BILINGUAL PUBLISHING GROUP

Research in Ecology
https://journals.bilpubgroup.com/index.php/re

ARTICLE

Monitoring Post-Fire Severity and Recovery in "La Danta" Eco-Reserve in Colombia, Using Remote Sensing Data

Carlos E. Oliveros-Valero [1], Mauricio Galvis-Patiño [2], Jose Manuel Monsalve-Tellez [1], Bernardo Enrique Forero Duarte [3], Jhon Alexander Mogollon Modesto [3], Yeison Alberto Garcés-Gómez [1]*

[1] *Faculty of Engineering and Architecture, Universidad Católica de Manizales, Manizales 170001, Colombia*

[2] *NanoTech Group, Faculty of Engineering and Basic Sciences, Fundación Universitaria Los Libertadores, Bogotá 11001, Colombia*

[3] *Colombian Petroleum Company – ECOPETROL, Bogotá 110110, Colombia*

ABSTRACT

Wildfires represent a growing threat to transitional ecosystems of the Colombian Orinoquía, where savannas and gallery forests converge under increasing anthropogenic pressure and climate variability. This study assesses fire severity and post-fire vegetation recovery in the La Danta Eco-Reserve using high-resolution multispectral imagery from Sentinel-2 processed within the Google Earth Engine (GEE) cloud-computing platform. A multi-temporal analysis was conducted for the period 2021–2025, during which a cumulative burned area of 1845 hectares was identified. Fire severity was quantified using the Differenced Normalized Burn Ratio (dNBR), allowing spatial discrimination of burn impacts across heterogeneous land covers. Results indicate that 73.8% of the burned area was affected by low to moderate-low severity fires, while 26.2% experienced moderate-high to high severity, leading to substantial biomass loss and structural vegetation damage. Post-fire vegetation dynamics were evaluated through time-series analysis of the Normalized Difference Vegetation Index (NDVI), revealing marked contrasts in ecosystem resilience. Savanna formations exhibited rapid recovery, reaching pre-fire NDVI levels within 6 to 12 months, reflecting high adaptive capacity to fire disturbances. In contrast, gallery forests and areas subjected to high-severity fires showed delayed and incomplete recovery even after 24 months, suggesting long-term ecological degradation. Additionally, fire

*CORRESPONDING AUTHOR:
Yeison Alberto Garcés-Gómez, Faculty of Engineering and Architecture, Universidad Católica de Manizales, Manizales 170001, Colombia; Email: ygarces@ucm.edu.com

ARTICLE INFO
Received: 9 October 2025 | Revised: 4 December 2025 | Accepted: 15 December 2025 | Published Online: 13 March 2026
DOI: https://doi.org/10.30564/re.v8i2.12293

CITATION
Oliveros-Valero, C.E., Galvis-Patiño, M., Monsalve-Tellez, J.M., et al., 2026. Monitoring Post-Fire Severity and Recovery in "La Danta" Eco-Reserve in Colombia, Using Remote Sensing Data. Research in Ecology. 8(2): 80–92. DOI: https://doi.org/10.30564/re.v8i2.12293

recurrence analysis identified persistent hotspots spatially associated with roads, settlements, and other anthropogenic infrastructure. Overall, the results demonstrate the effectiveness of Sentinel-2 imagery for fine-scale fire monitoring and provide actionable insights to support targeted ecological restoration and fire management strategies in vulnerable Orinoquía ecosystems.

Keywords: Sentinel-2; Fire Severity; Vegetation Recovery; dNBR; Colombian Orinoquía

1. Introduction

Wildfires have emerged as a critical driver of degradation in tropical transitional ecosystems, particularly in the neotropics, where the interaction between climate variability and anthropogenic pressure is intensifying. Recent global assessments indicate that extreme fire seasons are becoming more frequent in South America's dry forests and savannas, often resulting in carbon emissions that exceed historical averages and compromising long-term ecosystem resilience [1]. In the Orinoquía region, the synergy between prolonged droughts and the expansion of the agro-industrial frontier has altered natural fire regimes, transforming fire from an ecological maintenance factor into a destructive disturbance that threatens biodiversity and carbon stocks.

To address this challenge, high-resolution remote sensing has become indispensable for monitoring fire impacts in fragmented tropical landscapes. While traditional global products (e.g., MODIS) often fail to detect small-scale burns characteristic of these regions, recent studies demonstrate that Sentinel-2 imagery provides the necessary spatial and spectral detail to accurately map burn severity and post-fire vegetation dynamics [2,3]. This capability is particularly relevant for assessing differential recovery rates between savanna and gallery forest ecosystems, a critical knowledge gap for adaptive management in the Colombian Orinoquía.

Satellite remote sensing has proven to be an invaluable tool for environmental monitoring, offering precise, up-to-date, and cost-effective data for the management of protected areas [4–7]. However, its application in tropical contexts faces challenges [8]. Technologies for detecting active fires, such as products from low-resolution satellites like MODIS (Moderate Resolution Imaging Spectroradiometer, 1 km) [4,5,9,10] and VIIRS (Visible Infrared Imaging Radiometer Suite, 375 m) [7,11], are very useful for large-scale monitoring due to their wide spatial coverage and high revisit frequency. However, their moderate spatial resolution can limit the early detection of incipient or small-scale fires, which is especially problematic in ecosystems where fire spreads rapidly. For example, it has been documented that VIIRS products can miss up to 59–93% of fires smaller than 10 hectares [8]. Scientific literature has established that fires can spread at alarming rates, reaching 500 to 900 hectares per hour, and up to 8240 hectares per hour in extreme events. In this scenario, the ability to detect a fire outbreak in its early stages is crucial for damage mitigation, as a delay of just minutes can lead to an exponentially growing catastrophe [9].

In this regard, high-spatial-resolution sensors emerge as an optimal solution. The European Space Agency's (ESA) Copernicus program, through its Sentinel-2 satellites, provides multispectral images with a spatial resolution of up to 10 m and a revisit time of 5 days. These characteristics make it ideal for monitoring environmental dynamics at detailed scales, enabling the precise identification of areas affected by fire. The Near-Infrared (NIR) and Short-Wave Infrared (SWIR) spectral bands of Sentinel-2 are particularly sensitive to changes in vegetation reflectance caused by water stress, the presence of char and ash, and subsequent regeneration [12–17]. By leveraging these bands, spectral indices like the Normalized Burn Ratio (NBR) and the Normalized Difference Vegetation Index (NDVI) can be calculated to quantitatively assess both fire severity and the ecosystem's recovery trajectory. Integrating this data with cloud-based processing platforms like Google Earth Engine (GEE) allows for the efficient handling of large data volumes, overcoming the limitations of local infrastructure.

The general objective of this study is to develop and apply a high-resolution remote sensing methodology for the detailed monitoring of wildfire impacts in the Danta Eco-Reserve. The specific objectives are:

(i) To accurately map and quantify the extent of fire-affected areas in the Danta Eco-Reserve over the study period.
(ii) To assess fire severity patterns across different vegetation types and their spatial distribution.
(iii) To analyze the dynamics of post-fire vegetation recovery using NDVI time series, comparing burned zones with unaffected reference areas.
(iv) To examine the effect of fire recurrence on ecosystem resilience by identifying overlapping burn scars.

2. Materials and Methods

2.1. Study Area

"La Danta" (from now on Danta) Eco-Reserve, spanning 10,249 hectares in the municipality of Puerto Gaitán, Meta, Colombia, stands as a strategic biological corridor in the transitional zone between the Orinoquía and the Amazon [18]. This ecotone is a mosaic of fragile ecosystems, including natural savannas, wetlands, and riparian forests, which play a fundamental role in water regulation, climate change mitigation through carbon storage, and biodiversity conservation. The region is home to remarkable biological wealth, with 23,487 registered species of fauna and flora, representing 29% of the total species observed in Colombia [19]. Of this vast inventory, 491 species are currently under some category of threat, a figure that corresponds to 23% of the national total [19]. Specifically, the Humboldt Institute has documented the presence of endemic and migratory species, such as the white-tailed deer (Odocoileus virginianus) and the curassow (Crax alector), which the International Union for Conservation of Nature (IUCN) has classified as vulnerable.

Despite their ecological value, these ecosystems are under significant pressure, driven by a complex interplay of factors. Over the past four decades, the Orinoquía has experienced a 35% increase in the human spatial footprint, a trend that is expected to continue [19]. This expansion is directly linked to the advance of the agro-industrial frontier, with the cultivated area growing from 1000 km² to 8000 km² in the last two decades, which exerts direct and increasing pressure on natural ecosystems [19]. In this context, wildfires emerge as one of the most critical threats, whose frequency and intensity have been exacerbated by both anthropogenic activities and climate variability, particularly extreme events like El Niño [6]. Wildfires not only cause an immediate loss of vegetation cover and habitats, but also trigger a cascade of long-term impacts, such as the alteration of biogeochemical cycles, habitat fragmentation, and the reduction of essential ecosystem services [15]. The degradation of gallery forests, for instance, can accelerate the expansion of savannas, resulting in a net loss of ecosystem services and a decrease in landscape resilience [6].

The Danta Eco-Reserve is in the Santa Helena hamlet, under the jurisdiction of the municipality of Puerto Gaitán, in the department of Meta, Colombia (see **Figure 1**). The reserve's total area is 10,249 hectares, composed of four main properties: "Bel Rey", "Talanqueras", "La Cascada", and "El Refugio". The reserve is strategically located in a high-biodiversity area and is situated within the Andean-Eastern Regional division of Ecopetrol S.A., which operationally links it to the Rubiales Oil Field. This unique characteristic highlights the relevance of a management approach that integrates environmental protection with productive activities, reflecting the company's commitment to sustainability and responsible management. The landscape is characterized by a mosaic of tropical savanna and gallery forest ecosystems, which are especially vulnerable to fire disturbances.

2.2. Forest Fires and Their Consequences in Tropical Ecosystems

Forest fires in the Colombian Orinoquía are not isolated incidents; they are manifestations of a complex dynamic between land use and climatic conditions. A 2021 study by the Humboldt Institute documented forest fires as one of the main threats in the region [19]. Most fires are of socio-natural origin, often started by agricultural burns or livestock activities that get out of control during dry periods [4,7]. Fire in the tropical savanna is a disturbance factor that modifies the landscape structure and the composition of plant communities. The effects on vegetation and soil are profound and direct. The heat from the fire can alter soil hydrology, increase hydrophobicity, reduce organic matter, and decrease the stability of aggregates, which leads to a greater susceptibility to erosion and desertification [18].

The impact on fauna is equally severe. Fires cause the disappearance of habitats, territories, and refuges, such as hollow trees, which are crucial for mammals like monkeys, bats, and cavity-nesting bird species. This triggers a mass displacement of fauna, which often lacks safe places to migrate, potentially leading to the local loss of wildlife. The destruction of fruit trees drastically reduces food sources for birds and frugivorous animals, while the disappearance of leaf litter eliminates the sustenance for arthropod communities, in turn affecting the carnivores and omnivores that depend on them [20]. Habitat fragmentation and the decline of small mammal populations in burned areas have been specifically documented in the Orinoquía, underscoring the urgency of implementing effective conservation measures. Forest fire risk management must advance in the understanding of ecosystems, their services, and species adaptations.

The fire regime in the reserve is characterized by seasonal events. For this study, we analyzed the fire events occurring between 2021 and 2025, which represent the peak of fire activity. A detailed chronology of the daily active fire detections and affected areas is provided in the **Supplementary Material**.

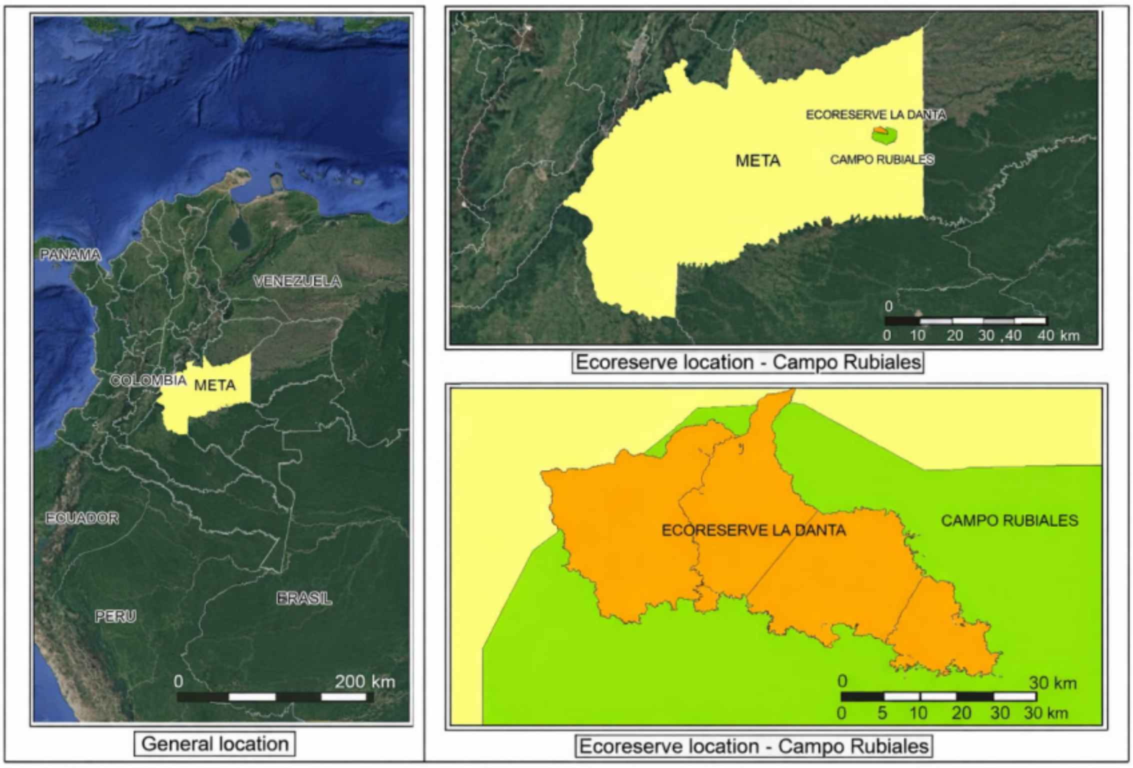


Figure 1. Geographical location of the La Danta Eco Reserve.

2.3. Acquisition and Pre-Processing of Sentinel-2 Imagery

The satellite data set used in this study consists of multispectral images from the Sentinel-2 mission of the ESA's Copernicus program. The images were obtained through the Google Earth Engine (GEE) platform [12,21], which allows for efficient access and processing of large volumes of data without requiring local infrastructure. Images from both Sentinel-2A and Sentinel-2B sensors were selected to maximize temporal coverage. The spatial resolution of the bands used is 10 m for the visible (VIS) and near-infrared (NIR) spectral bands, and 20 m for the shortwave infrared (SWIR) bands. The 5-day revisit frequency of the Sentinel-2 constellation is a significant advantage for monitoring dynamic events such as fires.

Image pre-processing is a critical step, especially in tropical regions prone to high cloud cover. The Sentinel-2 surface reflectance product (L2A) was used, which has been atmospherically corrected to mitigate aerosol interference, a recurring factor in the study area. Atmospheric correction is an essential process for multitemporal comparison and was performed using the algorithm.

Using the SEN2COR algorithm or its equivalent within GEE, which transforms data from Level-1C to Level-2A [13]. Additionally, pixel quality filters were applied to mask clouds and cloud shadows, selecting only those images with low or no cloud cover. The combination of data from Sentinel-2 and Landsat-8 has proven to be an effective strategy for increasing the frequency of cloud-free observations in the tropics, a method that could be explored in future research [16].

2.4. Mapping Fire Severity

To identify and evaluate burned areas, the Normalized Burn Ratio (NBR) was used. This index leverages the high reflectance of healthy vegetation in the Near-Infrared (NIR) band and its low reflectance in the Short-Wave Infrared (SWIR) band. In contrast, the opposite occurs in burned areas, with reduced reflectance in the NIR and increased reflectance in the SWIR due to the presence of char and ash. The NBR is calculated using Equation (1):

$$NBR = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

In this study, the following Sentinel-2 bands were used: band 8A (NIR, 842 nm) and band 12 (SWIR, 2202 nm).

To quantify fire severity, the Differenced Normalized Burn Ratio (dNBR) was calculated, which compares the condition of the terrain before and after the fire. This multi-temporal dNBR methodology reduces confusion with other land cover types and allows for a more precise classification of the damage [21]. Calculated from Equation (2) [17]:

$$dNBR = NBR_{pre\text{-}fire} - NBR_{post\text{-}fire} \quad (2)$$

Once the dNBR was calculated, the values were reclassified to generate a fire severity map. This classification is based on standardized dNBR ranges that correlate the magnitude of the spectral change with the level of vegetation damage. The classification used in this study is presented in **Table 1**, which was adapted from the scientific literature for fire monitoring [16].

Table 1. Fire Severity Classification Based on dNBR Values.

DNBR Value Range	Severity Class	Interpretation
< 0.1	No affectation	Unburned areas, intact vegetation, or slight regrowth.
0.1–0.27	Low severity	Minimal damage to vegetation. Likely to recover in the short term.
0.27–0.44	Moderate-low severity	Significant damage to undergrowth and lower branches.
0.44–0.66	Moderate to high severity	Severe damage to above-ground biomass. Possible damage to canopy structure.
> 0.66	High severity	Almost total loss of vegetation. Biomass consumed, soil exposed.

2.5. Monitoring of Vegetation Recovery

Monitoring post-fire recovery is essential for understanding ecosystem resilience. The Normalized Difference Vegetation Index (NDVI) was used as an indirect indicator of green biomass and vegetation health. The NDVI is calculated as the difference between the reflectance in the Near-Infrared (NIR) band and the reflectance in the Red band.

$$NDVI = \frac{NIR - red}{NIR + red} \quad (3)$$

A time series of NDVI values was generated for the areas identified as burned, covering a period that included a pre-fire date, an immediate post-fire date, and several subsequent dates over time. The NDVI values from these zones were then compared with those from unaffected control zones that had similar floristic compositions and phenological characteristics. This comparison allows for isolating the effect of the fire disturbance from the normal seasonal variations of the ecosystem. The saturation of NDVI in areas with high vegetation cover makes it particularly suitable for monitoring the initial stages of recovery after a severe disturbance.

2.6. Accuracy Assessment

To validate the burned area map generated with

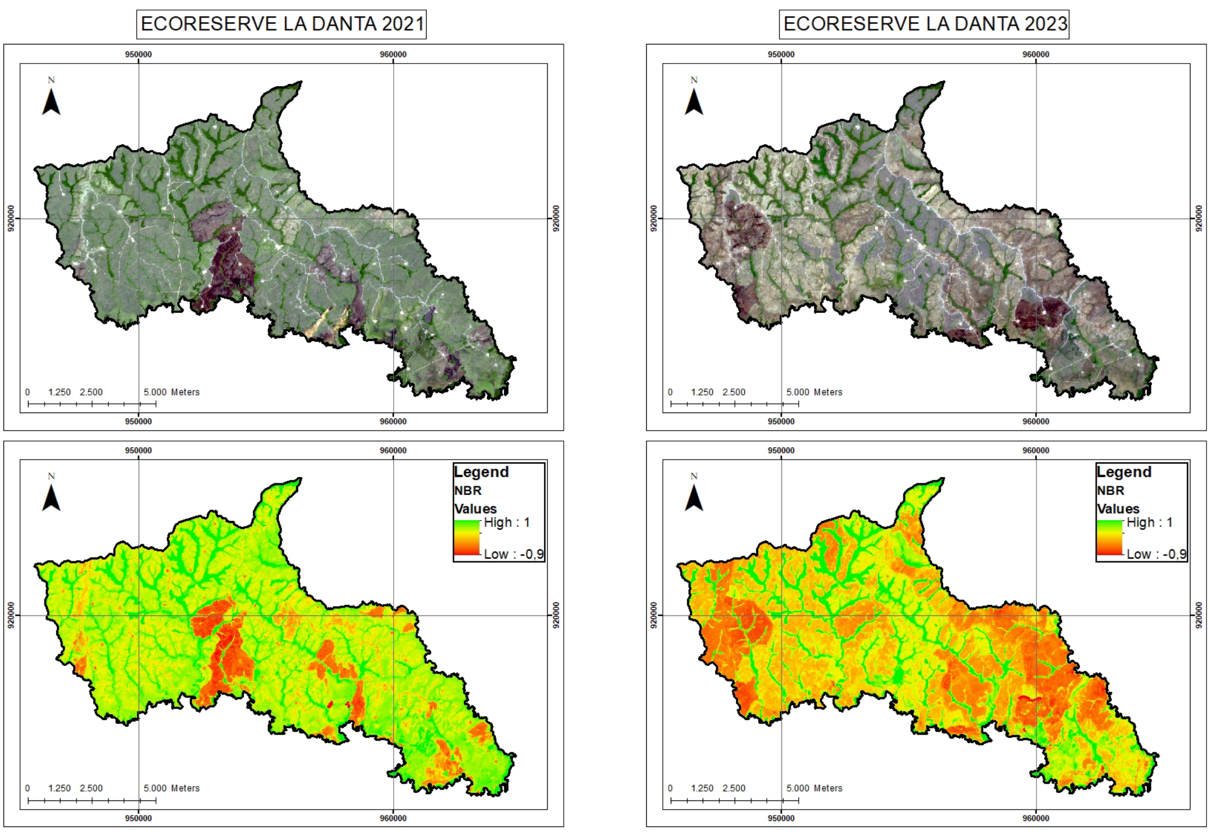
Sentinel-2, a rigorous accuracy assessment was conducted using ground truth data collected via GPS receivers [22]. A confusion matrix was constructed based on 431 verified control points. Of these, 183 corresponded to confirmed burned areas, while the remaining 248 points served as controls in unaffected zones with healthy vegetation cover.

The resulting confusion matrix showed 168 true positives (areas correctly classified as burned) and 225 true negatives (areas correctly identified as unburned), along with 15 false negatives (burned areas not detected) and 23 false positives (incorrectly classified as burned). Based on these values, the analysis yielded an Overall Accuracy of 91%, confirming the reliability and robustness of the spatial delimitation of fires in the reserve during the analyzed period.

3. Results

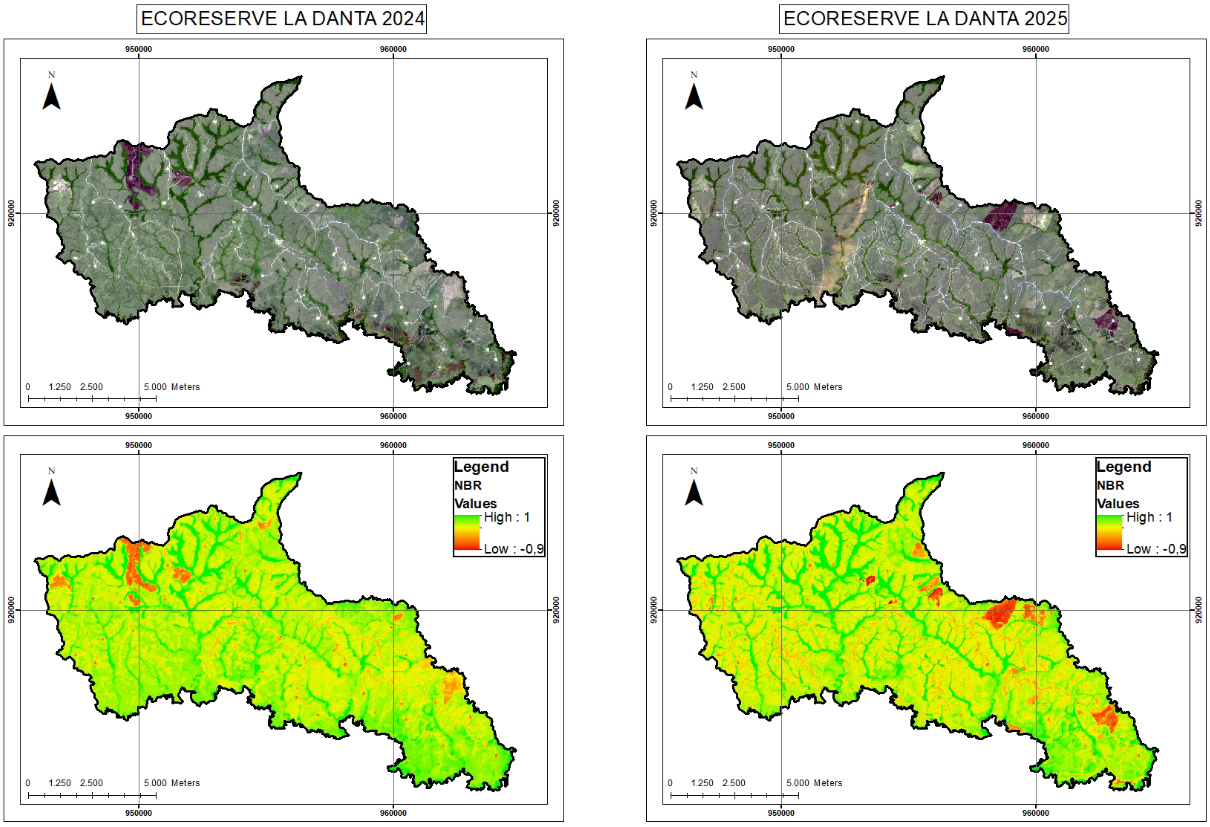
3.1. Extent and Spatial Distribution of Burned Areas

The analysis of Sentinel-2 images throughout the study period allowed for the identification and quantification of a total of 1845 hectares affected by fires in the Danta Eco-Reserve. The distribution of these burned areas was not homogeneous over time; most incidents were concentrated in the dry seasons, with a peak of activity in the first quarter of 2025. The resulting map from the dNBR analysis (**Figure 2**) shows the spatial distribution of the burn scars, revealing that the fires were primarily located in savanna zones, with variable penetration into the surrounding gallery forests.



(**a**) (**b**)

Figure 2. *Cont.*



(**c**) (**d**)

Figure 2. NVR distribution patterns. (**a**) 2021; (**b**) 2023; (**c**) 2024; (**d**) 2025.

The analysis of fire severity, based on the dNBR ranges, provided a detailed understanding of the fire's impact. **Table 2** summarizes the distribution of the burned area by year and severity level.

Table 2. Burned Area and Severity Distribution by Year.

Year	Total Area Burned (ha)	Low Severity (%)	Moderate-Low Severity (%)	Moderate-High Severity (%)	High Severity (%)
2021	350	45	30	15	10
2023	225	55	25	10	10
2024	550	40	35	20	5
2025	720	30	40	25	5
Total	**1845**	**40.6**	**33.2**	**18.7**	**7.5**

These results indicate that most fires were of low or moderate-low severity, suggesting that much of the damage was limited to the understory and surface biomass. However, 26.2% of the burned area (moderate-high and high severity) experienced significant damage to the canopy structure or a near-total loss of biomass. The identification of these high-severity zones is crucial for planning more intensive ecological restoration interventions.

The resulting map (**Figure 2**) illustrates the spatial distribution of the burn scars using the Normalized Burn Ratio (NBR). Unlike the discrete severity classification (dNBR), we utilized the continuous NBR scale to visualize the dynamic gradient of the fire impact. High NBR values (near 1) represent healthy vegetation, while low values (approx. −0.9) indicate burned areas with significant biomass loss. This visualization strategy allows for a more detailed understanding of the fire's spatial continuity and recurrence patterns across the landscape, serving as a baseline for the severity quantification presented in **Table 2**.

3.2. Dynamics of Post-Fire Vegetation Recovery

The NDVI (Normalized Difference Vegetation Index) is a valuable tool for La Danta Eco Reserve, as it allows for accurate monitoring of vegetation health and density. Its ability to identify areas with water stress or environmental damage facilitates informed decision-making in natural resource management. In addition, the NDVI is useful for assessing the impact of interventions in ecosystem conservation and restoration, providing data to support research and strategic planning.

The analysis of NDVI time series (see **Figure 3**) demonstrated the capacity of the reserve's ecosystems to regenerate after fire, although with significant variations. In low-severity savanna zones, NDVI values showed an abrupt drop immediately after the fire but began to recover in the following weeks, coinciding with the start of the rainy season. In these areas, the NDVI reached values close to pre-fire levels within 6 to 12 months, indicating a remarkable resilience of the herbaceous and shrub vegetation.

In contrast, zones that experienced moderate-high and high severity showed a much slower recovery. In these areas, the NDVI drop was more pronounced, and regeneration was incomplete even after 24 months. The comparison with unburned control zones, which maintained high and stable NDVI values over time, confirmed that the dynamics observed in the burned areas were a direct effect of the fire and not due to seasonal phenological variations.

These NDVI recovery patterns act as a window into the ecosystem's resilience, where a rapid recovery might suggest an adaptation of the local flora to fire, while a slow and incomplete recovery could be a sign of irreversible degradation.

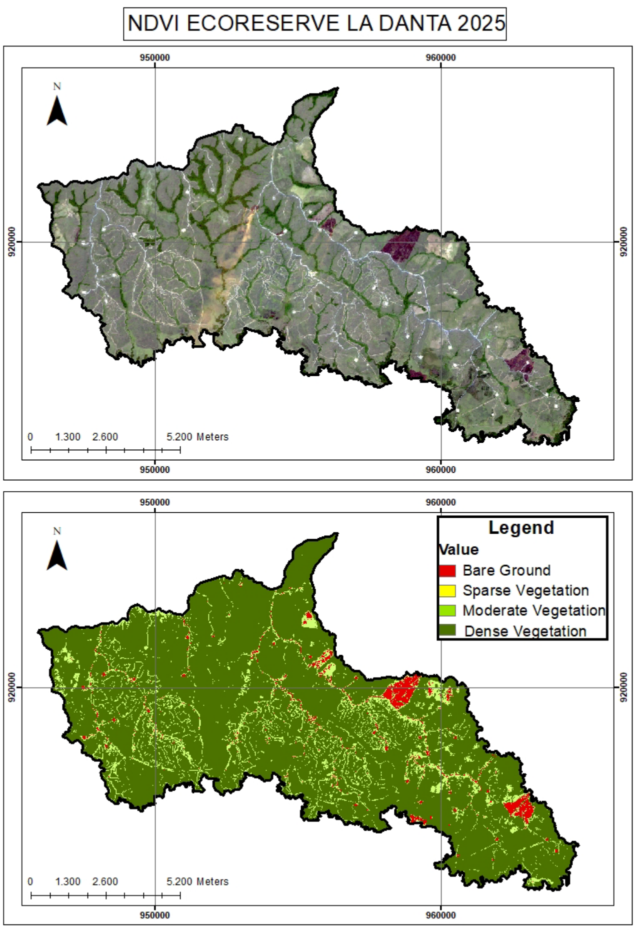


Figure 3. NDVI patterns.

3.3. Identification of Recurrence Patterns and Critical Zones

The DNBR (Normalized Burn Difference Index) is an essential tool for La Danta Eco Reserve, as it allows for effective assessment of the impact of fires and other disturbances on vegetation. This index helps identify areas affected by fire, providing information on the severity of burns and the state of ecosystem recovery. Its use is fundamental for natural resource management, as it facilitates informed decision-making in the planning of conservation and restoration strategies. In addition, the DNBR contributes to monitoring the effects of interventions on environmental recovery, supporting research that seeks to improve the resilience of ecosystems.

The temporal analysis of burn scars allowed for the identification of overlapping fires over the years, which revealed the existence of recurrence patterns in specific zones of the reserve. The recurrence map (see **Figure 4**) highlights these critical zones, which represent the intersection of both anthropogenic and biophysical risk factors. A spatial correlation was found between fire recurrence and proximity to access roads and infrastructure associated with the Rubiales Oil Field, suggesting a strong influence of human activities on ignition.

These zones, which experienced repeated fires, showed a slower NDVI recovery and a higher percentage of severe damage compared to areas burned for the first time. These "hot spots" are indicators of a systemic problem rather than isolated incidents. This information is fundamental for decision-making, as it allows for the prioritized allocation of prevention resources to the most vulnerable areas.

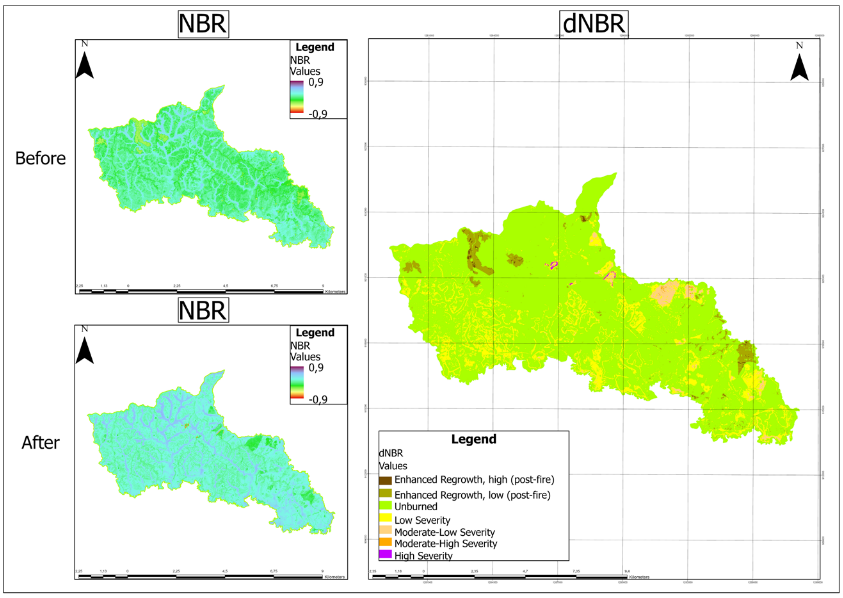


Figure 4. Fire recurrence map in the Danta Eco-Reserve.

4. Discussion

4.1. Implications for the Management and Conservation of the Danta Eco-Reserve

The results of this study have direct and significant implications for the management and conservation of the Danta Eco-Reserve. The ability to map the extent of burned areas and classify fire severity provides environmental managers with a solid basis for strategic decision-making. Severity maps allow for the prioritization of zones that require more urgent and intensive ecological restoration, such as those classified with moderate-high and high severity, where damage to biomass and soil is more severe. Similarly, the identification of fire recurrence areas, often correlated with human infrastructure, allows for focusing prevention efforts on these high-risk zones. This could include the implementation of fire patrols, the construction of firebreaks, or the creation of rapid response community brigades, as has been suggested in the literature.

Understanding the dynamics of vegetation recovery is equally vital. Post-fire NDVI trajectories are not just data; they are an indicator of ecosystem resilience. A rapid recovery in savanna zones could indicate an ecological adaptation, while the incomplete recovery in gallery forest zones underscores the vulnerability of these ecosystems to fire and the need to actively protect them. The study, therefore, is not limited to mapping the problem but offers the necessary information to design fire management plans that consider species adaptations and strengthen long-term monitoring in the transitional zones between savanna and forest.

4.2. Comparative Analysis of Vegetation Recovery

Our findings regarding the rapid recovery of savanna vegetation (6–12 months) versus the slower regeneration of gallery forests align with recent pantropical and Mediterranean studies, highlighting the structural dependence of ecosystem resilience. For instance, Vetrita et al. (2025) reported that tropical savanna vegetation in Indonesia can initiate regrowth as early as two weeks post-fire, reaching pre-fire NDVI levels significantly faster than tree-dominated areas [3]. This pattern is consistent with the "La Danta" savanna dynamics, where herbaceous species exhibit high adaptability to fire recurrence.

However, the slow recovery observed in our high-severity and forest zones mirrors trends described in Mediterranean ecosystems. A recent study by Zabeo et al. (2025) on post-fire variability demonstrated that while shrublands often recover rapidly from a first fire event, forest resilience is critically linked to fire severity and drought conditions, often requiring years to recover lost biomass [23]. Furthermore, our use of NDVI trajectories complements the framework proposed by Bright et al. (2019), who emphasized that while NBR is superior for severity mapping, multispectral time series are essential for distinguishing true phenological recovery from ephemeral herbaceous pulses [24]. The contrast between our once-burned and recurrently burned areas further suggests that, similar to findings in other fire-prone regions, repeated disturbances may erode the resilience of transitional forests, potentially driving a localized savannization process.

4.3. Methodological Value

The high-resolution remote sensing methodology developed in this study represents a significant advance in fire monitoring in the tropics. This contrasts with global burned area products derived from low-resolution sensors like MODIS (1 km) or VIIRS (375 m), which often underestimate the total extent of burns and miss small fires. The use of Sentinel-2 (10–20 m) allowed for much more precise detection and mapping. This is especially important in the Orinoquía, where fires can be small but frequent, and their early detection is crucial to prevent exponential damage. The presented results demonstrate that the combination of NBR and dNBR with NDVI time series is a robust and reproducible strategy for mapping severity and monitoring ecosystem recovery.

The field of fire remote sensing is evolving rapidly, and this study aligns with recent trends in the scientific literature. The limitation of cloudiness, a recurring challenge in the tropics, can be mitigated not only with pixel quality filters but also with data synergy from different sensors. For example, recent studies have explored combining optical images from Sentinel-2 with radar data from Sentinel-1 (SAR). Radar information can penetrate clouds and is sensitive to vegetation structure and moisture, providing complementary data that improves the accuracy of land cover maps and fire detection.

Additionally, the application of machine learning and deep learning algorithms has proven to be promising for improving the accuracy and automation of burned area mapping, achieving high classification accuracy. These advances point toward even more sophisticated methodologies that can be integrated into future research for monitoring the Danta Eco-Reserve. The present study, by establishing a basic but robust method, serves as a solid foundation for the adoption of these advanced techniques in the region.

4.4. Study Limitations and Future Directions

Despite the methodology's robustness, the study presents some limitations inherent to remote sensing in tropical environments. The persistence of cloud cover, although mitigated by pixel quality filters and the high revisit frequency of Sentinel-2, can still create temporal gaps in the data, hindering the continuous monitoring of recovery dynamics.

Greater access to field validation data would be invaluable for confirming severity classifications and recovery rates with even greater precision. The lack of hyperspectral or LiDAR remote sensing data also limits the analysis to a two-dimensional perspective of the vegetation, without considering vertical structure or lost biomass, parameters that are crucial for a complete assessment of fire damage.

Consequently, future research could explore several directions. The fusion of data from Sentinel-2 with Sentinel-1 could create a more robust monitoring system that is less susceptible to atmospheric interference. The inclusion of LiDAR or hyperspectral data (such as from the PRISMA satellite) would allow for estimating consumed biomass and carbon emissions associated with fires. Furthermore, the use of artificial intelligence, such as convolutional neural networks for near-real-time fire detection or the development of predictive risk models, could transform monitoring into a proactive early warning system. Finally, the integration of remote sensing with citizen science and the participation of local communities in ground-truthing the results would strengthen environmental governance in the region.

5. Conclusions

This study has demonstrated that high-resolution remote sensing, using Sentinel-2 imagery, constitutes an effective and economically accessible tool for the detailed monitoring of wildfire impacts in the La Danta Eco-Reserve, a vulnerable transitional ecosystem. The proposed methodology, which combines fire severity mapping with dNBR and vegetation recovery monitoring with NDVI time series, provides a comprehensive understanding of fire dynamics in the landscape. The fire severity and recurrence maps generated from this analysis are direct inputs for adaptive environmental management, allowing conservation managers to prioritize zones for ecological restoration and design prevention strategies focused on the highest-risk areas. This approach not only optimizes available resources but also establishes a methodological precedent for the protection of strategic ecosystems in Colombia. By providing a detailed and continuous view of fire threats, this study contributes to the ecosystem's resilience in the face of climate change and human activity, ensuring the long-term conservation of the invaluable biodiversity of the Orinoquía.

Supplementary Materials

The supporting information can be downloaded at https://journals.nasspublishing.com/files/RE-12293-Supplementary-Material.xlsx.

Author Contributions

Conceptualization, C.E.O.-V., J.M.M.-T. and Y.A.G.-G.; methodology, C.E.O.-V., J.M.M.-T. and Y.A.G.-G.; software, C.E.O.-V. and J.M.M.-T.; validation, M.G.-P., B.E.F.D. and J.A.M.M.; formal analysis, C.E.O.-V., J.M.M.-T. and Y.A.G.-G.; investigation, C.E.O.-V.; resources, M.G.-P., B.E.F.D. and J.A.M.M.; data curation, C.E.O.-V.; writing—original draft preparation, Y.A.G.-G.; writing—review and editing, Y.A.G.-G.; visualization, C.E.O.-V.; supervision, M.G.-P., J.M.M.-T., B.E.F.D., J.A.M.M. and Y.A.G.-G.; project administration, C.E.O.-V.; funding acquisition, C.E.O.-V. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were generated in this study. The datasets used and/or analyzed during the current research are not publicly available due to confidentiality and embargo restrictions but may be made available from the corresponding authors upon reasonable and justified request.

Conflict of Interest

The authors declare no conflict of interest.

References

[1] Kelley, D.I., Burton, C., Di Giuseppe, F., et al., 2025. State of wildfires 2024–2025. Earth System Science Data. 17, 5377–5488. DOI: https://doi.org/10.5194/essd-17-5377-2025

[2] Guiop-Servan, R.E., Cotrina-Sanchez, A., Puerta-Culqui, J., et al., 2025. Remote sensing for wildfire mapping: A comprehensive review of advances, platforms, and algorithms. Fire. 8(8), 316. DOI: https://doi.org/10.3390/fire8080316

[3] Vetrita, Y., Diwyacitta, K., Sukarno, K.M., et al., 2025. Evaluating the capabilities of high-resolution PlanetScope and Sentinel-2 images for mapping burned area and vegetation regrowth in Indonesia's savannas. International Journal of Remote Sensing. 46(18), 6803–6825. DOI: https://doi.org/10.1080/01431161.2025.2546154

[4] Giglio, L., Schroeder, W., Justice, C.O., 2016. The collection 6 MODIS active fire detection algorithm and fire products. Remote Sensing of Environment. 178, 31–41. DOI: https://doi.org/10.1016/j.rse.2016.02.054

[5] Justice, C.O., Giglio, L., Korontzi, S., et al., 2002. The MODIS fire products. Remote Sensing of Environment. 83(1–2), 244–262. DOI: https://doi.org/10.1016/S0034-4257(02)00076-7

[6] Bowman, D.M.J.S., Balch, J.K., Artaxo, P., et al., 2009. Fire in the Earth system. Science. 324, 481–484. DOI: https://doi.org/10.1126/science.1163886

[7] Schroeder, W., Oliva, P., Giglio, L., et al., 2014. The new VIIRS 375 m active fire detection data product: Algorithm description and initial assessment. Remote Sensing of Environment. 143, 85–96. DOI: https://doi.org/10.1016/j.rse.2013.12.008

[8] Zhu, X., Xu, X., Jia, G., 2023. Recent massive expansion of wildfire and its impact on active layer over pan-Arctic permafrost. Environmental Research Letters. 18, 084010. DOI: https://doi.org/10.1088/1748-9326/ace205

[9] Dimyati, M., Kustiyo, K., Dimyati, R.D., 2019. Paddy field classification with MODIS-Terra multi-temporal image transformation using phenological approach in Java Island. International Journal of Electrical and Computer Engineering. 9, 1346–1358. DOI: https://doi.org/10.11591/ijece.v9i2.pp1346-1358

[10] Bernardes, T., Alves-Moreira, M., Adami, M., et al., 2012. Monitoring biennial bearing effect on coffee yield using MODIS remote sensing imagery. In Proceedings of the IEEE International Geoscience and Remote Sensing Symposium, Munich, Germany, 22–27 July 2012; pp. 3760–3763. DOI: https://doi.org/10.1109/IGARSS.2012.6350499

[11] Devkota, J.U., 2019. Statistical analysis of night radiance RH using VIIRS day/night band satellite time series data. International Journal of Advances in Applied Sciences. 8(1), 26–33. DOI: https://doi.org/10.11591/ijaas.v8.i1.pp26-33

[12] Eisfelder, C., Boemke, B., Gessner, U., et al., 2024. Cropland and crop type classification with Sentinel-1 and Sentinel-2 time series using Google Earth Engine for agricultural monitoring in Ethiopia. Remote Sensing. 16(5), 866. DOI: https://doi.org/10.3390/rs16050866

[13] Chabalala, Y., Adam, E., Ali, K.A., 2022. Machine learning classification of fused Sentinel-1 and Sentinel-2 image data towards mapping fruit plantations in highly heterogeneous landscapes. Remote Sensing. 14(11), 2621. DOI: https://doi.org/10.3390/rs14112621

[14] Clerici, N., Valbuena Calderón, C.A., Posada, J.M., 2017. Fusion of Sentinel-1A and Sentinel-2A data for land cover mapping: A case study in the lower Magdalena region, Colombia. Journal of Maps. 13(2), 718–726. DOI: https://doi.org/10.1080/17445647.2017.1372316

[15] Drusch, M., Del Bello, U., Carlier, S., et al., 2012. Sentinel-2: ESA's optical high-resolution mission for GMES operational services. Remote Sensing of Environment. 120, 25–36. DOI: https://doi.org/10.1016/j.rse.2011.11.026

[16] Zheng, Q., Huang, W., Cui, X., et al., 2018. New spectral index for detecting wheat yellow rust using Sentinel-2 multispectral imagery. Sensors. 18(3), 868. DOI: https://doi.org/10.3390/s18030868

[17] Pahlevan, N., Sarkar, S., Franz, B.A., et al., 2017. Sentinel-2 multispectral instrument data processing for aquatic science applications: Demonstrations and validations. Remote Sensing of Environment. 201, 47–56. DOI: https://doi.org/10.1016/j.rse.2017.08.033

[18] Etter, A., McAlpine, C., Pullar, D., et al., 2006. Modelling the conversion of Colombian lowland ecosystems since 1940: Drivers, patterns and rates. Journal

of Environmental Management. 79(1), 74–87. DOI: https://doi.org/10.1016/j.jenvman.2005.05.017

[19] Botero Pito, A.M., Rincón, A., Santos Rocha, A.C., et al., 2024. Biodiversity, Orinoquia: Status and Trends of Colombia's Continental Biodiversity. Bio Report. Alexander von Humboldt Biological Resources Research Institute: Bogotá, Colombia. Available from: https://repository.humboldt.org.co/entities/publication/75990b72-5a35-429d-bc50-eca7aaa78828 (cited 11 August 2025). (in Spanish)

[20] Sheriff, R., Meer, M.S., Aslam, R.W., et al., 2025. Machine learning-based forest fire susceptibility mapping using random forest and CART models. Rangeland Ecology & Management. 102, 96–109. DOI: https://doi.org/10.1016/j.rama.2025.06.004

[21] Gorelick, N., Hancher, M., Dixon, M., et al., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment. 202, 18–27. DOI: https://doi.org/10.1016/j.rse.2017.06.031

[22] Valencia, G.M., Anaya, J.A., Velásquez, É.A., et al., 2020. About validation-comparison of burned area products. Remote Sensing. 12(23), 3972. DOI: https://doi.org/10.3390/rs12233972

[23] Zabeo, C., Mengist, M., Ogunyemi, O.J., et al., 2025. Unveiling short-term variability in post-fire recovery of Mediterranean vegetation with Sentinel-2 time series analysis. Ecological Informatics. 92, 103508. DOI: https://doi.org/10.1016/j.ecoinf.2025.103508

[24] Bright, B.C., Hudak, A.T., Kennedy, R.E., et al., 2019. Examining post-fire vegetation recovery with Landsat time series analysis in three western North American forest types. Fire Ecology. 15, 8. DOI: https://doi.org/10.1186/s42408-018-0021-9