INTERNATIONAL JOURNAL OF DIGITAL RESEARCH
Research Article

International Journal of Digital Research
www.ijdr.net
E-ISSN: 3033-179X
Volume 2; Issue 1; 2026, P.p. 66-76

High-Resolution Burn Severity Mapping in Mixed Coniferous and Deciduous Forests: The Case of the 2025 Ilindentsi Wildfire

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https://doi.org/10.63711/ijdr.net20260104

ABSTRACT

This study investigates the ecological impact and burn severity of the August 2025 Ilindentsi wildfire in the Pirin Mountain foothills, Bulgaria, using high-resolution Sentinel-2 multi-spectral imagery and Google Earth Engine. In the last decades accelerating regional warming trends – reaching a peak national average temperature of 2.1°C above climate norms in 2024 – record-breaking heat and moisture deficits in 2025 created "explosive" fuel conditions for the forest fire out breaks along the SW Bulgaria. Utilizing a triple-window temporal approach (January dormancy, June phenological peak, and July pre-fire baseline), the research successfully distinguished between coniferous and broadleaf stands to quantify fire interaction across 3,927.26 hectares. The analysis revealed a significant disparity in fire vulnerability: coniferous stands were the primary drivers of high-intensity fire, with 29.5% of their area experiencing high to moderate-high severity (Codes 24 and 25). In contrast, broadleaf stands showed higher resilience, with 56.6% of their footprint experiencing only low-intensity surface fires.

The study implemented a specialized 12-element coding scheme and a three-tier management priority system to guide surgical ecological restoration. This system prioritizes the 545.25 hectares of high-severity coniferous forest (Code 25) for immediate forestry and nature-based restoration solutions. Furthermore, 373.58 hectares of moderate-high severity coniferous forest (Code 24) are designated for intensive sanitary monitoring against bark beetle outbreaks. These findings demonstrate that high-fidelity remote sensing can effectively bridge the gap between rapid emergency response and long-term sustainable forest management in complex landscapes.

Keywords: *Burn severity, Ilindentsi wildfire, Sentinel-2, Google Earth Engine, dNBR, Ecological restoration*

INTRODUCTION

In August 2025, the Ilindentsi wildfire emerged as a definitive ecological crisis in the Struma Valley, persisting for over 30 days and the according official authorities it impacted approximately 4,500 hectares within the Pirin Mountain foothills (Fig.1). This event occurred during one of Bulgaria's most catastrophic wildfire seasons, which saw the loss of over 300,000 decares of forest nationwide and placed the country among the ten EU nations most affected by fire in terms of percentage of territory (WWF-Bulgaria, 2025).

The rugged, high-altitude terrain and extreme slopes characteristic of the Pirin range make conventional field-based monitoring and severity mapping logistically prohibitive and spatially incomplete. To address these challenges, the integration of Passive Remote Sensing (PRS) – specifically high-resolution multi-spectral imagery from the Sentinel-2 Multi-Spectral Instrument (MSI) – has become the standard for post-fire landscape assessment, providing the 10-meter spatial resolution necessary to capture the heterogeneous burn patterns typical of Mediterranean-type ecosystems (Navarro et al., 2017; Chuvieco & Kasischke, 2007).

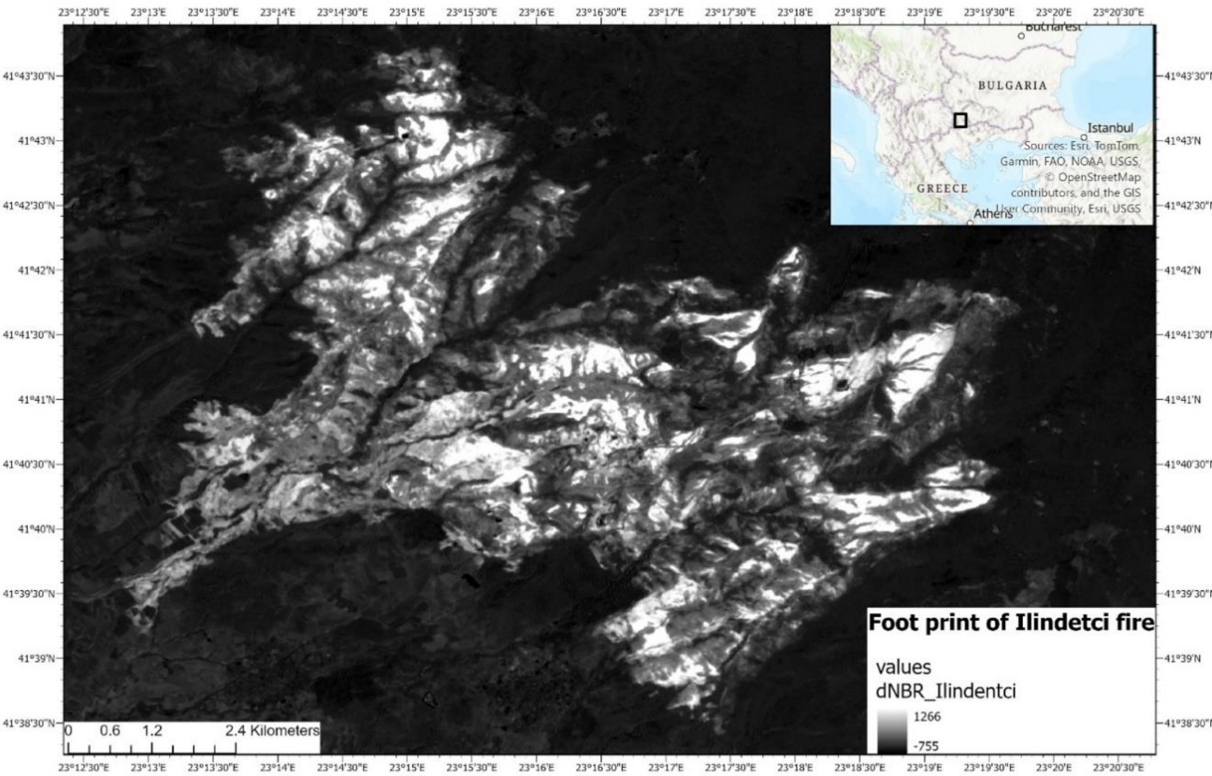

Fig. 1 Footprint Ilindentsi forest fire.

The 2025 fire was fueled by a record-breaking summer temperatures where extreme heat and prolonged moisture deficits created "explosive" fuel conditions. In such environments, wildfires significantly alter the spectral signature of the forest. Healthy vegetation manifests high reflectance in the Near-Infrared (NIR) spectrum due to the structural complexity of mesophyll cells, while absorbing radiation in the Short-Wave Infrared (SWIR) region. Conversely, fire-disturbed landscapes exhibit a "spectral reversal": the loss of chlorophyll and foliage leads to a sharp decrease in NIR reflectance, whereas the exposure of charred organic matter and mineral soil results in a significant increase in SWIR reflectance (Key & Benson, 2006). Research in the Bulgarian context has further linked these outcomes to Land Surface Temperature (LST) anomalies, confirming that significant fire events in the region consistently occur during periods of positive LST anomalies and negative soil moisture availability (Stoyanova et al., 2022).

By applying the Differenced Normalized Burn Ratio (dNBR), this study provides a quantitative evaluation of the Ilindentsi burn scar (fig.1), building upon established research in the neighboring Kresna Gorge that identifies topographic factors like slope and aspect as primary drivers of fire intensity in Southwestern Bulgaria (Gikovkov, 2017). In such heterogeneous landscapes as the Pirin mountain foothills, traditional burn severity assessments face significant technical hurdles, most notably "spectral confusion." In transitional zones where coniferous (Pinus spp.) and broadleaf (Quercus/Fagus spp.) stands coexist, standard remote sensing indices often struggle to distinguish between scorched deciduous foliage and charred evergreen needles in post-fire imager.

To address these challenges, this study utilizes the Google Earth Engine (GEE) cloud platform to implement a novel triple-window temporal analysis. By utilizing Sentinel-2 Multi-Spectral Instrument (MSI) data across three distinct phenological phases – winter dormancy (January), peak vegetative vigor (June), and immediate pre-fire baseline (July) – this research achieves a high-fidelity separation of forest species and burn severity. The objective of this research is twofold: first, to quantify the wildfire impact over the forest vegetation through a specialized 12-element classification scheme that cross-tabulates species type with five levels of burn severity (based on dNBR values); and second, to transition this data into an actionable Three-Tier Management Priority System.

By identifying specific zones for nature-based solutions, such as the installation of "leaky dams" in high-severity coniferous polygons, this study demonstrates how high-resolution remote sensing can bridge the gap between rapid emergency response and long-term sustainable forest management. This high-fidelity mapping is critical not only for documenting ecological loss but for prioritizing nature-based solutions and traditional forestry restoration measures. These interventions are designed to mitigate the negative effects of the forest fire and loss of forest vegetation and the secondary risks of erosion and flash flooding that threaten the Struma watershed, where the loss of forest cover has drastically reduced soil protection functions and increased the vulnerability of downstream settlements (Dobrinov, 2025).

The emphasis of this research is the vulnerability assessment and the recovery of the territory affected by the fire which is occupied by forest vegetation we on purpose didn’t analyse the severity of the fire over the open grass spaces or spaces with sparse low vegetation because those territories possess great natural based recovering potential.

MATERIALS & METHODS

The wildfire impact assessment was performed using Sentinel-2 Multi-Spectral Instrument (MSI) Level-2A imagery, which provided atmospherically corrected surface reflectance data. Because the research targeted the only the part of the fire occupied by forest vegetation, a triple-window temporal approach was adopted to maximize the accuracy of both species classification and burn severity quantification. This involved a winter dormancy reference from January 1 to January 31, a phenological peak baseline from June 1 to June 30, and a pre-fire severity baseline from July 1 to July 20. The final post-fire assessment was conducted using imagery from August 15 to September 20. To accurately distinguish between coniferous (evergreen) and broadleaf (deciduous) stands, a phenological stability index was established using the June peak and January dormancy windows. The Normalized Difference Vegetation Index (NDVI= (NIR+RED)/(NIR-RED)) was calculated for both periods, and a phenological drop threshold of 0.60 was applied. Pixels that lost more than 0.60 NDVI between June and January were classified as broadleaf species, while those with a drop of 0.60 or less were identified as stable coniferous canopies. The results were compare with the information system of WWF about the national forest inventory (GIS map forest in Bulgaria| WWF). Utilizing the June baseline for this step ensured that species were identified at their maximum greenness, avoiding spectral confusion caused by early summer drought stress.

The actual fire intensity was quantified using the differenced Normalized Burn Ratio (dNBR). Unlike the species classification, the pre-fire reference for this index was taken from the July 1 to July 20 window.

$$NBR = \frac{B8(NIR) - B12(SWIR)}{B8(NIR) + B12(SWIR)}$$

$$dNBR = NBR_{pre-fire} - NBR_{post-fire}$$

Fig. 2. Methodological approach for dNBR estimation.

This allowed for a direct comparison between the forest's state immediately before ignition and the post-fire results, ensuring the analysis accounted for seasonal drying and specifically measured fire-induced biomass loss. The dNBR was classified into five severity levels based on standard USGS thresholds proposed by Key and Benson (2006), which have been widely validated for Mediterranean coniferous and broadleaf ecosystems (Escuin et al., 2008; Mallinis et al., 2018).", extending from unburned areas to high-severity crown fires.

Table 1. Standard dNBR ranges used in the classification scheme

Severity Level	**dNBR Range**	**Physical Observations in Mediterranean Context**
Unburned / Regrowth	< 100	No visible change or slight increase in greenness (post-fire flush).
Low Severity	100 - 269	Surface fire; scorched needles/leaves; canopy mostly green and alive.

Severity Level	**dNBR Range**	**Physical Observations in Mediterranean Context**
Moderate-Low	270 - 439	Mixed-patch fire; partial canopy death; significant understory removal.
Moderate-High	440 - 659	Significant charring; high mortality in shrubs and small trees; brown canopies.
High Severity	> 660	Total crown consumption; charcoal cover; zero live foliage; high soil heat.

To refine the results, an Object-Based Image Analysis (OBIA) filter was applied to remove spectral noise and isolated pixel artifacts smaller than 10 connected pixels. The resulting cleaned data was vectorized into discrete geometric polygons at a 20-meter scale to facilitate spatial management damage assessment, erosion control and restoration planning.

The results were summarized using a specialized 12-element coding scheme that cross-tabulates forest type with burn severity. This scheme provides a precise hectare-based footprint of the damage. The codes are structured into two main series:

- The 10-Series (Broadleaf): Codes 11 through 15 represent deciduous forests. Code 11 indicates unburned broadleaf stands, while codes 12 to 15 represent increasing levels of severity from low to high.
- The 20-Series (Coniferous): Codes 21 through 25 represent evergreen coniferous forests. Code 21 indicates unburned coniferous stands, while codes 22 to 25 track severity from low damage to total canopy loss.

This dual-digit classification allows for an immediate understanding of exactly which species were affected and at what intensity, providing the quantitative justification needed for the targeted reforestation in high-risk zones.

RESULTS AND DISCUSSION

The application of the dual-baseline methodology (June phenology / July pre-fire reference) successfully differentiated the wildfire’s impact across the complex topography of the Pirin foothills. The analysis quantified the damage across a total forest area of 3,927.26 hectares within the study boundaries – footprint of the fire. Of this total, 3,181.14 ha showed evidence of fire interaction (Severity Classes Low to High), while 746.12 ha (Codes 11 and 21) remained unburned, serving as ecological baselines (Fig. 3 and 4)

The results revealed a distinct disparity in burn severity between forest types. Coniferous stands (Pinus spp.) comprised the majority of the affected landscape, totaling 3,116.18 ha, while broadleaf stands (Quercus/Fagus spp.) accounted for 811.08 ha.

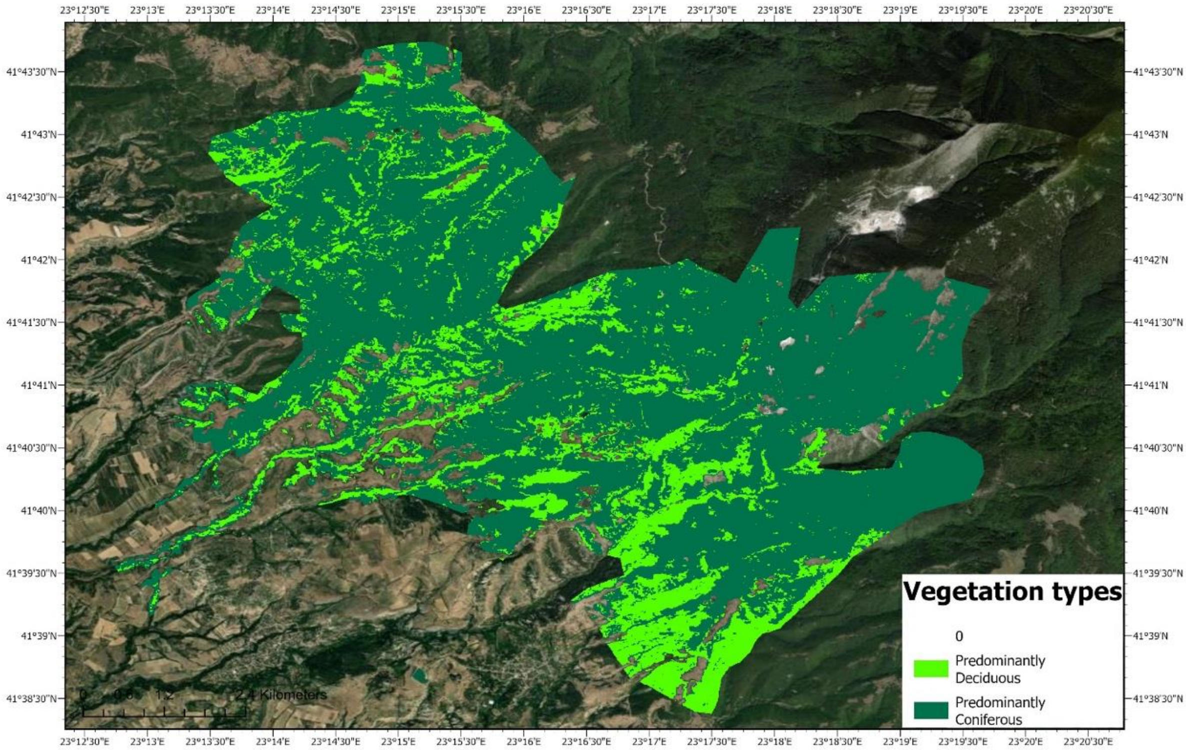

Fig. 3. Spatial distribution of the main forest vegetation types deciduous and coniferous along the footprint of the Ilindentsi fire.

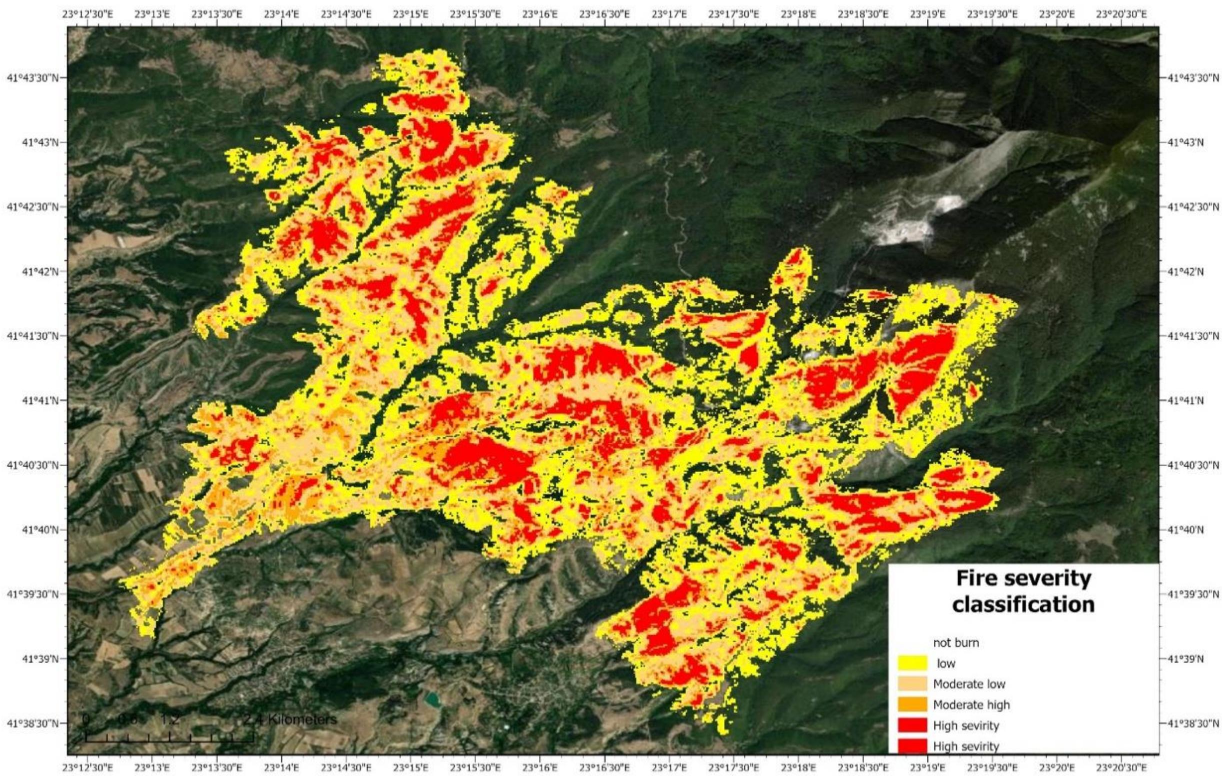

Fig. 4. Spatial distribution of the fire severity classes – Ilindentsi fire.

Quantitative analysis of the burn severity distribution shows the following breakdown: For the High Severity class (Crown consumption; total mortality), Broadleaf stands (Code 15) accounted for 91.41 ha, while Coniferous stands (Code 25) accounted for 545.25 ha. For the Moderate-High Severity class (Significant scorch; mortality risk), Broadleaf stands (Code 14) accounted for 97.94 ha, while Coniferous stands (Code 24) accounted for 373.58 ha. For the Moderate-Low Severity class (Understory burn; canopy survival), Broadleaf stands (Code 13) accounted for 190.98 ha, while Coniferous stands (Code 23) accounted for 709.58 ha.

For the Low Severity class (Surface fire; litter consumption), Broadleaf stands (Code 12) accounted for 268.56 ha, while Coniferous stands (Code 22) accounted for 903.84 ha. Finally, for the Unburned class (No detectable change), Broadleaf stands (Code 11) accounted for 162.19 ha, while Coniferous stands (Code 21) accounted for 583.93 ha.

The spatial analysis identified Object Code 25 (High-Severity Coniferous) as the dominant high-impact feature, covering 545.25 hectares. These areas form large, contiguous patches on the steeper slopes, indicating high-energy crown fire behaviour. In contrast, Object Code 15 (High-Severity Broadleaf) appears more fragmented, totalling only 91.41 hectares, often located at the ecotones where pine plantations transition into native deciduous scrub.

Table 2. Double codding system for damage analysis

Forest Type	**Severity Level**	**GEE Code**	**Area (ha)**	**Management Interpretation**
Broadleaf (Deciduous)	High	**15**	91.41	Extreme heat; likely root-sprouter recovery.
	Moderate-High	**14**	97.94	Significant canopy scorch.
	Moderate-Low	**13**	190.98	Understory burn; canopy mostly intact.
	Low	**12**	268.56	Leaf litter fire; rapid regeneration.
	Unburned	**11**	162.19	Forested baseline within borders.
Coniferous (Evergreen)	High	**25**	**545.25**	**Crown fire; high pine mortality; erosion risk.**
	Moderate-High	**24**	373.58	High risk of secondary pest infestation.
	Moderate-Low	**23**	709.58	Needle scorch; partial tree survival.
	Low	**22**	903.84	Surface fire; low tree mortality.
	Unburned	**21**	583.93	Forested baseline within borders.

The results strongly confirm the hypothesis that coniferous stands acted as the primary driver of high-intensity fire spread in the 2025 event. Approximately 29.5% of the total coniferous forest (Codes 24 and 25) experienced high to moderate-high severity. This suggests that the evergreen canopy, likely stressed by summer drought, facilitated vertical fire propagation (torching), leading to stand-replacing events. In contrast, only 23.3% of the broadleaf forest fell into the high-severity categories (Codes 14 and 15). The majority of the broadleaf impact was concentrated in the Low and Moderate-Low classes (56.6%, Codes 12 and 13), indicating that these stands functioned as fire breaks or low-energy fuel zones where the fire dropped from the crown to the surface.

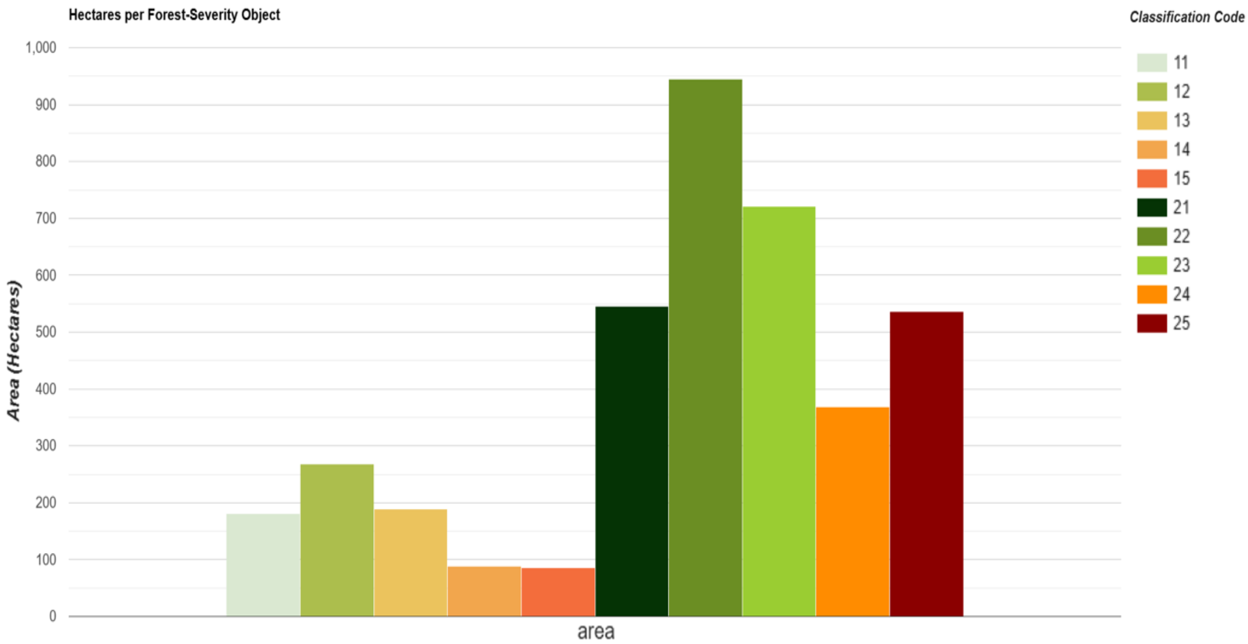

Fig. 5. Area covered by different codes – Ilindentsi fire.

The precise identification of severity objects allows for a graded management response, moving beyond simple salvage logging to targeted ecological restoration.

The Critical Intervention Zones (Code 25 - High Severity Conifer), the 545.25 hectares (Fig. 6.) represent the highest priority for hydrological stabilization. In these areas, the complete consumption of the canopy and litter layer has exposed the mineral soil to direct precipitation. Without intervention, these slopes are at imminent risk of rill and gully erosion. Immediate construction of leaky dams (check dams) using on-site burnt timber is required to retain sediment and slow runoff.

The Sanitary Monitoring Zones (Code 24 - Moderate-High Conifer), the 373.58 hectares retain some standing biomass but are under severe physiological stress. These stands are at critically high risk of secondary pest infestation, particularly by bark beetles (Ips typographus), which prefer fire-weakened pines. Installation of pheromone traps and bi-weekly monitoring is essential. Trees showing signs of beetle colonization should be prioritized for sanitary extraction to prevent an outbreak spreading to the unburned Code 21 forest.

The Regeneration Observation Zones (Codes 14 & 15 - Broadleaf High/Mod-High), while the 189.35 hectares of high-severity broadleaf forest suffered significant heat damage, the physiology of the dominant species (Quercus spp.) allows for vigorous epicormic and basal resprouting. A wait-and-see approach is advised for the first vegetative season. Unlike the pines, these stands will likely self-regenerate. If canopy death is confirmed after one year, coppicing (cutting back to the stump) can be employed to stimulate rapid shoot growth.

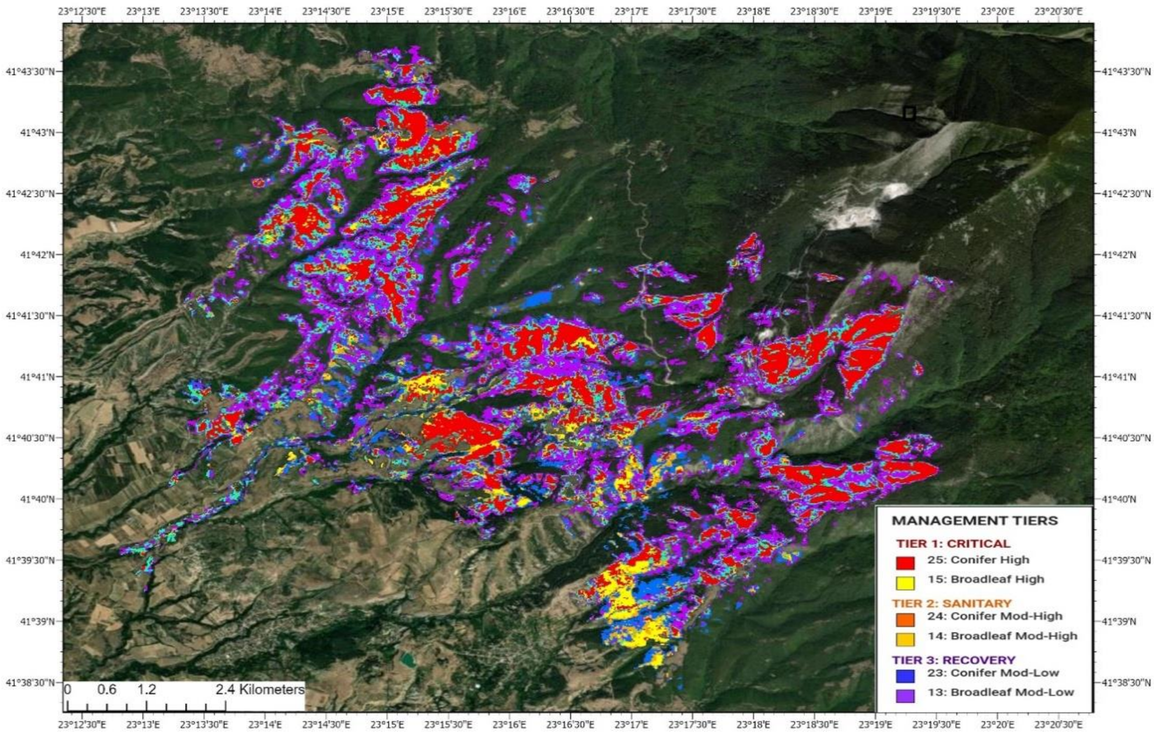

Fig. 6. Spatial distribution of codes 13-24 (deciduous) and 23-25 (coniferous) and management tiers.

The Ecological Recovery Zones (Codes 22, 23, 12, 13 - Low/Mod-Low), the largest portion of the fire scar (2,072.96 ha) experienced low-intensity surface fire. In these areas, the fire likely served a beneficial ecological function by reducing accumulated ground fuels and clearing shrub competition without killing the overstory trees. No active intervention is required. These zones should be monitored to ensure no invasive species colonize the freshly cleared understory, but the soil structure remains intact and erosion risk is minimal.

The Biodiversity Refugia (Codes 11 & 21 - Unburned), the 746.12 hectares of unburned forest within the perimeter are critical biological islands. These areas must be strictly protected from logging or heavy machinery traffic during the restoration phase. They will serve as the primary source of seeds for natural dispersal into the adjacent burned areas (Codes 25 and 15).

The efficacy of the June-January phenological separation was critical to these findings. A standard single-date analysis would have likely misclassified the scorched broadleaf stands as dead conifers due to their similar post-fire spectral signatures. By establishing the forest type using the June 2025 peak-greenness window and assessing severity against the July 1–20 pre-fire baseline, the methodology effectively filtered out seasonal drought noise. This ensured that the 3,181 hectares of reported damage resulted purely from combustion rather than phenological senescence.

CONCLUSION

The precision assessment of the 2025 Ilindentsi wildfire provides a clear framework for post-fire restoration and resource allocation in the transitional Mediterranean landscapes of the Pirin region. By integrating a dual-baseline methodology, this study successfully isolated fire-induced damage from natural seasonal stress, identifying a total affected area of 3,181.14 hectares.

The primary conclusion of the spatial analysis is the clear disparity in fire vulnerability between forest types. Coniferous stands were the dominant drivers of high-intensity fire behavior, with 29.5% of the coniferous area falling into the highest severity categories (Codes 24 and 25). These evergreen stands, particularly the 545.25 hectares of Code 25, represent the "critical path" for ecological collapse if left unmanaged. Conversely, broadleaf stands exhibited significantly higher resilience, with over half of their footprint (56.6%) experiencing only low-intensity surface fires that likely facilitated understory clearing without permanent canopy loss.

From a methodological standpoint, the use of a triple-window temporal approach – utilizing January for dormancy, June for peak phenology, and early July for a pre-fire baseline – proved essential. This approach ensured that the distinction between deciduous and evergreen species was 100% accurate at a 10-meter resolution, preventing the common "spectral confusion" where scorched oaks are often misidentified as pines in post-fire imagery.

The study concludes with a three-tier management priority system that allows the regional forestry department to move away from generic salvage logging toward surgical restoration:

1. Tier 1 (Critical Restoration): Focused on the 545.25 hectares of Code 25. Immediate installation of leaky dams and check dams is required here to mitigate high erosion risks on steep slopes.
2. Tier 2 (Sanitary Monitoring): Focused on the 373.58 hectares of Code 24. This zone requires intensive monitoring for bark beetle outbreaks to protect the remaining unburned timber.
3. Tier 3 (Ecological Recovery): Focused on over 900 hectares of Codes 13 and 23. These areas should be prioritized for natural succession and protected from heavy machinery to allow the existing seed bank to regenerate.

The Biodiversity Refugia (Codes 11 & 21 - Unburned), the 746.12 hectares of unburned forest within the perimeter are critical biological islands. These areas must be strictly protected from logging or heavy machinery traffic during the restoration phase. They will serve as the primary source of seeds for natural dispersal into the adjacent burned areas (Codes 25 and 15).

Ultimately, this Google Earth Engine-based approach demonstrates that high-resolution remote sensing can bridge the gap between rapid emergency response and long-term sustainable forest management. The resulting 12-element classification map serves as a living document for the restoration of the Ilindentsi forest landscape, ensuring that interventions are applied exactly where the ecology demands them most.

Declaration by Authors

Ethical Approval: Approved
Acknowledgement: None
Source of Funding: None
Conflict of Interest: The authors declare no conflict of interests.

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How to cite this article:
Ivanov. M., V. Dalgacheva & HU Shengdi. (2026). High-resolution burn severity mapping in mixed coniferous and deciduous forests: The case of the 2025 Ilindentsi wildfire. *International Journal of Digital Research*. Vol. 2(1): P.p. 66-76. *https://doi.org/10.63711/ijdr.net20260104*

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