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ASSESING AND MAPING FOREST FIRE RISK IN BEJAIA, ALGERIA, USING GIS TEHNIQUE AND REMOTE SENSING

Abstract: Each year, Forest fires pose significant socio-economic and environmental challenges, particularly in Mediterranean regions. In this respect, the wilaya of Bejaia, located in the northeastern part of Algeria, is an illustrative example of forest fires. In this study, we used multi-source remote sensing data (MODIS, Landsat 8) and the Google Earth Engine (GEE) platform to assess and map the burn severity of forest fires that occurred in 2021. In addition, the Normalized Difference Vegetation Index (NDVI) and the Differenced Normalized Burn Ratio (dNBR) were applied to identify and analyze severity and extent of the damage. Results showed that approximately 15281.86 hectares, (4.69 % of the study area) were burned, with 7156.33 hectares classified as high-severity burns, mostly located in the northwestern part of the region, such as Adekar, El Kseur, and Kendera. Further analysis showed that topographical and environmental factors such as elevation, aspect and slope played a significant role in fire propagation. This research shows how GIS and remote sensing can be valuable tools for policymakers in designing targeted strategies for fire prevention and mitigation in high-risk areas.

Keywords: forest fire, NDVI, dNBR, burn severity, Bejaia

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Introduction

Forest fires (FF) have become a growing and major global problem, due to both human activities and natural disturbances. This problem is particularly grave in Mediterranean regions, including North Africa, where forest fires cause enormous environmental, human health and socio-economic problems (Anteur et al., 2021; Bar et al., 2020; Dixon et al., 2022; Yilmaz et al., 2023). The combination of climatic factors, increasing human pressure and poor forest management have greatly contributed to the increasing frequency and severity of these fires. The Mediterranean region is highly exposed to forest fires due to its hot, dry summers, dense vegetation and strong winds, which provide a favorable environment for rapid fire propagation (Masinda et al., 2022). Over the past 15 years, countries such as Spain, France, Italy and Algeria have seen a severe increase in fire activity, resulting in significant environmental degradation, soil erosion and biodiversity loss (Boulghobra, 2021). The main drivers of these fires include land use changes, climate change, increased human activities, such as deforestation urbanisation and uncontrolled agricultural burning. Climate change aggravates these risks by increasing temperatures, prolonging droughts, and reducing soil moisture, all of which can contribute to prolonging and intensifying fire seasons (Masson-Delmotte et al., 2021).

In addition to their direct destructive impacts on ecosystems, FF emit large amounts of gaseous trace substances and particulate matter including carbon dioxide (CO_2), sulfur oxide (SO_x) and methane (CH_4) into the atmosphere. These emissions change the chemical composition of the atmosphere resulting in accelerating climate change and influencing air quality and human health (Andreae, 2019; Crutzen et al., 1979). The Long-term environmental impacts include variations in local climate patterns, irregularities in water cycles and increased risk of desertification.

Algeria's forest ecosystems occupy around 4.1 million hectares, which is 17 per cent of the country's total land area (Anteur et al., 2021). These forests are divided into natural forests (1,427,000 hectares), scrublands (1,662,000 hectares) and reforested areas (718,000 hectares) (DGF 2018). The northern regions, including Bejaia, are particularly fragile due to their dense vegetation, high population density and difficult terrain, which increases the risk of fires (Bouhabila, 2019). The Bejaia region, part of the Djurdjura mountain range, has suffered increasingly frequent and severe forest fires over the past two decades. In 2021, large-scale forest fires caused damage to thousands of hectares between June and September, with the most affected areas being the municipalities of El Ksour, Kharta, Kendeira and Adikar (DGF 2022). These fires have been aggravated by extreme heat waves, strong winds and extreme drought conditions, which have accelerated the spread of the fires and complicated efforts to suppress them. The combination of steep slopes and difficult terrain also hindered traditional techniques of firefighting (Bouhabila, 2019). Given these challenges, satellite-based remote sensing has emerged as an essential tool for fire surveillance and damage evaluation (Zennir & Khallef, 2023). Compared to traditional land surveying, remote sensing makes for large-scale, high-resolution mapping of burned areas.

Numerous studies have shown the efficiency of using spectral indices, such as Normalized Difference Vegetation Index (NDVI) and Normalized Burn Index (NBR), to analyze fire severity and vegetation loss by comparing pre- and post-fire satellite imagery (Key & Benson, 2006; Khallef & Zennir, 2023) (Djaber et al., 2024; Guehaz & Venkataraman, 2023).

This study aims to identify and map the areas affected by the 2021 forest fires in the Djurdjura region of Bejaia using satellite data from Landsat 8 and MODIS. By employing NBR and NDVI spectral indices, this research provides a detailed analysis of burn severity and examines the impact of environmental and topographical factors on the fire spread (Fekir et al., 2022; Nouar et al., 2022; Yilmaz et al., 2023).

Materials and methods

Presentation of the study area

The Bejaia region, situated in northeastern Algeria, extends between longitudes 5.15°E to 5.5°E and latitudes 36.2°N to 37°N, covering an area of approximately 326 800 hectares (Fig. 1). It is located within a sub-humid bioclimatic zone, characterized by cold and moderate winters and an average annual temperature of 30.3 degrees Celsius (Nouar et al., 2022).

Moreover, the region's topography is predominantly mountainous, with slopes of more than 25% and elevations ranging from 600 to 1,000 m above sea level (Dahmana et al., 2006; Idir, 2013).while these rough terrains supports high biodiversity, it also increases its vulnerability to wildfires due to the rapid spread of fires along the steep slopes.

Wind conditions increase the risk of wildfires. Predominant winds, primarily from the north northeast, average up to 7 m/s during the summer months, creating favourable conditions for the fire spread (https://globalwindatlas.info/fr).

Ecologically, Bejaia is one of the most important forested areas in northern Algeria, with approximately 122,500 hectares of forests; it is home to nearly 55,000 hectares of Brutian pine (Pinus brutica) forests. This species highly susceptible to fire due to its resinous composition and dense structure. It is particularly vulnerable to the risk of forest fires.

It is well known that the likelihood of forest fires is directly influenced by the climatic conditions of a particular region. However, it is equally important to determine which areas are most vulnerable to fires under these conditions (Ćurić et al., 2022; Jovanović & Stojković, 2023). This necessitates analyzing additional natural factors that influence an area's susceptibility to wildfires, such as vegetation type and terrain characteristics. Additionally, to climatic and environmental factors, human activities significantly contribute to fire risk. Key factors include proximity to roads and pathways, agricultural land use, and the closeness of settlements to fire-prone areas (Novkovic et al., 2021).

The interaction between topographic, climatic, and ecological factors makes Bejaia a hotspot for forest fire risk evaluation and management.

Fig. 1. Location of the study area (Source: Authors)

Data acquisitions, processing and analysis

This study used data from Google Earth Engine (GEE), a cloud-based system designed for large-scale geospatial analysis, accessible at https://earthengine.google.com**.** GEE has proved to be an invaluable tool in many studies for burned area mapping due to its computational efficiency and powerful data processing capabilities (Chew et al., 2023; Gholamrezaie et al., 2022; Wagle et al., 2020).

To estimate the effect of forest fires in Bejaia, we combined data from two primary satellite sources: the Moderate Resolution Imaging Spectro-radiometer (MODIS) sensors used for large-scale fire monitoring and detection (Giglio et al., 2013; Justice et al., 1998). and Landsat-8 multispectral imagery, which gives high-resolution data for fire severity evaluation and post-fire vegetation assessment (Genç et al., 2023; Mirmazloumi et al., 2022). (Table 1).

Table 1. Data parameters and sources

Fire Event	Sensor	Data	Acquisition Date	ID
Djurdjura , Bejaia 2021	Landstat 8	Pre-fire	2021/03/17	LC08_L1TP_195035_20210307_20210317_02_T1
		Post-fire	2022/03/15	LC08_L1TP_195035_20220310_20220315_02_T1
Fire Event	Sensor	Data	Acquisition Date	ID
Djurdjura , Bejaia 2021	Landstat 8	Pre-fire	2021/03/17	LC08_L1TP_195035_20210307_20210317_02_T1
		Post-fire	2022/03/15	LC08_L1TP_195035_20220310_20220315_02_T1

According to the Algerian Forestry Directorate (DGF 2022), Bejaia wilaya experienced the most severe fire season in 2021, with an estimated 13,000 hectares burned. To assess and map the impact of these fires, Landsat 8 satellite imagery for the year 2021 was processed via the GEE platform to generate detailed analyses of burn severity and spatial distribution. To determine the spatial extent and intensity of these fires, Landsat 8 images from 2021 were analyzed on GEE, which enabled the creation of detailed maps of fire intensity and fire spread patterns. The use of the spectral indices such as Normalized Burning Ratio (NBR) and Normalized Difference Vegetation Index (NDVI) provided valuable insight into fire severity and affected vegetation.

Spatial maps showing distribution of forest burnt area

To evaluate the spatial extent of burned areas in the Bejaia region, we used the Google Earth Engine (GEE) platform, specifically using the MCD64A1 Burned Area product to identify and quantify the fire-affected zones. (Chew et al., 2023; Fornacca et al., 2017). This database used extensively for fire mapping due to its global coverage and high temporal resolution. However, The MCD64A1 product integrates two types of MODIS data sources: 500 m surface reflectance data, which determines the spectral changes in land cover and vegetation after a fire, and 1 km thermal anomaly data, which determines active fire hotspots according to changes in temperature (Giglio et al., 2018; Zhu et al., 2017) . By combining these datasets, the MCD64A1 allows for a comprehensive analysis of the spatial distribution and extent of burned areas, providing a reliable means of analyzing the impact of forest fire.

Normalized difference vegetation index (NDVI)

The Normalized Difference Vegetation Index (NDVI) is widely considered the most effective index for vegetation analysis in remote sensing applications (Rouse et al., 1974). It is calculated using the near infrared (NIR) and red (R) bands of the electromagnetic spectrum. This index is calculated based on the variance of the reflection between these two ranges (Pettorelli et al., 2005) (Eq. 1).

$$NDVI = \frac{NIR-R}{NIR+R} \quad (1)$$

NIR – near infrared reflectance (Band 5 for Landsat 8, extracted via Google Earth Engine - GEE);
R – red reflectance (Band 4 for Landsat 8, extracted via Google Earth Engine - GEE).

The NDVI is a highly valuable tool in remote sensing for assessing vegetation changes. It ranges from -1 to +1, where negative values correspond to water bodies, values around zero represent arid areas such as rocks or sand, and values close to +1 indicate a high density and healthy vegetation.

In this study, the NDVI values was obtained and analyzed using a JavaScript code editor within the (GEE) platform (Amiri & Pourghasemi, 2022). Additionally, to assess fire-impacted areas, we calculated the Difference Normalized Difference Vegetation Index (dNDVI) using pre-fire and post-fire satellite imagery (Kurnaz et al., 2020) (Eq. 2).

$$\mathrm{dNDVI} = \mathrm{dNDVI}_{\mathrm{prefire}} - \mathrm{dNDVI}_{\mathrm{postfire}} \quad (2)$$

The resulting DNDVI maps give a spatial illustration of burn severity, categorizing affected areas into different degrees of burn severity (Morante-Carballo et al., 2022;

Pattanasak, 2023) (Table 2). This categorization was made using QGIS 3.16 software, which ensures an accurate evaluation of the vegetation changes caused by the fires.

Table 2. Burn severity (dNDVI) classification

Severity Level	dNDVI Value
Very High	>0.45
High	0.33–0.44
Moderate	0.20–0.33
Low	0.13–0.20
Very Low	0.08–0.13
Unburned	<0.07

Normalized Burn Ratio (NBR)

The normalized burn ratio (NBR) is a remote sensing index specifically designed to detect burned areas, especially in large fire-affected regions (Key & Benson, 2006). This index uses the near infrared (NIR) and the short-wave infrared (SWIR) bands of the electromagnetic spectrum. The NBR is calculated by determining the normalized difference between the reflectance values in the NIR and SWIR bands (Escuin et al., 2008) (Eq. 3).

$$NBR = \frac{NIR-SWIR}{NIR+SWIR} \quad (3)$$

Where: SWIR – short-wave infrared (Band 7 for Landsat 8, extracted via Google Earth Engine - GEE).

The differenced Normalized Burn Ratio (dNBR) is used to assess fire severity (Chen et al., 2021; Mallinis et al., 2018). The dNBR is calculated by subtracting the post-fire NBR value from the pre-fire NBR value, were negative values indicating areas unaffected by fire, while positive values represent burned areas (Miller & Thode, 2007) (Eq. 4).

$$\mathrm{dNBR} = \mathrm{dNBR}_{\mathrm{prefire}} - \mathrm{dNBR}_{\mathrm{postfire}} \quad (4)$$

In this study, the dNBR maps were classified into different degrees of fire severity based on the classification framework developed by (Key & Benson, 2006) (Table 3). This classification process was conducted using GIS software.

Table 3. Burn severity levels obtained from dNBR (not scaled) (Key & Benson, 2006)

Severity Level	dNBR Values
High	>0.66
Moderate-High	0.44–0.65
Moderate-Low	0.27–0.43
Low	0.1–0.26
Unburned	<0.1

Results

Analysis of the results using the Google Earth Engine (GEE) platform, specifically utilizing the MCD64A1 Burned Area product indicates the total burned area in the Bejaia region during 2021 was 26,306.03 hectares, which accounts for 8.04 % of the total study area (Fig. 2). The spatial distribution of burned areas by administrative units showed that the north-western municipalities of Toudja, El Ksour, Adikar, Kendeira, Boukhlifa and Tifra were the most affected by the forest fires.

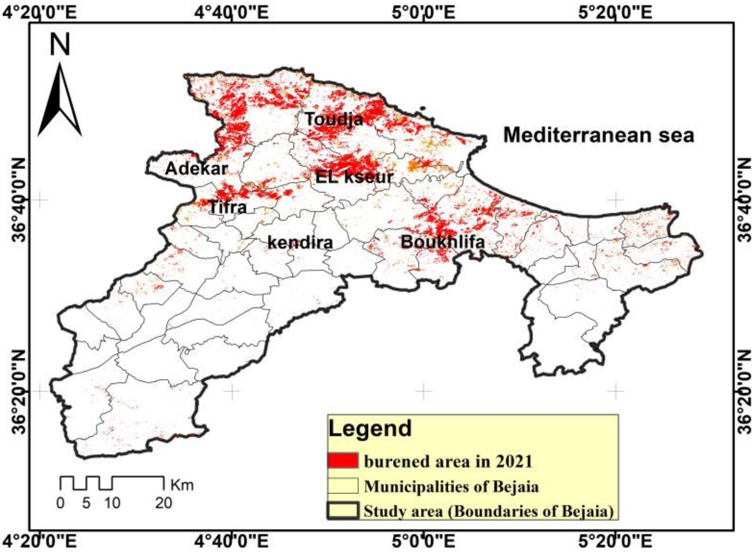

Fig. 2. Spatial distribution of burned areas in the Bejaia region (Source: Authors)

The fire severity map, produced using the dNDVI index is illustrated in (Fig. 3). The NDVI values, calculated for two different dates (pre-fire and post-fire), showed significant variations. Pre-fire NDVI values ranged from -0.29 to 0.63, while post-fire NDVI values varied between -0.3 and 0.61. This shows that vegetation health declined after the fire.

The maximum NDVI value between the pre-fire and post-fire observations declined to 1.16, with the most significant decrease observed in the municipalities most affected by the fires, including Adekar, Kharrata, El Ksour, Kendira, and Boukhelifa.

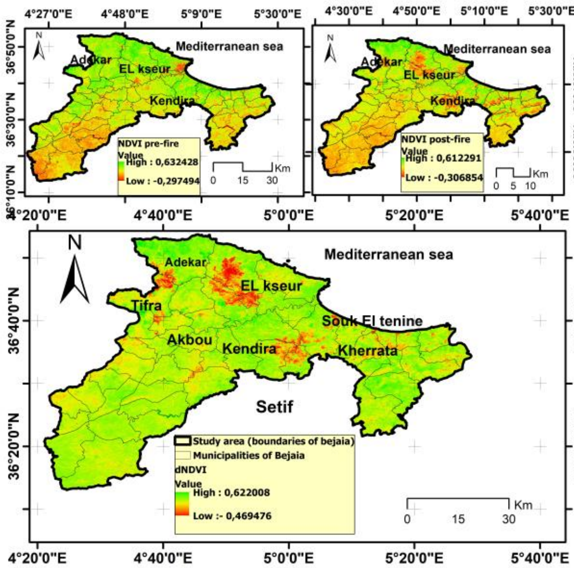

Fig. 3. The Normalized Difference Vegetation Index (NDVI) in Bejaia province: (A) NDVI pre-fire; (B) NDVI post-fire; (c) dNDVI (Source: Authors)

According to the fire map and an analysis of the burned areas using the (dNBR), the total unburned area in the study area was found to be 25,941.68 hectares, representing 7.95 % of the total study area (Table 4).

Table 4. Estimating the forest fires area of different fire severities

Severity Level	Area (ha)	(%)
High	628,18	0,19
Moderate-High	6528,15	2,00
Moderate-Low	8125,53	2,49
Low	284916,52	87,36
Unburned	25941,68	7,95

Source: Authors

While, approximately 15,281.86 hectares of the study area were affected by fire, with varying levels of severity (moderate and high). High-severity class accounted for 2.19 % of the total area, approximately 7,156.33 hectares. The most areas impacted by fires were located in El Ksour, Kendira, Adekar and Tifra (Fig. 4).

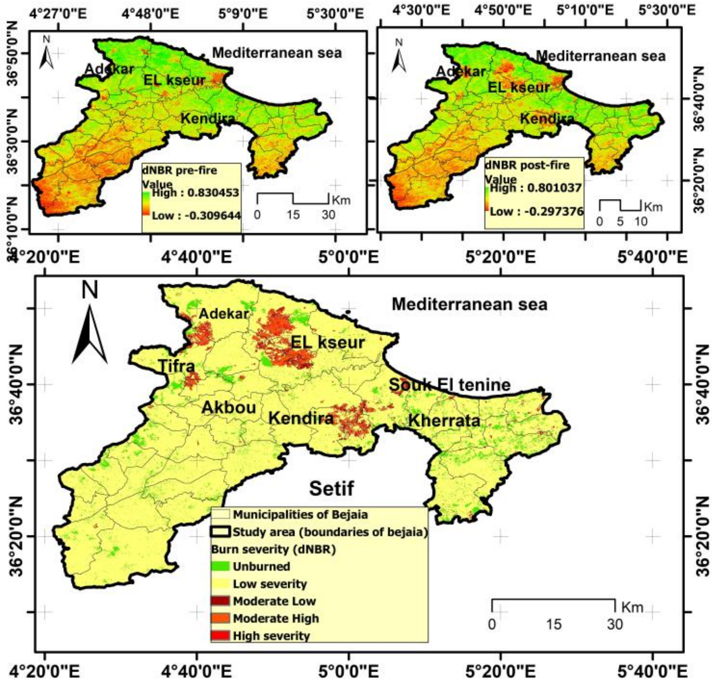

Fig. 4. The Normalized Burn Ratio (NBR) in Bejaia province: (A) NBR pre-fire; (B) NBR post-fire; (c) dNBR. (Source: Authors)

Discussion

Remote sensing indices acquired from Landsat 8 and MODIS satellite imagery, such as NDVI and NBR, are important tools for identifying fire-affected areas (Chen et al., 2021; Pelletier et al., 2021). In the present study, using these indices illustrated a significant impact of forest fires in the study area, with approximately 15,281.86 hectares of burned forest.

Using the dNBR index, the obtained value is relatively similar to the official report of the Algerian Forestry Directorate (DGF 2022), which registered 13,000 hectares burned in the wilaya of Bejaia. This close proximity indicates that the dNBR index gives a reasonable estimate of the damage caused by fires. In contrast, the MCD64A1 Burned Area product, extracted from MODIS data in Google Earth Engine (GEE) estimated the burned area at 26,306.03 hectares, which is much higher than both the DGF and dNBR estimates.

To validate these findings, satellite imagery was analyzed before and after the fire in the most affected areas (Fig. 5). However, this analysis confirms the efficiency of dNDVI and dNDB for identifying burned area. Additionally, the results of this study align with data from the Forestry Directorate (DGF 2022), which confirms the spatial distribution of the areas most affected by the fires in Bejaia. Similarly, Forestry Directorate statistics also indicate a marked increase in the number of wildfires during the fire season, with 157 incidents reported between June and October 2021 (DGF, 2022). These recurrent fire events underscore Bejaia's status as a high-risk area for wildfires.

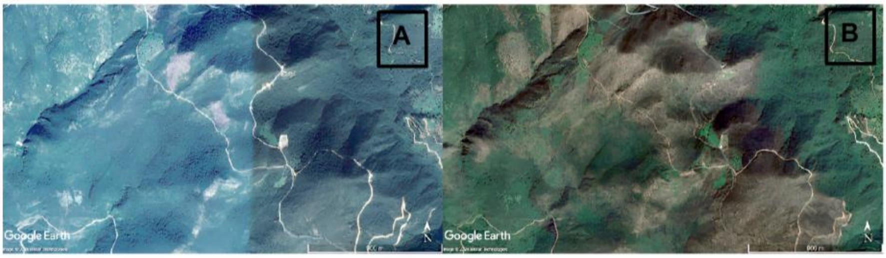

Fig. 5. Google Earth images of a burnt area: pre-fire (A) and post-fire (B)

The specific ecological and environmental characteristics of this wilaya played an important role in the recurrence of FF. This situation highlights the importance of conducting a detailed analysis of vegetation, as vegetation is a key factor in fire risk mapping.

In addition to vegetation analysis, topographic and morphological parameters, including slope, elevation and aspect extracted from Digital Elevation Model (DEM) data, are equally important for fire risk mapping (Aini et al., 2019). However, Elevation plays a more important role in wildfires spread in mountainous areas, particularly due to the challenges of accessing higher elevations. Additionally, the study area is mostly characterized by steep terrain, with slopes exceeding 20%. Furthermore, terrain aspect affects the frequency of fires, with north-facing slopes, which are more exposed to dry and hot winds (Fig. 6).

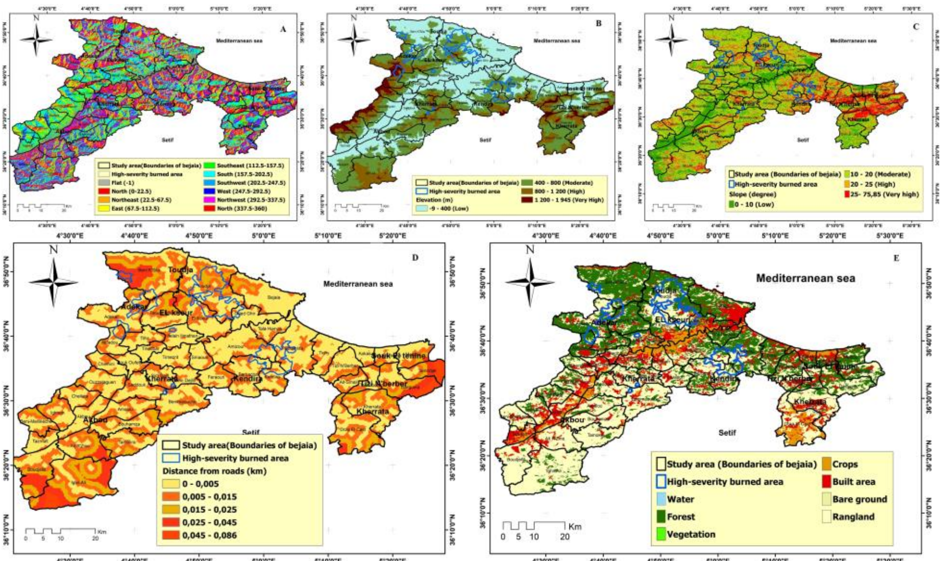

Fig. 6. Morph-topographic characteristics of the study area: (A) Aspect angle, (B) Altitude, (C) Slope, (D) roads Network and pathways, (E) Cover land (Source: Authors)

Conclusion

During the summer of 2021, forest fires devastated the Mediterranean region, including the wilaya of Bejaia. These fires resulted in catastrophic human losses, environmental degradation and significant economic challenges. In this study GEE was combined with multi-source remote sensing data from MODIS and Landsat 8 to detect and analyse burned areas affected by forest fires at a local scale.

This study utilized two methodologies to detect and identify burned areas affected by forest fires: the Difference Normalised Difference Vegetation Index (dNDVI), which evaluates changes before and after the fire and Difference Normalised Burn Ratio (dNBR), which assesses variations in burn severity and post-fire vegetation conditions. Additionally, the severity of the fires was categorized based on a standardized scale developed by the U.S. Geological Survey (USGS).

More to the point, the results showed that 2.19% of the total study area experienced high burn severity, with the most affected areas located at higher elevations and characterized by dense vegetation.

Furthermore, the integration of remote sensing and GIS techniques facilitated a detailed spatial analysis of forest fire patterns. These tools provide valuable information to forest managers, enabling them to determine areas most at risk of fire and optimize fire management strategies.

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