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Prioritization of areas degraded by forest fires for rehabilitation

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ABSTRACT

Objective: To assess fire severity in affected areas through spectral analysis and geographic information systems in order to identify priority areas for restoration and strengthen the sustainable management of natural resources.

Design/methodology/approach: Field and remote sensing data from areas affected by forest fires were used to determine and classify fire severity using the differenced Normalized Burn Ratio (dNBR) spectral index, thereby enabling the identification and quantification of priority areas exhibiting the greatest severity. In addition, an analysis of the topographic factors influencing fire regimes was incorporated to establish management and prevention strategies.

Results: The period from November to April accounts for the highest number of events, with 90% corresponding to surface fires, mainly triggered by anthropogenic activity. The most severely affected sites, which require rehabilitation, are associated with pine and fir forest ecosystems, slopes of 31° (difficult access and greater fire spread), a southeastern aspect of 135° (high solar exposure), and transitional zones between forested areas and high-mountain grasslands.

Limitations on study/implications: The availability of open-access data, remote sensors, and spectral analysis constitutes a strategic resource; however, these tools may present technical limitations that affect accuracy. Accordingly, future research directions are proposed to evaluate the dynamics of ecological recovery and thereby strengthen methodological robustness.

Findings/conclusions: Anthropogenic pressure and climate change intensify the degree of impact, thereby compromising ecosystem functions. Therefore, differentiated rehabilitation measures are required, supported by policy instruments that reinforce territorial governance oriented toward environmental security and productive sustainability.

Keywords: Fire severity, ecological restoration, erosion processes, geospatial modeling, sustainability.

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INTRODUCTION

Humankind appropriates nearly one-third of the Earth's potential net primary production for food, feed, fiber, timber, and energy (IPCC, 2022), thereby constituting a fundamental basis for human subsistence and well-being. However, this same proportion of terrestrial surface is also subject to degradation, as evidenced by soil erosion rates in

agricultural fields that are ten times higher under no-tillage systems and more than one hundred times higher under conventional tillage than the natural rate of soil formation (IPCC, 2022).

In addition, climate change exacerbates land degradation, with increasingly intensified effects, as exemplified by forest fires of greater intensity and extent. These account for five percent of the burned land area and contribute more than 80 percent of greenhouse gas (GHG) emissions, with unsustainable land use, deforestation, rising temperatures, and changes in plant community patterns, among other factors, being the principal drivers (IPCC, 2020).

As a consequence of climate change, forest fires have markedly increased in frequency, intensity, and hazard over the last decade, resulting in alterations in forest fuel dynamics, species composition, vegetation structure, and soil moisture. Depending on these factors, fires generate direct impacts, such as biodiversity loss and soil degradation, as well as indirect effects, including soil erosion and water contamination, thereby affecting ecological processes (FAO, 2019).

Within the Mexican context, 1998, 2011, 2017, and 2022 stand out as the most critical years in terms of damaged area. During the 2012-2022 period, the affected area increased from 347 thousand ha to 660 thousand ha, with the greatest concentration occurring in central Mexico (CONAFOR, 2022). In 2023, 7,611 fires were recorded over an area exceeding one million hectares, with Jalisco and the State of Mexico being the most affected federal entities. During 2024, the Volcanes region (Ixtapaluca, Tlalmanalco, Amecameca, Chalco, among others) was among the areas most severely affected (PROBOSQUE, 2024).

After a fire, soil becomes highly susceptible to erosion processes due to its exposure to wind and water, which leads to soil material loss, reduced water infiltration, increased surface runoff, and hydrophobicity (Caon *et al.*, 2014). Moreover, post-fire harvesting of burned timber may further increase vulnerability to erosion and soil degradation because of the use of heavy machinery and log dragging operations (García-Orenes *et al.*, 2017).

With regard to soil, nutrient content increases in the uppermost surface layers owing to ash deposition, nutrient mineralization, and the formation of stable structures. However, over time, nutrient levels decline because of volatilization, transformation, and removal by gravity and wind. Their retention therefore requires site stabilization through the implementation of post-fire measures aimed at limiting erosion, surface runoff, and wind-driven ash removal (Caon *et al.*, 2014).

Forest ecosystems are among the planet's most important natural resources because they contribute to climate change mitigation and constitute the principal carbon sink (Rojas *et al.*, 2021). Accordingly, post-fire forest management represents a critical step toward ecosystem recovery. Such management includes interventions such as the treatment of burned trees, soil protection, and practices specifically oriented toward ecosystem restoration through the improvement of its components or processes (García-Carmona *et al.*, 2023).

Although severity indices derived from remote sensing are widely used, their systematic application for prioritizing restoration actions at the regional scale remains insufficient or heterogeneous (Key & Benson, 2006; Chuvieco *et al.*, 2019). In the specific case of the State of Mexico, there is limited integration of spatial analyses of forest fire severity based on objective and standardized criteria for delimiting priority rehabilitation areas, which in turn constrains decision-making for sustainable post-fire management.

Thus, in a context marked by the intensification of wildfires and climate change, the objective of this contribution was to analyze areas impacted and degraded by forest fires in the State of Mexico through the determination of fire severity, in order to contribute to the delimitation of priority sites for rehabilitation and, consequently, to the sustainable use of natural resources. This study is guided by the following question: how is forest fire severity distributed across the State of Mexico, and which areas should be prioritized for rehabilitation?

MATERIALS AND METHODS

Source of information and study area

This was a quantitative study; therefore, data collection was conducted through two complementary approaches: the use of Geographic Information Systems (GIS) and remote sensing, and field surveys for validation in municipalities of the Volcanes region, State of Mexico (Amecameca, Chalco, Ixtapaluca, and Tlalmanalco) (Figure 1), one of the areas most affected by forest fires in the state (PROBOSQUE, 2024). The study was based on the severity of all fires recorded between January 1, 2020, and December 31, 2024.

For the GIS component, the following were used: 1) polygons of the affected areas, 2) land use and vegetation maps from INEGI Series VII (2024), 3) multispectral Landsat satellite images of the affected areas, selected for their spatial resolution, radiometric quality, and spectral availability, 4) a Digital Elevation Model (DEM), and 5) the political-administrative boundaries of the municipalities (INEGI, 2024).

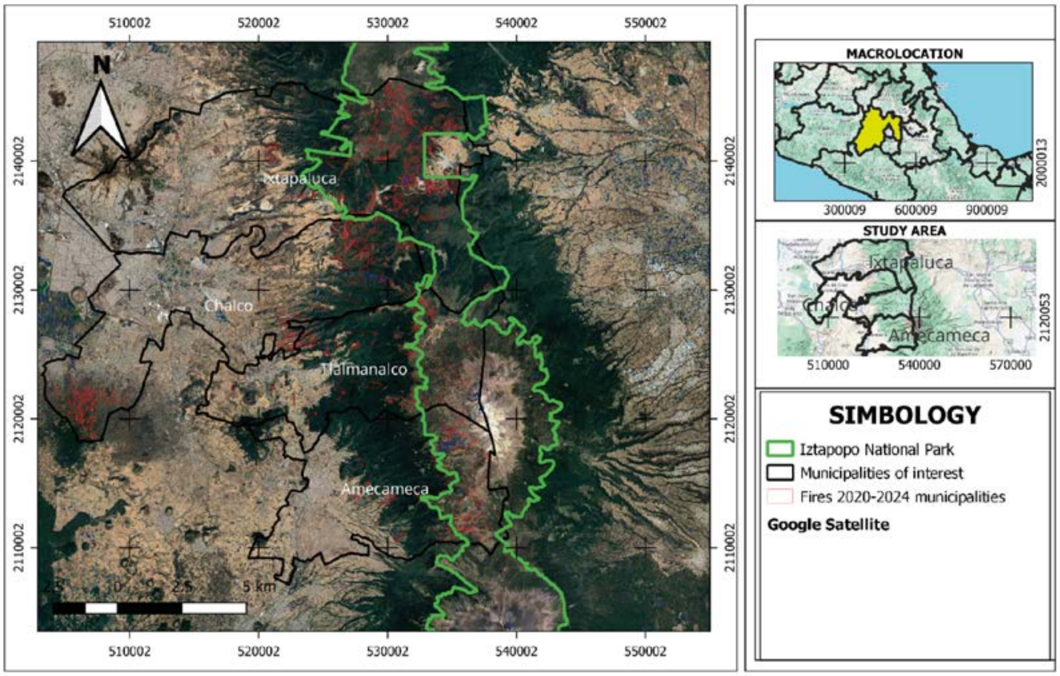

Figure 1. Municipalities of the Volcanes Region affected by fires during 2020-2024. Source: Prepared by the authors based on field information.

For input 3, pre- and post-fire images were obtained.

Systematization of information

To determine fire severity, the dNBR (differenced Normalized Burn Ratio) spectral index was used, based on pre- and post-fire satellite images and field sampling (Vales *et al.*, 2020; Zhu *et al.*, 2006). The use of dNBR is supported by its spectral sensitivity to fire impact (pre- and post-fire spectral difference), empirical validation and standardization (correlations between dNBR values and the severity of ecological effects), as well as its availability and reproducibility through open-access satellite data (Hudak *et al.*, 2011; Parente *et al.*, 2014).

First, the NBR was calculated, one of the most widely used indices in burned-area mapping, through the near-infrared and shortwave infrared bands (NIR and SWIR, respectively) (Key & Benson, 2006; van Gerrevink & Veraverbeke, 2021). The NIR (near-infrared) band highlights vegetation health and structure, since living plants reflect more light in this portion of the spectrum than burned vegetation.

In turn, the SWIR (shortwave infrared) band reflects plant moisture and water content; dry and burned areas, with lower moisture, reflect more light than healthy vegetation. Their combined use makes it possible to identify burned areas and zones with live vegetation. These are defined as follows:

$$dNBR = NBRpre - NBRpost$$

$$NBR = (NIR - SWIR)/(NIR + SWIR)$$

where: $dNBR$=Differenced Normalized Burn Ratio; NBR=Normalized Burn Ratio; NIR=Near-infrared band; $SWIR$=Shortwave infrared band; $NBRpre$=Pre-fire NBR value; $NBRpost$=Post-fire NBR value.

Based on the model values, the level of fire severity was then classified in order to locate and quantify priority areas, that is, those with the greatest severity (Table 1). Higher values indicate greater damage severity (vegetation loss), whereas values close to zero or negative indicate unburned areas or vegetation regrowth (Lutes, 2006).

Table 1. dNBR values.

Value	Description
< -0.250	High post-fire regrowth
-0.250 to -0.100	Low post-fire regrowth
-0.100 to 0.100	Unburned or stable areas
0.100 to 0.270	Low severity
0.270 to 0.440	Moderate-low severity
0.440 to 0.660	Moderate-high severity
> 0.660	High severity

Source: Prepared by the authors based on Lutes (2006).

In addition, based on the DEM, topographic factors influencing fire regimes, such as aspect and slope (Table 2), were analyzed (Gholami *et al.*, 2021). Both factors make it possible to identify priority intervention areas, define differentiated management strategies, and prevent secondary impacts (Tiwari *et al.*, 2020).

RESULTS AND DISCUSSION

Characterization of the burned areas

The study area recorded 623 fires during the period from January 1, 2020, to December 30, 2024, affecting a total area of 17,000 hectares; Ixtapaluca was the most affected municipality, with 5,200 hectares. More than 50% of the damaged area corresponds to the Iztaccíhuatl-Popocatépetl National Park, which is recognized as a Protected Natural Area (Figure 2). The months from November to April concentrate the highest number of events, with 90% classified as surface fires, spreading from the ground surface up to 1.5 meters in height.

Table 2. Topographic parameters analyzed.

Factor	Description
Aspect	Aspect, or slope exposure, determines the amount of incident solar radiation and influences soil temperature and moisture; therefore, it affects fire severity and vegetation resilience (Ibarra-Bonilla *et al.*, 2024).
Slope	Slope influences fire spread and behavior (Taylor *et al.*, 2020), as well as erosion processes and surface runoff (Shakesby & Doerr, 2006).

Source: Prepared by the authors based on field information.

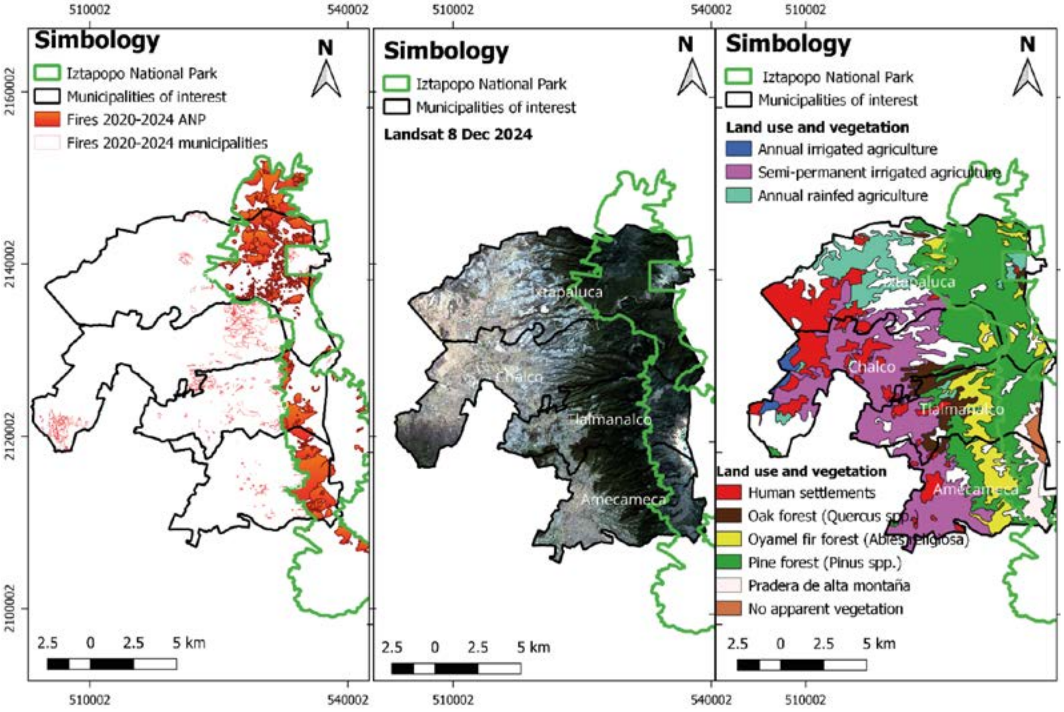

Figure 2. Municipalities of the Volcanes Region affected by fires during 2020-2024. Source: Prepared by the authors based on field information.

The phenomenon analyzed may occur at any time of the year; however, it depends on the presence of combustible material, its moisture content, and prevailing meteorological conditions. Fire severity during the summer has increased over recent decades, and within a context of climatic warming, in the absence of strategic management, further increases are likely to occur (Alvarez *et al.*, 2024).

According to land-use cover, the burned areas correspond predominantly to pine forest, fir forest, high-mountain grassland, and agricultural land, thereby revealing a multifactorial vulnerability that is further amplified under climate change conditions. Fir forest constitutes an ecologically sensitive relict, highly vulnerable to variations in temperature and drought. It develops under specific moisture and altitudinal conditions; however, global warming is forcing it toward increasingly higher altitudinal limits.

The impact on high-mountain grasslands is particularly critical, since these ecosystems function as carbon sinks and water reservoirs. More broadly, the severe degradation of high-mountain forests by fire increases their vulnerability to climate change; the loss of forest cover accelerates soil erosion and surface runoff, which in turn compromises water capture. Regarding agricultural areas and pine forests, fire recurrence underscores the risk posed by prolonged droughts and by a vicious cycle of wildfires, whereby dry vegetation and crop residues become new sources of fuel.

The analysis revealed that illegal land-use change and uncontrolled agricultural and livestock burning constitute the main triggers; that is, the phenomenon is a direct consequence of human actions (Figure 3), whereby changes in land use and land cover, together with anthropogenic activities, promote the occurrence of forest fires (Pereira *et al.*, 2020).

dNBR and classification of the burned areas

The analysis of the fire severity index (dNBR) made it possible to distinguish healthy vegetation from burned areas and revealed that the greatest damage occurred in pine and fir forest zones, both within the Protected Natural Area (PNA) and in its surrounding areas (Figure 4).

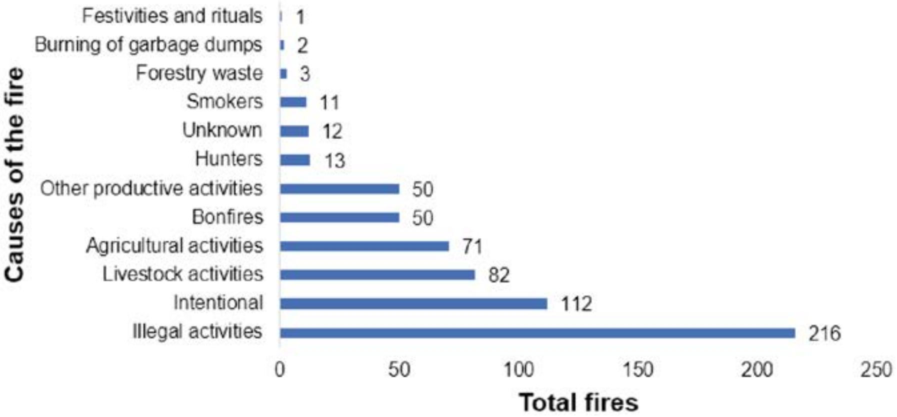

Figure 3. Main causes of fires in the Volcanes Region, 2020-2024. Source: Prepared by the authors based on field information.

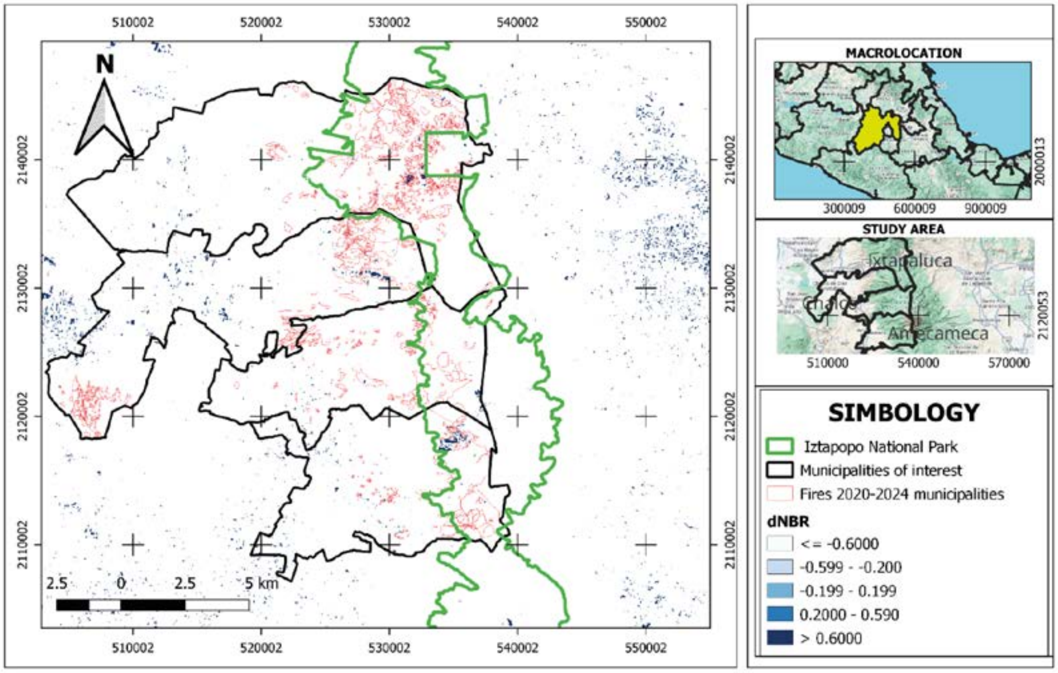

Figure 4. Fire severity in the Volcanes Region, 2020-2024. Source: Prepared by the authors based on Landsat satellite imagery.

The results indicate that 88% of the fires recorded during the analysis period exhibited low severity (5,955 ha), 11% showed moderate severity (8,896 ha), and only 2% presented high severity (2,241 ha), thereby identifying these areas as priority sites for intervention; these are located in Amecameca and Tlalmanalco, respectively. These events were primarily associated with campfires and livestock-related activities, with direct impacts on pine forests and high-mountain grasslands. Notably, part of the burned area is located within the Protected Natural Area (PNA).

Knowledge of dNBR values can contribute to sustainable forest management, which is essential for forest sustainability, particularly by focusing on severity mitigation and forest resilience (Fernandes, 2013). However, forest fire management has historically emphasized suppression measures rather than strategic management, which has further contributed to the large-scale accumulation of fuel loads (Castellnou *et al*., 2019; Moreira *et al*., 2020).

Topographic factors

The highest severity values (dNBR) were recorded in southeast-facing areas (135°) (Figure 5), which typically receive high morning solar radiation, thereby accelerating the drying of surface fuels and increasing their flammability during the most critical hours of the day. These areas present an average slope of 31°, under which fire spreads rapidly and intensely. Under such conditions, ground-based suppression becomes particularly hazardous, as these zones are characterized by extreme topographic vulnerability.

Terrain aspect, as a component of topography, constitutes a consistent and context-dependent predictor of fire severity. It influences species composition, vegetation structure,

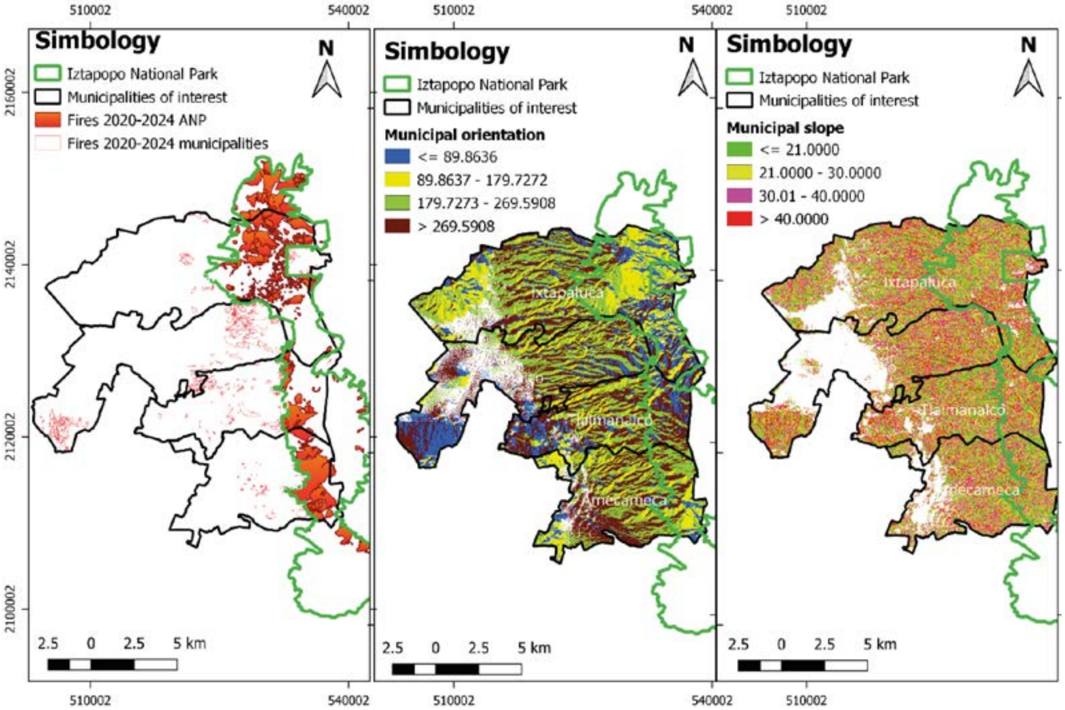

Figure 5. Aspect and slope of fires in the Volcanes Region, 2020-2024. Source: Prepared by the authors based on Landsat satellite imagery.

and biodiversity patterns. North-facing slopes exhibit greater biomass, cover, height, and species diversity, which is consistent with the higher soil nutrient content on these slopes and the insolation processes affecting southern exposures (Yang *et al.*, 2020). A southeastern aspect (135°) is associated with fires that cause greater structural damage to the ecosystem (Estes *et al.*, 2017).

Likewise, on slopes of 31°, fire spreads rapidly and intensely, since this factor determines both fire propagation and fire intensity (Ortiz-Mendoza *et al.*, 2024). Under these conditions, ground-based suppression is particularly hazardous because these areas present extreme topographic vulnerability. The concentration of damage in terrains with these characteristics not only compromises forest regeneration, but also increases the risk of post-fire erosion and landslides.

The analysis of fire severity levels, land use, and topographic variables is consistent with the fact that, in recent years, forest management objectives have expanded to enhance ecosystem resilience under future climate conditions (Franklin & Johnson, 2012). In this context, strengthening strategies that prioritize smart fire management, together with policies based on payments for ecosystem services, represents a policy pathway capable of incentivizing forest stewardship and preventing forest fires (Lecina-Díaz *et al.*, 2023).

The incorporation of topographic variables, particularly slope and aspect, strengthens this analysis by explaining the spatial heterogeneity of fire severity, given that steeper slopes and south-southwest exposures tend to experience greater water stress and more rapid fire spread. Accordingly, the observed severity results from the interaction between topographic conditions and fire dynamics, thereby increasing the risk of degradation in specific geomorphological contexts.

A proactive approach constitutes a compelling alternative to defensive and reactive strategies. In this case, institutional strengthening and intergovernmental coordination are essential elements for consolidating integrated fire management. Addressing priority areas requires a territorial duality based on coordination between municipalities and the administration of the Protected Natural Area (PNA). Such coordination contributes to resource optimization and ensures an efficient emergency response, supported by permanent prevention, surveillance, and restoration mechanisms tailored to territorial conditions.

For areas outside the PNA, strengthening regulations on agricultural and livestock burning, together with the implementation of surveillance programs and reporting mechanisms for illicit activities, is crucial. Within the PNA, investment in and reinforcement of monitoring brigades, as well as the harmonization of regulatory and local planning instruments, may constitute effective starting points.

Strengthening fire management and combating illicit and criminal activities are imperative, since human action constitutes the principal trigger of the phenomenon and of vulnerability to fire. In addition, climate change increases the probability of occurrence (Ribeiro *et al.*, 2021), fragmenting the landscape and generating impacts on wildlife, water quality, and ecosystem services (Basso *et al.*, 2020; Legarreta-Miranda *et al.*, 2021; Taboada & Calvo, 2021).

The findings of this contribution translate into technical criteria for the allocation of public resources, the delimitation of critical areas, and the design of forest restoration and soil conservation programs. Likewise, the use of standardized satellite information facilitates the replicability and periodic updating of the diagnosis, thereby strengthening decision-making at both the municipal and regional scales.

The identification of spatial patterns provides a solid basis for risk management and makes it possible to focus prevention and active restoration strategies on slopes prone to maximum severity (Lecina-Díaz *et al.*, 2023). An approach grounded in mitigation and prevention, rather than in the exclusion of fire, is both logical and pragmatic, with a greater likelihood of reducing its negative socioeconomic and ecological effects (Moreira *et al.*, 2020).

dNBR analysis makes it possible to interpret the relative intensity of damage to vegetation cover and, consequently, the degree of post-fire degradation, since it reflects spectral changes associated with the loss of aboveground biomass and canopy alteration. However, it depends to a large extent on Landsat's spatial resolution (30 m), the presence of cloud cover, and the temporal selection of pre- and post-fire imagery, which may lead to the underestimation of small or low-severity fires. Because it does not capture belowground impacts or delayed effects, it should be regarded as a proxy for severity rather than a direct measurement of ecological damage; therefore, its interpretation as ecological degradation must be complemented according to vegetation type, fire regime, and ecosystem resilience capacity.

This contribution makes it possible to prioritize rehabilitation areas, identify fires with greater average impact, and guide differentiated restoration actions. In particular, fires with high dNBR values on steep slopes may be considered priority cases because of their greater risk of erosion and soil loss, in line with adaptive post-fire management approaches.

CONCLUSIONS

The burned areas requiring priority rehabilitation are those exhibiting the highest levels of fire severity (dNBR>0.66), steep slopes (31°), and a southeastern aspect. These conditions reflect the relationship between the recurrence and intensity of forest fires and the pressures imposed by climate change. Anthropogenic action constitutes the principal trigger of these events, thereby compromising the resilience capacity of temperate forests, particularly in mountainous areas characterized by high ecological and social vulnerability. As part of rehabilitation, differentiated actions are recommended on the basis of topographic variables, accompanied by environmental education programs, mechanisms for surveillance and monitoring of illicit activities, and the design of policy instruments such as economic incentives and regulations that consolidate territorial governance by articulating environmental security and productive sustainability. As a methodological contribution, the study demonstrates the feasibility of integrating fire-aggregated dNBR and topographic variables to characterize severity at the regional scale, an approach that is replicable through satellite imagery and standardized basic cartography. The findings support the formulation of hypotheses regarding the relationship among severity, topography, and fire recurrence, as well as the temporal monitoring of vegetation recovery through multitemporal series. The availability of open-access satellite data constitutes a strategic resource for the academic community. However, such data may present technical limitations that affect accuracy; consequently, future lines of research are proposed, including predictive risk models and monitoring systems designed to evaluate the dynamics of ecological recovery.

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