

GIS-BASED WILDFIRE RISK ASSESSMENT IN A MEDITERRANEAN PROTECTED AREA: A MULTI-CRITERIA ANALYSIS OF DAJTI NATIONAL PARK, ALBANIA

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ABSTRACT

Wildfires represent a major environmental threat in Mediterranean landscapes, particularly within protected mountainous areas where complex topography, vegetation patterns, climatic variability, and increasing human pressure interact. In this context, spatially explicit fire risk assessment is essential for effective prevention planning and sustainable ecosystem management. This study presents a GIS-based multi-criteria analysis for forest fire risk assessment in Dajti National Park, Albania. A comprehensive set of spatial factors was integrated, including terrain slope, aspect, land cover and land use, vegetation density derived from the Normalized Difference Vegetation Index (NDVI), temperature, rainfall, wind speed, and proximity to roads and settlements. Each factor was processed as a thematic raster layer and reclassified into standardized fire susceptibility classes ranging from very low to very high risk. The layers were subsequently combined using a weighted overlay approach to generate a composite wildfire susceptibility index. The resulting forest fire risk map reveals that moderate to high-risk zones dominate the study area, particularly in sectors characterized by steep terrain, dense or degraded vegetation cover, elevated temperatures, lower precipitation, higher wind exposure, and close proximity to infrastructure. Very high-risk zones are mainly concentrated along peripheral areas and access corridors, where anthropogenic influence overlaps with favorable natural conditions for fire ignition and spread. The results demonstrate the effectiveness of GIS-based multi-criteria analysis as a robust decision-support tool for forest wildfire susceptibility zoning in protected areas. The proposed methodological framework supports the identification of priority zones for fire prevention and management measures and is transferable to other Mediterranean and mountainous environments facing similar wildfire challenges.

Keywords: *Wildfire risk; GIS; Weighted overlay; NDVI; Multi-Criteria analysis; Protected areas; Disaster risk reduction.*

1. INTRODUCTION

Wildfires constitute one of the most critical natural hazards affecting Mediterranean regions, with severe consequences for ecosystems, human safety, and socio-economic systems. In recent decades, the frequency, intensity, and spatial extent of wildfire events have increased markedly, driven by the combined effects of climate change, land-use transformations, and the expansion of human activities at the wildland–urban interface (Bowman et al., 2009). Recent assessments indicate that Mediterranean Europe is experiencing longer fire seasons and an increasing likelihood of extreme wildfire events, underscoring the growing urgency of proactive and spatially informed risk reduction strategies (San-Miguel-Ayanz et al., 2021).

Mediterranean landscapes are particularly vulnerable to wildfires due to their climatic conditions—characterized by hot, dry summers—combined with complex topography and highly flammable vegetation types such as pine forests and shrublands (Pausas & Keeley, 2009).

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In these environments, wildfires represent not only a recurrent ecological disturbance but also a major disaster risk capable of generating cascading impacts, including biodiversity loss, soil erosion, air pollution, and threats to nearby settlements and infrastructure (FAO, 2020). These risks are especially pronounced in protected areas, where conservation objectives increasingly intersect with recreational pressure, accessibility, and infrastructural development.

Geographic Information Systems (GIS) and remote sensing have become essential tools for wildfire risk assessment, enabling the integration and spatial analysis of heterogeneous environmental and anthropogenic factors (Chuvienco & Salas, 1996). Recent advances in spatial wildfire science emphasize the importance of combining vegetation characteristics, topographic conditions, climatic variables, and human influence to enhance susceptibility mapping and to support disaster risk reduction and land-management policies (Chuvienco et al., 2021). Among available approaches, GIS-based multi-criteria analysis (MCA), including weighted overlay techniques, remains widely applied due to its transparency, adaptability, and suitability for regions where long-term fire records or detailed calibration data are limited.

Despite substantial progress in wildfire risk modeling at global and continental scales, significant gaps persist in Southeastern Europe. In Albania, spatially explicit wildfire susceptibility assessments remain scarce, particularly for protected areas, even as wildfire occurrence and human pressure continue to intensify. This lack of localized risk mapping constrains prevention planning, limits the effectiveness of early warning systems, and reduces the capacity of authorities to prioritize mitigation measures in the most vulnerable zones. Dajti National Park, located adjacent to the metropolitan area of Tirana, exemplifies these challenges. The Park is characterized by steep terrain, diverse forest ecosystems, and intense seasonal visitation, factors that collectively increase the probability of wildfire ignition and rapid fire spread. Its position at the wildland–urban interface further amplifies potential environmental and socio-economic impacts. While European-level monitoring systems provide valuable large-scale fire information, site-specific susceptibility assessments remain essential for operational risk reduction, protected area management, and local decision-making (San-Miguel-Ayanz et al., 2021).

In this context, the present study aims to assess wildfire susceptibility in Dajti National Park using a GIS-based MCA framework. By integrating key natural and anthropogenic factors—including topography, land cover, vegetation density, climatic variables, and proximity to infrastructure—this research identifies spatial patterns of wildfire risk and delineates zones requiring priority intervention. The study contributes to disaster risk reduction by providing a reproducible and transferable methodological approach that supports evidence-based prevention strategies and the sustainable management of wildfire-prone protected areas in Mediterranean environments.

2. MATERIALS AND METHODS

2.1. Study area

Dajti National Park is located in central Albania, immediately east of the Tirana metropolitan area, and covers approximately 28,561.85 ha. The Park represents a mountainous protected landscape characterized by steep slopes, complex terrain morphology, and a high diversity of forest ecosystems. Following the 2022 boundary redefinition (Decision of the Council of Ministers No. 59, 26 January 2022), the park includes not only Mount Dajti itself but also parts of the adjoining Mali me Gropa–Bizë–Martanesh massif on its eastern side. The area is influenced by a Mediterranean–continental climate, with hot and dry summers and increased precipitation during the winter season.

The park's close proximity to urban and peri-urban settlements, combined with intensive recreational activities during summer months, places it within a pronounced wildland–urban interface. Such conditions are widely recognized as significantly increasing wildfire ignition probability and potential impacts, particularly in Mediterranean protected areas (Moreira et al., 2011; San-Miguel-Ayanz et al., 2021) (**Fig. 1**).

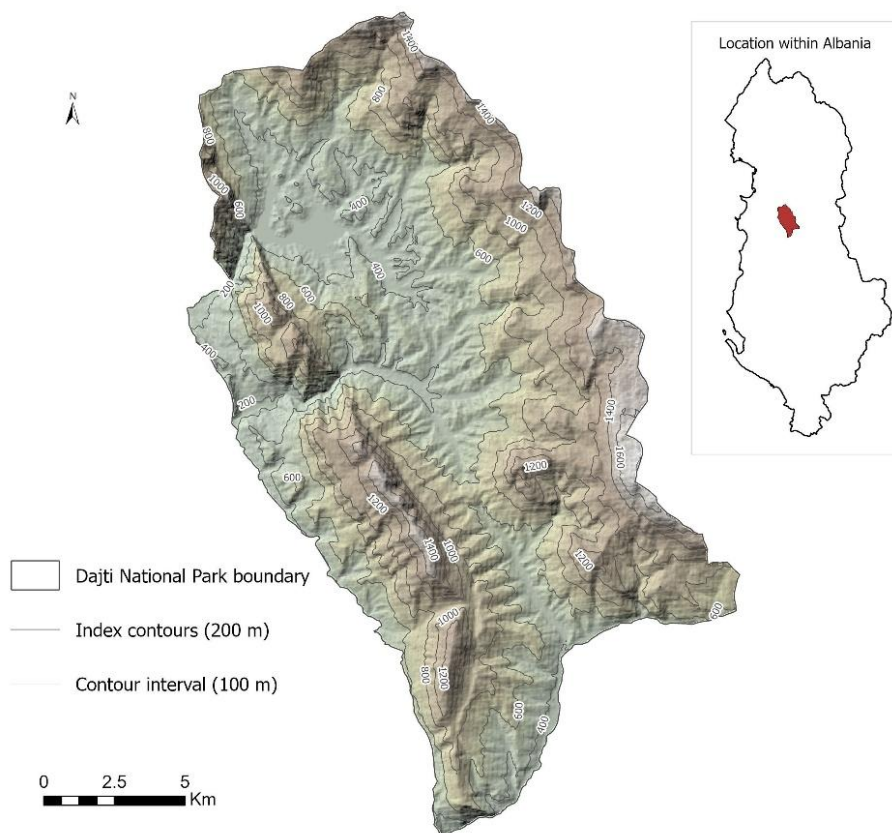


Fig. 1. Study area and topographic characteristics of Dajti National Park. The 30 m-resolution Digital Elevation Model (DEM) is displayed using a 100 m contour interval and 200 m index contours. Elevation ranges from 132 to 1,813 m above sea level (a.s.l.), with the highest values located in the eastern Mali me Gropa sector of the park. The coordinate reference system is WGS 1984 / UTM Zone 34 N.

2.2. Data sources and preprocessing

The wildfire susceptibility assessment was conducted using a GIS-based multi-criteria spatial analysis framework widely applied in wildfire hazard and environmental risk studies (Chuvieco et al., 2010; Pourghasemi et al., 2016). All spatial datasets were integrated into a unified geodatabase to ensure spatial consistency, geometric accuracy, and analytical reliability. Prior to analysis, all raster and vector layers were projected into a common coordinate reference system (WGS 1984 / UTM Zone 34N), resampled to a uniform spatial resolution of 30 m, and clipped to the boundary of Dajti National Park to ensure spatial alignment among all variables.

Topographic influence on wildfire susceptibility was represented by terrain slope derived from a 30 m DEM obtained from the United States Geological Survey (USGS) Earth Explorer database. Slope was calculated in degrees using standard terrain analysis tools within the GIS environment. Steeper slopes are known to accelerate fire spread and increase fire intensity due to enhanced heat transfer and fuel pre-heating processes (Sharples, 2009; Chuvieco et al., 2010).

Land use and land cover (LULC) information was derived from supervised classification of Landsat imagery obtained from the USGS Earth Resources Observation and Science (EROS) Center archive. Landsat imagery with 30 m spatial resolution was processed in ArcGIS Pro to generate land-cover classes representing the dominant surface types within the study area. Training samples were manually collected using the Training Samples Manager tool, and five land-cover classes were defined: water bodies, bare/urban surfaces, grasslands, shrublands, and forests.

The classification was performed using a Random Trees classifier, a machine-learning algorithm widely applied in remote sensing classification due to its ability to handle nonlinear relationships between spectral variables and land-cover categories. Following classification, a majority filter was applied to reduce isolated pixels and improve spatial coherence of the resulting LULC map. The final classified raster was subsequently clipped to the Dajti National Park boundary and used as an input variable in the wildfire susceptibility model. Landsat imagery is widely used for environmental monitoring and land-cover mapping due to its long-term temporal coverage and consistent spatial resolution (Wulder et al., 2019).

Vegetation density and fuel availability were represented using the NDVI derived from Landsat imagery. NDVI was calculated using the standard formula:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}$$

where NIR represents near-infrared reflectance and RED represents red spectral reflectance (Rouse et al., 1974).

Multi-temporal NDVI layers derived from Landsat imagery for the period 2022–2024 were analyzed to represent vegetation density and fuel load conditions during the peak vegetation season. NDVI is widely used in wildfire studies as an indicator of vegetation biomass, fuel continuity, and vegetation health (Chuvieco et al., 2004).

Table 1.

Data sources and characteristics of spatial variables used in the wildfire susceptibility analysis.

Variable	Data Source	Spatial Resolution	Temporal Coverage	Data Format	Description
Elevation (DEM)	USGS Earth Explorer	30 m	Static	Raster	DEM used to derive terrain slope and aspect
Slope	Derived from DEM (USGS)	30 m	Static	Raster	Terrain slope calculated in degrees
Aspect	Derived from DEM (USGS)	30 m	Static	Raster	Terrain orientation influencing solar radiation and fuel drying
Land Use / Land Cover	Landsat imagery (USGS EROS)	30 m	2023	Raster	Supervised classification using Random Trees algorithm
NDVI	Landsat imagery (USGS EROS)	30 m	2022–2024	Raster	Vegetation density and biomass indicator
Temperature	ERA5 (ECMWF)	Resampled to 30 m	Multi-year average	Raster	Climatic variable influencing fuel drying
Precipitation	ERA5 (ECMWF)	Resampled to 30 m	Multi-year average	Raster	Climatic variable affecting vegetation moisture
Wind Speed	ERA5 (ECMWF)	Resampled to 30 m	Multi-year average	Raster	Climatic variable influencing fire spread
Distance to Roads	OpenStreetMap (OSM)	30 m	Current	Raster	Euclidean distance from road network
Distance to Buildings	OpenStreetMap (OSM)	30 m	Current	Raster	Euclidean distance from building points
Fire Occurrence Data	MODIS Active Fire (NASA FIRMS)	~1 km	2001–2023	Point	Used for wildfire susceptibility model validation

Climatic variables including temperature, precipitation, and wind speed were obtained from the ERA5 climate reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 provides globally consistent atmospheric and land-surface variables derived from data assimilation and numerical weather prediction models (Hersbach et al., 2020). Climatic variables were extracted for a multi-year period and interpolated to raster surfaces with 30 m spatial resolution using the Inverse Distance Weighting (IDW) interpolation method in order to match the spatial resolution of the other environmental variables used in the analysis. IDW interpolation estimates unknown values based on spatially weighted averages of surrounding observations and is commonly applied in environmental spatial modeling where station density is limited (Li & Heap, 2014).

Anthropogenic influence was incorporated through proximity analysis, reflecting the well-documented role of human activity as a dominant ignition source in Mediterranean wildfire regimes (Catry et al., 2010; Moreira et al., 2011). Vector datasets representing road infrastructure and building location points obtained from OpenStreetMap (OSM) were converted into Euclidean distance rasters. These layers were used to calculate distance-to-road and distance-to-building indicators, representing potential anthropogenic ignition sources. Areas located closer to infrastructure were assumed to have higher wildfire ignition probability due to increased accessibility and recreational pressure.

To enhance methodological transparency and reproducibility, a Data Source Summary Table (**Table 1**) is provided, presenting the source, spatial resolution, temporal coverage, and data format of all variables used in the analysis. This table clarifies the characteristics of each dataset used for wildfire susceptibility modeling and for validation using historical fire occurrence data derived from MODIS active fire detections (2001–2023).

2.3. Selection of fire risk factors and Reclassification of thematic layers

The selection of wildfire risk factors was guided by consulting the literature addressing wildfire susceptibility in Mediterranean and mountainous environments, where fire occurrence results from the interaction of topographic, vegetation, climatic, and anthropogenic drivers (Jaiswal et al., 2002; Chuvieco et al., 2010; Vilar et al., 2016; Pourghasemi et al., 2016). To capture these interacting influences, the analysis incorporated a combination of natural and human-related variables representing both fuel conditions and ignition probability.

Based on data availability and their documented influence on wildfire dynamics, nine factors were selected for the susceptibility assessment: terrain slope, aspect, land use/land cover (LULC), vegetation density derived from the NDVI, temperature, precipitation, wind speed, distance from roads, and distance from buildings (mostly representing settlements). These variables are widely recognized as key determinants of fuel availability, ignition likelihood, and fire spread behavior in Mediterranean ecosystems (Jolly et al., 2015; Abatzoglou & Williams, 2016). Because the selected variables differ in measurement units and value ranges, all thematic layers were standardized prior to integration. Each variable was reclassified into five ordinal susceptibility classes ranging from 1 (Very Low risk) to 5 (Very High risk). This standardization approach is commonly used in GIS based multi-criteria wildfire susceptibility modeling to enable the integration of heterogeneous spatial variables within a unified analytical framework (Jaiswal et al., 2002; Chuvieco et al., 2014).

The reclassification procedure combined three complementary criteria: the statistical distribution of each variable within the study area, the physical interpretation of its influence on wildfire ignition and propagation and threshold values reported in comparable wildfire susceptibility studies conducted in Mediterranean environments.

This approach ensures methodological consistency with established wildfire modeling practices while allowing thresholds to be adapted to local environmental conditions. Terrain slope was derived from the DEM and classified into five categories representing increasing potential for fire spread. Steeper slopes promote faster uphill fire propagation due to enhanced convective heat transfer and fuel pre-heating (Sharples, 2009). The slope-based susceptibility classification used five classes: 0–5, 5–15, 15–25, 25–35, and >35, corresponding to increasing fire spread potential (**Fig. 2**).

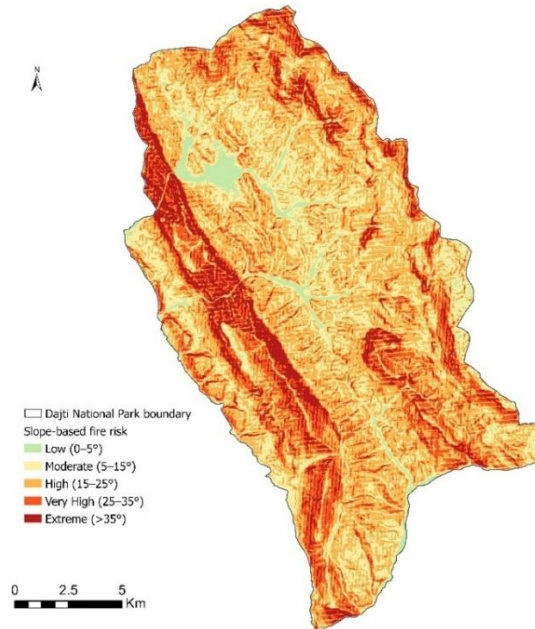


Fig. 2. Slope-based fire risk classification of Dajti National Park derived from a 30 m resolution DEM.

LULC classes were reclassified according to their potential fuel characteristics and combustibility. Grassland and shrubland formations were assigned higher susceptibility values due to greater fuel continuity and biomass accumulation, whereas water bodies and noncombustible surfaces were assigned lower susceptibility levels (**Fig. 3**).

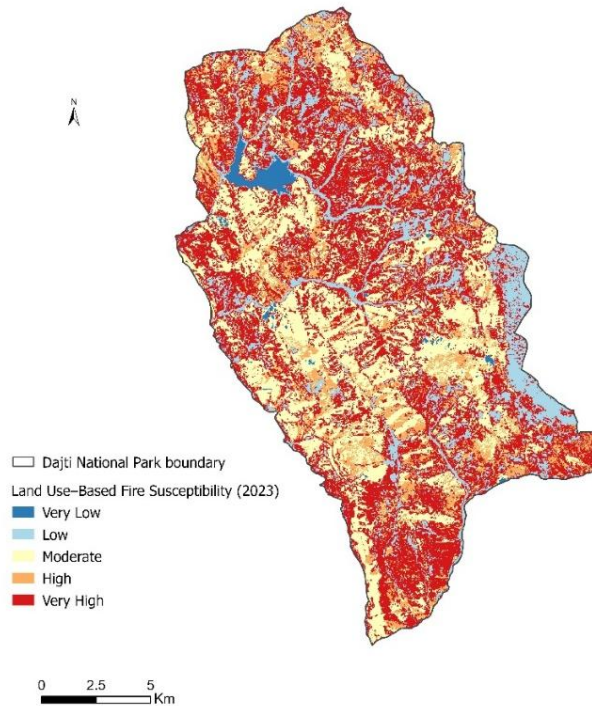


Fig. 3. LULC classes reclassified into five fire susceptibility levels (very low to very high) based on vegetation type and ignition potential. The resulting layer was used as an input factor in the weighted overlay model.

Vegetation density was further represented through NDVI values derived from Landsat imagery. Higher NDVI values indicate denser vegetation cover and therefore greater fuel availability, resulting in higher susceptibility classes (Chuvieco et al., 2004) (Fig. 4). The resulting reclassified layers represent spatially comparable indicators of wildfire susceptibility and constitute the input datasets for the subsequent multi-criteria overlay analysis.

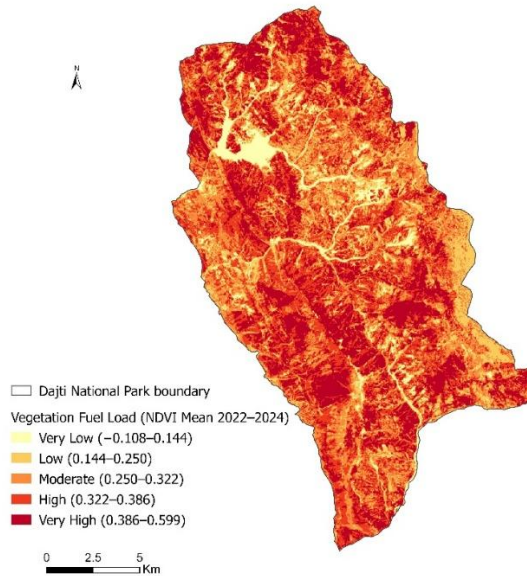


Fig. 4. NDVI-derived vegetation fuel load classes in Dajti National Park based on the multi-annual mean NDVI (2022–2024). NDVI values were classified into five categories using the Natural Breaks (Jenks) method and standardized to a 1–5 scale. Higher NDVI values indicate increased vegetation density and fuel availability. This layer was incorporated as the fuel component in the weighted overlay fire risk model.

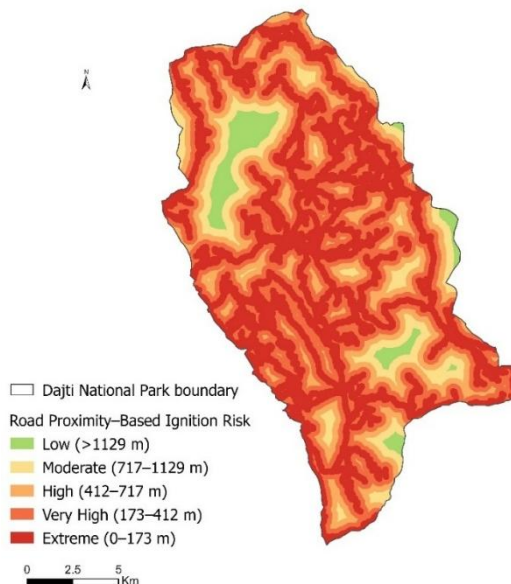


Fig. 5. Road proximity–based ignition risk map of Dajti National Park derived from Euclidean distance analysis (30 m spatial resolution). Distance values were classified using the Natural Breaks (Jenks) method and reclassified into five ignition risk categories, with areas closer to roads assigned higher ignition risk.

Climatic variables including temperature, precipitation, and wind speed were incorporated to represent environmental conditions influencing fuel moisture, ignition probability, and fire spread dynamics. Higher temperatures and stronger winds were associated with increased wildfire susceptibility due to enhanced fuel desiccation and fire propagation potential, while higher precipitation values were associated with reduced susceptibility due to increased fuel moisture (Jolly et al., 2015; Abatzoglou & Williams, 2016).

Anthropogenic factors were represented through distance-based indicators derived from road infrastructure and building location data. Proximity to roads and settlements is widely recognized as a key determinant of wildfire ignition in Mediterranean landscapes, where the majority of fires are human-induced (Catry et al., 2010; Moreira et al., 2011). Euclidean distance analysis was therefore used to generate distance-to-road (Fig. 5) and distance-to-settlement layers (Fig. 6). Areas located closer to infrastructure were assigned higher susceptibility values due to increased accessibility and human activity.

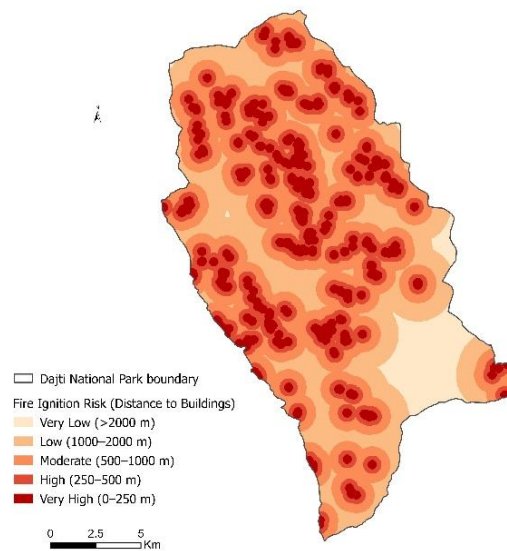


Fig. 6. Building proximity–based ignition risk map of Dajti National Park derived from Euclidean distance analysis (30 m spatial resolution). Distance values were calculated from building point locations obtained from OpenStreetMap (OSM) data and classified into five ignition risk categories (>2000 m, 1000–2000 m, 500–1000 m, 250–500 m, and 0–250 m). Areas located closer to buildings were assigned higher ignition susceptibility due to increased human presence and potential ignition sources.

The resulting reclassified layers represent standardized spatial indicators of wildfire susceptibility and constitute the input variables used in the subsequent weighted overlay analysis. To improve methodological transparency and reproducibility, the classification thresholds applied to each factor are summarized in **Table 2**, which presents the raw value ranges corresponding to each susceptibility class and the literature references supporting the adopted thresholds.

2.4. Weighting scheme, multi-criteria overlay analysis, and wildfire risk zoning

Following the reclassification of all thematic layers into a standardized wildfire susceptibility scale ranging from 1 (very low susceptibility) to 5 (very high susceptibility), the variables were integrated using a weighted overlay analysis within a Geographic Information System (GIS) environment. Weighted overlay analysis is a widely used approach in environmental risk assessment and spatial decision-support modeling because it enables the integration of multiple spatial variables with different units and value ranges into a single composite susceptibility index (Malczewski, 2006; Feizizadeh et al., 2014).

Table 2.

Reclassification scheme applied to wildfire susceptibility factors used in the weighted overlay model.

Factor	Class	Range / Category	Susceptibility Score
Slope (°)	Very Low	0–5	1
	Low	5–15	2
	Moderate	15–25	3
	High	25–35	4
	Very High	>35	5
Aspect	Low	North & Flat	1
	Moderate	East / West	3
	High	South	5
Land Use/Land Cover	Very Low	Water	1
	Low	Bare / Urban	2
	Moderate	Forest	3
	High	Shrubland	4
	Very High	Grassland	5
NDVI	Very Low	Lowest vegetation density	1
	Low		2
	Moderate		3
	High		4
	Very High	Highest vegetation density	5
Temperature (°C)	Very Low	Lowest values	1
	Low		2
	Moderate		3
	High		4
	Very High	Highest values	5
Precipitation (mm)	Very High	Highest rainfall	1
	High		2
	Moderate		3
	Low		4
	Very Low	Lowest rainfall	5
Wind Speed (m/s)	Very Low	Lowest wind speeds	1
	Low		2
	Moderate		3
	High		4
	Very High	Highest wind speeds	5
Distance to Roads (m)	Very High	0–173	5
	High	173–412	4
	Moderate	412–717	3
	Low	717–1129	2
	Very Low	>1129	1
Distance to Buildings (m)	Very High	0–250	5
	High	250–500	4
	Moderate	500–1000	3
	Low	1000–2000	2
	Very Low	>2000	1

In this study, each factor was assigned a specific weight representing its relative influence on wildfire ignition probability and fire spread potential. The weighting scheme was defined based on a review of wildfire susceptibility studies conducted in Mediterranean and mountainous environments, combined with the ecological interpretation of each variable within the study area. Factors representing human accessibility and ignition probability, such as distance to roads and distance to buildings, were assigned higher weights because human activities are widely recognized as the dominant ignition source in Mediterranean landscapes (Catry et al., 2010; Moreira et al., 2011; Vilar et al., 2016). Vegetation-related variables, including land use/land cover (LULC) and NDVI, were

also given relatively high weights because they represent fuel availability and continuity, which strongly influence wildfire behavior and fire intensity (Chuvienco et al., 2004; Pausas & Keeley, 2009).

Topographic and climatic variables were incorporated with moderate weights reflecting their influence on fire propagation and fuel moisture conditions. Terrain slope affects fire spread rate and direction due to convective heat transfer and fuel preheating (Sharples, 2009), while climatic variables such as temperature, precipitation, and wind speed influence vegetation dryness, ignition probability, and fire spread dynamics (Jolly et al., 2015; Abatzoglou & Williams, 2016). Aspect was included with a lower weight because its influence is mainly indirect, affecting solar radiation exposure and local microclimatic conditions.

Based on these considerations, the following weighting scheme was applied in the weighted overlay model: distance to buildings (17%), distance to roads (17%), NDVI (14%), land use/land cover (14%), slope (12%), temperature (8%), precipitation (8%), wind speed (5%), and aspect (5%). The sum of all weights equals 100%, ensuring proportional contribution of each factor to the final susceptibility index.

The weighted overlay analysis was implemented using the Weighted Overlay tool in ArcGIS, which multiplies the standardized susceptibility score of each factor by its assigned weight and then sums the resulting weighted layers to generate a composite wildfire susceptibility index.

The resulting continuous wildfire susceptibility surface was subsequently classified into wildfire susceptibility zones using the Natural Breaks (Jenks) classification method, which groups values based on inherent statistical patterns in the data and maximizes differences between classes while minimizing within-class variance. The final wildfire susceptibility map was divided into five categories: very low, low, moderate, high, and very high susceptibility.

The resulting wildfire susceptibility map provides an integrated spatial representation of the combined influence of environmental conditions and anthropogenic pressures within Dajti National Park. Given the park's proximity to the Tirana metropolitan area and its intensive recreational use during the summer season, this susceptibility zones provide a valuable spatial framework for identifying priority areas for wildfire prevention, monitoring, and management within a wildland–urban interface context (Moreira et al., 2011; San-Miguel-Ayanz et al., 2021).

3. RESULTS AND VALIDATION

3.1. Historical wildfire occurrence patterns

An analysis of historical wildfire occurrence was conducted in order to identify spatial patterns of fire activity within the study area and to support the subsequent validation of the wildfire susceptibility model. Historical fire data were obtained from the MODIS active fire detection dataset available through the NASA FIRMS platform, covering the period 2001–2023.

The spatial distribution of fire detections indicates that wildfire events are not evenly distributed across Dajti National Park but tend to cluster in specific areas characterized by greater human accessibility and favorable environmental conditions for fire ignition. Several clusters of fire occurrences can be observed in areas located close to transportation corridors and settlement zones, highlighting the importance of anthropogenic factors in wildfire ignition.

To further analyze the spatial concentration of wildfire events, a Kernel density estimation (KDE) analysis was performed, to generate a continuous surface representing the density of fire occurrences across the study area, allowing the identification of zones with a higher frequency of wildfire events. The kernel density map (Fig.7) reveals clear hotspots of wildfire activity, particularly in areas located near the park boundaries and in zones with higher accessibility. These spatial patterns are consistent with wildfire regimes in Mediterranean protected areas where human activities represent a major ignition source.

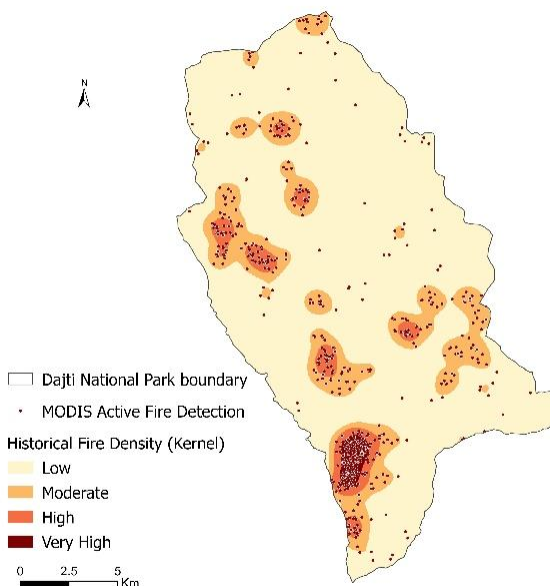


Fig. 7. Historical wildfire occurrences and kernel density distribution in Dajti National Park derived from MODIS active fire detections (2001–2023).

3.2. Spatial distribution of wildfire susceptibility

The GIS-based weighted overlay analysis produced a spatially continuous wildfire susceptibility surface representing the combined influence of topographic, vegetation, climatic, and anthropogenic factors within Dajti National Park (**Fig. 8**). The resulting wildfire susceptibility index was classified into five categories—very low, low, moderate, high, and very high—using the Natural Breaks (Jenks) classification method in order to preserve the natural distribution of the data.

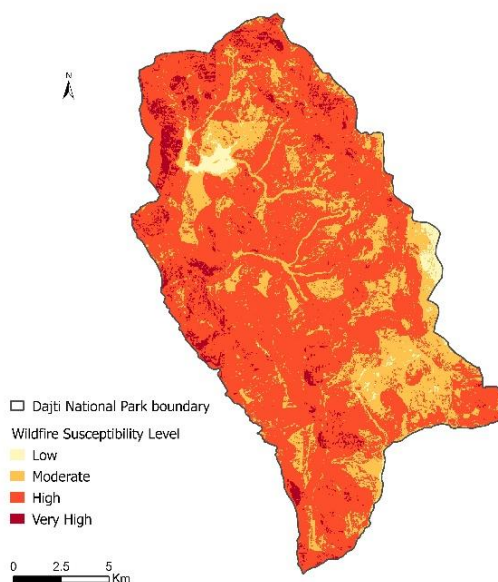


Fig. 8. Final wildfire susceptibility map of Dajti National Park derived from the GIS-based weighted overlay analysis integrating topographic, vegetation, climatic, and anthropogenic factors.

The final wildfire susceptibility map highlights a heterogeneous spatial distribution of wildfire risk across the park. Areas classified as high and very high susceptibility are mainly concentrated in zones characterized by dense vegetation cover, steep slopes, and close proximity to roads and settlements. These conditions facilitate both ignition probability and fire spread potential. Moderate susceptibility areas are distributed in intermediate zones where vegetation density remains relatively high but human accessibility is more limited. In contrast, low and very low susceptibility zones generally correspond to areas with limited vegetation cover, greater distance from infrastructure, or topographic conditions that reduce fire propagation potential. The spatial pattern observed in the susceptibility map reflects the interaction between environmental drivers and anthropogenic pressure within the study area. The proximity of Dajti National Park to the metropolitan area of Tirana and the high level of recreational use during the summer season contribute significantly to wildfire risk patterns within the park.

3.3. Validation of the Susceptibility Model Using Historical Fire Data

To evaluate the reliability of the wildfire susceptibility model, the spatial distribution of historical wildfire occurrences was compared with the predicted wildfire susceptibility classes. Fire occurrence data derived from MODIS active fire detections were overlaid with the final wildfire susceptibility map in order to assess the spatial correspondence between observed fire events and predicted risk zones. The results show that the majority of wildfire detections occurred within the moderate and high susceptibility classes, which together account for 97.37% of all recorded fire events. Specifically, 68.42% of fire occurrences were located in the High susceptibility class, while 28.95% were located in the Moderate class, indicating strong spatial agreement between the modeled wildfire risk and the observed fire activity. A smaller proportion of fires (2.32%) occurred within the Very High susceptibility class, which occupies a relatively small portion of the study area. Only 0.31% of fire detections were located within the Low susceptibility class, further supporting the ability of the model to distinguish between areas of lower and higher wildfire risk.

When normalized by area, the spatial distribution of fire occurrences reveals clear clustering patterns associated with zones of higher predicted susceptibility. These patterns are consistent with the influence of both environmental conditions and human activity on wildfire ignition and propagation. To statistically evaluate the relationship between wildfire occurrences and susceptibility classes, a Chi-square goodness-of-fit test was applied. The Chi-square goodness-of-fit test confirmed that wildfire occurrences are not randomly distributed across susceptibility classes (χ^2 test, $p < 0.001$), supporting the statistical validity of the wildfire susceptibility model (**Table 3**).

Overall, the strong correspondence between observed wildfire events and the predicted susceptibility classes demonstrate the effectiveness of the GIS-based multi-criteria model in identifying spatial patterns of wildfire risk within Dajti National Park.

Table 3.
Distribution of historical fire occurrences across wildfire susceptibility classes.

Risk Level	Raster Value	Number of Fires	Fire (%)
Low	2	2	0.31
Moderate	3	187	28.95
High	4	442	68.42
Very High	5	15	2.32

3.4. Quantitative Distribution of Wildfire Risk Classes and Identification of Priority Areas for Risk Reduction

The spatial distribution of wildfire susceptibility classes provides important insights into the wildfire risk structure within Dajti National Park. The analysis indicates that a substantial portion of the park falls within the moderate and high wildfire susceptibility classes, which together represent the dominant wildfire risk categories across the landscape (**Fig. 9**). Although very high susceptibility zones occupy a relatively small proportion of the total park area, they form spatially coherent clusters

that represent critical hotspots for wildfire prevention and management interventions. These areas are typically located near transportation corridors, recreational facilities, and settlement boundaries where human activities increase the probability of wildfire ignition. In contrast, low susceptibility areas are limited in spatial extent and are generally associated with zones characterized by lower vegetation density or reduced accessibility. These areas exhibit comparatively lower wildfire risk due to less favorable conditions for ignition and fire spread.

The final wildfire susceptibility map therefore provides a robust spatial framework for identifying priority areas for wildfire risk reduction and management planning. Very high-risk zones located near infrastructure and recreational areas represent critical locations where fuel management, monitoring programs, and access control measures should be prioritized. Furthermore, the presence of extensive high susceptibility zones forming continuous spatial belts across the landscape suggests that wildfire prevention strategies should also consider broader landscape-level processes rather than focusing exclusively on isolated hotspots.

Moderate risk areas also warrant attention, as they may transition into higher susceptibility classes under extreme climatic conditions such as prolonged drought or heat waves. Overall, the results highlight the importance of spatially explicit wildfire risk mapping in supporting evidence-based wildfire prevention strategies and sustainable management of protected mountain landscapes.

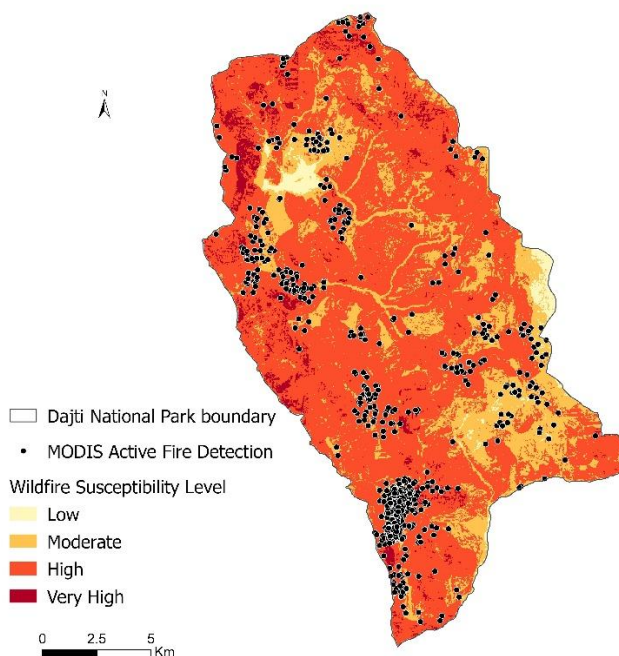


Fig. 9. Spatial validation of the wildfire susceptibility model through overlay analysis of historical fire detections and predicted wildfire risk classes in Dajti National Park. Historical fire occurrences (MODIS active fire detections, 2001–2023) are superimposed on the wildfire susceptibility map to assess the spatial correspondence between observed fire events and modeled risk zones.

4. DISCUSSION

4.1. Spatial Patterns of Wildfire Susceptibility

The wildfire susceptibility assessment conducted for Dajti National Park reveals a spatial configuration that reflects the combined influence of environmental and anthropogenic drivers typical of Mediterranean mountainous landscapes. The predominance of moderate and high susceptibility

classes across large portions of the park indicates that wildfire risk is not restricted to isolated hotspots but rather represents a landscape-scale phenomenon shaped by multiple interacting factors.

Topographic conditions play an important role in shaping the observed spatial patterns of susceptibility. Areas characterized by steeper slopes are systematically associated with higher wildfire risk levels. Steep terrain promotes faster fire propagation through increased flame tilt and enhanced pre-heating of fuels, while simultaneously limiting accessibility for fire suppression operations. These relationships have been widely documented in wildfire behavior studies and are particularly relevant in mountainous protected areas where complex terrain influences both ignition dynamics and fire spread (Chuvieco & Salas, 1996; Sharples, 2009).

Vegetation-related variables also contribute significantly to the spatial distribution of wildfire susceptibility. Areas with high vegetation density, as represented by NDVI, correspond to zones with greater fuel availability and biomass accumulation, which can increase potential fire intensity once ignition occurs. At the same time, LULC characteristics influence ignition susceptibility. In the present study, grassland and shrubland areas exhibited higher susceptibility levels due to the presence of fine and highly flammable fuels, while forest areas were associated with moderate susceptibility levels. This distinction reflects the fact that fine fuels generally ignite more easily and promote rapid fire spread, whereas forest fuels may support higher fire intensity but may require stronger ignition conditions (Pausas & Keeley, 2009; Silva et al., 2019). The resulting spatial pattern therefore reflects the interaction between fuel availability, terrain characteristics, and accessibility, which together determine wildfire susceptibility across the landscape.

4.2. Anthropogenic Influence and the Wildland–Urban Interface

Anthropogenic factors represent a key driver of wildfire susceptibility in the study area. The spatial analysis demonstrates that areas located in close proximity to roads and buildings tend to exhibit higher wildfire susceptibility levels. This pattern reflects the strong influence of human activity on wildfire ignition in Mediterranean environments, where the majority of fires are caused by accidental or intentional human actions (Moreira et al., 2011).

Dajti National Park is situated immediately adjacent to the metropolitan area of Tirana and therefore represents a pronounced wildland–urban interface (WUI) environment. The presence of recreational facilities, tourism infrastructure, and transportation corridors increases human presence within the park, particularly during the summer season when climatic conditions are also most favorable for wildfire ignition and spread. Under such circumstances, wildfire risk is shaped not only by environmental factors but also by patterns of land use, accessibility, and human behavior. The results of the susceptibility analysis highlight the need for wildfire prevention strategies that integrate ecological management measures with spatial planning and public awareness initiatives, particularly in protected areas experiencing increasing recreational pressure.

4.3. Implications for Disaster Risk Reduction and Protected Area Management

From a disaster risk reduction perspective, the spatial delineation of wildfire susceptibility zones provides a valuable framework for prioritizing prevention and mitigation measures within Dajti National Park. Areas classified as high and very high susceptibility, particularly those where dense vegetation, steep slopes, and proximity to infrastructure overlap, represent priority zones for wildfire risk management. In these areas, targeted interventions such as fuel management, vegetation thinning, improved monitoring systems, and early detection measures could significantly reduce wildfire risk. The spatial identification of such zones allows management authorities to allocate resources more efficiently and to focus preventive actions where they are most needed.

At the same time, the widespread presence of moderate susceptibility zones suggests that wildfire risk management should adopt a broader landscape perspective. Moderate-risk areas may become highly susceptible under extreme climatic conditions such as prolonged drought or heat waves. Therefore, preventive strategies should address landscape-level fuel continuity and connectivity rather than focusing exclusively on localized hotspots. In this context, GIS-based wildfire susceptibility mapping provides a practical decision-support tool for integrating wildfire risk considerations into protected area management and spatial planning processes.

4.4. Methodological Considerations, Limitations and Future Research

The GIS-based MCA framework applied in this study provides a transparent and reproducible approach for wildfire susceptibility assessment in data-limited contexts. The integration of environmental and anthropogenic variables within a weighted overlay model allows the identification of spatial patterns of wildfire risk even where detailed fire occurrence datasets are limited.

One methodological limitation concerns the use of literature-based weighting for the susceptibility factors rather than deriving weights through statistical calibration. Although such approaches are widely applied in wildfire susceptibility studies (Malczewski, 2006; Pourghasemi et al., 2016), they may introduce a degree of subjectivity in the relative influence assigned to individual variables. Nevertheless, the comparison between the wildfire susceptibility map and historical fire occurrences derived from MODIS active fire detections demonstrates a strong spatial agreement between predicted risk zones and observed wildfire events. The majority of recorded fires occurred within the moderate and high susceptibility classes, supporting the predictive capability of the model.

Future research could further improve the accuracy of wildfire susceptibility assessments by incorporating higher-resolution vegetation data, longer-term fire occurrence datasets, and dynamic climatic indicators that capture seasonal variations in fuel moisture and fire weather conditions. Such developments would allow more detailed statistical calibration and enable the development of dynamic wildfire risk models capable of supporting adaptive management strategies.

5. CONCLUSIONS

This study applied a GIS-based MCA framework to assess wildfire susceptibility in Dajti National Park, a protected mountainous landscape located at the wildland–urban interface of the Tirana metropolitan region. By integrating topographic, vegetation, climatic, and anthropogenic factors within a weighted overlay model, the analysis produced a spatially explicit wildfire susceptibility map that reveals significant spatial variability in wildfire risk across the park.

The results indicate that moderate and high wildfire susceptibility zones dominate the park landscape, demonstrating that wildfire hazard represents a structurally embedded environmental risk rather than a localized phenomenon. High and very high susceptibility zones are primarily associated with the combined presence of steep terrain, dense vegetation cover, and proximity to roads and settlements. These findings highlight the importance of both environmental conditions and human accessibility in shaping wildfire risk patterns within protected areas located near urban centers.

The validation of the susceptibility model using historical wildfire detections further confirms the reliability of the proposed methodological approach. The majority of recorded wildfire events occur within areas classified as moderate and high susceptibility, demonstrating strong spatial correspondence between modeled risk zones and observed fire activity.

From a disaster risk reduction perspective, the study demonstrates the value of GIS-based wildfire susceptibility mapping as a decision-support tool for prevention-oriented wildfire management.

The identification of spatial risk gradients provides a practical basis for prioritizing intervention areas and supporting more efficient allocation of resources for fuel management, monitoring, and access control.

Although the analysis relies partly on literature-based weighting due to data limitations, the transparency and reproducibility of the adopted methodology make it particularly suitable for data-scarce environments such as many protected areas in Southeastern Europe. The proposed framework therefore provides a useful basis for supporting wildfire risk awareness, improving spatial planning, and guiding sustainable management strategies in wildfire-prone protected landscapes.

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