 4 (high-risk) and the less favorable is expressed with the number 0 (risk-free). Each layer is then evaluated based on its risk of forest fires and a forest fire risk index map is produced. To do this, a weighted overlay analysis is performed where the assigned weighted value of each thematic layer together with their assigned influence on forest fire is calculated based on pixel points. The risk map is then produced based on this analysis with a classification of

Received: 03.09.2023 Accepted: 12.10.2023

areas ranging from high to risk-free zones. Area distribution and the percentage of risk zones are estimated based on this analysis.

2.3. Land use Map

The land use map of the study area was generated from the CORINE database. The study area was classified into multiple classes (see Figure 3a). Forest boundaries were generated by delineating the forest area from the land use map. This was used in producing the forest area layer of the NDMI and that of the NBR. Roads and settlement layers were generated by clipping and extracting the road lines and settlement polygons from the land use type map obtained from OSM.

2.4. Forest Cover or Fuel types

To understand the vegetation type within the forest area, a Normalized Difference Moisture Index (NDMI) was performed on satellite data obtained from earth explorers with the help of ArcGIS. This index defines the moisture levels in vegetation mostly in drought and fire-prone areas (www.esri.com). It uses the NIR and SWIR bands (bands 5 and 6 respectively) to create a ratio designed to mitigate illumination and atmospheric effects. The calculation of the NDMI was performed by employing the following formula.

$$\mathbf{NDMI = (NIR - SWIR1) / (NIR + SWIR1) \qquad (1)}$$

The NDMI data identified several individual moisture classes within the forest area but this was then classified into five classes based on the classification criteria: 1) Very Dry 2) Dry 3) Moderate Moist 4) Moist 5) High Moist. This helps to differentiate between vegetation and fuel types based on their moisture index to understand the sensitivity of various parts of the forest to fire. This layer was included because fuel type plays a vital role in fire ignition and propagation (Keenan et al., 2015). Forest areas with low moisture index were considered to be more of a coniferous forest when overlapped with the land cover of the area and more prone to forest fire and those with high moisture index were discovered to be more of a deciduous forest and as such less prone to fire (Gazzard, 2012; Akay, 2019).

2.5. Topographic features

Two scenes of ASTER Global Digital Elevation Model (DEM) data were obtained from www.earthdata.nasa.gov. These scenes were combined, using mosaicking. Slope and aspect maps were generated by using the mosaic DEM of the study area with the help of ArcGIS. The slope was classified into the following five classes: Steep (>30^0), High (20-30^0), Middle (10-20^0), Low (5-10^0), Gentle (<5^0). Hill shade, water, and road layer enabled the verification of the slope information accuracy. The slope classes enabled the identification of high and low-risk areas. These features are factors known to contribute significantly to the spread and speed of fires (Akay, 2019). The spread intensity of forest fire increases as the surface slope increases which results in high fire risk and vice versa (Jaiswal et al., 2002). Likewise, the rate of forest fire and its risks rise as aspects face the sun directly as compared to those shadowed by mountains and fuels (Gülçin & Deniz, 2020). The flat direction was considered risk-free, the north was low risk, the east was moderate, the west was risky, and the south direction was considered high risk.

2.6. Roads and Settlements Proximity to the Forest

Settlement and road data layers were generated based on land use data from OSM. These data were extracted to suit the study area using ArcGIS. To assess the risk of forest fires in the study area, a distance (Euclidean) analysis was carried out around these features to understand their proximity to the forest. Forest areas closer to these features are considered to be more susceptible to fire and vice versa. Forest fire risk increases as the distance of the forest to the roads and settlements reduces (Sivrikaya et al., 2014). The proximity of the forest to roads and settlements is significant due to human influence on forest fire within the study area (see Gugliette et al., 2011; Malik et al., 2013; Castro et al. 2020).

2.7. Pre and Post-Fire Indices

Considering the date of the fire, two Landsat 8 ETM images were acquired one just after the fire had been extinguished and one a year before the fire. They were obtained from www.usgs.gov/earthexplorer. NDVI was used to identify the vegetation cover of the study area before the fire. This index represents the vegetation pattern of the earth's surface (Chen et al. 2016). This was utilized to determine the pre and post-fire NDVI and assess NBR to understand the area of damage caused by the fire in the study area. This will also help to distinguish between burned and unburned areas. These spectral indices were calculated by using the following equation (see Table 1).

Table 1. Indices and Equations Applied

Spectral Index	Abbreviation	Formula
Normalized Difference Vegetation Index	NDVI	$NDVI = \frac{NIR-R}{NIR+R}$
Normalized Burn Ratio	NBR	$NBR = \frac{NIR-SWIR}{NIR+SWIR}$

Source: author's research

The NDVI values range from -1 to +1. Areas representing a value of around 0 are poor in vegetation (built-up land, bare lands, etc.) whereas areas closer to +1 portray healthy vegetation, and areas near -1 show water bodies (ww.esri.com). Where NIR, R, and SWIR indicate the reflectance of the near-infrared, red, and short-wave Infrared bands respectively. NBR values ranging from -1 to 1 represent burned and unburned areas respectively. Conducting NBR by employing Landsat thermal bands provides enhanced results of burned and unburned land separation (Veraverbeke et al., 2011).

2.8. Weighted Value (AHP)

Based on previous studies (Malik et al., 2013; Akay, 2019; Gulcin & Deniz, 2020), a weighting index was assigned to each parameter based on their level of sensitivity to forest fires and the relative importance of each element. Vegetation had the highest weighted value of 30% since its contribution to forest fire is high. According to the individual vegetation, weighted values areas with low moisture content had high scores, and high moisture content had low values (Table 3). The slope was given the second-highest weighted value. The weighted value of slope indicated that slopes between 0-5 degrees had the maximum weights while high slopes had low weights. Distance from the roads and distance from the settlements were given the third and fourth weighted values respectively. In terms of distance, the weighted value rises as the distance between the forest area and these features reduces (Table 3). The aspect was given the fifth weighted score. Overall weighted values can be seen in Table 2.

Table 2. The Weighted Values of Criteria

Criteria	Influence (weighted values)
Vegetation/fuel type	30
Slope	25
Distance to Roads	20
Distance to Settlements	15
Aspect	10

Source: author's research

2.9. Validation

To validate the accuracy of the final forest risk, the 2017 fire incidence that occurred within the study area was adopted. Attributes of the fire event such as geographical coordinates were used to overlay with the final fire risk map produced. The value of the fire risk class on the pixel that corresponds to the fire incident was extracted to assess the distribution of the estimated fire risk classes that correspond to the recorded fire event. Land use data and other selected variables were also overlaid with the 2017 fire to validate their potential and degree to fires as well as the type of activities prone to fires in the study area.

Table 3. Weights Assigned to Each Applied Variable

Variable (weight)	**Class**	**Rating**	**Risks**
Vegetation	Very Dry	4	High Risk
	Dry	3	Risky
	Moderate Moist	2	Moderate
	Moist	1	Low Risk
	High Moist	0	Risk-Free
Distance to Road	<300	4	High Risk
	600	3	Risky
	1200	2	Moderate
	1800	1	Low Risk
	>1800	0	Risk Free
Distance to Settlement	<1000	4	High Risk
	2000	3	Risky
	2500	2	Moderate
	3000	1	Low Risk
	>3000	0	Risk Free
Slope	Up to 5	4	High Risk
	5-10	3	Risky
	10-15	2	Moderate
	15-20	1	Low risk
	>20	0	Risk Free
Aspect	South	4	High Risk
	West	3	Risky
	East	2	Moderate
	North	1	Low Risk
	Flat	0	Risks Free

Source: author's research

Received: 03.09.2023 Accepted: 12.10.2023

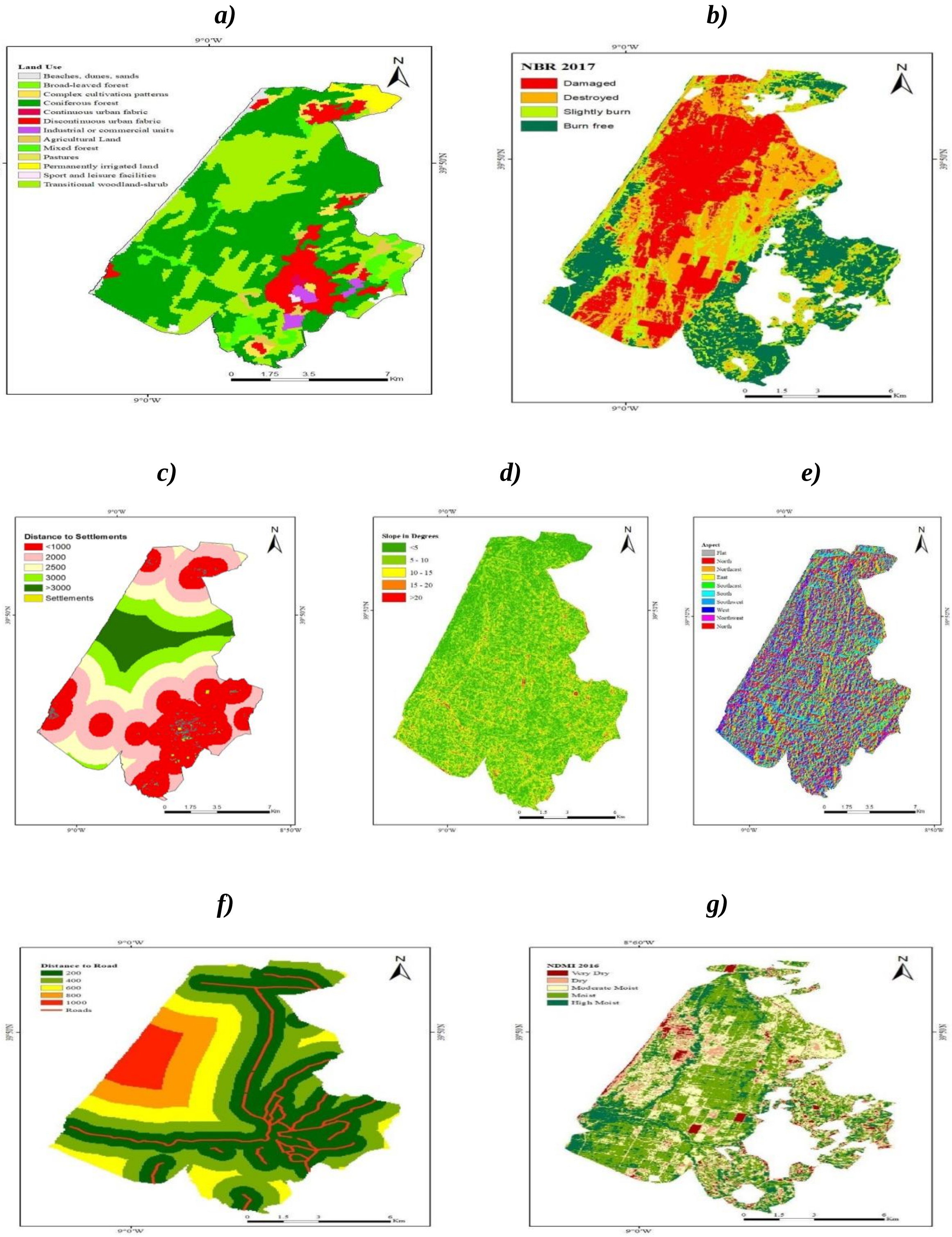

Figure 3. The seven individual variables adopted in this study (a) Land use *(Corine LULC Map, 2018)* **(b), NBR 2017 (c), Distance from settlement (d), Slope (e), Aspect (f) Distance from road (g) Fuel Type**

Source: author's research

Received: 03.09.2023 Accepted: 12.10.2023

4. Results

The final forest fire risk map was generated based on the thematic layers associated with fire ignition and propagation (vegetation type, proximity to settlements and roads, and topography (slope, aspect,) in Meta National de Leira. Five risk classes were set exclusively for each layer, namely risk-free, low-risk, moderate, high-risk, and risky (Table 3). The forest fire map showing the fire susceptibility zones was put forth through an overlay analysis in ArcGIS. This was generated by combining the weighted values of each variable (layers) based on their level of influence or their sensitivity to forest fire risk (Table 2). According to the risk map, 2% and 44% of the study area were found to fall within the high-risk and risky zones respectively. Besides, 50.8% had moderate risk, 2.9 % had low risk and 0.002% had risk-free forest fire risk. The degree of sensitivity together with the area is presented in a pie and bar graph respectively (Figure 5).

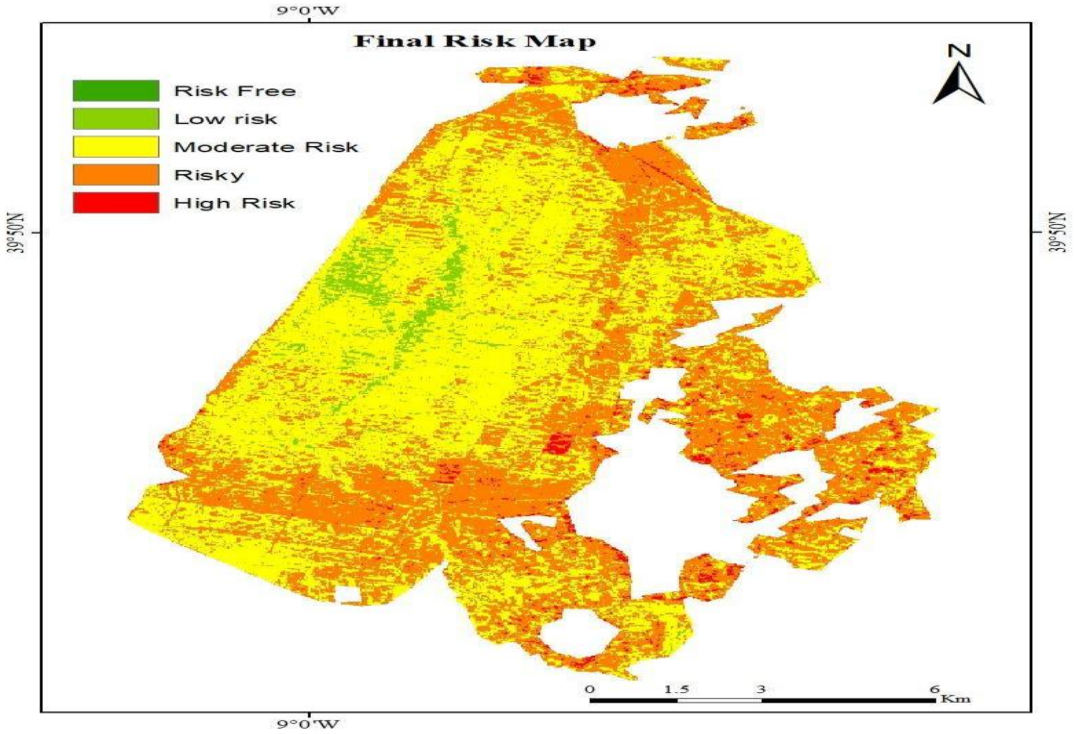

Figure 4. Final Forest Fire Risk Zone Map

Source: author's research

Received: 03.09.2023 Accepted: 12.10.2023

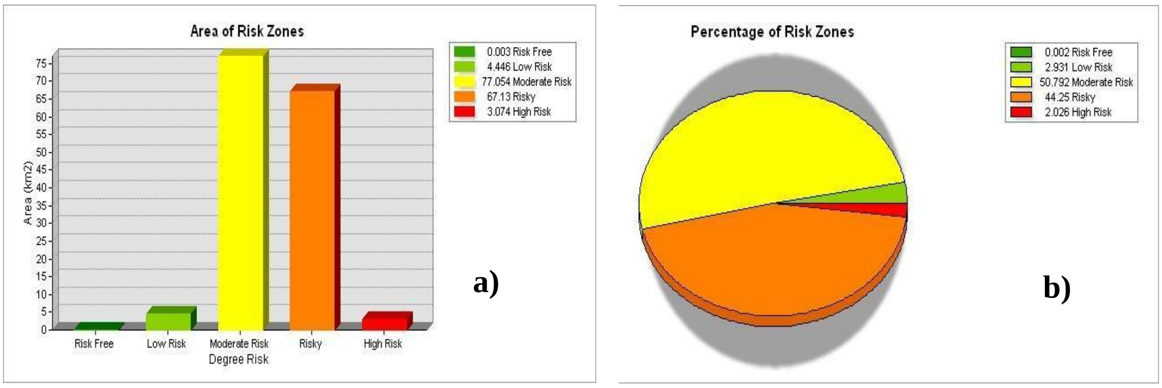

Figure 5. (a) Difference in Forest Fire Risk Zones, (b) Percentage of Forest Fire Risk Zones
Source: author's research

4. Discussion

Climate change, human and environmental processes have had a significant imprint on multiple forest resources, functions, and ecosystem services in Portugal (ICNF, 2017). One of the most apparent phenomena of these emerging catastrophes on forest resources is forest fires. Forest fires have been known to cause significant destruction to diverse forest ecosystems (Gülçina & Deniza, 2020). Forest fires have caused permanent damage and the extinction of many biological (biodiversity) and ecological features of Portugal's forests (Botequim et al. 2017). Besides, the cultural and economic values are greatly affected as a result of severe impacts on various tree species, and agricultural lands. This has greatly altered the sustainability of the forest across the jurisdiction (Oliveira et al., 2017; Aguiar et al., 2021; Casau et al., 2022). This has led to the need to understand forest fires to help plan, restore, and manage forest resources. To do this it is imperative to identify forest fire risk zones. Available literature posits that among the forest fire management techniques, determining risk areas is the most crucial stage of all as it allows the prediction and reduction of its threat (Yang et al., 2007; Gigović et al., 2018; Naderpour et al. 2021; Nuthammachot & Stratoulias, 2021).

Our analysis enabled us to assess, predict, and understand the sensitivity of future forest fire risk in Meta National de Leira after the 2017 forest fire that occurred within the jurisdiction. The finding from this study allows for a robust and realistic understanding of future forest fire risk and thus serves as an important decision tool for forest monitoring and management within the locality.

In this study, we mapped the forest fire susceptibility areas by adopting remote sensing and GIS techniques (Guney et al. 2016). Thus employing this method offers an effective and feasible understanding and identification of fire occurrence as well as mapping of potential fire risk areas (Renard et al. 2012). The forest fire risk zone map was developed based on the sensitivity of the forest area to fires. Both natural and human factors (fuel type, slope, aspect, distance to road and settlements) responsible for fires generally and that of previous forest fires within the study area were investigated and incorporated with the creation of the potential areas of future fire maps. This strategy was adopted because the usage of past forest fire information serves as a useful guide to assess and manage possible future fires (Yakubu et al., 2013). It is crucial to note that although tree species type and crown closure serve as vital factors in forest fire risk assessment (see Akay, 2019), due to the limitation of data acquisition the study could not incorporate that into its factors. A Normalized Difference Moisture Index was conducted in this regard. This was done in line with the assertation of the critical significance moisture plays in forest fire ignition, and spread, and helping to accurately predict the behavior of fire (Dover et al., 2011). The analysis of these factors enabled the identification and fire sensitivity ratings of the fuel types, topographic features (slope and aspect), and distance to road and settlement in the study location.

Each of these factors was analyzed individually based on their level of risk to forest fires. In terms of vegetation, the amount of fuel that feeds forest fires is determined. The study revealed that the rate of fire risk increases with decreasing moisture content of available vegetation (Pereira et al. 2013). The results demonstrate that about 57.8% of the forest area is in the high moist and moist zones while about 14.85% is in the dry and very dry areas (Figure 3g). This implies a little over half of the area is moist which will equate to low fire risk in terms of fuel type. However, it is important to note that the relationship may not be always linear (McAllister et al. 2012) when other factors are taken into consideration. Analysis of topographic features (slope and aspect) revealed that the biggest portion (55.1%) of the area was on high-risk slopes (0-5 degrees) while 0.2% of it (>20 degrees) was on low-risk whereas 30.3% was observed to be on high risks aspect (southern aspect) and 39.6% on low-risk aspects (Northern) (Figure 3d). Similarly, a large section (41.5% and 39.7%) of the forest area was within close proximity to roads and settlements respectively. This indicates that a significant proportion of assessed factors that contribute to forest fires have shown to exist in a considerable portion of the area. However, to get an overall understanding of risks, a final forest fire risk map analysis was conducted.

The final forest fire risk zones were produced by combining generally the weighted score of all individual factors. A new outlook of the forest fire risk map of the study area was generated through an overlay analysis (see Figure. 4) which was then classified into 1. Risk-free 2. Low risk 3. Moderate risk 4. Risky and 5. High risk. The results indicated that a large portion of the forest area was found to be within the high and risky zones (46%) (Figure 4). As much as 50.8% of the forest area was found within the moderate risk zones and a considerable area of about 3% was classified as low and risk-free zones.

Our study found that high and risky zones are mostly located in the south-eastern and northern parts of the study area whereas low and risk-free zones were found on the eastern side of the area. A clear comparison between the final risks map (Figure 4) and the vegetation types (Figure 3G) based on moisture indices indicates that high-risk areas are mostly low moisture fuel types while risk-free areas are high-moisture forest. A

Received: 03.09.2023 Accepted: 12.10.2023

comparison with the land use map also reveals that risky areas are mainly coniferous forest which is known to have low moisture that contributes significantly to the spread of fire (Gazzard, 2012). This confirms the assertion that species-related moisture is critical to forest fire risks (Peirera et al., 2013; Akay, 2019). It was also established that the observed high-risk and risky zones could be attributed to distance to roads and settlements as areas close to these features are more prone to fire risk (Leblon et al. 2012) coupled with differences in slope and aspect. This observation is consistent with previous forest fire risk empirical studies (see Yakubu et al., 2013; Akay, 2019; Castro et al., 2020). Risk-free and low-risk portions could also be due to their high moisture fuel type, unfavorable slope, and aspect as well as farther distance from roads and settlements of the forest area. An overlap of the final risk map with that of the previous fire revealed that the majority of the areas damaged by the fire were within the high, risky, and moderate risk zones of the final risk map generated while a considerable portion was within the low and risk-free zones. These results thus suggest an increased risk of future forest fires under the prevailing conditions and a hiking potential of increased burnt areas. This is consistent with studies done by Pereira et al. (2013) which project an increased likelihood of forest fire danger, frequency, and severity within the study region (under future climate scenarios). There is therefore the need to consider proactive management and preventive plans to ensure minimum risk of fire and avert possible future fires.

Conclusion and Recommendation

This study examines the forest fire risk in MNL through the consideration of vital factors responsible for fire ignition and propagation within the area. Through the integration of GIS approaches and data, five fire risk classes were established (risk-free, low risk, moderate risk, high risk, and risky). Although the general findings of this study did not take into account other crucial factors. The result has provided new and valuable information about future forest fire risk areas in Meta National de Leira through the forest fire risks and sensitivity assessment as highlighted in the study. Likewise, it has made available data that will enable the formulation of future forest fire strategic management and long-term forest conservation plans since the prediction and understanding of forest fire risk play a vital step in preventing unwanted fires and ensuring the sustainability of the forest ecosystem. This study with the help of the final risk map can significantly assist the forest agencies and managers within the study location in understanding and managing possible potential future fires. The spatial demarcation of risky zones can serve as a focal point for fuel management and also help forest rangers design effective preventive measures to augment the risk of fire propagation. While there has been a strategy that was drafted in 2010 outlining the required measures to fight against forest fires, among these measures are education and awareness, recovery and rehabilitation of the ecosystem, fire management, and organizational structure, and increased resilience to forest fire (AFN, 2010), however, these are not efficiently implemented (Castro et al. 2020). Based on these findings a fire management plan recommendation will be proposed;

- Given that human factors play a critical role in fire occurrence there is a need to improve social awareness: Making people aware or informed of the dangers their activities can pose to forest fires and their recurring effects on the sustainability of the forest ecosystem and functions will go a long way to proactively prevent future possible forest fires.
- To consider restricting activities that are likely to result in fires. Putting in place measures that prohibit or restrict people's activities such as extensive burning, use of cooking stoves and grills, pest control and fumigation, fireworks, etc. across designated areas of the forest will help prevent likely forest fires.
- To undertake early detection and prevention of fire using remote sensing techniques (Radar, thermal, optical, etc.): Through remote sensing (MODIS, GOES, SEVIRI, etc.) conditions critical to fires as well as active fires within the forest area could easily be identified, monitored and for quick preventive and management measures to be taken to prevent or restrict fires and it spread across broader areas.
- To incorporate a fire management plan into the overall forest management plan; The forest fire management plan should include preventive forestry operations: clearing bushes, creating fuel management strips, and using controlled fire to create discontinuity mosaics will influence the danger of forest fire, and significantly reduce it.
- To adopt an effective adaptive management approach (fuel-reduction techniques and fire prevention management of the forest). Since previous fires led to the increasing dominance of shrubs over trees in the forest, this, combined with other external factors such as climate, rise in biomass, etc., will increase the risk of forest fires. There is therefore the need to set up strategic areas of different fuel loads backed by an effective fuel management approach to ensure a more resilient landscape to the risk of likely future forest fires. Firefighting management must also be effectively prioritized.

Limitations and Future Research

This study aimed to understand the risk of forest fire through the consideration of factors such as vegetation, slope, aspect, and proximity to roads and settlements. Although the study had a broad goal of including other essential factors such as stand structure, soil, water, etc. to understand how various species' characteristics, proximity to water, soil type, etc. contribute to forest fire risks within the study area, unfortunately, this goal was not manifested. Acquisition of needed data from concerned agencies, time, and resources at the disposal of the researchers became a backlog.

Since stand structures (species type, crown closure, age, and height of tree), soil, climate, proximity to water, and firefighting stations play a practical role in forest fire risk assessment, management, and fighting. Thus further research could examine the forest fire risk sensitivity of the area and deeply understand the relationship between the spread and intensity of fires and surrounding environmental and logistic conditions and how this could proactively be prevented or managed by considering the factors stated above.

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