

Estimation of forest fire burned area and burn severity degrees using Sentinel-2 data

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Thematic field: Forest disturbances and management challenges

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Abstract

A study has been conducted to identify burned areas in the region Otets Paisievo village in Plovdiv District, Bulgaria. The research aims at locating the burned areas and determining the degree of damage caused by a wildfire which occurred in the summer of 2024. Remote sensing and GIS methods were applied for the study. Various spectral indices (NDVI, MIRBI, NBR, NBR2, RBR, BAI, BAIS2) were generated using data from the Sentinel-2 satellite. The separability index (SI) was calculated, which showed the highest values for dMIRBI, dNBR2, dNBR and dBAIS2. Based on these four differential index differences, the burn area was determined and compared with data from the European Forest Fire Information System (EFFIS) and the local and national forestry sector. The results demonstrated a strong correlation with the actual burned area. Based on the analysis of spectral index values and the corresponding histograms, the study area was classified into four burn severity categories: unchanged, low, moderate, and high. The research indicates that for the surveyed area, indices based on shortwave infrared (SWIR) bands are effective in detecting and mapping forest fire burned areas.

Key words: burn area mapping, forest fire, Sentinel-2, separability index, spectral indices.

Introduction

The wildfires occurrence along with the increase in their frequency and intensity lead to the disruption of the essential ecological functions of forests.

The consequences of forest fires have various aspects – ecological, economic,

and social. Providing reliable information about forest areas affected by fires and tracking the processes related to their recovery are of utmost significance for informed decision-making and the implementation of effective forest management measures.

The use of remote sensing technolo-

gies for monitoring large areas from a distance, combined with GIS, will enhance public awareness and improve control over activities in forested areas (Asenova 2023).

In recent years, the availability of high-resolution optical data providing spectral information across different areas of the electromagnetic spectrum has enabled the tracking of environmental processes and performing analyses related to the identification, mapping, and assessment of fire-affected areas.

The use of an ever-increasing range of spectral indices expands the possibilities for distinguishing burned from unburned areas (Tran at al. 2018, Gikov and Dimitrov 2019, Alcaras at al. 2022, Arisanty at al. 2022, Farhadi at al. 2022, Vandansambuu at al. 2023, Guo at al. 2024). Despite the large number of studies related to spectral indices, there is still a challenge to determine which index is most suitable under specific conditions. The difference in fire intensity, type of vegetation, its condition before fire, local characteristics of observed area/region, such as climate, topography, vegetation composition, and initial plant mortality, are all factors that influence the assessment of burned areas and the speed of vegetation recovery (Avetisyan at al. 2022). The behaviour of indices may vary across various ecosystems, suggesting that functionally distinct types of forests have different spectral responses. Therefore, the same index may not perform equally well in detecting burned areas (Mpakairi at al. 2020). As a result, analyses cannot be based on a single, standardised spectral index.

Each index has specific characteristics and applications in the mapping of burned areas. Normalised Difference Vegetation Index (NDVI) is one of the most popular indices, not only for determining vegetation

status and conducting analyses related to susceptibility to erosion, mudflow, and rockslides (Baltakova at al. 2018, Nikolova at al. 2024), but also for assessing the severity of fires. This index uses the ratio of reflectance in the Red and Near-Infrared (NIR) spectral bands and shows that the lower the values of the ratio, the more intense the damage to vegetation is, i.e. the more severe the fire impact is (Kesgin and Ersoy 2020).

Normalised Burn Ratio (NBR) is used to identify burned areas and to assess the severity of burning. It is a ratio of the difference to the sum of reflectance on NIR and SWIR bands. Vegetation before the fire will have a high reflectance value relative to the NIR wavelength and a low reflectance value relative to SWIR wavelength, while the opposite will occur in the post-fire image (Sukmono at al. 2023). In other words, the difference between the spectral responses of healthy vegetation and burned areas peaks in the NIR and SWIR regions of the electromagnetic spectrum. Normalised Burn Ratio 2 (NBR2) modifies the Normalised Burn Ratio (NBR) to highlight water sensitivity in vegetation and may be useful in post-fire recovery studies. NBR2 is calculated as a ratio between SWIR values of Sentinel-2 (B11 and B12), substituting the NIR band used in the NBR with band B11 of the Sentinel-2 (Kesgin and Ersoy 2020). Another widely accepted index used for identifying burned areas, in addition to Normalised Burn Ratio (NBR), is Burn Area Index (BAI). Both indices can be automatically calculated and achieve relatively high accuracy in detecting burned land by means of a simple algebraic algorithm applied to pixels (Wu at al. 2022). It is specifically designed for discriminating burned land in the red-NIR spectral region, highlighting the signal from charcoal in post-fire images. There-

fore, this index is highly dependent on the temporal stability of charcoal after the fire (Chuvieco at al. 2002). Burned Area Index for Sentinel-2 (BAIS2) is a fire detection index specifically designed for the spectral characteristics of Sentinel-2, with its innovation lying in the combination of the red-edge band ratio (used to describe vegetation characteristics) and the response of the short-wave infrared (SWIR) band. This combination demonstrates significant efficiency in identifying burned areas, enabling more precise detection and identification of fire-affected regions (Liu at al. 2025). Relative Burn Ratio (RBR) spectral index is a variant of differential NBR (dNBR), where $dNBR = NBR_{pre} - NBR_{post}$. The RBR index takes into account the relative amount of change before and after the fire by dividing dNBR by pre-fire NBR value. This revitalised index was created to eliminate the bias caused by vegetation type and density before the fire (Chuvieco at al. 1998). Medium Infrared Burn Index (MIRBI) has the ability to differentiate burned areas from bare land (Arisanty at al. 2022). It is designed in the discriminative middle-infrared space, with short and long wavelength bands (referring to Sentinel-2 bands 11 and 12). This

index is highly sensitive to spectral changes caused by burning and relatively insensitive to noise (Trigg and Flasse 2001).

One advantage of using spectral indices is the easy, standardised processing of images, which provides more precise information compared to visual interpretation or automatic classifications (Dimitrov and Gikov 2009).

The main objective of the present study is to determine the burned area and burn severity degrees in the region of the village of Otets Paisievo, using remote sensing and GIS. To achieve this, a methodology has been developed that includes testing various spectral indices and evaluating them, as well as determining optimal threshold values for burned areas and burn severity levels.

Materials and Methods

Study area

The object of the study covers forested areas in the vicinity of the village of Otets Paisievo, located at 40 km from Plovdiv, in the municipality of Kaloyanovo, Southern Bulgaria (Fig. 1).



a)



b)

Fig. 1. Study area: a) Location of the study site – Otets Paisievo village, Plovdiv district, Bulgaria; b) The forest fire in the study area.

The area is hilly, typical of the southern slopes of the Sredna Gora Mountains. The climate is characterised by warm summer, dry autumn, and mild winter. Deciduous and coniferous forests dominate in the surroundings of the village. The main broadleaf tree species are oak (*Quercus* sp.), beech (*Fagus sylvatica* L.), and hornbeam (*Carpinus betulus* L.). The coniferous forests are represented by black pine (*Pinus nigra* J.F.Arnold), Scots pine (*Pinus sylvestris* L.), and spruce (*Picea abies* (L.) H.Karst.), as they are frequently planted in these regions.

On 16 July 2024, a large fire broke out in the village of Otets Paisievo, destroying over 20 houses and forcing the evacuation of 15 residents. The fire affected approximately 900 ha of deciduous and coniferous forests and other areas, such as meadows and pastures (Bulgarian News Agency (BNA) 2024) on the territory in the municipality of Kaloyanovo with available data of burned area in the Executive Forest Agency (EFA) (EFA 2025).

The fire was classified as a top tree

fire, where the flames engulf the treetops, often without visible flames on the ground. Although the terrain was hilly and access was hard, the fire was contained by 18 July 2024. However, smouldering hot-spots remained in some areas and those required monitoring.

Dataset

For this study, data from Sentinel-2 satellite mission provided by the European Space Agency (ESA) (2015) were used. They were downloaded from Copernicus Data Ecosystem website, 2024, the new portal of ESA launched at the beginning of 2023. Sentinel-2 has a set of 13 spectral bands (spectral ranges), covering from the visible and near-infrared to the short-wave infrared bands. It includes four spectral bands with 10 m spatial resolution, six with 20 m, and three with 60 m (Sentinelhub 2025). The specification of Sentinel-2 is shown in Table 1.

Compared to other satellites used for fire localisation, such as Landsat (Gikov

Table 1. Description of the band features of Sentinel-2 images.

Bands	Central wavelength, nm	Bandwidth, nm	Spatial resolution, m
B1 – Coastal aerosol	443	20	60
B2 – Blue	490	65	10
B3 – Green	560	35	10
B4 – Red	665	30	10
B5 – Vegetation Red Edge	705	15	20
B6 – Vegetation Red Edge	740	15	20
B7 – Vegetation Red Edge	783	20	20
B8 – NIR	842	115	10
B8A – Vegetation Red Edge	865	20	20
B9 – Water Vapour	945	20	60
B10 – SWIR – Cirrus	1375	30	60
B11 – SWIR 1	1610	90	20
B12 – SWIR 2	2190	180	20

Source: ESA (2015).

and Dimitrov 2019), Sentinel-2 provides relatively high spatial (Table 1) and temporal resolution (each satellite captures a given area every 10 days; thus, using data from each satellite renders the period between two captures as 5 days).

This study uses data from Sentinel-2, Level-2A as it provides products with atmospherically corrected surface reflectance (SR) from Level-1C products (Gascon et al. 2017, Copernicus 2025). In some studies, corrections related to cloud presence are performed (Gascon et al. 2017), but no such correction was applied in this study because there were no clouds over the study area on the relevant dates.

The images used before the fire date and the closest possible date after it was extinguished are Sentinel-2A, MSIL2A, T35TLH: 08.07.2024 and 28.07.2024.

Methods

The proposed workflow includes the following stages: selection of appropriate images for the purposes of the study, sub-setting, resampling, stacking, generation of spectral indices and their differ-

ence, evaluation of the spectral indices' performance, application of water/cloud mask, determination of precise threshold values using histogram analysis and forestry data, and analysis.

Image processing was carried out in the ArcGIS Pro 3.4.0 software environment (ESRI 2024). A shapefile was created to crop the image dataset so that it would cover only the studied area. The metadata in the generated subsets are linked to the original dataset, ensuring the preservation of essential information from the original image (Stoyanova and Katsarska-Filipova 2023). This step is important as it ensures the analysis of the same area when comparing different time periods and optimises data processing by reducing the data volume and speeding up calculations. One of the subset images is shown in Figure 2.

When calculating indices, such as BAIS2, NBR, etc., bands with different spatial resolutions are used (e.g., B8 – 10 m and B12 – 20 m for NBR), which required them to be standardised to the same resolution. For resampling, the nearest neighbour algorithm was used, which does not alter any of the cell values from the input raster dataset (ESRI 2025).

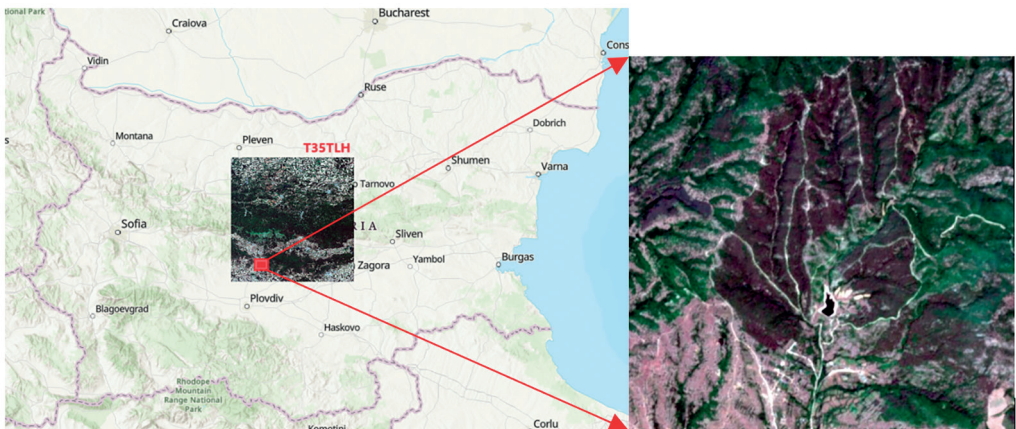


Fig. 2. The entire image on the left and the subset image on the right.

After the pre-processing stage, the creation of spectral indices was carried out. Based on a preliminary review of the topic, a set of characteristic spectral indices were selected for localising burned areas and determining burn severity.

The applicability of seven vegetation indices, both general and specific for identifying burned areas (NDVI, NBR, NBR2, MIRBI, BAI, BAIS2, RBR), were tested for identifying burned zones based on changes in land cover before and after the fire. The spectral indices are listed in Table 2.

A water body was located within the study area, and for this reason, a water mask was created using Normalized Difference Water Index (NDWI). By maximising the reflectance of the water body in the green spectral range and minimising the reflectance of the water body in the

near-infrared spectral range, NDWI index is particularly effective in distinguishing open water areas from other types of land cover, such as vegetation and bare soil. The index values range from -1 to +1, with higher positive values indicating the presence of water (McFeeters 2013, Stoyanova and Katsarska-Filipova 2023). This approach enhanced the reliability of the information in the affected area.

For the accurate calculation of burned areas, determining the threshold value of the index is of critical importance. This threshold defines the point above which pixels are considered to belong to burned areas and below which they are classified as unburned. There is no standardised method for defining burn severity degrees (thresholds).

For example, one widely used scale

Table 2. Description of the spectral indices used in this study adapted for Sentinel-2.

Spectral indices	Algorithm	References
NDVI	$NDVI = \frac{B8 - B4}{B8 + B4}$	Tucker 1979
NBR	$BBR = \frac{B8 - B12}{B8 + B12}$	Key and Benson 1999
Differential NBR	$dNBR = NBR_{pre} - NBR_{post}$	
NBR2	$NBR2 = \frac{B11 - B12}{B11 + B12}$	Key and Benson 2006
BAI	$BAI = \frac{1}{(0.1 - B4)^2 + (0.06 - B8)}$	Chuvieco et al. 1998
BAIS2	$BAIS2 = \left(1 - \sqrt{\frac{B6 \cdot B7 \cdot B8A}{B4}} \right) \cdot \left(\frac{B12 - B8A}{\sqrt{B12 + B8A}} + 1 \right)$	Filipponi 2018
MIRBI	$MIRBI = 10 \cdot B11 - 9.8 \cdot B12 + 2$	Trigg and Flasse 2001
RBR	$RBR = \frac{dNBR}{\sqrt{ NBR_{pre} } - 1}$	Parks et al. 2014
NDWI	$NDWI = \frac{B3 - B8}{B3 + B8}$	McFeeters 1996

for assessing burn severity using the dNBR index is the USGS FireMon scale. It differentiates five classes of areas: unburned, low severity, low to moderate severity, moderate to high severity, and high severity (Key and Benson 2006). In some cases, the two moderate severity classes are combined.

For this study, burn severity is classified into four classes: unburnt/unchanged, low severity, moderate severity, and high severity (Dimitrov and Gikov 2009). These severity levels correspond to the data on the official website of the Ministry of Agriculture and Food by the Executive Forestry Agency in Bulgaria:

- Low severity (25 %) – These are areas with light burn severity, where part of the vegetation has survived. Trees may have scorched branches, but the soil remains relatively unaffected. Rapid ecosystem recovery is expected.

- Moderate severity (50 %) – These are moderately affected areas where approximately half of the vegetation has been destroyed. Some trees may be scorched, but surviving vegetation is still present. Recovery will take longer and may require additional restoration efforts.

- High severity (100 %) – These are completely burnt areas. All trees, shrubs, and grasses have been destroyed, and the soil may be affected by high temperatures. A long-term restoration strategy is needed, including re-forestation and soil rehabilitation.

To determine the precise threshold values (i.e. to avoid marking pixels outside the actual burned area), field data from the local Forest Service were used for validation. These data were collected using mobile GPS devices. However, some areas of the territory are difficult to access and no measurements have been made in them, and the burn severity has been de-

termined indirectly (visually). Therefore, the MIRBI threshold map and the field data have been compared visually. Furthermore, an analysis of the histograms of the individual indices was conducted using natural breaks, enabling a more precise determination of the threshold values. The separability index (SI) is widely used to evaluate the performance of spectral indices in terms of their ability to discriminate burned and unburned areas (Kesgin and Ersoy 2020, Farhadi et al. 2022, Pacheco et al. 2023, Afifah and Astuti 2025). Therefore, it is also used in the present study. It is calculated for each image before and after the fire using equation (1).

$$SI = \frac{|\mu_b - \mu_{ub}|}{\sigma_b + \sigma_{ub}}, \quad (1)$$

where μ_b and μ_{ub} are the average, and σ_b and σ_{ub} are the standard deviations of the samples from the burnt and unburnt areas.

Higher SI values indicate that the given spectral index has a strong separability attribute, whereas lower values reflect that the discrimination of burned and unburned pixels are not as good as the higher SI values. Therefore, $SI > 1$ depicts fine separation, whereas values of $SI < 1$ represent poor separation (Mthembu and Marwala 2008).

Results and Discussion

Burn area delimitation and fire severity

Based on the obtained separability index results, presented in Table 3, it can be stated that the best performance in distinguishing between burned and unburned areas is shown by the MIRBI spectral index, followed by NBR2. Similar results were also obtained in another study with a similar focus (Pacheco et al. 2023).

Table 3. Separability index and burned threshold for various indices.

Spectral index	SI	Burned threshold
NDVI	1.2985	dNDVI ≥ 0.074
NBR	1.7168	dNBR ≥ 0.108
NBR2	2.2572	dNBR2 ≥ 0.036
BAI	3 ⁻⁸	dBAI $\leq -1.791e^{-08}$
BAIS2	1.7538	dBAIS2 ≤ -0.360
MIRBI	2.4263	dMIRBI ≥ 0.280
RBR	0.6013	dRBR ≤ -0.327

Similar close results were also shown by the indices BAIS2 and NBR. These were followed by the NDVI index. The separability indices for RBR and BAI were significantly lower, respectively, indicating lower performance in distinguishing between burned and unburned areas compared to the indices described above.

The dMIRBI spectral index had the highest discriminative ability, whereas the dBAI and dRBR indices showed the lowest performance. Although RBR demonstrated good results for distinguishing burn severity in other studies (Sobrino et al. 2024), in our case, the results were low. This may be due to the presence of agricultural plots of land in the southern part of the study area. In literature, the dBAI index is noted for its strong ability to detect recently burned areas, particularly where the vegetation is predominantly woody and the charcoal rate is high (Chuvieco et al. 2002). Similarly, low results for this index were reported in another study (Kesgin and Ersoy 2020). This is likely because, as in our case, a large portion of the study area contains a mixed presence

of woody and herbaceous vegetation (Scheepers et al. 2014). Accordingly, the results indicate that dNDVI also demonstrates a strong ability to differentiate between burned and unburned areas. Nevertheless, the study focused on those with the highest values.

Although the separability index values of dBAI and dRBR are the lowest, this does not mean that they are unable to distinguish burned areas. Rather, for the studied area, they show greater errors compared to the other indices.

Further evaluation of the capabilities of spectral indices, the application of water masks/cloud masks when necessary, as well as conducting histogram analysis combined with the use of field data, leads to an increase in the reliability of the obtained results. Table 4 presents precise threshold values for the indices in the study.

For all four indices, it was found that the smallest portion of the burned area is characterised by high burn severity, followed by moderate severity, while the largest portion corresponds to areas with low burn severity. According to the dMIRBI values, the distribution of burned areas and their percentage is as follows: high burn severity – 18.9 % (119.44 ha), moderate severity – 28.6 % (181.47 ha), and low severity – 52.5 % (332.70 ha). The fire had the most significant impact on coniferous forests. Areas with a higher tree density covered by coniferous vegetation showed correspondingly higher burn severity. Deciduous and mixed vegetation, as well as agricultural lands located in the

Table 4. Thresholds for some indices.

from – to	dMIRBI	dNBR2	dBAIS2	dNBR
Unburn area	-0.755 $\div$ 0.349	-0.045 $\div$ 0.035	-0.360 $\div$ 0.225	-0.046 $\div$ 0.107
Low severity	0.350 $\div$ 0.944	0.036 $\div$ 0.092	-0.361 $\div$ -0.701	0.108 $\div$ 0.256
Medium severity	0.945 $\div$ 1.667	0.093 $\div$ 0.166	-0.702 $\div$ -1.081	0.257 $\div$ 0.441
High severity	1.668 $\div$ 2.857	0.167 $\div$ 0.268	-1.082 $\div$ -2.138	0.442 $\div$ 0.726

southern part of the study area, were affected to a lesser extent, showing low to moderate burn severity.

Figure 3 illustrates the map of the study area by burn severity derived using dMIRBI.

The map of the study area by burn severity derived using dMIRBI including a 'low severity' category reveals additional affected areas that are not reported on the official website of EFA. However, in relation to the total burned area in the EFFIS database, such a category should be present. This confirms that the use of spectral indices (such as dMIRBI) provides a more comprehensive and objective picture of

the fire's impact on the territory.

Comparison with existing source data

To compare the results obtained using spectral indices and to determine the areas affected by the fire, data from the European Forest Fire Information System (EFFIS) were used (Copernicus Emergency Management Service 2025). Table 5 presents the burned areas estimated using the selected spectral indices, compared to the area determined by EFFIS, along with the percentage difference between them.

Figure 4 illustrates the boundaries of

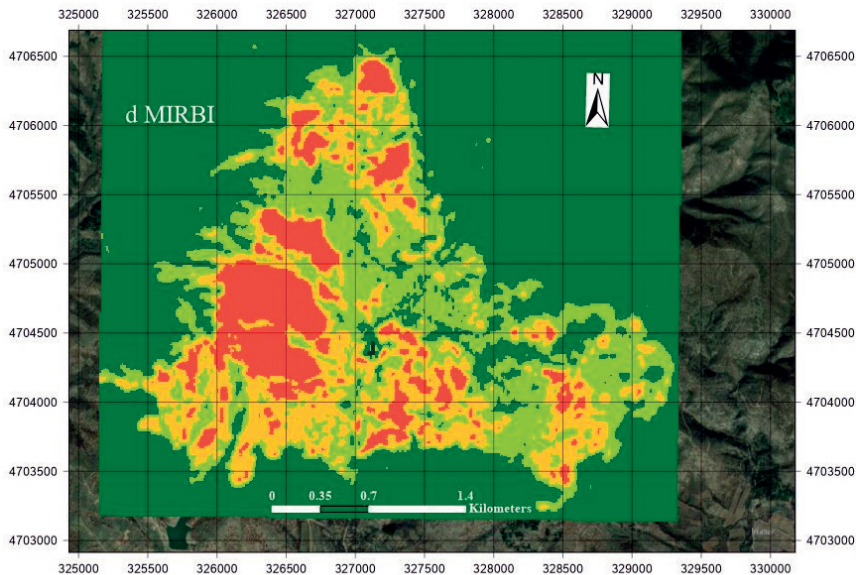


Fig. 3. Map of the study area by burn severity.

Table 5. Comparison of the burnt area estimates derived from the spectral indices with the highest separability values and the reference data from EFFIS.

Index	Area, ha	Area difference, ha	Area difference, %
Reference value (EFFIS)	634	-	-
dMIRBI	633.61	0.39	0.06
dNBR2	625.04	8.96	1.41
dNBR	622.27	11.73	1.86
dBASIS2	620.04	13.96	2.20

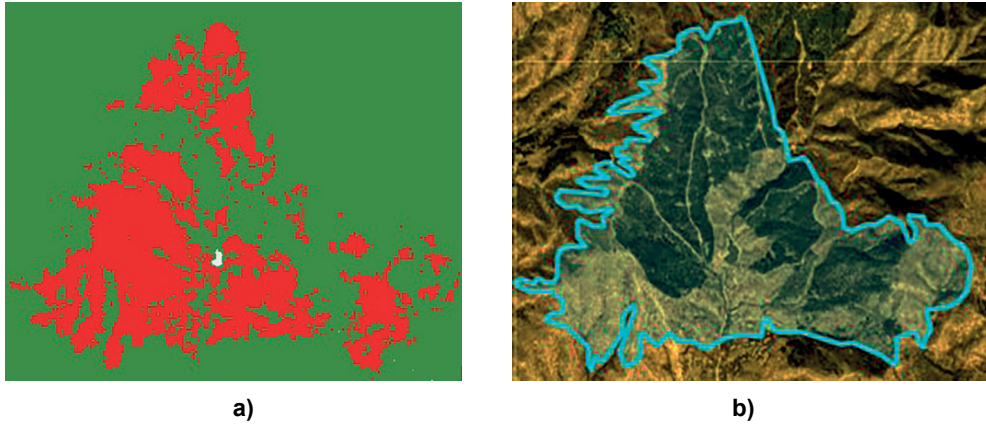


Fig. 4. Burnt area obtained from: a) dMIRBI and b) EFFIS.

the burnt areas derived using dMIRBI and those presented on the EFFIS website.

Based on the comparison of the burned areas, it can be stated that the differences between the indices with the highest separability values are minimal. Nevertheless, it should be noted that additional studies are necessary to confirm the reliability of the obtained results.

Forest stands often fall within the protected areas of Bulgaria. Wildfires in these regions can lead to the loss of priority habitats and disrupt the ecological processes taking place within them. Accurate localisation and measurement of the burned areas are essential for an objective assessment of the impact on biodiversity and for the development of effective strategies for the restoration of plant and animal life. For this reason, an analysis was conducted using data on the boundaries of protected areas provided by EFA. The analysis established that the studied site does not fall within any protected territory.

Conclusion

The study presents the results of applying various spectral indices, like NBR, NBR2,

BAI, BAIS2, MIRBI, RBR, and NDVI, to delineate burned areas' boundaries and determine burn severity. Based on a statistical evaluation using the separability index and on a comparison of the fire-affected areas, it was found that the BAIS2, MIRBI, NBR2, and NBR indices demonstrated the highest separability. Despite their close values, the MIRBI spectral index had the highest score in the present study (Table 4). This is consistent with other studies (Pacheco et al. 2023), which show that the reflectance values in the SWIR1 and SWIR2 bands represented in dMIRBI offer greater potential for discriminating and detecting changes in fire severity. This is also confirmed by the fact that the separability index values of NBR2 are very close to those of MIRBI for the study area.

Therefore, for detecting burned areas, we recommend the use of indices based on the two SWIR bands (Sentinel-2 bands – B11 and B12).

The results show that spectral indices are a valuable tool for locating and assessing burned areas in a mid-mountain region characterised by a temperate climate, forest vegetation, pastures, and meadows. These findings are supported by previous studies, which indicate that

the effectiveness and performance of spectral indices in distinguishing between burned and unburned areas strongly depend on the types of vegetation, as well as on the temporal intervals of the imagery and spectral ranges used.

The proposed methodology has the potential to be applied in other areas with analogous characteristics, thereby enhancing the reliability and generalisability of the obtained results. To reinforce the results of the present study related to the identification and mapping of burned areas and the adverse effects of those on vegetation, further research could be conducted based on these indices in other regions, thereby expanding the study area.

In the future, further in-depth studies could also be carried out with a focus on the analysis of fire severity across different vegetation types, as well as monitoring forest recovery after fire events.

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