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Ecological Restauration / Restauración Ecológica

Forest fire risk zones delimited with the Normalized Differentiated Burning Radius (DNBR) in the Sierra Norte of Oaxaca, Mexico

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Abstract

Background: Forest fires play a crucial role in ecosystem dynamics, bringing both positive and negative effects that significantly impact areas like the Sierra Norte de Oaxaca (SNO).
Question: What levels of severity most influence the distribution of trees in a forest?
Studied species: Temperate Forest species.
Study area: Oaxaca, Sierra Norte, January - December 2023
Methods: Data reported by CONAFOR from 1992 to 2020 was utilized. Spatial analysis was conducted using the Normalized Burning Index with SENTINEL satellite images in the SNO. Variables related to human activities, such as transportation routes and population, were included in the index. A total of 151 fire records were collected from 2006 to 2020.
Results: Ixtlán had the highest number of fires during the evaluated period. The forest fire risk index indicated that the largest area at Very High risk is located in the Mixe district, highlighting the need for decision-makers to focus efforts on this region.
Conclusions: Conclusions: Very High risk is distributed in the Mixe district, so it is important that decision makers focus efforts on this study area.
Key words: risk index, Santa María Jaltianguis, severity fire, Ixtlán, Mixe.

Resumen

Antecedentes: Los incendios forestales juegan un papel importante en la dinámica de los ecosistemas, pueden traer consigo efectos positivos o negativos que son de gran importancia, como es el caso de la Sierra Norte de Oaxaca (SNO).
Preguntas: ¿Cuáles son las severidades que más contribuyen a la distribución de los árboles riparios en un bosque?
Especies estudiadas: especies de bosques templados.
Zona de estudio: Oaxaca, Sierra Norte, enero-diciembre 2023.
Métodos: Se utilizó la información reportada por la CONAFOR en un periodo de 1992-2020. Se realizó un análisis espacial a través del Índice Normalizado de Quema, mediante imágenes satelitales SENTINEL en el SNO. Para el índice se utilizaron variables relacionadas con las actividades humanas, como las vías de comunicación y la población. Se recolectaron 151 registros de incendios en un periodo de 2006-2020.
Resultados: Ixtlán fue el que presentó el mayor número de incendios ocurridos en el periodo evaluado. Con el índice de riesgo de incendios forestales se identificó que la mayor superficie con riesgo Muy Alto se distribuye en el distrito Mixe.
Conclusiones: El riesgo Muy Alto se distribuye en el distrito Mixe, por lo que es importante que los tomadores de decisiones enfoquen esfuerzos en esta zona de estudio.
Palabras clave: índice de riesgo, Santa María Jaltianguis, severidad de incendio, Ixtlán, Mixe.

Forest fires play a significant role in ecosystem dynamics. Depending on their characteristics and the specific conditions in which they occur, they can generate positive effects, supporting the maintenance of certain ecosystems as part of their natural processes, or negative effects, causing extensive damage in a short period and consuming large forested areas (Villers 2006, SEMARNAT 2020). Negative effects may be direct, such as loss of fauna, vegetation, and soil degradation, or indirect, including soil erosion, water pollution, and landslides (Úbeda & Sarricolea 2016). In Mexico, only 3 % of forest fires are caused by natural events, such as thunderstorms, while 97 % result from human activities, including production systems that use burning to remove vegetation cover or for fertilization and pest control, as well as recreational activities in forested areas (CONAFOR 2014). Managing and controlling these fires is complex, as many areas lack the training, tools, and access needed to locate and respond to forest fires, leading to significant impacts on vegetation when fires become unmanageable.

According to reports from the National Forestry Commission (CONAFOR 2022a), the area affected by forest fires in Mexico increased significantly from 269,266 ha in 1991 to 378,928 ha in 2020, with an annual average of 336,000 ha affected. The average number of fires per year was 7,828 (González-Rosales & Ortiz-Paniagua 2022). Similar trends are observed in Oaxaca, where the area affected by forest fires rose from 15,344 ha to 20,693 ha over the same period (CONAFOR 2022a). In 1998, 2001, 2002, and 2003, Oaxaca ranked first nationally in affected area, with more than 60,000 ha burned (CONAFOR 2022b).

Researchers have sought strategies to identify the factors that increase the risk of forest fires and to develop methods for mitigating their negative impacts on the environment and society (Quiroga & Santiago 2019). Studies on forest fires in Mexico focus on three key aspects: 1) the effects of fire on forest ecosystems; 2) the use of fire as a tool in forestry and pastoral practices; and 3) prevention and control activities, which include both operational measures and the development of behavioural and risk indices. Building on this, models have been created to assess real-world vulnerability and the risk level of specific locations. These models take into account the elements required for combustion, the environmental history of the area, and the forest management practices in place (Villers 2006).

Various tools are currently available to help reduce the risk of forest fires, including the identification of key factors in fire occurrence through the use of remote sensing and Geographic Information Systems (GIS). When combined with GIS, these tools enable the analysis of areas most susceptible to fires, allowing authorities to implement preventive measures and provide training for fire management. For example, Manzo-Delgado & López-García (2020) conducted a spatial and temporal analysis of burned areas in 1998, 2003, and 2015 in the Montes Azules Biosphere Reserve, Chiapas, Mexico, demonstrating the value of remote sensing in the protection and management of Natural Protected Areas. Similarly, Gutiérrez *et al*. (2019) focused on zoning priority areas for fire protection in San Esteban Atatlahuca, Oaxaca, underscoring the importance of GIS in managing satellite data and environmental variables to identify risks. Additionally, López-García (2020) analyzed the severity of the 2012 fire and the regeneration of vegetation in the La Primavera Forest, Mexico, using LANDSAT 7 images, demonstrating the effectiveness of this methodology for assessing forest fires.

The identification of areas affected by forest fires over time, along with the analysis of factors contributing to their occurrence, plays a key role in fire prevention and control, particularly in regions where forestry or agricultural activities are common, such as the Sierra Norte de Oaxaca (SNO). The SNO is a priority region for biodiversity conservation, featuring a diverse physiography that supports a variety of ecosystems, including extensive areas of pine, oak, pine-oak, and oak-pine forests, as well as medium, high, and low forests. It is also home to some of the largest and best-preserved cloud forests in Mexico (Arriaga *et al*. 2000). Forest management is a major economic activity in the region, with environmental services, ecotourism, and shade-grown coffee production also contributing to both the local economy and the conservation of these forest ecosystems (Castellanos-Bolaños *et al.* 2010, Rosas-Baños & Correa-Holguín 2016, Lucas-González & Viveros-Hernández 2017). Given the threats posed by fast-spreading phenomena such as forest fires, it is essential to develop tools to prevent further ecosystem deterioration.

In the SNO region, there is limited knowledge about which areas are most prone to forest fires, as no comprehensive analysis has been conducted in the area, hindering community-level prevention efforts. The Mario Molina Center identified areas at High and Very High risk for landslides and forest fires (CMM 2014), which could potentially affect more than 30,000 residents in the Villa Alta district. Similarly, the Risk Atlas of the State of Oaxaca of State Coordinación Estatál de Protección Civil (CEPC 2003) indicated that the Mixe district faces a higher probability of forest fire risk. Therefore, this research aimed to identify areas at risk for forest fires in the Sierra Norte region of Oaxaca, Mexico, and to assess the severity of a forest fire that occurred in the region, with the goal of providing a foundation for prevention and firefighting strategies.

Materials and methods

The SNO region comprises the political-administrative districts of Ixtlán de Juárez, Villa Alta, and Mixe (Figure 1), which are inhabited by Zapotec, Mixe, and Chinantec peoples, covering approximately 9 % of the state of Oaxaca's territory (Hernández-Díaz 2012). The region spans an area of 8,950 km² (INEGI 2020). It is located between 16º 52' and 17º 47' North latitude, and -95º 7' to -96º 45' West longitude, with elevations ranging from 4 to 3,403 meters (INEGI 2013). The climate is predominantly warm and humid (Am), with an average annual temperature between 22 and 26 °C, and the coldest month averaging 18 °C. The region experiences a winter dry season, with precipitation in the driest month below 60 mm (García & CONABIO 1998). The predominant vegetation is pine-oak forest (INEGI 2018), and the most common soil type is humic acrisol (Ah) (INEGI 2005).

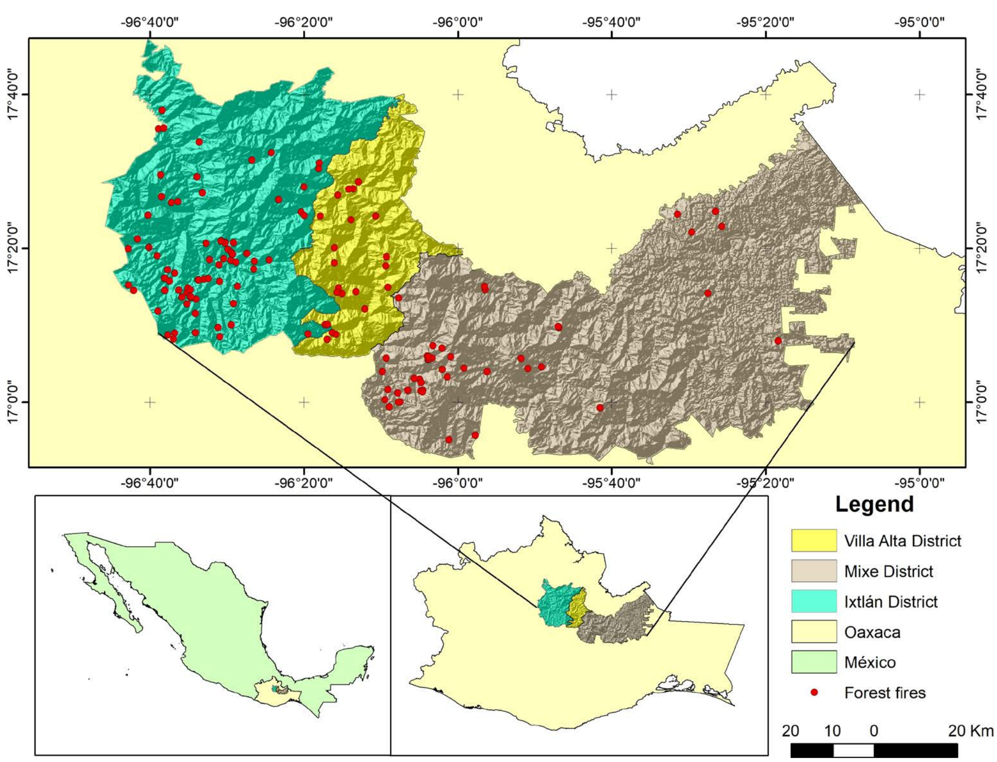

Figure 1. Geographical location of the Sierra Norte region in Oaxaca, México and records of forest fires that occurred between 2006 and 2020.

Time analysis. Records of forest fires in the SNO region, beginning in 2005, were obtained from the National Forestry Commission (CONAFOR 2021a) and refined by discarding duplicates that were outside the study area or had incorrect georeferencing. These records were further supplemented with fire polygons provided by CONAFOR (2021b). The data were then analyzed based on the year and municipality of occurrence, affected area, vegetation strata, and the months with the highest number of fires.

Satellite analysis. An analysis of the fire that occurred in Santa María Jaltianguis on March 25, 2020, was conducted using SENTINEL 2B satellite images and the Normalized Burn Ratio (NBR) to delineate the affected area. These images were obtained from the United States Geological Service (USGS) website (earthexplorer.usgs.gov), corresponding to Path 23 and Row 48, with a UTM (Universal Transverse Mercator) projection.

Valdez-Zavala *et al.* (2019) state that the Normalized Burn Ratio (NBR) is one of the most widely used indices for mapping burned areas. It relies on two spectral bands: near-infrared (NIR) and shortwave infrared (SWIR2). In the NIR band, reflectivity decreases as vegetation is lost, as it is highly sensitive to chlorophyll content, which is linked to plant vitality. In contrast, in the SWIR2 band, reflectivity increases due to moisture loss, exposed soil, and reduced shadows caused by the absence of vegetation, as this band is more sensitive to changes in water content. The NBR is used not only to delineate burned areas but also to assess the severity of fires (Gómez & Martín 2008, Montorio *et al.* 2014). For the NBR calculation, Band 8 (NIR) and Band 12 (SWIR2) were utilized. The processing was done in ArcGIS using the raster calculator tool with the following formula (López & Caselles 1991):

$$NBR = \frac{NIR - SWIR2}{NIR + SWIR2}$$

Where: NBR stands for Normalized Burn Ratio; NIR refers to near-infrared, and SWIR2 to shortwave infrared. The NBR index ranges between -1 and 1, measuring the amount of energy reflected by vegetation relative to incident solar energy. A value of -1 indicates areas affected by fire, while a value of 1 represents unaffected vegetation or areas in the regeneration phase after a fire (Manzo-Delgado & López-García 2020). To verify the area delineated by the NBR, the polygon marked by community technical personnel using a GPS (Global Positioning System) after the fire occurred was used as a reference.

Severity analysis. The severity of the forest fire in the municipality of Santa María Jaltianguis was determined using the Differenced Normalized Burn Ratio (DNBR). This was calculated by subtracting the NBR values of two time periods, before and after the fire, using the following formula (Key & Benson 2006):

$$DNBR = NBR(before\ year) - NBR\ (after\ year)$$

The values of the DNBR index range from -1 to 1 and can be adjusted depending on the study area, though the values provided by Key & Benson (2006) are often used as a reference (Table 1). Based on these values, the burned areas and the severity of their impact on the Santa María Jaltianguis property were classified. These areas were then verified in the field using photographic evidence, capturing a 1 m² surface area vertically to document the condition of the trees. The selected points represented the different levels of severity indicated by the index.

Determination of the risk to forest fires. To generate the risk index, the methodology proposed by Flores *et al*. (2016) was followed, with modifications to suit the characteristics of the region (Fernández-Méndez *et al*. 2016, Flores *et al*. 2016). This process involved constructing variables related to human activities that contribute to the occurrence of forest fires (Table 2), which were weighted with values from 1 to 4, assigning higher values to factors that pose a greater risk. Finally, the sum of each weighted variable was calculated, and the results were categorized into five different risk levels. This approach allowed for the identification of areas at risk for forest fires in the Sierra Norte region of Oaxaca, classified by municipalities and political districts.

Results

*Time analysis***.** CONAFOR (2021a) records a total of 351 fire incidents from 2006 to 2020 for the SNO (Figure 1). The year with the highest number of fires was 2013, with 30 events, while 2007 and 2008 had the lowest occurrences, each with only 3 recorded incidents (Table 3).

Table 1. Severity levels of the Differenced Normalized Burn Ratio (DNBR) recorded in the Sierra Norte of Oaxaca.

DNBR value	Severity of the fire
< -0.25	High restocking
-0.25 to -0.1	Low restocking
-0.1 to 0.1	Unburned
0.1 to 0.27	Low severity
0.27 to 0.44	Moderate severity
0.44 to 0.66	Moderate-high severity
> 0.66	High severity

Table 2. Weighted values (risk levels) of the variables used to construct the risk index in the Sierra Norte of Oaxaca, Mexico.

Weighting	Proximity of localities (m)	Number of inhabitants	Proximity of communication routes (m)	Type of track	Proximity of fire occurred (m)	Causes of fires	Fire ranges occurred
4	0-500	-	0-500	-	-	Agricultural activities, smokers and campfires of visitors	-
3	501-1,000	2,001 and more	501-1,000	-	0-500	Forestry, clearing of road waste and poachers	-
2	1,001-2,000	1,001-2,000	1,000-1,501	Sub-grade	501-1,000	Other productive activities, such as garbage dumps, litigation, quarrels and electric shocks	Fire registration
1	2,001-2,500	0-1,000	1,501-2,000	Other coating	1,001-2,000	Exploitation and illicit crops	-
Source:	(INEGI, 2019)	(CONABIO, 2014a)	(CONABIO, 2014b)	(SCT 2012)	(CONAFOR, 2021a)	(CONAFOR, 2021b)	(CONAFOR 2021a)

The municipalities most affected by fires during the evaluation period were Ixtlán de Juárez (16), San Pedro and San Pablo Ayutla, and Santa María Tlahuitoltepec (14 each), and Santa Catarina Ixtepeji (13). Other municipalities, including Asunción Cacalotepec, San Bartolomé Zoogocho, and Santa María Tepantlali, experienced only a single fire during the reporting period.

Fires of varying magnitudes were recorded, with some having a greater impact, such as the fire in San Pablo Macuiltianguis (2009), which affected 868 hectares, and the fire in San Juan Quiotepec (2013), which burned 365 hectares-these two being the largest recorded events.

According to CONAFOR (2021a), different vegetation layers were affected depending on the type of fire, the vegetation type, and land use at the site. In San Pablo Macuiltianguis (2009) and San Juan Quiotepec (2013), four vegetation strata were impacted: herbaceous, shrub, tree, and regeneration layers. In contrast, in the municipality of Abejones (2013 and 2016), only the shrub stratum was affected, while in Totontepec Villa de Morelos (2017), only the herbaceous layer was impacted. It is important to note that not all reported fires include data on the area affected, meaning that some larger-scale fires may not have been fully documented. The herbaceous layer was found to be the most frequently affected, followed by shrubs, trees, and, to a lesser extent, regeneration vegetation (CONAFOR 2021a).

Table 3. Chronological record of fires in the Sierra Norte of Oaxaca, Mexico over a 14-year period (2006-2020). Pine Forest (PF), Oak Forest (OF), Pine-Oak Forest (POF), Mountain Mesophilic Forest (MMF), Medium Deciduous Forest (MDF), Low Deciduous Forest (LDF), High Evergreen Forest (HEF), High Sub-Evergreen Forest (HSEF).

Year	Number of fires	Communities affected	Types of vegetation affected	Affected area (ha)
2006	6	4	1 (PF)	36.00
2007	3	2	2 (PF, POF)	60.00
2008	3	2	2 (PF, OF)	90.00
2009	7	7	3 (PF, OF, POF)	934.25
2010	10	8	2 (PF, POF)	489.5
2011	5	5	2 (PF, POF)	72.00
2012	0	0	---	0
2013	30	16	4 (PF, OF, POF, MDF)	613.50
2014	16	9	3 (OF, POF, LDF)	176.00
2015	5	4	2 (OF, POF)	8.25
2016	21	9	4 (PF, OF, POF, LDF)	385.00
2017	13	8	4 (PF, OF, POF, HEF)	1,383.16
2018	5	4	2 (OF, POF)	83.00
2019	13	12	4 (OF, POF, MMF, HSEF)	311.11
2020	14	9	4 (PF, OF, POF, LDF)	362.85
Mean	10.07	6.6	--	352.33
Standard deviation	7.97	4.21	--	397.09
Variation Coefficient	1.07	0.49	--	1.40
Minimum	0.00	0.00	--	0.00
Maximum	30	16	--	1,383.16
Total	151	43	--	5,004.62

The forest fire season in the SNO region of Oaxaca spans from January to August, with the highest number of incidents occurring in February (22), March (34), April (60), and May (30). These months are the most critical for the region, as over 95 % of forest fires during the evaluated period occurred within this timeframe.

NBR in the municipality of Santa María Jaltianguis. The map generated using the NBR for the Santa María Jaltianguis fire was overlaid with the area delineated in the field by the community's technical staff, showing a 68 % overlap, indicating an overestimation of the burned area (Figure 2). In terms of vegetation before and after the fire, the change in color (from green to brown) in the affected area is clearly visible (Figure 2). Field measurements determined that the burned area covers 116.9 hectares, which does not align with the 162 hectares reported by CONAFOR (2021a). These discrepancies highlight differences both in the reported size and the delineation of the affected property, with the two areas overlapping by only 43 %.

Severity analysis. Key & Benson (2006) propose six categories to classify fire impact severity by comparing the initial state of vegetation with its post-fire condition. Unburned indicates not burned. Low severity indicates that only the herbaceous layer was burned, leaving the vegetation in a similar state. Low Moderate severity indicates that shrub was affected. Moderate severity indicates that less than half of the trees were affected, while Moderate-High severity means both the trunks and tree canopies were burned. High severity refers to areas where only tree stumps remain standing. Five of these categories were observed in the municipality of Jaltianguis (Figure 3). Specifically, 1.62 hectares were unburned, 51.34 hectares showed low severity, 47.73 hectares had moderate severity, 12.51 hectares experienced moderate-high severity, and 3.72 hectares were classified as high severity (Table 4). The high repopulation class was not observed because, at the time of the NBR analysis, the vegetation had not yet undergone a recovery process.

The site visit to the affected area took place two years after the fire, and the severity levels indicated by the DNBR matched the observed condition of the vegetation. Shrub and tree species were identified, suggesting that the plant strata were not completely affected, as their growth indicates a moderate severity impact (Figure 4A). Field verification confirmed the reliability of the data, as the health of the tree and shrub species appeared consistent with the severity classifications. Herbaceous plants were also observed to have re-established in the areas where the fire occurred.

In areas where the fire caused moderate-high severity (Figure 4B), such as in the municipality of Jaltianguis, only the stems of trees and shrubs remained standing, as their crowns had been entirely burned. Herbaceous plants were present, but the absence of pines, which were once the dominant species, was notable. Pine species did not show

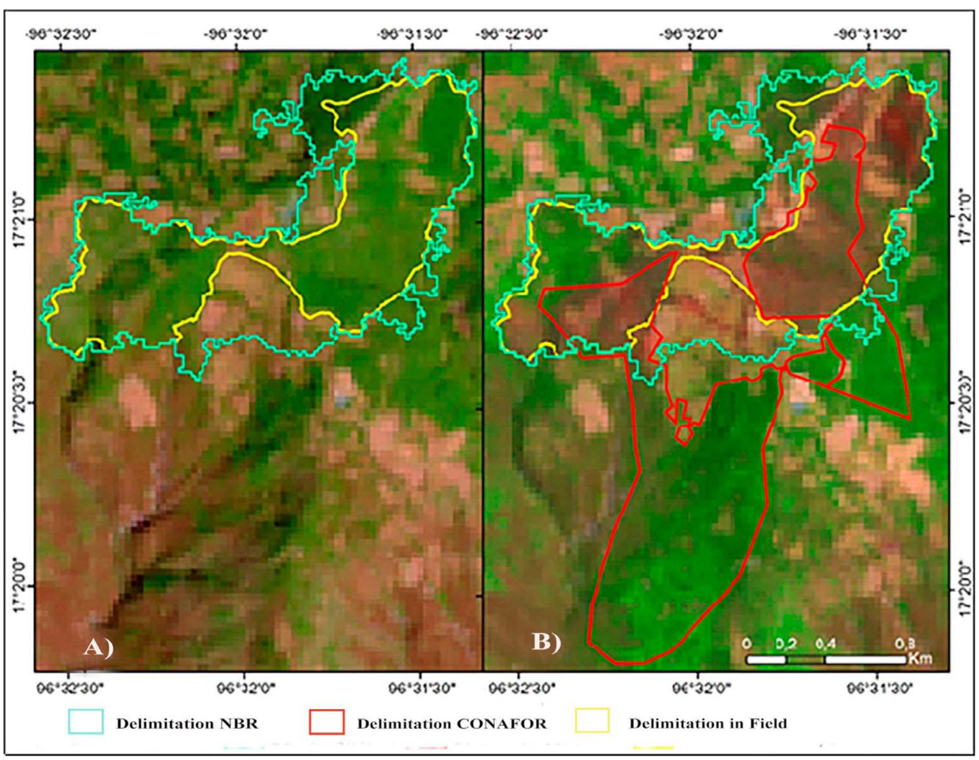

Figure 2. Comparison of the burned area in the municipality of Santa María Jaltianguis in 2020. (A) Pre-fire, (B) Post-fire.

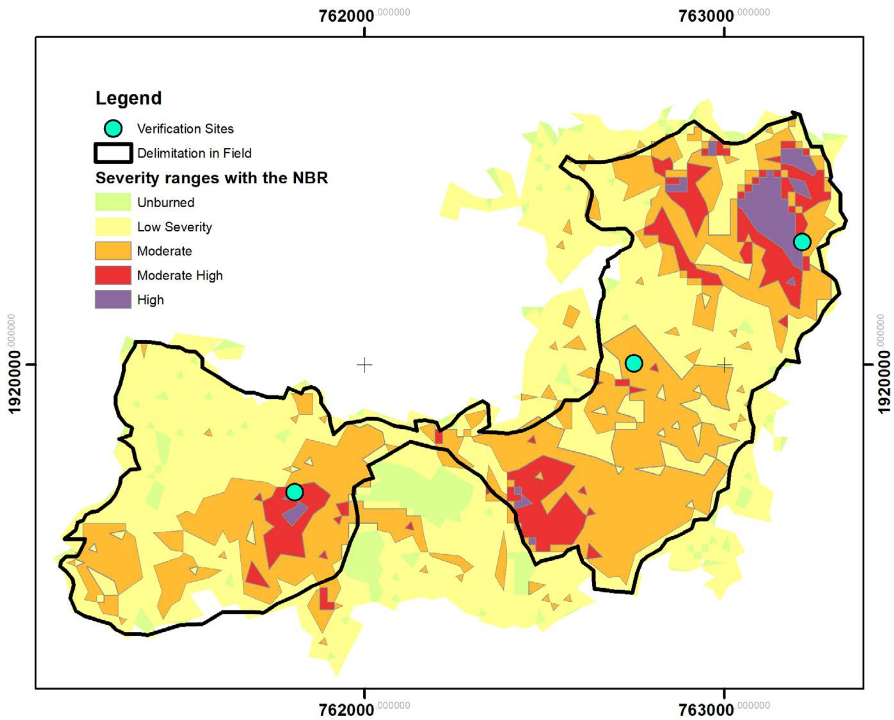

Figure 3. Area delineated using the Differenced Normalized Burn Ratio (DNBR) index in the region affected by the forest fire in Santa María Jaltianguis, Sierra Norte, Oaxaca, Mexico. (A) Area affected by the forest fire; (B) Area affected as reported by the dNBR index and CONAFOR.

Table 4. Affected area by fire severity levels in the Sierra Norte of Oaxaca, Mexico. Source: Own elaboration based on Key & Benson (2006).

Severity	Area (ha)
Unburned	1.62
Low severity	51.34
Moderate severity	47.73
Moderate-high severity	12.51
High severity	3.72
Total	116.92

signs of natural regeneration. It is important to note that restoration activities have already intervened in the area, as well as the extraction of timber.

The area with high severity (Figure 4C) was previously dominated by oak trees. However, the fire severely impacted the area, leaving the soil bare and consuming even the organic matter. This has left the soil vulnerable to water erosion and has negatively affected its infiltration capacity (Montorio *et al.* 2014).

Risk analysis. Based on the variables used, the largest portion of the Sierra Norte region (892,452.41 ha) falls within the Very Low (39.18 %, 349,702.30 ha) and Low (34.84 %, 310,947.60 ha) risk categories for forest fires. The other risk categories cover smaller areas: Medium (16.43 %, 146,644.70 ha), High (7.43 %, 66,313.80 ha), and Very High (2.11 %, 18,844.01 ha) (Figure 5). In terms of political divisions, the Mixe district has the largest area in the "Very High" risk category, followed by Ixtlán, with the smallest area in the "Villa Alta" district. This pattern is similar across other risk levels (Table 5). However, when comparing the proportion of land at risk within each district, 3.48 % of the Villa Alta district is classified as Very High risk, followed by Ixtlán (2.46 %) and the Mixe district (1.58 %).

The 'Very High' fire risk category includes 43 municipalities, with Ixtlán de Juárez, San Juan Cotzocón, Nuevo Zoquiápam, Santa María Tlahuitoltepec, and San Pedro y San Pablo Ayutla having over 1,000 hectares in this category. On the other hand, the 'Very Low' risk category includes 62 municipalities, with San Juan Mazatlán, Ixtlán de Juárez, and Santiago Camotlán having the largest surface areas within this risk level (INEGI 2019, CONABIO 2014a).

Discussion

In Mexico, forest fires occur more frequently during the dry months, a pattern consistent across different states. For example, in the State of Mexico, Gutiérrez *et al.* (2015) report that most forest fires take place in April, which aligns with the SNO region, where 60 fires were recorded in the same month. This pattern is also reflected in the Risk Atlas

Figure 4. Vegetation affected by the effects of the forest fire in the municipality of Santa María Jaltianguis: (A) Moderate severity, (B) Moderate-high severity, (C) High severity.

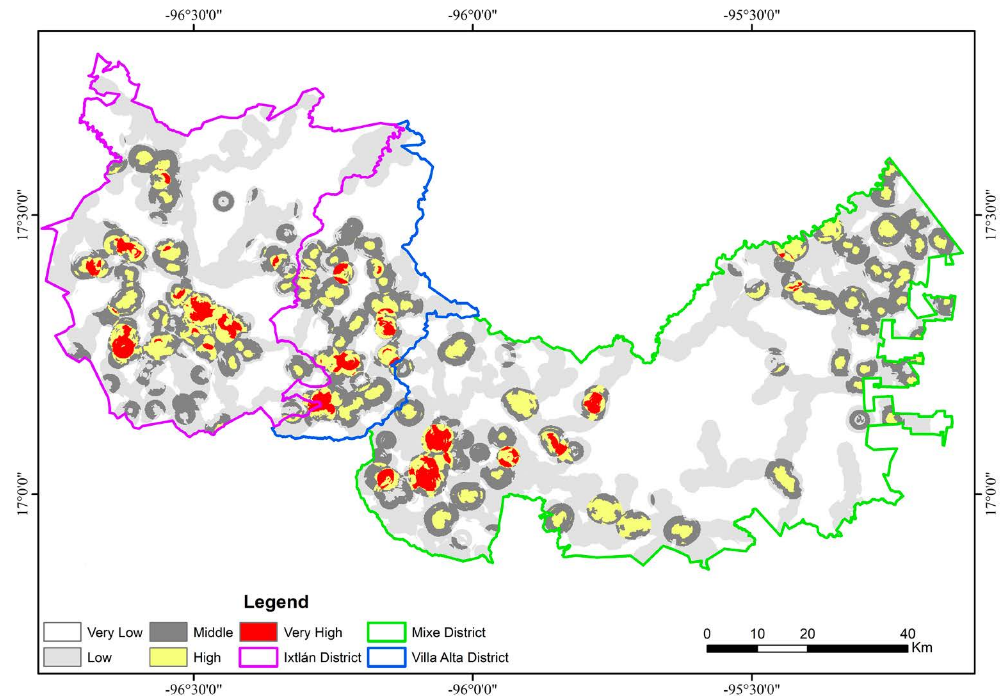

Figure 5. Forest Fire Risk Map of the Sierra Norte de Oaxaca.

of the State of Oaxaca (CEPC 2003). Additionally, April coincides with the slash-and-burn season in the region's agricultural cycle, contributing to the increased spread of fires (CEPC 2003).

The health of trees can be compromised after a forest fire, as they become more vulnerable to pests and diseases, these changes may manifest over time, making it crucial to monitor affected areas to assess vegetation recovery and the speed of regeneration until pre-fire vegetation levels are restored (López-García 2020). In this study, only the immediate impact of the fire that occurred on March 25, 2020, in Santa María Jaltianguis was evaluated. However, continued monitoring is recommended to track the area's recovery and assess the effectiveness of active restoration efforts. In this case, it was possible to verify that the affected tree species were mainly *Pinus oaxacana* Mirov, *P. patula* Schl. et Cham, *Quercus crassifolia* Humb. & Bonpl., *Q. laurina* Humb. & Bonpl., among others that could not be recognized due to the severity of the fire. These species must be considered in the restoration plans. The species *Leucaena leucocephala* (Lam.) de Wit is of special interest due to its significant benefits for eroded soils, nearly restoring them almost completely. Its fire tolerance further enhances its value, enabling its use as an effective fire barrier (Bernal-Toro & Montoya-Santacruz 2003). Monitoring forest fires using satellite images has become widely utilized due to its precision and numerous advantages, particularly through techniques like vegetation indices (Reynosa 2016). The spectral behaviour of vegetation is determined by the leaves that form the canopy (Manzo-Delgado & Meave 2003). The reflectivity linked to the canopy structure helps detect forest fires, mainly due to the heat energy reflected by the tree canopy, which differs from that of the understory (Valladares 2006, Promis 2013). However, if a fire affects only the understory without damaging the treetops, it may go undetected by vegetation indices, leading to an inaccurate estimate of the affected area. Additionally, the NBR can either underestimate or overestimate the burned area by mistaking shaded regions, exposed rock, or bodies of water for burned areas (Heredia *et al*. 2003).

The area affected by the fire in the community of Santa María Jaltianguis was reported by CONAFOR (2021a) as 162 hectares. However, fieldwork determined an affected area of 116.9 hectares, indicating a discrepancy of 45.1 ha significant difference. This discrepancy could be attributed to the physical condition of the firefighting personnel when mapping the affected polygon, as exhaustion may have led to only a partial marking of the burned area. Additionally, the inaccessibility of the terrain could have posed a danger to the combatants, further influencing the accuracy of the

Table 5. Area affected by forest fires per district, categorized by degree of risk. Source: Own elaboration based on Flores *et al*. (2016).

Risk level	Area at risk (ha)		
	Ixtlan	Villa Alta	Mixe
Very low	108,856.00	41,021.30	199,825.00
Low	102,462.00	31,634.60	176,851.00
Middle	45,230.10	26,331.80	75,082.80
High	19,506.30	14,667.50	32,140.00
Very High	6,959.44	4,102.42	7,782.15

delineation. Accurate data is crucial for the historical analysis of forest fires, making it necessary to update or verify the information using techniques such as remote sensing to avoid skewing statistics and mismanaging burned areas.

The Normalized Difference Vegetation Index (NDVI) has been used to analyze forest fire-affected areas (Delgado 2017). However, Valdez-Zavala *et al*. (2019) confirm that the Normalized Burn Ratio (NBR) is more effective than NDVI and other indices, such as the Burn Area Index Modis (BAIM) and the Burn Area Index (IAQ). Opazo & Rodríguez-Verdú (2007) note that the delimited burned area can vary due to factors like soil moisture or the time of year, with the type of vegetation being the most important factor to consider. In this study, the NBR produced reliable results, which were corroborated both in the field and with the dNBR, as the verification points aligned with the severity levels of the impact.

The Risk Atlas of the State of Oaxaca (CEPC 2003) identified the Mixe district as having the highest risk of forest fires, using variables such as the causes of fires (agricultural activities, smokers, fires caused by tourists and hunters, disputes, forestry activities, burning of garbage dumps, and unidentified activities). This finding aligns with the results of this study, although different variables were used, as the causes of fires were only one of the seven factors considered. The high-risk level identified in the Mixe district highlights the need to focus on activities involving the use of fire for improving soil and vegetation conditions, or, if necessary, to ensure better fire management practices to prevent it from getting out of control. However, the rest of the Sierra Norte region should not be overlooked, as Villar-Hernández *et al*. (2022) identified clusters of hot spots from MODIS imagery throughout this area, indicating a level of risk that also requires attention.

The most affected vegetation stratum was the herbaceous layer, followed by the shrub, arboreal, and to a lesser extent, the regeneration layer. These findings differ from those reported by Gutiérrez *et al*. (2015) in the State of Mexico, where 57.1 % of the affected area consisted of shrubs and 37.5 % was grasslands. This variation is likely due to the environmental differences and plant structure in the Sierra Norte region of Oaxaca. The lack of up-to-date and accurate data is a significant limitation when generating information about forest fires in the region. Based on the data collected, it was determined that the occurrence and extent of forest fires do not follow a predictable pattern but are closely linked to human activities. SENTINEL images offer a valuable alternative for accurately delineating burned areas, particularly when assessing the severity of forest fires.

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