

Comparing Sentinel-2 Spectral Indices for Mapping Forest Fire Damage in Pollino National Park, Italy

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Abstract

In recent years, climate change has significantly increased the severity and frequency of wildfires across Europe, with the 2025 season marking an unprecedented peak of one million hectares burned. Rapid and cost-effective mapping of these damaged areas is crucial for environmental recovery, making satellite remote sensing an indispensable tool. This study evaluates and compares the performance of four Sentinel-2 spectral burn indices for mapping forest fire damage within the Pollino National Park (Italy) occurred in September 2025, an area severely affected by the devastating summer fires of 2025. The analyzed indices include the Normalized Burn Ratio (NBR), Normalized Burn Ratio Plus (NBR+), Normalized Burn Ratio Short Wave Infrared (NBR-SWIR), and Normalized Difference Short Wave Infrared (ND-SWIR). An image differencing technique was applied to pre-fire (June 7, 2025) and post-fire (November 14, 2025) datasets, followed by a supervised Maximum Likelihood classification to map burned and unburned classes. Accuracy assessment via confusion matrices showed that NBR and NBR+ delivered the highest performance, achieving an Overall Accuracy (OA) of 0.976 and 0.974, respectively. ND-SWIR performed closely at 0.966, whereas NBR-SWIR yielded a lower OA of 0.873 due to the misclassification of bare soil transitions as burned areas. These findings highlight the critical role of specific SWIR-band combinations in optimizing automated wildfire monitoring systems.

1. Introduction

Over the past 10 years, wildfires have been on the rise across Europe, characterized by increasingly intense, frequent, and extended fire seasons. Driven by global climate change, which brings prolonged droughts and unprecedented high temperatures, these catastrophic events are progressively reaching further northward into regions historically less prone to severe burning. While some years have experienced isolated peaks in burned areas, the 2025 fire season stood out as an unprecedented crisis for wildfire severity on the European continent. During the 2025 European wildfire season, over 1.4 million hectares of forest and scrubland were destroyed across Europe. This unprecedented fire activity was directly attributed to increasingly dry, extreme summer conditions and persistent heatwaves that severely reduced fuel moisture content, creating an ideal environment for rapid fire ignition and propagation.

Given the vast scale and rapid evolution of these events, traditional ground-based survey methods are often unfeasible, time-consuming, and economically prohibitive. In this context, satellite-based remote sensing techniques have emerged as fundamental, objective, and highly effective tools for mapping burned areas. Satellite Earth observation provides spatially and temporally consistent information over vast, often inaccessible geographic areas, making it particularly well-suited for the rapid and systematic assessment of post-fire damage.

Furthermore, accurate mapping of fire-affected zones is crucial for quantifying the immediate ecological and economic impacts of fires, supporting emergency responses, and guiding long-term landscape monitoring and post-fire management strategies at both regional and global levels.

Multispectral satellite imagery, such as that provided by the European Space Agency's (ESA) Sentinel-2 constellation, is essential for wildfire mapping due to its high spatial and temporal resolution. Sentinel-2 features specific

bands in the Near-Infrared (NIR) and Short-Wave Infrared (SWIR) spectra, which are highly sensitive to changes in vegetation health and moisture content. When a fire occurs, healthy green vegetation which reflects strongly in the NIR is replaced by ash, charcoal, and bare soil, which exhibit a sharp increase in SWIR reflectance due to the loss of water and photosynthetic material.

To exploit these spectral alterations, numerous spectral burn indices have been proposed in the literature. However, the performance and consistency of these indices are not uniform, as they are heavily influenced by the specific multispectral bands employed, the local topography, and pre-existing land cover types. A critical challenge in automated mapping is the frequent misclassification of unburned surfaces such as agricultural plowed fields, quarries, or excavated areas which display low moisture contents like burned scars, leading to significant false positives. Therefore, verifying and comparing the accuracy of different indices under real-world, severe conditions is crucial for developing robust monitoring workflows.

To address this challenge, this study provides a comprehensive analysis and performance comparison of four prominent Sentinel-2 spectral indices applied to a real-world disaster scenario: the Normalized Burn Ratio (NBR), the Normalized Burn Ratio Plus (NBR+), the Normalized Burn Ratio Short Wave Infrared (NBR-SWIR), and the Normalized Difference Short Wave Infrared (ND-SWIR). The experiments focus on a critically impacted section of the Pollino National Park (Italy), which suffered devastating ecological damage during the record-breaking summer season of 2025. By employing a direct change detection technique (image differencing) coupled with a supervised Maximum Likelihood classification, this paper evaluates the capabilities, limitations, and operational reliability of each index using rigorous confusion matrix metrics.

2 Materials and Methods

2.1 Study Area

Pollino National Park, with its 192,565 hectares, is the largest newly established protected area in Italy.

It extends approximately between 39°40' and 40°10' North latitude and 15°45' and 16°35' East longitude. Figure 1 illustrates the geographical location of the Pollino National Park within Southern Italy.

The park's territory encompasses 56 municipalities located in two regions, Calabria and Basilicata. The landscape is characterized by several prominent mountain massifs that constitute the southern Apennine chain, including the Pollino Massif, the Orsomarso Mountains, and Mount Alpi. This complex topography hosts highly diverse ecosystems, ranging from typical Mediterranean bioclimates at lower elevations to Alpine habitats on the highest peaks.

The park's vegetation is predominantly characterized by Turkish oak (*Quercus cerris*) forests and some groups of mixed oak forests (composed primarily of oaks such as *Quercus pubescens* and *Quercus cerris*), beech (*Fagus sylvatica*), and silver fir (*Abies alba*), some of which are present in small groups. Together with beech, these represent natural relict vegetation of forests that once extended across these areas; Within the deforested areas, large mesophytic grasslands are often found.

The most common natural vegetation type is high-mountain Mediterranean scrub (juniper forests), while the park's most distinctive feature is the presence of Bosnian pine.

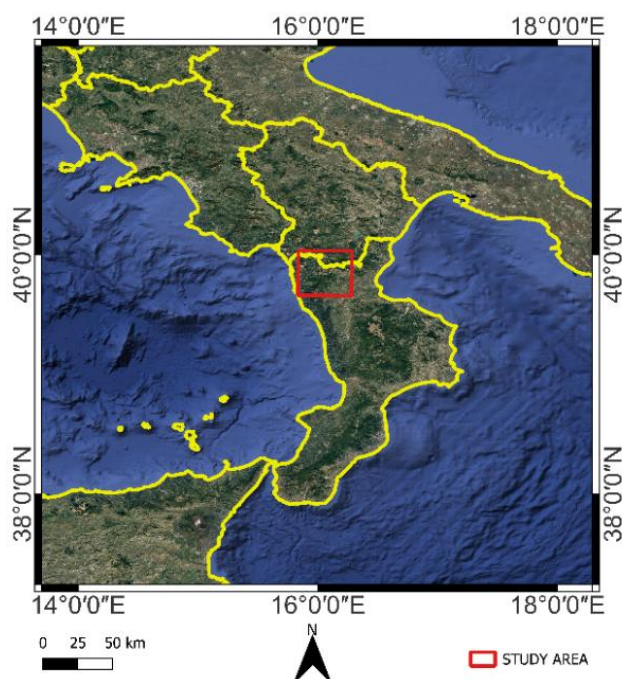


Figure 1. Geographical location of the Pollino National Park in Southern Italy, displayed in an equirectangular cartographic projection with geographic coordinates referred to the World Geodetic System 1984 (WGS84).

2.2. Satellite Data and Pre-processing

To evaluate fire damage within the study area, multi-temporal optical imagery from the Sentinel-2 satellite constellation was

utilized. The Copernicus Sentinel-2 mission is an Earth observation satellite mission managed by the European Space Agency (ESA) that provides high-resolution multispectral optical imagery of the Earth's surface and coastal areas. The mission utilizes a constellation of twin satellites. Currently, Sentinel-2A, Sentinel-2B, and Sentinel-2C are operational in orbit, ensuring frequent data acquisition and high spatial resolution imagery.

The Sentinel-2 dataset consists of imagery acquired across 13 distinct spectral bands with varying spatial resolutions: four bands at 10 meters, six bands at 20 meters, and three bands at 60 meters. Sentinel-2 products are distributed at different processing levels, with the primary tiers classified as Level 1 (Top-of-Atmosphere reflectance with systematic geometric and radiometric corrections) and Level-2A (Bottom-of-Atmosphere atmospheric corrected surface reflectance).

The key characteristics of Sentinel-2 images are summarized in Table I.

Sentinel-2		
Bands	Central Wavelength (μm)	Resolution (m)
B2—Blue	0.490	10
B3—Green	0.560	10
B4—Red	0.665	10
B8—NIR	0.842	10
B5 - Red Edge 1	0.705	20
B6 - Red Edge 2	0.740	20
B7 - Red Edge 3	0.783	20
B8 - NIR	0.842	10
B8A - Narrow NIR	0.865	20
B9 - Water Vapor	0.945	60
B10 - SWIR - Cirrus	1.375	60
B11 - SWIR 1	1.610	20
B12 - SWIR 2	2.190	20

TABLE 1. KEY CHARACTERISTICS OF SENTINEL-2 IMAGES

In this study, multi-temporal datasets were acquired to represent the surface conditions before and after the wildfire event. As illustrated in Figure 2, the post-fire true-color composite clearly highlights the spatial distribution and the visual impact of the burn scar within the park's boundaries.

Both datasets were processed following an identical methodological workflow to guarantee the absolute comparability of the radiometric observations between the two dates.

The use of spectral information acquired before and after a fire event is a well-established change-detection approach for identifying and characterizing fire-induced environmental

disturbances. Specifically, the differences between spectral indices derived from the pre- and post-fire acquisition dates are typically utilized to assess alterations in vegetation health and surface properties associated with the burn scar.

Since all the spectral burn indices examined in this study incorporate at least one Short-Wave Infrared (SWIR) band with a native spatial resolution of 20 meters, a uniform spatial resolution of 20 meters was adopted for all input bands. This strategy avoids downscaling resampling techniques, which could induce artificial spatial artifacts by generating a 10-meter resolution in bands that are not natively captured at that scale. Consequently, although the visible and Near-Infrared (NIR) bands used in the formulation of specific indices are natively available at 10 meters, their corresponding 20-meter resampled versions were utilized. This approach ensured complete spatial consistency and grid alignment across all spectral bands involved in the index and difference matrix calculations.

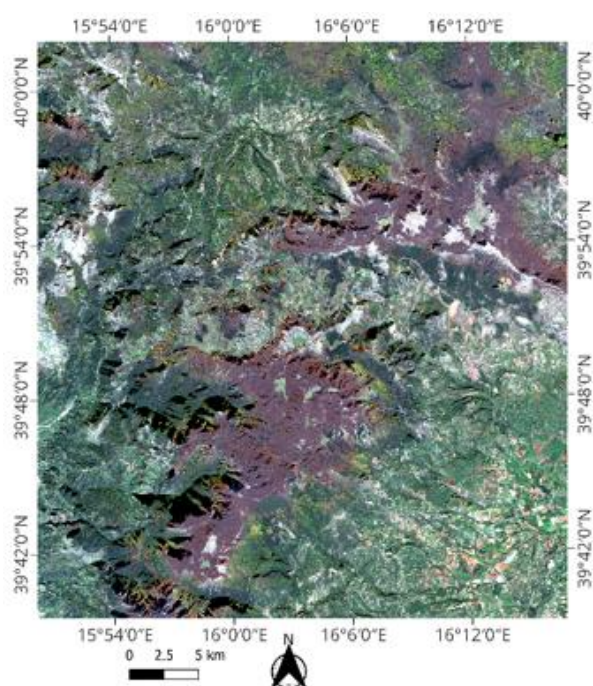


Figure 2. Sentinel-2 True Color (RGB: B4-B3-B2) composite of the study area captured on November 14, 2025, showing the visible extent of the wildfire scar within the Pollino National Park.

2.3. Spectral Burn Indices and Image Differencing

To evaluate the effectiveness of Sentinel-2 imagery for mapping fire damage, four distinct spectral burn indices were selected and compared. These indices exploit the radiometric response of fire-affected vegetation, characterized by a decrease in Near-Infrared (NIR) reflectance and a simultaneous increase in Short-Wave Infrared (SWIR) reflectance. The mathematical formulations of the four indices utilized in this study are detailed below.

Normalized Burn Ratio (NBR)

This index represents the traditional international benchmark for mapping fire scars and severity.

It exploits the opposite biophysical response of healthy canopy (high NIR and low SWIR reflectance) and burned surfaces (low NIR and high SWIR reflectance due to ash and water loss), compressing these dynamics into a standardized range.

Using Sentinel-2, this standard index combines the NIR (Band 8) and the second SWIR band (Band 12) according to the formula:

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

Normalized Burn Ratio Plus (NBR+)

This optimized index was introduced to enhance burned area discrimination in complex ecosystems by expanding the traditional formula. By simultaneously incorporating the green band (B3), the narrow NIR (B8A), and both SWIR bands (B11 and B12), it reduces atmospheric noise and minimizes the misclassification of stable bare soils.

$$NBR+ = \frac{(B12 - B8A - B11 - B3)}{(B12 + B8A + B11 + B3)}$$

Normalized Burn Ratio Short Wave Infrared (NBR-SWIR)

This index isolates the radiometric transitions strictly within the short-wave infrared spectrum by normalizing Band 11 and Band 12). It is highly sensitive to vegetation moisture drops and charcoal deposition, though its performance can be affected by background soil exposure due to the lack of an NIR reference.

$$NBR - SWIR = \frac{(B11 - B12)}{(B11 + B12)}$$

Normalized Difference Short Wave Infrared (ND-SWIR)

The Normalized Difference Shortwave Infrared Index (ND-SWIR) combines near-infrared (NIR) and shortwave-infrared (SWIR) reflectance. Originally introduced by Gao (1996) as the Normalized Difference Water Index (NDWI) to monitor canopy liquid water content, this mathematical formulation was later employed by George et al. (2006) for the retrospective mapping of burned areas and fire scar detection. When adapted to Sentinel-2 imagery, the ND-SWIR pairs the primary NIR band (B8) with the first SWIR band (B11). This specific band combination is highly effective for post-fire environmental assessments, as it systematically tracks the severe canopy moisture loss and structural vegetation degradation induced by thermal stress.

$$ND - SWIR = \frac{(B8 - B11)}{(B8 + B11)}$$

To isolate and quantify the environmental changes directly caused by wildfire, an image differencing technique (change detection) was applied to each index. For each investigated spectral index, the pre-fire grid was subtracted from the respective post-fire grid. The resulting differential index ($\Delta Index$) captures the magnitude of multi-temporal spectral variation, computed as follows:

$$\Delta Index = Index_{post-fire} - Index_{pre-fire}$$

Consequently, each output raster explicitly represents the environmental changes observed between the two acquisition dates. These spectral-index differences derived from multi-temporal observations provide valuable information for assessing fire-induced disturbances; indeed, biomass burning results in

substantial alterations to canopy structure and surface properties that are readily detectable through multispectral satellite imagery.

2.4. Image Classification and Accuracy Assessment

The image processing, index computation, and subsequent spatial analyses were entirely performed using the open-source geographic information system QGIS (v3.x). To automatically segregate the study area into two distinct landscape classes "Burned Area" and "Unburned Area" a supervised classification approach was executed on each of the four differential index (Δ Index) rasters. Specifically, the Maximum Likelihood classifier was implemented. This algorithm calculates the probability that a given pixel belongs to a specific class based on the mean vectors and covariance matrices of user-defined training samples, assigning the pixel to the class with the highest probability. Training sites representing pristine vegetation, bare soils, urban features, and severely burned zones were carefully selected via visual photointerpretation of the pre- and post-fire Sentinel-2 color composites.

To evaluate and compare the mapping performance of each spectral index, a rigorous accuracy assessment was conducted. Evaluating the classification of burned areas using independent reference data and accuracy metrics based on the confusion matrix is a commonly adopted approach in satellite-based burned area mapping studies. In this study a total validation dataset of 6,000 independent test pixels was utilized, equally distributed between the two classes (3,000 pixels for "Burned Area" and 3,000 pixels for "Unburned Area"). These validation points were checked via high-resolution visual inspection to confirm their actual post-fire state. For each index classification output, a confusion matrix was computed by cross tabulating the classified pixels against the validation data. From these matrices, the Overall Accuracy (OA), Producer's Accuracy (PA), and User's Accuracy (UA) metrics typically used for classification result evaluation were derived to quantify omission and commission errors, providing a statistically robust basis to determine the most reliable index for automated wildfire monitoring.

3 Results and discussion

The classification performance and mapping accuracy of the four differential spectral burn indices (ΔNBR , $\Delta NBR+$, $\Delta NBR-SWIR$, $\Delta ND-SWIR$) were evaluated using the confusion matrices derived from the 6,000 independent validation pixels. The summary of the accuracy metrics, including Overall Accuracy (OA), Producer's Accuracy (PA), and User's Accuracy (UA) for both classes, is presented in Table 2.

The spatial distribution of the classified classes across the study area is visually represented in Figure 3, which illustrates the final burn scar map derived from the Maximum Likelihood classification of the ΔNBR index. Furthermore, to provide a clear visual comparison of the thematic outputs generated by each tested method, detailed close-up views of the classified areas are presented in Figures 4, 5, 6, and 7 for ΔNBR , $\Delta NBR+$, $\Delta NBR-SWIR$, $\Delta ND-SWIR$, respectively. These spatial outputs demonstrate how the radiometric differences among the spectral combinations translate into distinct classification boundaries.

Method	Class	PA	UA	OA
ΔNBR	Burn	0.963	0.989	0.976
	No burned	0.990	0.964	
$\Delta NBR+$	Burn	0.961	0.986	0.974
	No burned	0.987	0.962	
$\Delta NBR-SWIR$	Burn	0.968	0.813	0.873
	No burned	0.777	0.961	
$\Delta ND-SWIR$	Burn	0.958	0.973	0.966
	No burned	0.974	0.959	

TABLE 2. ACCURACY ASSESSMENT METRICS (OVERALL ACCURACY, PRODUCER'S ACCURACY, AND USER'S ACCURACY) FOR THE FOUR SENTINEL-2 DIFFERENTIAL SPECTRAL INDICES.

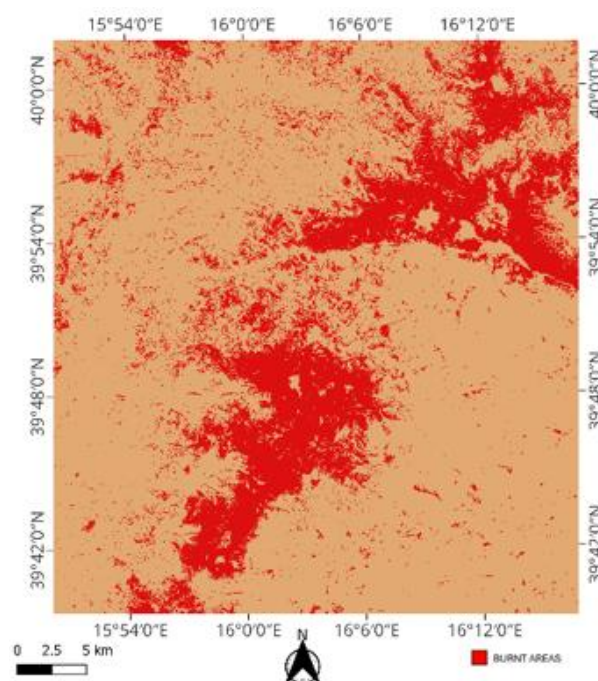


Figure 3. Post-fire supervised classification map (Burned vs. Unburned areas) derived from the ΔNBR spectral index using the Maximum Likelihood algorithm.

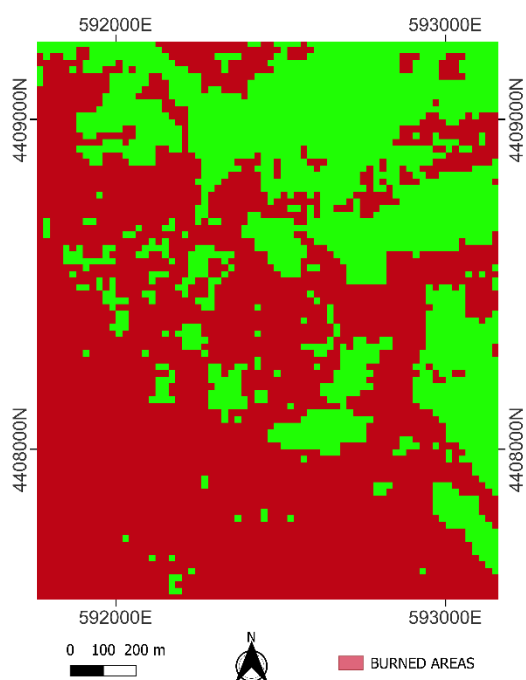


Figure 4. Detailed subset of the study area illustrating the application of the ΔNBR (Normalized Burn Ratio) spectral index, derived from the Maximum Likelihood classification.

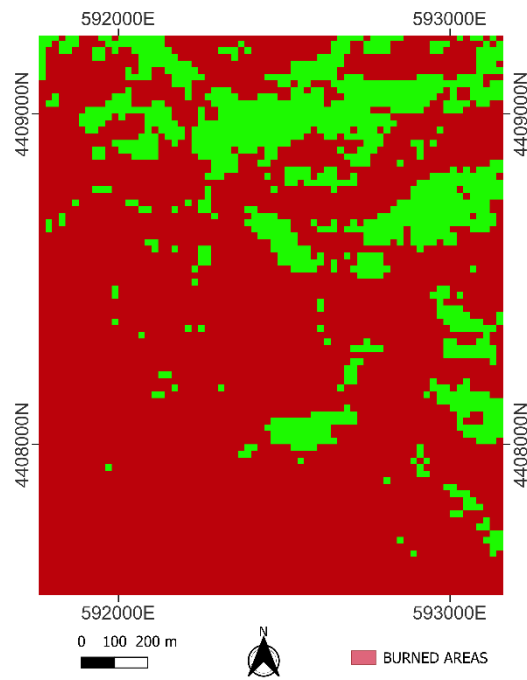


Figure 6. Detailed subset of the study area illustrating the application of the $\Delta NBR-SWIR$ (Normalized Burn Ratio - Short Wave Infrared) spectral index, derived from the Maximum Likelihood classification.

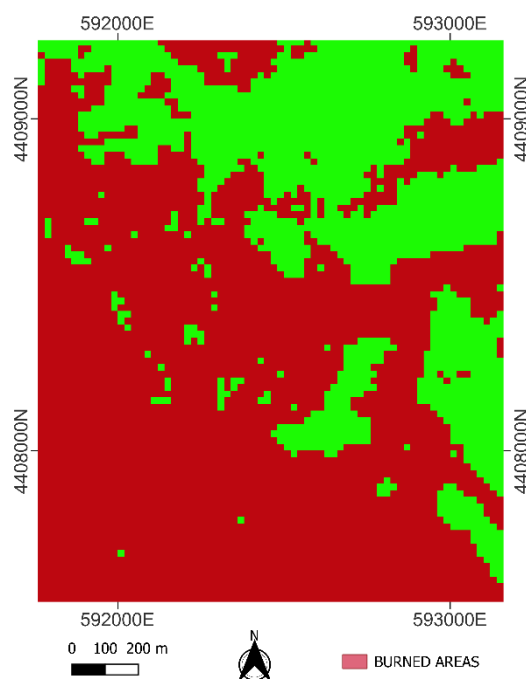


Figure 5. Detailed subset of the study area illustrating the application of the $\Delta NBR+$ (Normalized Burn Ratio Plus) spectral index, derived from the Maximum Likelihood classification.

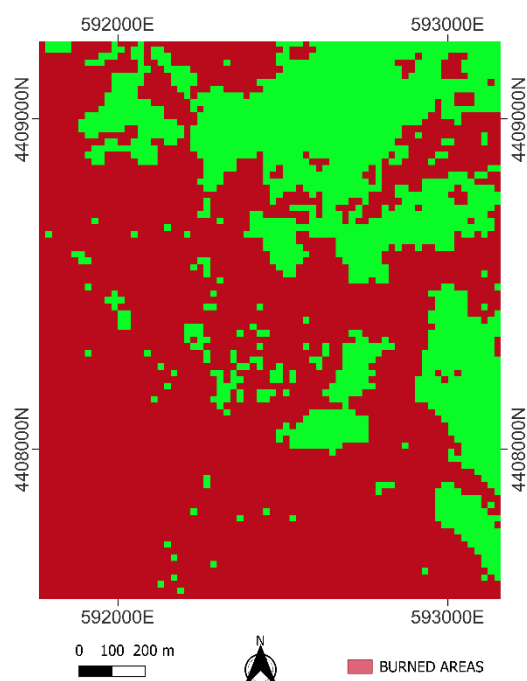


Figure 7. Detailed subset of the study area illustrating the application of the $\Delta ND-SWIR$ (Normalized Difference Short Wave Infrared) spectral index, derived from the Maximum Likelihood classification.

The experimental results demonstrate that both ΔNBR and $\Delta NBR+$ achieved outstanding and nearly identical performance, yielding the highest Overall Accuracies of 0.976 and 0.974, respectively. These indices proved to be highly robust in discriminating against the fire scar boundaries within the Pollino National Park. The high User's Accuracy for the burned class (0.984 for ΔNBR and 0.983 for $\Delta NBR+$) highlights a minimal occurrence of commission errors, meaning that unburned surrounding landscape features were rarely misclassified as burned vegetation.

Similarly, $\Delta ND-SWIR$ delivered a strong performance with an OA of 0.966, confirming that the combination of NIR and SWIR bands (specifically Band 8 and Band 11) is highly effective for capturing canopy water loss and structural canopy degradation.

Conversely, a significant drop in mapping performance was observed for $\Delta NBR-SWIR$, which yielded a lower Overall Accuracy of 0.873. A detailed analysis of the error metrics reveals that while its Producer's Accuracy for the burned class remained acceptable (0.941), its User's Accuracy dropped drastically to 0.829. This indicates a high rate of commission errors (false positives). This performance degradation is primarily attributed to the index's mathematical formulation, which relies exclusively on the normalization of the two short-wave infrared bands (Band 11 and Band 12). Because it lacks a reference band in the visible or NIR spectrum, $\Delta NBR-SWIR$ is highly sensitive to soil moisture transitions but struggles to differentiate between true burn scars and bare soil exposures, such as agricultural plowed fields, unvegetated mountain slopes, or quarries. In these specific areas, the drying of the soil surface mimics the spectral behavior of ash and charred wood, leading to extensive misclassifications.

Therefore, while $\Delta NBR-SWIR$ remains a useful tool for highlighting moisture variations, it is less reliable than standard NIR-SWIR combinations for automated and unsupervised wildfire monitoring systems in heterogeneous Mediterranean protected areas.

4 Conclusion

This study provided a comprehensive comparative evaluation of four Sentinel-2 differential spectral burn indices (ΔNBR , $\Delta NBR+$, $\Delta NBR-SWIR$, $\Delta ND-SWIR$) for mapping forest fire damage within the Pollino National Park, following the critical 2025 European wildfire season. By applying an image differencing technique combined with a supervised Maximum Likelihood classifier, the research demonstrated that ΔNBR and $\Delta NBR+$ offer the highest operational reliability, both achieving exceptional Overall Accuracies above 0.97. These indices successfully minimized commission errors, effectively delineating complex burn scars within highly heterogeneous Mediterranean ecosystems. Conversely, the exclusive use of SWIR-band combinations in $\Delta NBR-SWIR$ led to a significant performance drop (OA of 0.873) due to its high sensitivity to bare soil transitions, which frequently mimicked the spectral signature of burned areas.

A key strength of this methodological workflow lies in its reliance on completely open-source and freely accessible tools, specifically utilizing ESA's Sentinel-2 satellite constellation and the QGIS geographic information system. This combination ensures that the proposed framework is not only statistically robust and highly accurate but also highly cost-effective,

reproducible, and scalable for environmental agencies and park authorities responsible for rapid post-fire damage assessment and long-term landscape recovery monitoring.

Future research directions will focus on expanding this comparative framework to other protected areas characterized by different vegetation structures and topographical complexities. Additionally, future developments will investigate the integration of multi-temporal Synthetic Aperture Radar (SAR) data from the Sentinel-1 mission. Combining optical indices with radar backscatter metrics could overcome the limitations of cloud cover during emergency phases and significantly improve the discrimination boundaries between true burn scars and unvegetated bare soils.

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