Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

GIS and Remote Sensing-Based Forest Fire Risk Assessment Using a Multi-Criteria Fire Risk Index in the Potohar Region, Pakistan

Aftab Ahmad Khan
Global Climate-Change Impact Studies Centre (GCISC), MOCCEC Islamabad, Pakistan Email: aftabalam_2005@yahoo.com

Usman Mughal
Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, 46300, Pakistan
Email: usman36m@gmail.com

Fiaz Hussain*
Pir Mehr Ali Shah Arid Agriculture University Rawalpindi, 46300, Pakistan
Email: engr.fiaz@uaar.edu.pk

Muhammad Arif Goheer
Global Climate-Change Impact Studies Centre (GCISC), MOCCEC Islamabad, Pakistan Email: arifgoheer@gmail.com

Huma Aziz
Scientific Officer (S.O), Natural Resources Division NRD PARC, Pakistan Agricultural Research Council PARC Pakistan Email: humaaziz@parc.gov.pk

Muhammad Ijaz
Global Climate-Change Impact studies Centre (GCISC), MOCCEC Islamabad, Pakistan Email: muhammad.ijazmalik@gmail.com

ABSTRACT

Forest fires are becoming increasingly frequent and severe worldwide due to climate change, prolonged dry periods, and expanding human activities, posing substantial threats to forest ecosystems, biodiversity, and socio-economic resources. In Pakistan, the Potohar region, particularly the Margalla Hills National Park, has experienced recurrent wildfire incidents that highlight the need for reliable fire-risk assessment tools. This study presents a Geographic Information System (GIS) and remote sensing-based approach for assessing forest fire risk by integrating multiple environmental and anthropogenic factors into a Fire Risk Index (FRI). Seven variables, including vegetation condition derived from the Normalized Difference Vegetation Index (NDVI), land surface temperature (LST), slope, aspect, elevation, distance from roads, and burned area identified using the Normalized Burn Ratio (NBR), were extracted from Landsat 8/9 imagery, ASTER Digital Elevation Model (DEM), and ancillary spatial datasets. A weighted multi-criteria overlay analysis was performed in ArcGIS to generate a spatially explicit forest fire risk map of the Potohar region. The resulting map identified the Margalla Hills and surrounding forested

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

landscapes as the most fire-prone areas during the pre-monsoon season, primarily due to elevated temperatures, dense vegetation, steep terrain, and proximity to human activities. Burn severity analysis revealed approximately 8.09 km² of forest area affected during the June 2022 wildfire event, while land surface temperature increased by nearly 8°C in the burned region following the fire. The predictive performance of the proposed model was evaluated using Kernel Density Estimation (KDE), which demonstrated good agreement between historical fire occurrences and high-risk zones. The developed framework provides an efficient and cost-effective decision-support tool for identifying vulnerable areas, improving wildfire preparedness, prioritizing resource allocation, and supporting sustainable forest management in Pakistan. The methodology is transferable to other fire-prone landscapes with similar ecological and climatic characteristics.

Keywords: Forest fire risk assessment; Geographic Information System (GIS); Remote sensing; Fire Risk Index (FRI); Landsat; Multi-criteria analysis; Potohar Region; Pakistan.

Introduction

Forest fires are among the most destructive natural hazards affecting terrestrial ecosystems worldwide (Pourghasemi et al., 2020). They play a significant role in shaping vegetation dynamics, nutrient cycling, carbon emissions, and biodiversity while simultaneously threatening human lives, infrastructure, and ecosystem services. Over the past few decades, the frequency, intensity, and spatial extent of forest fires have increased considerably due to climate change, prolonged droughts, rising temperatures, and expanding human activities. These changes have intensified wildfire risks across many regions of the world, making forest fire management an important component of environmental conservation and disaster risk reduction (Bowman et al., 2020; Jones et al., 2022).

Wildfires are influenced by a complex interaction of environmental and anthropogenic factors. Environmental variables such as vegetation type, fuel moisture, land surface temperature, precipitation, wind conditions, topography, and elevation determine the susceptibility of an area to fire ignition and spread. Human activities, including agricultural burning, tourism, road networks, urban expansion, and accidental or intentional ignitions, further increase the likelihood of wildfire occurrence, particularly in forests located near populated areas (Chuvieco et al., 2023). Consequently, understanding the spatial distribution of these controlling factors is essential for identifying fire-prone landscapes and developing effective mitigation strategies.

Recent advances in Geographic Information Systems (GIS) and remote sensing have significantly improved the capability to monitor, analyze, and predict forest fire hazards. Satellite-derived products provide continuous observations of vegetation conditions, thermal characteristics, and burned areas at regional to global scales. Vegetation indices, particularly the Normalized Difference Vegetation Index (NDVI), are widely used to assess vegetation density and fuel availability, while the Normalized Burn Ratio (NBR) is an established indicator for mapping burn severity following wildfire events (Key & Benson, 2006). Likewise, land surface temperature

Online ISSN 3007-3197
Print ISSN 3007-3189

(LST) derived from thermal infrared satellite imagery provides valuable information on surface heating and vegetation moisture conditions, both of which strongly influence fire ignition potential. When integrated with topographic parameters such as slope, aspect, and elevation, these datasets provide a comprehensive framework for evaluating wildfire susceptibility.

Multi-Criteria Decision Analysis (MCDA) (Saaty, 1980) implemented within a GIS environment has become one of the most widely adopted approaches for forest fire risk assessment because it enables the integration of multiple environmental and socio-economic variables into a single spatial decision-support model (Malczewski, 1999). John Wiley & Sons. Previous studies have successfully applied weighted overlay techniques using combinations of vegetation indices, temperature, topography, accessibility, and anthropogenic factors to delineate forest fire risk zones and support wildfire management planning (Jaiswal et al., 2002;Sivrikaya andKüçük, 2022). Such approaches are particularly valuable in regions where long-term wildfire inventories are limited but spatial environmental datasets are readily available.

Pakistan has experienced an increasing number of wildfire incidents in recent years, particularly in the Himalayan foothills and the Potohar Plateau. The Margalla Hills National Park, which forms an important ecological corridor between the Himalayan and sub-Himalayan regions, has repeatedly experienced severe forest fires during the pre-monsoon season. These fires have resulted in substantial losses of vegetation, wildlife habitat, and ecosystem services while posing significant challenges to forest managers and emergency response agencies. The combination of rugged terrain, dense vegetation, elevated temperatures, and increasing human interference has made the region particularly susceptible to wildfire events. Despite the ecological importance of the Potohar region, comprehensive spatial assessments integrating environmental and anthropogenic fire-risk factors remain limited.

Most existing studies in Pakistan have primarily focused on post-fire damage assessment or individual environmental variables, whereas relatively few have developed integrated fire-risk models that combine vegetation characteristics, thermal conditions, topographic features, and human accessibility into a unified framework. Furthermore, limited attention has been given to validating spatial fire-risk models using independent fire occurrence datasets, reducing confidence in their application for operational forest management. Addressing these limitations requires a robust geospatial framework capable of integrating multiple datasets for accurate identification of fire-prone areas.

Therefore, this study aims to develop a GIS and remote sensing-based Forest Fire Risk Index (FRI) for the Potohar region of Pakistan by integrating vegetation condition (NDVI), land surface temperature (LST), topographic characteristics (slope, aspect, and elevation), and anthropogenic influence represented by proximity to road networks. Burn severity was evaluated using the Normalized Burn Ratio (NBR), while the predictive performance of the developed model was assessed through Kernel Density Estimation (KDE) using historical fire occurrence data. The resulting fire-risk map is expected to support forest managers, policymakers, and disaster management authorities in identifying vulnerable areas, prioritizing prevention measures, and strengthening wildfire preparedness for sustainable forest management in Pakistan.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Materials and Methods

Study Area

The Potohar region, located in the northern part of Punjab, Pakistan, was selected as the study area because of its ecological importance and recurring wildfire incidents. The region extends across the districts of Islamabad, Rawalpindi, Attock, Chakwal, and Jhelum and is characterized by undulating plains, rugged hills, and fragmented forest landscapes. The Margalla Hills National Park, situated within the Potohar Plateau, has experienced several severe wildfire events during the pre-monsoon season, making it an appropriate case study for forest fire risk assessment.The climate of the region is classified as subtropical semi-arid, with hot summers and cool winters. Annual rainfall ranges from approximately 600 to 1,200 mm, most of which occurs during the monsoon season (July–September), while the pre-monsoon period (May–June) is generally characterized by elevated temperatures, low relative humidity, and dry vegetation conditions that favor wildfire ignition and rapid fire spread. The forests mainly consist of subtropical broad-leaved evergreen species, scrub vegetation, and chir pine in higher elevations, providing varying fuel loads that influence wildfire behavior.The combination of complex topography, increasing human activities, road accessibility, and seasonal climatic variability makes the Potohar region particularly vulnerable to forest fires. Therefore, understanding the spatial distribution of fire-prone areas is essential for effective forest management and disaster preparedness.

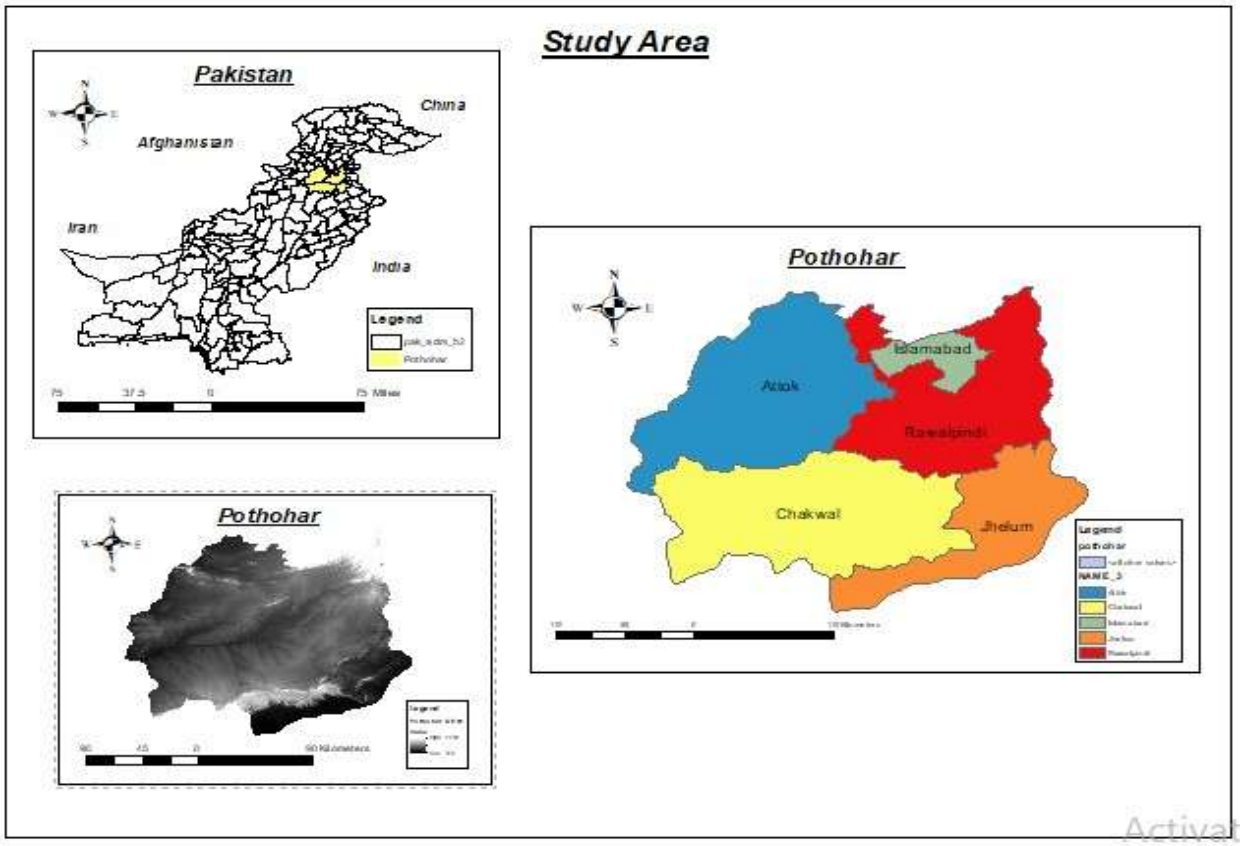


Figure 1: Study area location map

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

Data Sources

Multiple geospatial datasets were integrated to develop the Forest Fire Risk Index (FRI). These datasets represent vegetation conditions, thermal characteristics, topography, anthropogenic influences, and fire severity (Table 1).

Table 1: Data type and sources of information used in this study

Dataset	Source	Spatial Resolution	Purpose
Landsat 8 OLI/TIRS	USGS Earth Explorer	30 m	NDVI, LST, NBR
Landsat 9	USGS Earth Explorer	30 m	Post-fire analysis
ASTER DEM	NASA	30 m	Slope, Aspect, Elevation
Road Network	OpenStreetMap / Government Database	Vector	Distance from Roads
Fire Incident Data	Field Records / CDA / Historical Fire Records	Point	Model Validation

The Landsat images acquired before and after the June 2022 wildfire event were used to evaluate vegetation conditions, burn severity, and thermal changes. The ASTER Digital Elevation Model (DEM) provided topographic information, while road network data were used to estimate anthropogenic influences on fire occurrence.

Methodological Framework

The overall methodology adopted in this study is illustrated in Figure 2.
The workflow consisted of four major stages:
Collection of satellite imagery and ancillary datasets.
Pre-processing and generation of thematic layers (NDVI, LST, slope, aspect, elevation, road distance, and NBR).
Development of the Fire Risk Index (FRI) using a weighted multi-criteria overlay analysis.
Validation of the generated fire-risk map using historical wildfire occurrences and Kernel Density Estimation (KDE).
This framework integrates both biophysical and anthropogenic variables to provide a comprehensive representation of forest fire susceptibility.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

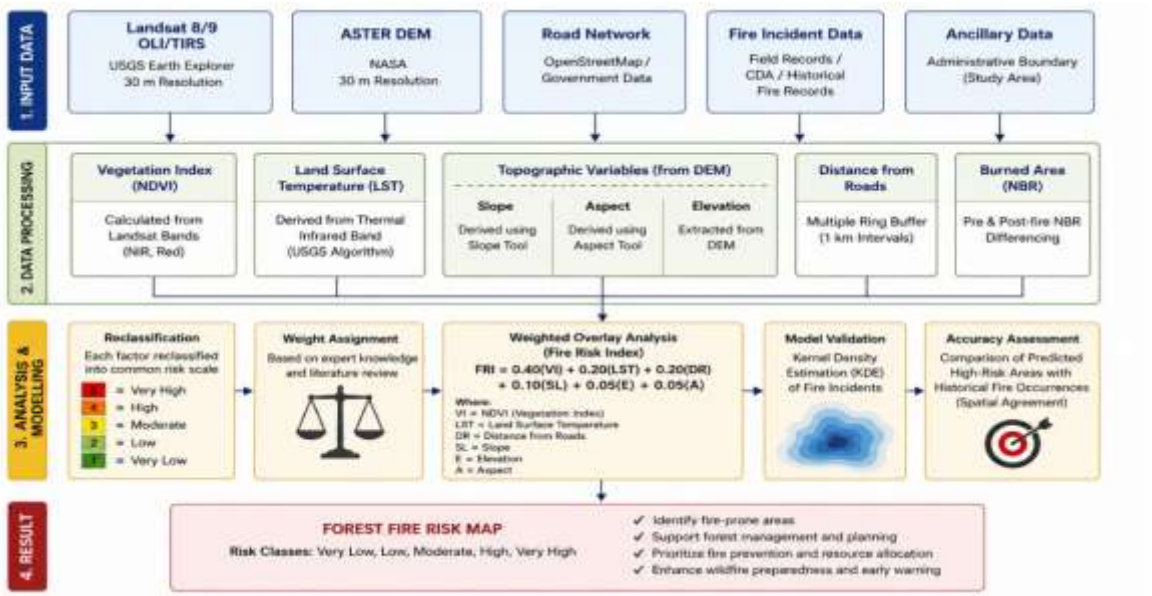


Figure 2: Methodological framework for GIS and remote sensing based forest fire risk assessment

Preparation of Fire Risk Factors

Vegetation Condition (NDVI)

Vegetation density was assessed using the Normalized Difference Vegetation Index (NDVI) derived from Landsat imagery. NDVI is one of the most widely used indicators for monitoring vegetation health and fuel availability.The index was calculated as:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

where NIR and Red represent the near-infrared and red spectral bands, respectively. Areas exhibiting dense vegetation were considered to contain greater combustible biomass, thereby increasing fire susceptibility during prolonged dry conditions.

Land Surface Temperature (LST)

Land Surface Temperature (LST) was estimated from the thermal infrared bands of Landsat imagery. Surface temperature strongly influences vegetation moisture content and fuel flammability.Higher LST values generally indicate drier environmental conditions, which increase the probability of ignition and fire spread. Temperature maps generated before and after the wildfire event were compared to evaluate thermal changes associated with fire occurrence.

Topographic Variables

Topography plays a critical role in wildfire behavior. Three terrain parameters were extracted from the ASTER DEM:

Slope

Aspect

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

Elevation
Slope affects the rate of fire spread because flames move more rapidly uphill due to increased heat transfer. Aspect controls solar radiation exposure and consequently vegetation moisture content, whereas elevation influences local climatic conditions and vegetation composition.

Distance from Roads
Human activities are among the leading causes of wildfire ignition. Therefore, the road network was used as an indicator of anthropogenic influence.Multiple buffer zones at 1 km intervals were generated using ArcGIS to calculate proximity to roads. Areas located closer to roads were assigned higher fire-risk scores due to increased accessibility and human disturbance.

Burn Severity (NBR)
The Normalized Burn Ratio (NBR) was used to identify burned areas and estimate fire severity.The index was computed using:

$$NBR = \frac{NIR - SWIR}{NIR + SWIR}$$

where SWIR denotes the shortwave infrared band.
The difference between pre-fire and post-fire NBR images was used to delineate burned areas and quantify fire severity.

Development of the Fire Risk Index (FRI)
A weighted overlay analysis was conducted in ArcGIS to integrate all thematic layers into a single Forest Fire Risk Index.The Fire Risk Index was calculated as:

$$FRI = 0.40(VI) + 0.20(LST) + 0.20(DR) + 0.10(SL) + 0.05(E) + 0.05(A)$$

where:
VI = Vegetation Index (NDVI)
LST = Land Surface Temperature
DR = Distance from Roads
SL = Slope
E = Elevation
A = Aspect
The assigned weights reflect the relative importance of each factor based on published literature and expert judgment. Vegetation condition received the highest weight because fuel availability is a primary determinant of wildfire occurrence, followed by land surface temperature and road accessibility.

Model Validation
The predictive performance of the developed Fire Risk Index was evaluated using Kernel Density Estimation (KDE) and historical wildfire occurrence data.Kernel Density Estimation provides a continuous probability surface representing the spatial concentration of fire incidents. The generated density map was compared with the predicted fire-risk zones to determine the consistency between observed wildfire events and model outputs.A high spatial agreement between historical fire occurrences and predicted high-risk zones indicates that the proposed model

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

effectively identifies wildfire-prone areas and can support operational forest fire management.

Results and Discussion

Topographic Characteristics of the Study Area

Topography is one of the most influential natural factors controlling wildfire occurrence and fire behavior because it directly affects fuel moisture, vegetation distribution, microclimatic conditions, and the rate of fire spread. To evaluate the influence of terrain on forest fire susceptibility, three topographic variablesslope, elevation, and aspectwere derived from the 30 m ASTER Digital Elevation Model (DEM) and incorporated into the Fire Risk Index (FRI).

Slope

The slope map (Figure 3a) revealed considerable variability across the Potohar region, with relatively gentle slopes dominating the southern plains and steeper terrain concentrated in the northern mountainous areas, particularly within the Margalla Hills National Park. These steep slopes are associated with accelerated wildfire propagation because heat rises upslope, preheating unburned vegetation ahead of the flame front and increasing combustion efficiency. Consequently, areas with higher slope gradients were assigned greater fire-risk values during the weighted overlay analysis.

The influence of slope on wildfire dynamics has been extensively documented in previous studies, which consistently report that fire spread rates increase with increasing slope due to enhanced convective and radiant heat transfer (Jaiswal et al., 2002; Chuvieco et al., 2010). Similar topographic effects have also been observed in mountainous ecosystems of South Asia and the Mediterranean, where steep terrain contributes significantly to rapid fire expansion and complicates firefighting operations.

Elevation

The elevation map (Figure 3b) demonstrates a gradual increase in altitude from the southern parts of the Potohar Plateau towards the northern mountainous landscapes. Elevation indirectly affects wildfire occurrence by regulating local temperature, relative humidity, precipitation patterns, and vegetation composition. Lower elevations generally experience higher temperatures and reduced moisture availability, whereas higher elevations often support denser vegetation with relatively cooler climatic conditions.

Although elevation alone does not determine wildfire occurrence, its interaction with vegetation characteristics and climatic conditions influences fuel accumulation and ignition probability. In the present study, elevation was therefore assigned a relatively lower weighting (5%) within the Fire Risk Index while still contributing to the spatial differentiation of fire susceptibility across the region.

Aspect

Aspect represents the direction toward which a slope faces and controls the amount of incoming solar radiation received by the land surface. The aspect analysis (Figure 3c) indicated substantial variation in slope orientation throughout the study area, resulting

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

in differences in vegetation moisture content and fuel drying rates.

South-, southwest-, and west-facing slopes generally receive greater solar radiation during the dry season, leading to increased evapotranspiration and lower fuel moisture. Consequently, these slopes become more susceptible to wildfire ignition than north-facing slopes, which typically retain higher moisture levels due to reduced solar exposure.

Previous research has consistently identified aspect as an important predictor of wildfire susceptibility because it influences both vegetation productivity and surface energy balance. Although its influence is generally smaller than vegetation condition or temperature, aspect improves the overall predictive capability of integrated fire-risk models when combined with other environmental variables.

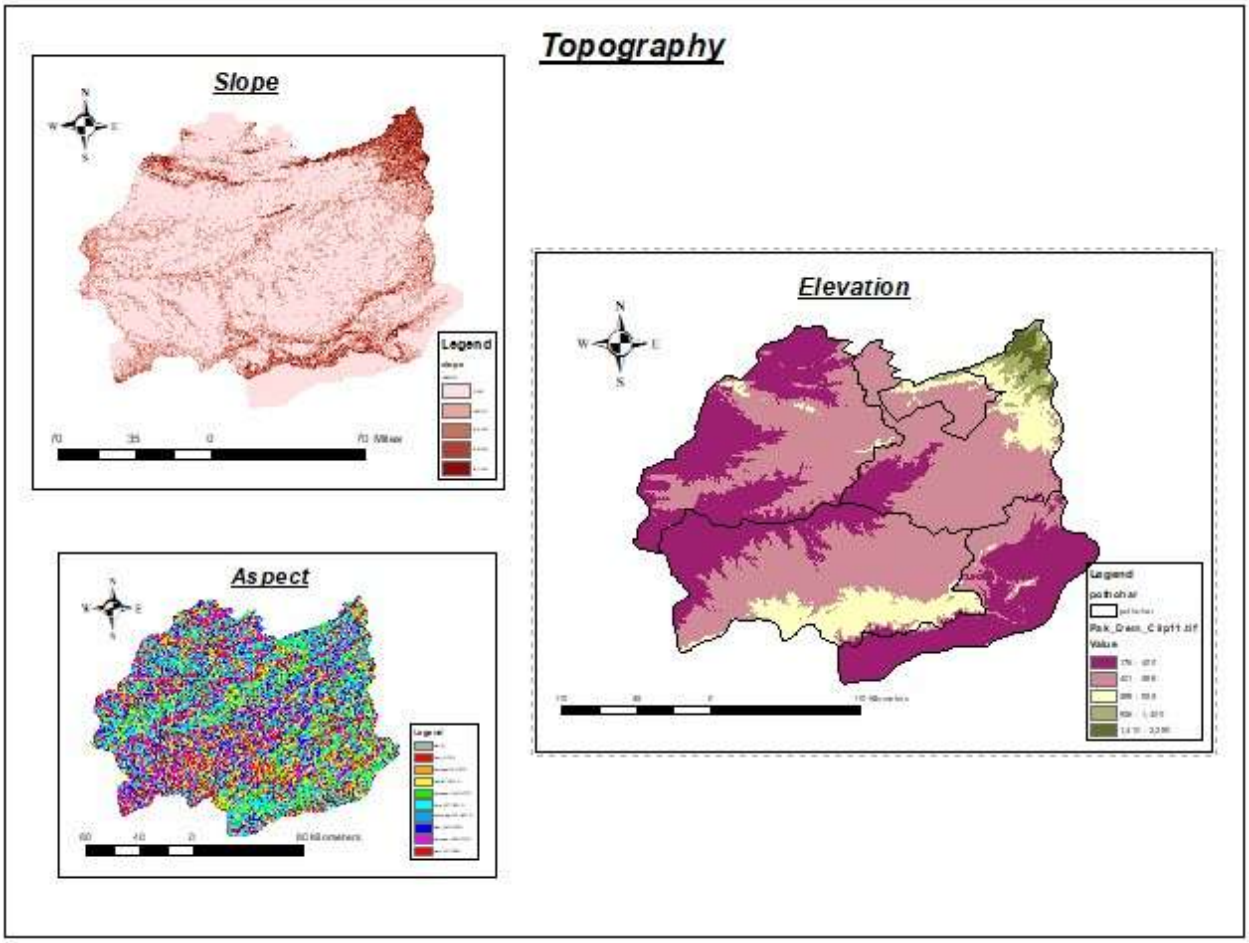


Figure 3. Topographic variables used in the Forest Fire Risk Index (FRI): (a) slope, (b) elevation, and (c) aspect derived from the 30 m ASTER Digital Elevation Model (DEM) for the Potohar region, Pakistan.

The combined topographic analysis indicates that wildfire susceptibility within the Potohar region cannot be attributed to a single terrain variable. Instead, slope, elevation, and aspect interact to create spatially heterogeneous environmental conditions that influence fuel availability, moisture dynamics, and fire spread potential. Areas characterized by steep slopes, moderate elevations, and south-facing aspects exhibit comparatively greater fire susceptibility, particularly when these

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189
http://amresearchreview.com/index.php/Journal/about

terrain characteristics coincide with dense vegetation and elevated land surface temperatures.

Therefore, topographic variables provide an essential physical foundation for the Fire Risk Index by representing the natural controls governing wildfire behavior. Their integration with vegetation, thermal, and anthropogenic factors enables a more comprehensive and realistic assessment of forest fire susceptibility across the Potohar region.

Influence of Road Proximity on Forest Fire Risk

Human activities are widely recognized as one of the primary causes of forest fire ignition, particularly in regions where forests are easily accessible through transportation networks. Consequently, the proximity to roads was incorporated into the Fire Risk Index (FRI) as an indicator of anthropogenic influence on wildfire occurrence. The road network was buffered at 1 km intervals, generating five distance classes ranging from 0–1 km to >4 km. These distance zones were subsequently reclassified according to their relative contribution to fire susceptibility, with areas closest to roads assigned the highest risk scores.

The spatial analysis (Figure 4) revealed that forest areas located within 1 km of major roads and access routes exhibited the greatest fire susceptibility. This pattern is primarily attributed to increased human activities, including recreational visits, agricultural residue burning, roadside litter disposal, cigarette smoking, illegal camping, and accidental ignitions. Roads also facilitate easier access to forested landscapes, thereby increasing the frequency of human-induced ignition sources. In contrast, forests located farther from road networks generally experienced lower levels of human disturbance and consequently lower probabilities of fire initiation.

Although roads improve accessibility for firefighting personnel and emergency response, they simultaneously increase the likelihood of wildfire occurrence by enhancing human presence within forest ecosystems. Similar findings have been reported in numerous wildfire susceptibility studies, where road density and accessibility consistently emerged as significant predictors of fire occurrence due to their close association with anthropogenic ignition sources (Chuvieco et al., 2023; Oliveira et al., 2012). These observations highlight that human accessibility is often a stronger determinant of fire ignition than many environmental variables, particularly in protected areas experiencing increasing tourism and urban expansion.

In the Potohar region, the influence of road proximity is especially evident in and around the Margalla Hills National Park, where extensive recreational activities and expanding urban development have increased human pressure on surrounding forests. During the dry pre-monsoon season, even minor ignition sources near accessible roads can rapidly develop into large wildfire events when combined with elevated temperatures, dry vegetation, and favorable topographic conditions.

Considering the dominant role of human-induced ignitions in the study area, proximity to roads was assigned a 20% weight in the Fire Risk Index model. This weighting reflects its substantial contribution to wildfire occurrence while recognizing that fire initiation results from the interaction between anthropogenic activities and environmental conditions rather than from a single factor. The integration of road proximity with vegetation condition, land surface temperature, and topographic

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

variables substantially improved the spatial representation of wildfire susceptibility across the Potohar region.

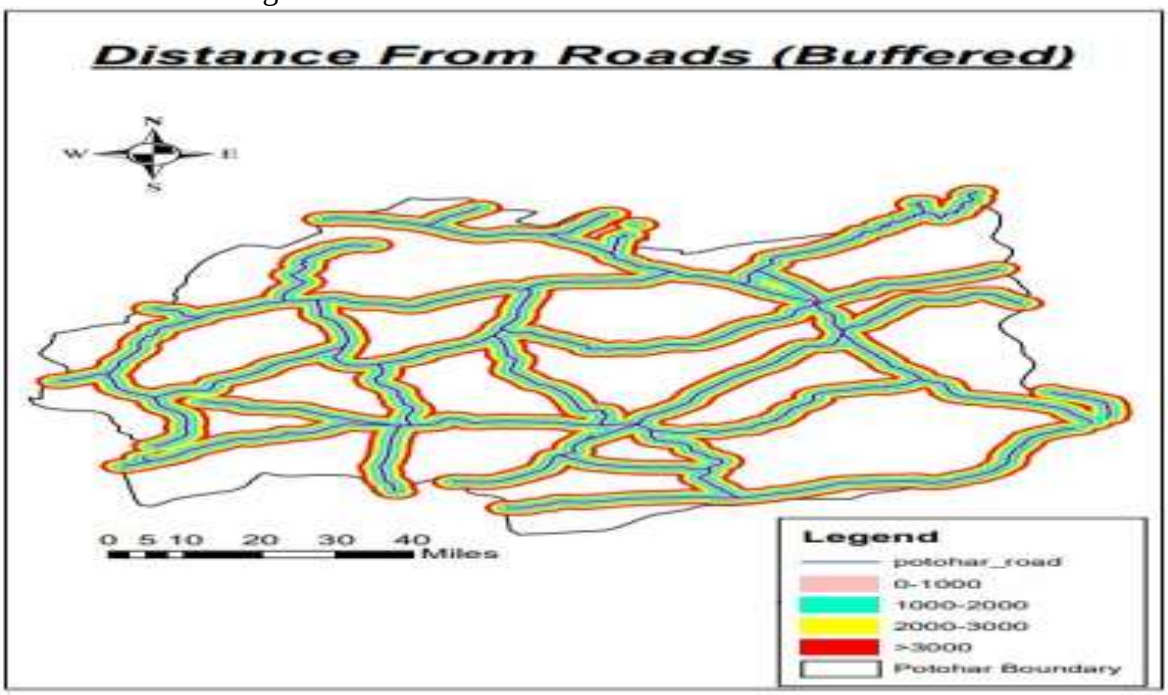


Figure 4. Distance-from-road classes derived using multiple-ring buffer analysis (1 km intervals) and incorporated as an anthropogenic factor in the Forest Fire Risk Index (FRI) for the Potohar region, Pakistan.

Land Surface Temperature (LST)

Land Surface Temperature (LST) is a key environmental variable influencing wildfire occurrence because it directly affects vegetation moisture content, fuel flammability, and ignition probability. Elevated surface temperatures accelerate evapotranspiration, reduce fuel moisture, and create favorable conditions for fire ignition and rapid fire spread. In this study, LST was derived from the thermal infrared bands of Landsat 8 and Landsat 9 imagery acquired before and after the June 2022 wildfire event to evaluate the thermal characteristics of the Potohar region.

The generated LST map (Figure 5) revealed considerable spatial variation in surface temperature across the study area. Higher temperatures were predominantly observed in the southern and central portions of the Potohar region, as well as in sparsely vegetated and exposed surfaces. In contrast, relatively lower temperatures were recorded within dense forest stands and higher elevations of the Margalla Hills, reflecting the cooling effect of vegetation cover and altitude. However, following the wildfire event, a noticeable increase in surface temperature was observed within the burned areas due to the removal of vegetation and exposure of bare soil.

The comparative analysis of pre- and post-fire imagery indicated an average increase of approximately 8°C in the burned portions of the Margalla Hills. This substantial thermal increase can be attributed to the destruction of vegetative cover, which reduced evapotranspiration and increased the absorption of solar radiation by exposed land surfaces. Similar post-fire temperature increases have been reported in previous

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

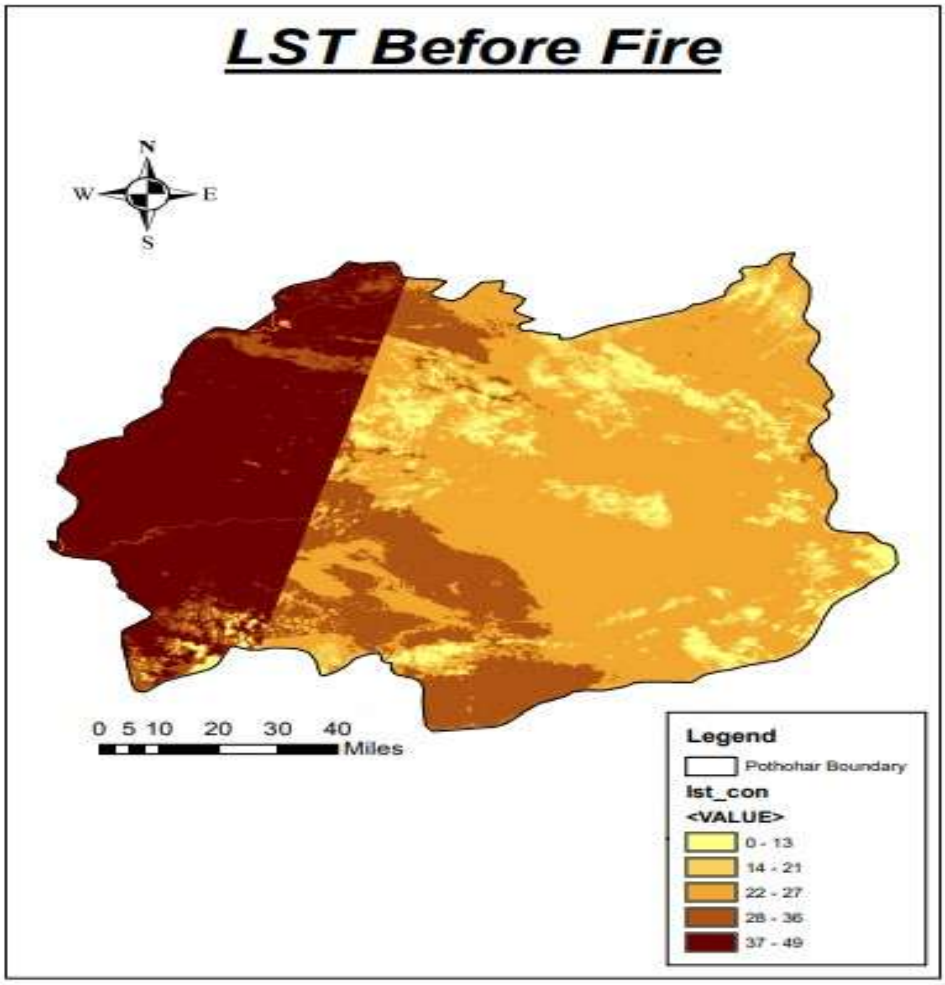
Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

studies, where burned landscapes exhibited significantly higher surface temperatures than surrounding unburned forests due to changes in surface albedo and energy balance (Veraverbeke et al., 2012; Roy et al., 2016).

Spatial comparison between the LST map and historical fire locations further demonstrated that wildfire incidents were predominantly concentrated in areas characterized by relatively high surface temperatures. These findings suggest that LST is a reliable indicator of fire-prone environments, particularly during the dry pre-monsoon season when vegetation experiences moisture stress. Although high temperatures alone do not initiate wildfires, they substantially increase fire susceptibility when combined with abundant fuel, favorable topographic conditions, and human-induced ignition sources.

Recognizing its significant contribution to wildfire occurrence, land surface temperature was assigned a 20% weight in the Fire Risk Index (FRI). This weighting reflects the strong influence of thermal conditions on vegetation dryness and fire behavior while maintaining balance with vegetation condition and anthropogenic factors within the multi-criteria framework. The integration of LST with other environmental variables improved the capability of the model to identify areas with elevated wildfire susceptibility across the Potohar region.



Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

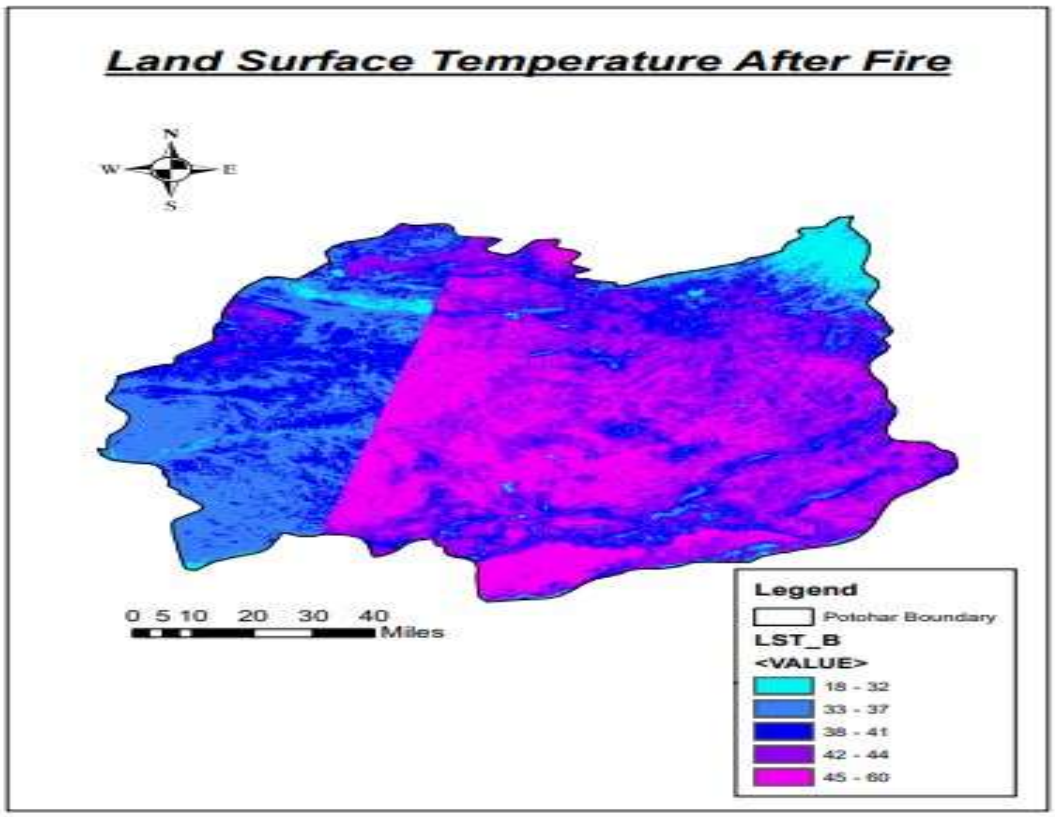


Figure 5. Land Surface Temperature (LST) derived from Landsat thermal infrared imagery showing the spatial distribution of surface temperatures across the Potohar region before and after the June 2022 wildfire event.

Scientific Interpretation

The observed increase in land surface temperature following the wildfire highlights the close interaction between vegetation loss and surface energy dynamics. The removal of canopy cover reduces evapotranspiration and exposes darker soil and charred surfaces, which absorb more solar radiation and consequently increase surface temperatures. This positive feedback can prolong dry conditions and increase the susceptibility of affected areas to subsequent fire events. Therefore, LST serves not only as an indicator of current fire risk but also as an important variable for monitoring post-fire environmental recovery and evaluating the resilience of forest ecosystems (Adab et al., 2011).

Vegetation Condition (Normalized Difference Vegetation Index, NDVI)

Vegetation plays a fundamental role in wildfire occurrence because it constitutes the primary fuel that sustains fire ignition and propagation. The quantity, density, and physiological condition of vegetation directly influence fire intensity, spread rate, and burn severity. To evaluate vegetation conditions across the Potohar region, the Normalized Difference Vegetation Index (NDVI) was derived from Landsat 8 and Landsat 9 imagery acquired before and after the June 2022 wildfire event. NDVI is one of the most widely used spectral indices for assessing vegetation greenness,

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

biomass, and canopy health, making it an effective indicator of fuel availability in wildfire studies.

The spatial distribution of NDVI (Figure 6) revealed substantial variability in vegetation density throughout the study area. High NDVI values were primarily observed within the forested landscapes of the Margalla Hills National Park and other densely vegetated areas, indicating healthy vegetation with abundant biomass. Conversely, lower NDVI values were associated with agricultural lands, built-up areas, barren surfaces, and sparsely vegetated regions where fuel availability is comparatively limited.

A comparison of the pre-fire and post-fire NDVI images demonstrated a noticeable reduction in vegetation greenness within the burned areas. Although the overall decrease in NDVI across the study area was relatively moderate, the affected forest patches exhibited clear signs of vegetation degradation resulting from the wildfire. The reduction in NDVI reflects the loss of green biomass and photosynthetically active vegetation following combustion, which is consistent with the ecological impacts commonly observed after wildfire events. Similar reductions in NDVI following forest fires have been widely reported in remote sensing studies and are considered reliable indicators of fire-induced vegetation damage and ecosystem disturbance.

The observed relationship between vegetation density and wildfire occurrence highlights the dual role of vegetation in fire dynamics (Rouse et al., 1974). Dense vegetation provides greater fuel continuity, allowing fires to spread more rapidly once ignition occurs. However, vegetation moisture content also influences fire behavior, meaning healthy forests are not necessarily more susceptible to ignition unless prolonged dry conditions reduce fuel moisture. During the pre-monsoon season, elevated temperatures and limited precipitation substantially decrease vegetation moisture in the Potohar region, increasing the flammability of forest fuels and contributing to higher wildfire susceptibility.

Given its direct influence on fuel availability, NDVI was assigned the highest weighting (40%) in the Fire Risk Index (FRI). This weighting reflects the dominant role of vegetation in determining wildfire potential and aligns with previous GIS-based wildfire susceptibility studies, where vegetation indices consistently represent the most influential component of fire-risk models. The integration of NDVI with land surface temperature, topographic characteristics, and anthropogenic factors significantly enhanced the spatial representation of wildfire susceptibility across the study area.

Overall, the NDVI analysis demonstrates that vegetation condition is a critical determinant of forest fire risk in the Potohar region. Areas characterized by dense forest cover, particularly within the Margalla Hills National Park, represent substantial fuel reservoirs that can support extensive wildfire development under favorable climatic and topographic conditions. Consequently, continuous monitoring of vegetation dynamics using satellite-derived indices is essential for improving wildfire preparedness and supporting sustainable forest management.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

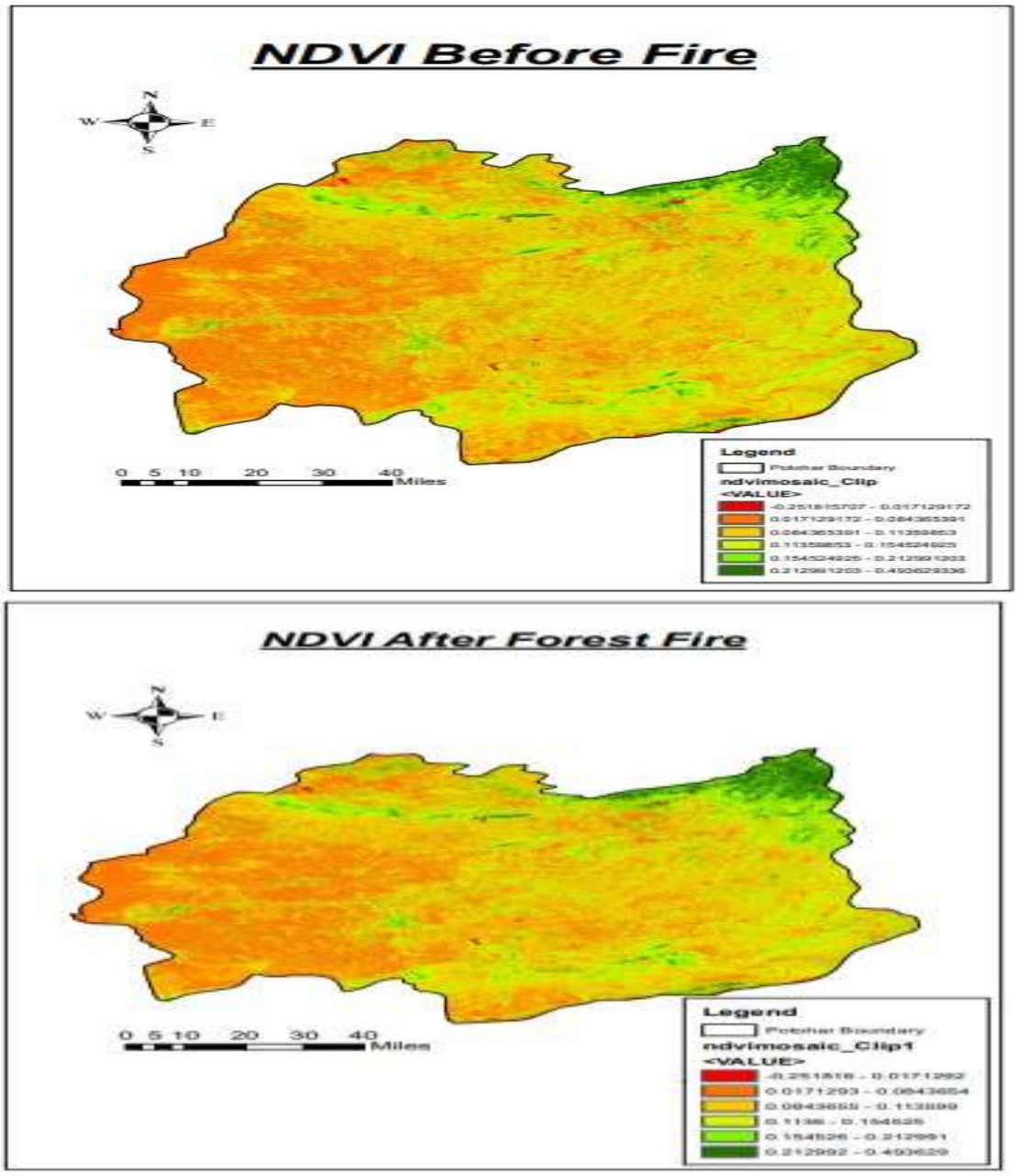


Figure 6. Spatial distribution of the Normalized Difference Vegetation Index (NDVI) derived from Landsat 8/9 imagery before and after the June 2022 wildfire event, illustrating vegetation condition and fuel availability across the Potohar region, Pakistan.

Burn Severity Assessment Using the Normalized Burn Ratio (NBR)

The Normalized Burn Ratio (NBR) was employed to delineate burned areas and evaluate the severity of the June 2022 wildfire event in the Potohar region. NBR is one of the most widely accepted spectral indices for post-fire assessment because it effectively captures changes in vegetation structure and soil exposure caused by fire. The index exploits the contrasting spectral responses of healthy vegetation in the near-

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

infrared (NIR) band and burned surfaces in the shortwave infrared (SWIR) band, enabling accurate discrimination between burned and unburned areas.

The NBR analysis (Figure 7) clearly identified the spatial extent of the wildfire within the Margalla Hills National Park. Comparison of pre-fire and post-fire Landsat imagery revealed a substantial reduction in NBR values across the affected landscape, indicating extensive vegetation damage and exposure of charred surfaces. Healthy forested areas exhibited relatively high NBR values due to dense vegetation cover, whereas burned areas showed markedly lower values following combustion. These spectral changes are consistent with the removal of green biomass, reduction in canopy cover, and increased reflectance from exposed soil and ash deposits.

The analysis estimated that approximately 8.09 km² of forest area was affected by the June 2022 wildfire event. The spatial distribution of burned pixels demonstrated that fire damage was concentrated within the densely forested sections of the Margalla Hills, where continuous vegetation cover, elevated temperatures, steep terrain, and human accessibility collectively created favorable conditions for wildfire development. According to available records, firefighting operations required approximately eight hours to bring the wildfire under control, highlighting both the intensity of the event and the operational challenges associated with suppression in mountainous terrain.

The burn severity assessment further demonstrated that the areas identified by NBR corresponded closely with regions exhibiting elevated land surface temperatures and reduced NDVI values. This strong spatial agreement confirms the complementary nature of these remote sensing indicators and reinforces the reliability of integrating vegetation condition, thermal characteristics, and burn severity into a comprehensive fire-risk assessment framework. Similar relationships between NBR, NDVI, and LST have been reported in previous wildfire studies, where combined spectral indices improved the characterization of fire impacts and post-fire ecosystem responses.

Beyond mapping burned areas, the NBR analysis provides valuable information for post-fire management and ecological restoration. Burn severity maps can assist forest managers in identifying areas requiring immediate rehabilitation, assessing vegetation recovery, and prioritizing conservation efforts. Moreover, integrating burn severity with wildfire susceptibility mapping contributes to more effective long-term fire management by identifying landscapes that are both highly vulnerable to ignition and severely affected by previous fire events.

Overall, the NBR-based assessment confirms the effectiveness of remote sensing techniques for rapid wildfire damage evaluation. When integrated with other environmental and anthropogenic variables, burn severity information enhances the predictive capability of the Fire Risk Index and provides a scientifically robust basis for supporting wildfire prevention, monitoring, and restoration planning in the Potohar region.

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

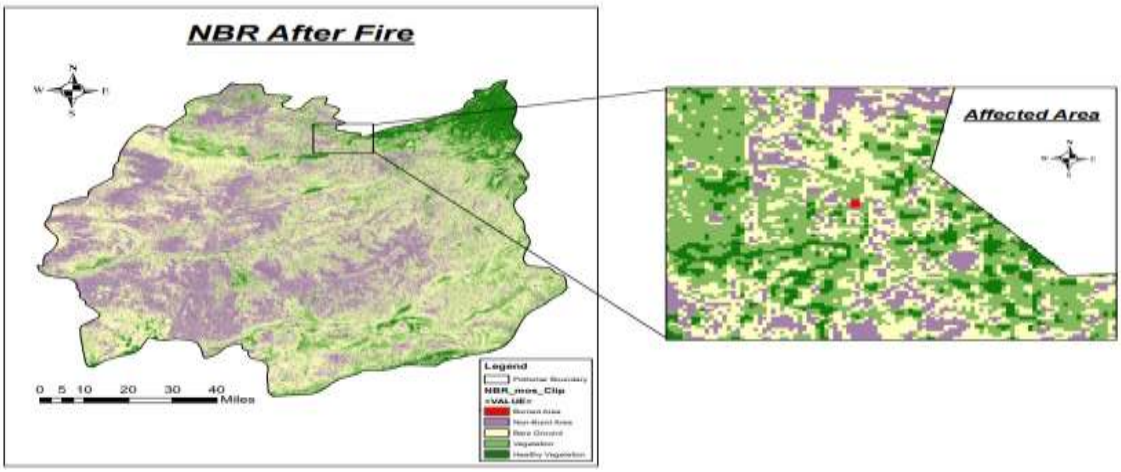


Figure 7. Burn severity map derived from the Normalized Burn Ratio (NBR) showing the spatial extent of the June 2022 wildfire in the Margalla Hills National Park, Potohar region, Pakistan.

Forest Fire Risk Assessment

The thematic layers representing vegetation condition (NDVI), land surface temperature (LST), topographic characteristics (slope, aspect, and elevation), and anthropogenic influence (distance from roads) were integrated using a weighted multi-criteria overlay analysis to generate the Forest Fire Risk Index (FRI). The resulting forest fire risk map (Figure 8) classifies the Potohar region into different fire susceptibility zones, providing a comprehensive spatial representation of wildfire risk.

The generated fire risk map revealed considerable spatial heterogeneity in wildfire susceptibility across the study area. Areas characterized by high and very high fire risk were predominantly concentrated within the Margalla Hills National Park and adjacent forested landscapes. These zones are characterized by dense vegetation, elevated land surface temperatures during the pre-monsoon season, steep slopes, and close proximity to transportation networks, creating conditions that are highly conducive to wildfire ignition and rapid fire propagation. In contrast, low-risk zones were generally associated with agricultural lands, urban areas, and sparsely vegetated regions where combustible fuel loads were comparatively limited.

The spatial distribution of fire-risk classes demonstrates that wildfire susceptibility is controlled by the interaction of multiple environmental and anthropogenic factors rather than by any single variable. Although dense vegetation provides the necessary fuel for fire propagation, ignition becomes significantly more likely when high temperatures, favorable topographic conditions, and human activities occur simultaneously. This interaction explains the concentration of high-risk zones within accessible forested landscapes, particularly around the Margalla Hills, where recreational activities, expanding urbanization, and road accessibility increase the likelihood of anthropogenic fire ignition.

The developed Fire Risk Index effectively captured these spatial relationships by assigning greater importance to vegetation condition (40%), followed by land surface temperature (20%) and road proximity (20%), while incorporating slope, elevation, and aspect as supporting topographic variables. The weighting scheme reflects the

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

dominant influence of fuel availability and environmental stress on wildfire occurrence and is consistent with previous GIS-based wildfire susceptibility studies employing multi-criteria decision analysis.

Comparison of the generated fire-risk map with the observed burn severity patterns indicated a strong spatial correspondence between predicted high-risk zones and the areas affected by the June 2022 wildfire event. Most of the burned areas identified through the NBR analysis were located within regions classified as high or very high fire risk by the developed model. This agreement suggests that the selected variables and weighting strategy successfully represent the principal drivers of wildfire occurrence within the Potohar region.

From a management perspective, the generated fire-risk map provides a valuable decision-support tool for forest managers, conservation agencies, and disaster management authorities. The spatial identification of fire-prone areas can support the prioritization of fuel management programs, allocation of firefighting resources, installation of early warning systems, and planning of surveillance activities during the high-risk pre-monsoon season. Furthermore, the map can assist policymakers in developing targeted wildfire prevention strategies while minimizing ecological damage and economic losses associated with future wildfire events.

Overall, the integrated GIS and remote sensing framework demonstrated strong capability for identifying wildfire-prone landscapes in the Potohar region. By combining multiple environmental and anthropogenic variables within a single spatial model, the developed Fire Risk Index provides a scientifically robust approach for forest fire risk assessment and offers a transferable methodology that can be adapted to other fire-prone ecosystems with similar environmental characteristics (Faramarzi et al., 2021).

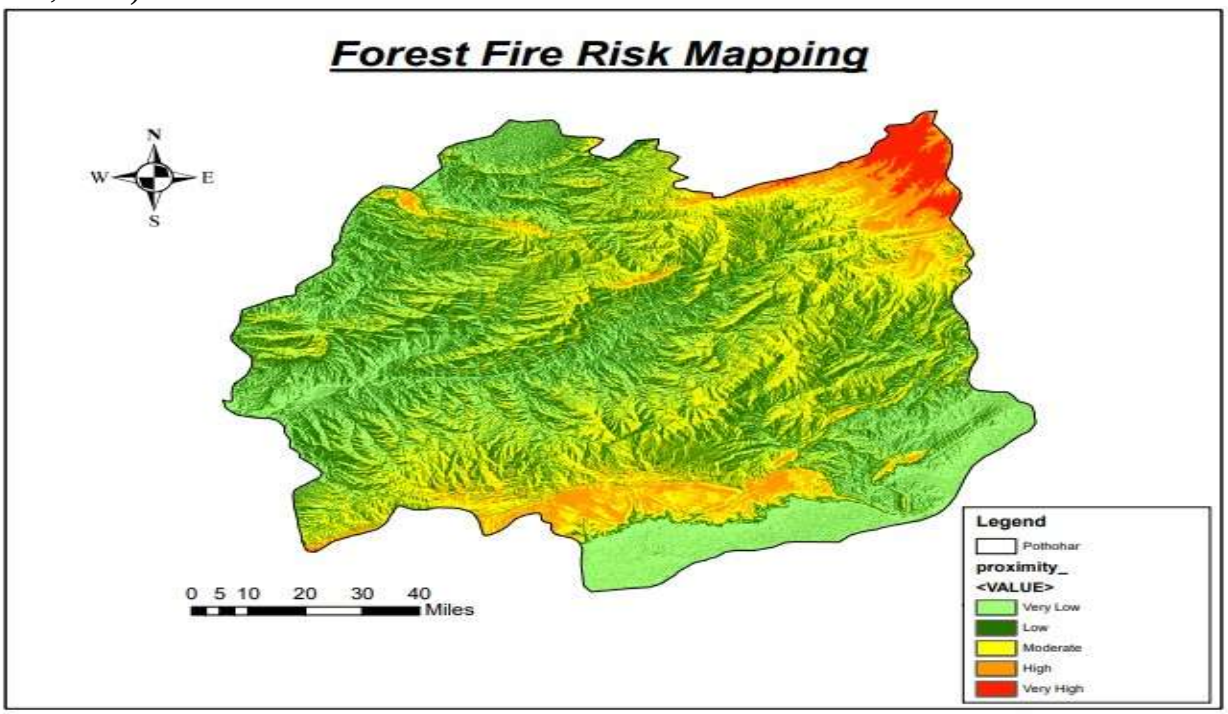


Figure 8. Forest Fire Risk Index (FRI) map generated using weighted multi-criteria

Online ISSN 3007-3197
Print ISSN 3007-3189

overlay analysis, showing the spatial distribution of low, moderate, high, and very high wildfire susceptibility zones across the Potohar region, Pakistan.

Model Validation

Model validation is a crucial step in assessing the reliability and predictive capability of wildfire susceptibility models. In this study, the performance of the developed Forest Fire Risk Index (FRI) was evaluated using Kernel Density Estimation (KDE) based on historical wildfire occurrence data. KDE is a non-parametric spatial analysis technique that estimates the density of point events and identifies areas with a high concentration of fire incidents. By comparing the spatial distribution of historical wildfire hotspots with the predicted fire-risk zones, the effectiveness of the proposed model in identifying fire-prone areas was assessed.

The KDE analysis revealed that historical wildfire incidents were predominantly concentrated within the high and very high fire-risk classes identified by the Fire Risk Index. The highest density of fire occurrences was observed in the Margalla Hills National Park and its surrounding forest landscapes, which correspond closely with areas characterized by dense vegetation, elevated land surface temperatures, steep slopes, and greater accessibility through road networks. This strong spatial agreement indicates that the selected environmental and anthropogenic variables adequately represent the primary factors influencing wildfire occurrence in the Potohar region.

The observed correspondence between KDE hotspots and predicted fire-risk zones demonstrates the capability of the proposed GIS-based framework to distinguish between areas of varying wildfire susceptibility. While isolated fire events were recorded outside the predicted high-risk zones, these occurrences are likely associated with stochastic human activities or localized environmental conditions that cannot be fully represented by regional-scale spatial datasets. Nevertheless, the overall consistency between observed fire locations and model predictions confirms the robustness of the developed Fire Risk Index (Alexandridis et al., 2008).

The validation results also emphasize the importance of integrating multiple variables within a single decision-support framework. Individual parameters such as vegetation condition, land surface temperature, or road proximity alone cannot fully explain wildfire occurrence; however, their combined influence significantly improves predictive performance. The weighted multi-criteria approach effectively captures the complex interactions among fuel availability, terrain characteristics, thermal conditions, and anthropogenic pressures, thereby providing a more realistic representation of wildfire susceptibility than analyses based on a single factor.

From an operational perspective, the validated fire-risk model offers significant practical value for wildfire management. The generated susceptibility map can support forest departments and disaster management agencies in prioritizing surveillance activities, strategically locating firefighting resources, planning fuel reduction measures, and implementing early warning systems in areas identified as highly vulnerable. Furthermore, the methodology can be updated periodically using newly acquired satellite imagery, allowing continuous monitoring of changing environmental conditions and improving preparedness for future wildfire events.

Although the validation demonstrated good agreement between observed fire occurrences and predicted susceptibility zones, several limitations should be

Annual Methodological Archive Research Review
http://amresearchreview.com/index.php/Journal/about
Volume 4, Issue 6 (2026)

Online ISSN 3007-3197
Print ISSN 3007-3189

http://amresearchreview.com/index.php/Journal/about

acknowledged. The weighting scheme adopted in this study was based on literature and expert judgment rather than a formal weighting optimization technique, and additional variables such as wind speed, relative humidity, precipitation, and lightning occurrence were not incorporated because of data limitations. Future studies may improve model performance by integrating these meteorological variables, employing advanced machine-learning algorithms, and validating predictions using long-term wildfire inventories.Overall, the KDE-based validation confirms that the proposed Forest Fire Risk Index provides a reliable and scientifically sound framework for wildfire susceptibility assessment in the Potohar region. The integration of GIS, remote sensing, and multi-criteria analysis offers an effective decision-support system for reducing wildfire risk and promoting sustainable forest management in Pakistan.

Conclusion

This study developed a GIS and remote sensing-based Forest Fire Risk Index (FRI) to assess wildfire susceptibility across the Potohar region of Pakistan by integrating vegetation condition, land surface temperature, topographic characteristics, and anthropogenic influence within a weighted multi-criteria framework. The integration of satellite-derived datasets with GIS-based spatial analysis provided a comprehensive approach for identifying areas vulnerable to wildfire occurrence and evaluating the spatial variability of fire risk.

The results demonstrated that wildfire susceptibility is governed by the interaction of multiple environmental and human-induced factors rather than any single variable. Dense vegetation, elevated land surface temperatures, steep slopes, favorable slope aspects, and close proximity to road networks collectively increased the probability of wildfire occurrence. The generated Forest Fire Risk Index successfully identified the Margalla Hills National Park and its surrounding forested landscapes as the most fire-prone areas during the pre-monsoon season. Burn severity analysis using the Normalized Burn Ratio (NBR) estimated that approximately 8.09 km² of forest area was affected during the June 2022 wildfire event, while post-fire thermal analysis indicated an increase of nearly 8°C in land surface temperature within the burned areas. Furthermore, validation using Kernel Density Estimation (KDE) showed good spatial agreement between historical wildfire occurrences and the predicted high-risk zones, demonstrating the reliability of the proposed model.

The developed fire-risk map provides an effective decision-support tool for forest managers, conservation authorities, and disaster management agencies. The spatial identification of high-risk areas can assist in prioritizing fuel management programs, optimizing the allocation of firefighting resources, improving surveillance during the fire season, and supporting the implementation of early warning systems. The methodology is cost-effective, reproducible, and can be updated periodically using newly acquired satellite imagery, making it suitable for operational wildfire monitoring.

Despite these encouraging findings, several limitations should be acknowledged. The weighting of fire-risk factors was based on published literature and expert judgment, and the model did not incorporate dynamic meteorological variables such as wind speed, relative humidity, precipitation, or lightning occurrence because of data constraints. Additionally, wildfire behavior is inherently dynamic, whereas the present

Online ISSN 3007-3197
Print ISSN 3007-3189

assessment represents a static spatial susceptibility model. Future research should integrate real-time meteorological observations, long-term fire inventories, and advanced machine learning techniques to improve predictive accuracy and develop operational early warning systems for wildfire management in Pakistan.Overall, this study demonstrates that integrating GIS, remote sensing, and multi-criteria spatial analysis provides a scientifically robust framework for forest fire risk assessment. The proposed Forest Fire Risk Index offers a practical and transferable methodology that can support sustainable forest management, biodiversity conservation, and disaster risk reduction in Pakistan and other regions with comparable environmental and climatic conditions.

Acknowledgements
The authors gratefully acknowledge the United States Geological Survey (USGS) for providing free access to Landsat imagery, the National Aeronautics and Space Administration (NASA) for the ASTER Digital Elevation Model, and all organizations that made ancillary spatial datasets available for this research. The authors also appreciate the support of institutions and agencies that facilitated data acquisition and technical guidance throughout the study.

Author Contributions: Conceptualization: Fiaz Hussain and Usman Mughal; Methodology: Fiaz Hussain and Aftab Ahmad Khan; Software: Usman Mughal; Data Curation: Fiaz Hussain; Formal Analysis: Usman Mughal; Visualization: Aftab Ahmad Khan; Writing – Original Draft: Fiaz Hussain; Writing – Review & Editing: Aftab Ahmad Khan and Usman Mughal; Supervision: Fiaz Hussain

Conflict of Interest: The authors declare that they have no known competing financial or personal interests that could have influenced the work reported in this study.

Data Availability: The datasets used in this study are publicly available or can be obtained from the corresponding author upon reasonable request. Landsat imagery was obtained from the USGS Earth Explorer, while the ASTER Digital Elevation Model was obtained through NASA data repositories.

Declaration on the Use of Artificial Intelligence
The authors used **ChatGPT (OpenAI)** solely to improve the language, grammar, readability, and academic writing of this manuscript. The AI tool was not used to generate research ideas, perform data analysis, interpret results, develop the methodology, or draw scientific conclusions. All scientific content, analyses, interpretations, and conclusions are the original work of the authors. The authors carefully reviewed, edited, and verified all AI-assisted text and accept full responsibility for the accuracy, originality, and integrity of the final manuscript.

References

Adab, H., Kanniah, K. D., &Solaimani, K. (2011). GIS-based probability assessment of fire risk in grassland and forested landscapes of Golestan Province, Iran.

Online ISSN 3007-3197
Print ISSN 3007-3189

International Conference on Environmental and Computer Science, 19, IACSIT Press, Singapore.

Alexandridis, A., Vakalis, D., Siettos, C. I., &Bafas, G. V. (2008). A cellular automata model for forest fire spread prediction: The case of the wildfire that swept through Spetses Island in 1990. *Applied Mathematics and Computation, 204*(1), 191–201.

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., Johnston, F. H., Van Der Werf, G. R., & Flannigan, M. (2020). Vegetation fires in the Anthropocene. *Nature Reviews Earth & Environment, 1*(10), 500–515.

Chuvieco, E., Aguado, I., Yebra, M., Nieto, H., Salas, J., Martín, M. P., ... Martínez, J. (2010). Development of a framework for fire risk assessment using remote sensing and geographic information system technologies. *Ecological Modelling, 221*(1), 46–58.

Chuvieco, E., Mouillot, F., Van der Werf, G. R., San Miguel, J., Tanase, M., Koutsias, N., ... Giglio, L. (2023). Towards an integrated approach to wildfire risk assessment:When, Where, What and How May the Landscapes Burn. *Fire, 6*(5), 215. https://doi.org/10.3390/fire6050215

Sivrikaya, F., Küçük, Ö. (2022). Modeling forest fire risk based on GIS-based analytical hierarchy process and statistical analysis in Mediterranean region. *Ecological Informatics, 68*, 101537.

Faramarzi, H., Hosseini, S. M., Pourghasemi, H. R., &Farnaghi, M. (2021). Forest fire spatial modelling using ordered weighted averaging multi-criteria evaluation. *Journal of Forest Science, 67*(2), 87–100. https://doi.org/10.17221/50/2020-JFS

Jaiswal, R. K., Mukherjee, S., Raju, K. D., & Saxena, R. (2002). Forest fire risk zone mapping from satellite imagery and GIS. *International Journal of Applied Earth Observation and Geoinformation, 4*(1), 1–10.

Jones, M. W., Abatzoglou, J. T., Veraverbeke, S., Andela, N., Lasslop, G., Forkel, M., ... Le Quéré, C. (2022). Global and regional trends and drivers of fire under climate change. *Reviews of Geophysics, 60*(3), e2020RG000726.

Key, C. H., & Benson, N. C. (2006). Landscape Assessment (LA): Sampling and analysis methods. In D. C. Lutes et al. (Eds.), *FIREMON: Fire effects monitoring and inventory system* (General Technical Report RMRS-GTR-164-CD). U.S. Department of Agriculture, Forest Service.

Malczewski, J. (1999). *GIS and multicriteria decision analysis*. John Wiley & Sons.

Oliveira, S., Oehler, F., San-Miguel-Ayanz, J., Camia, A., & Pereira, J. M. C. (2012). Modeling spatial patterns of fire occurrence in Mediterranean Europe using multiple regression and random forest. *Forest Ecology and Management, 275*, 117–129.

Pourghasemi, H. R., Gayen, A., Edalat, M., Zarafshar, M., &Tiefenbacher, J. P. (2020). Is multi-hazard mapping effectivein assessing natural hazards and integrated watershed management? *Geoscience Frontiers, 11(4)*, 1203-1217.

Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). *Monitoring vegetation systems in the Great Plains with ERTS*. Proceedings of the Third Earth Resources Technology Satellite Symposium (NASA SP-351), 309–317.

Roy, D. P., Boschetti, L., Justice, C. O., & Ju, J. (2008). The collection 5 MODIS

Online ISSN 3007-3197
Print ISSN 3007-3189

burned area product—Global evaluation by comparison with the MODIS active fire product. *Remote Sensing of Environment, 112*(9), 3690–3707.

Saaty, T. L. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, 9(3-5), 161-176.

Veraverbeke, S., Hook, S. J., & Hulley, G. (2012). An alternative spectral index for rapid fire severity assessments. *Remote Sensing of Environment, 123*, 72–80.