Investigaciones Geográficas • Instituto de Geografía • UNAM
eISSN: 2448-7279 • DOI: https://doi.org/10.14350/rig.60896 • ARTICLES
Issue 115 • December • 2024 • e60896
www.investigacionesgeograficas.unam.mx

Multitemporal analysis of burned areas in tropical ecosystems of Campeche, Mexico: meteorological and anthropogenic causes

Análisis multitemporal de las áreas quemadas en ecosistemas tropicales de Campeche, México: causas meteorológicas y antrópicas

Alfonso Carbajal-Domínguez,* Lilia de Lourdes Manzo-Delgado,** Claudia María Monzón-Alvarado*** and Christoph Neger****

Received: 12/14/2024. Accepted: 05/08/2024. Published: 07/11/2024

Abstract. Every day, 20,000 hectares of forests are lost worldwide due to fires in the intertropical zone. The sensitivity of forests to fire is a consequence of their high mortality rate, which threatens these ecosystems. This research analyzed the distribution of burned areas in the tropical forests covering the eastern region of the Escárcega municipality, Campeche, between 2013 and 2020, and explored the relationship of these areas with meteorological conditions and agricultural use of fire. Burned areas were detected using Landsat 8 OLI satellite imagery and the NBR and BAI spectral indices. An area of 29,151.82 hectares was burned, corresponding to 12.06 % of the tropical forest in the study area. The year 2019, a year of high temperatures and low precipitation, recorded the largest fire and burned area, confirming the relationship between drought and increased fires. Twenty-six interviews were held in nine ejidos that allowed us to investigate the causes of the fires, including poaching, agricultural burning, and changes in land use. Proper fire management is essential to preserve biodiversity and ecosystem services. The interplay between anthropogenic and meteorological variables influences the frequency of fires. Inappropriate fire management can lead to uncontrolled burns, and weather conditions can favor the spread of fire.

Keywords: multitemporal analysis, tropical ecosystems, forest fires, BAI and NBR indices, Escárcega, Campeche.

Resumen. Cada día se pierden 20 000 hectáreas de selvas debido al fuego en la zona intertropical del planeta. La sensibilidad de las selvas al fuego se debe a la alta tasa de mortalidad que amenaza a estos ecosistemas. La investigación se centra en analizar la distribución de áreas quemadas en las selvas de la región oriental del municipio de Escárcega, Campeche, entre 2013 y 2020, y explorar su vínculo con las condiciones meteorológicas y el uso agropecuario del fuego. Para la detección de áreas quemadas, se utilizaron imágenes de satélite Landsat 8 OLI y los índices espectrales NBR y BAI. Se quemaron 29 151.82 hectáreas, que corresponde al

* Posgrado en Geografía, Unidad de Posgrado, edificio E, Universidad Nacional Autónoma de México. Ciudad de México, México. 07510. Teléfono 55 11319311. Correo electrónico: alfonsocd88@gmail.com, ORCID: 0000-0001-6896-1113
** Laboratorio de Análisis Geoespacial, Instituto de Geografía, Universidad Nacional Autónoma de México. Circuito Investigación Científica s/n, Colonia Ciudad Universitaria, Ciudad de México, México, C.P. 04510. Teléfono: 55 5623 0222 Ext: 45501Correo electrónico: llmanzo@geografia.unam.mx, ORCID: 0000-0003-4833-6497
*** Departamento de Ciencias de la Sustentabilidad, El Colegio de la Frontera Sur Unidad Campeche, CONAHCYT. Av. Rancho Polígono 2-A, Ciudad Industrial, Lerma Campeche, Camp. C.P. 24500. Teléfono: (981) 12 7 3720 Ext: 2414. Correo electrónico: cmonzon@ecosur.mx, ORCID: 0000-0001-9131-9276
**** Unidad Académica de Estudios Territoriales Yucatán, Instituto de Geografía, Universidad Nacional Autónoma de México. C. 50 419B, Centro, 97000 Mérida, Yuc. Correo electrónico: neger@geografia.unam.mx, ORCID: 0000-0001-5210-5005. *Autor de correspondencia. * Corresponding author.

12.06% de la selva del área en estudio. En 2019 se registró la mayor extensión quemada, así como el incendio más extenso que corresponde con un año de altas temperaturas y baja precipitación, que confirma la relación entre las condiciones climáticas de sequía y el aumento de incendios. Se aplicaron 26 entrevistas en nueve ejidos que permitieron averiguar las causas de los incendios, entre las que destacan la caza furtiva, quemas agropecuarias y cambio de uso de suelo. La gestión adecuada del fuego es crucial para preservar la biodiversidad y los servicios ecosistémicos. La interacción entre acciones humanas y variables meteorológicas influye en la frecuencia de los incendios, donde un manejo inapropiado del fuego puede dar como resultado quemas descontroladas y las condiciones climáticas pueden favorecer su propagación.

Palabras-clave: análisis multitemporal, ecosistemas tropicales, incendios forestales, índices BAI y NBR, Escárcega, Campeche.

INTRODUCTION

A global estimate indicates that 20,000 ha of forests are lost to fire every day in intertropical zones, including extensive regions of Africa, Asia, Oceania, and America, with deforestation and agricultural fires as the main causes (Estrada & Coates-Estrada, 2003; Manzo-Delgado & López-García, 2020). Fire plays a central role in the functioning of ecosystems, contributing to their renewal provided that it remains within the limits of its natural regimes (Rodríguez Trejo, 2014). However, changes in forest fire regimes can adversely affect the functions and services provided by ecosystems (Moghli et al., 2021). Today, atmospheric conditions are changing worldwide, triggering changes in the behavior and regime of fire (Monzón Alvarado, 2018).

Under natural conditions, tropical forests undergo a low frequency of fires, with a frequency of one every 100 years or even less frequently (Rodríguez-Trejo et al., 2019). However, the combination of various factors associated with the use of fire by humans and the variability of meteorological conditions, such as temperature and precipitation, as part of the effects of climate change (González et al., 2011) and the El Niño-Southern Oscillation phenomenon (ENSO) (Manzo-Delgado & López-García, 2020; Pazmiño, 2019), has altered the pattern of occurrence of fires in tropical forests, making them a significant disturbance (Pagan et al., 2021; Zamora-Crescencio et al., 2017).

Within this framework, forests are considered sensitive to fire because of the high mortality rates that result (Rodríguez Trejo, 2014). In addition, ecological succession can take decades or even centuries to restore the composition and structure before a fire (Rodríguez Trejo et al., 2019). Given this situation, conserving the high biodiversity of these tropical ecosystems is essential (Rodríguez-Trejo et al., 2011; Román-Cuesta & Martínez-Vilalta, 2006).

The area affected by fire has been estimated through field observations, using GPS and topographic maps to obtain accurate measurements. However, this method is usually limited to particular areas, and its use is hard to apply for assessing extensive areas. For this reason, multispectral remote sensing images have been integrated into the development of standardized methods based on spectral indices. These indices facilitate the identification of areas affected by fire, reducing the time of analysis and field trips (Flores-Rodríguez et al., 2021; Pérez et al., 2022). One of these indices that has returned good results is the Normalized Burn Ratio (NBR) (Arellano et al., 2017). Likewise, the Burned Area Index (BAI) has also proven to be effective (Wu et al., 2022). The combined use of both indices and Landsat imagery has achieved good performance (Manzo Delgado & López García, 2013).

These tools are particularly relevant when considering that the tropical forests of southeastern Mexico have been seriously affected during the past century by agricultural practices or intentional burning (Alonso Velasco & Velázquez Torres, 2019). Other human and environmental factors that have influenced these forests include droughts caused by the El Niño-Southern Oscillation (ENSO) phenomenon, the accumulation of flammable materials due to hurricanes (Rodríguez-Trejo et al., 2011), and recently, in 2019, the launch of the 'Sembrando Vida' (Sowing Life) program (Pagan et al., 2021).

In this context, the state of Campeche, located in the southeast of the country, is notable for having one of the most extensive networks of Natural

Protected Areas, which largely overlap with vast extensions of ejido land. This has led to little surveillance, promoting changes in land use, conflicts over the expansion of the agricultural frontier, illegal logging and poaching, irregular human settlements, and extraction of timber resources (Pérez Rodríguez et al., 2018).

This research contributes to a deeper understanding of the causes of increased fires in tropical forests in southeastern Mexico, focusing on meteorological conditions and anthropic fire. Examining both factors can contribute to more effective prevention and management strategies. In addition, a better understanding of the current distribution of burned areas would also allow the analysis of the severity of fire, its impact on plant diversity in tropical forests, and the allocation of resources to conserve and restore these valuable ecosystems.

This work aims to analyze the distribution of burned areas in tropical forests in the eastern region of the Escárcega municipality, state of Campeche, during 2013–2020, considering the variability of weather conditions and anthropic fire, to lay the ground for the development of effective fire prevention strategies at the ejido level. The particular objectives are the following: (1) determine the frequency of fires and their location, extension, and vegetation affected in burned areas; (2) analyze the meteorological conditions associated with fires in the region; and (3) examine the anthropic factors associated with the ejidos that contribute to fires. The analysis is based on the use of heat spots derived from VIIRS imagery and the BAI and NBR indices generated with Landsat 8 OLI satellite images, temperature, precipitation, and extreme-events data, in addition to semi-structured interviews with local actors.

MATERIALS AND METHODS

The Escárcega municipality, Campeche, is prominently divided into two areas, one to the east and the other to the west (Figure 1). The western area has the largest population and has been significantly transformed by human activities. This work focuses on the eastern area, with less population density and extensive areas of natural vegetation. This area is located at 18°20' and 19°00' North and -90°00' and -90°40' West, spanning over 280,339.60 ha and including 19 ejido-type agrarian nuclei. It is worth mentioning that some of these agrarian nuclei also extend to the Calakmul and Hecelchakán municipalities (Figure 1). The dominant vegetation types in this area are medium sub-evergreen forest and low thorny sub-evergreen forest, along with agroecosystems and arboreal and scrub secondary vegetation derived from both tropical forest types (INEGI, 2008). The southern portion includes a section of the Balam Kú Biosphere Reserve, a protected natural area, comprising 110,417 ha of a total of 417,355.86 ha; to the north, there is a small section of the Balam Kin protected area, with 3,787 ha of a total of 102,344.15 ha; to the east, the region is adjacent to the Calakmul Biosphere Reserve (Figure 1). The study area covers an altitudinal range between 0 and 250 m a.s.l., with a flat topography that includes some hills and plains of lacustrine deposits formed by gleysol and leptosol soils (INEGI, 2001, 2010; INIFAP & CONABIO, 2008; IUSS Working Group WRB, 2015). The climate is warm subhumid (Aw1), with a mean annual temperature between 24 °C and 26 °C (García & CONABIO, 2001) and an annual precipitation between 1,000 mm and 1,500 mm (Cuervo-Robayo et al., 2014).

Data Collection

To determine the spatial and temporal distribution of burned areas, we downloaded heat spots of the National Aeronautics and Space Administration (NASA) Fire Information for Resource Management System (FIRMS, 2022), produced from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor of the Suomi - National Polar-Orbiting Partnership (S-NPP) sensor with a resolution of 375 m. A total of 7,398 hot spots were recorded for the study period (2013–2020), which were organized in vector format supported by a geographic information system.

Landsat OLI images were downloaded (*Path/Row* 20/47) with support from the U.S. Geological Survey's Global Visualizer (USGS, 2018). Eight images with cloud cover of less than 10%

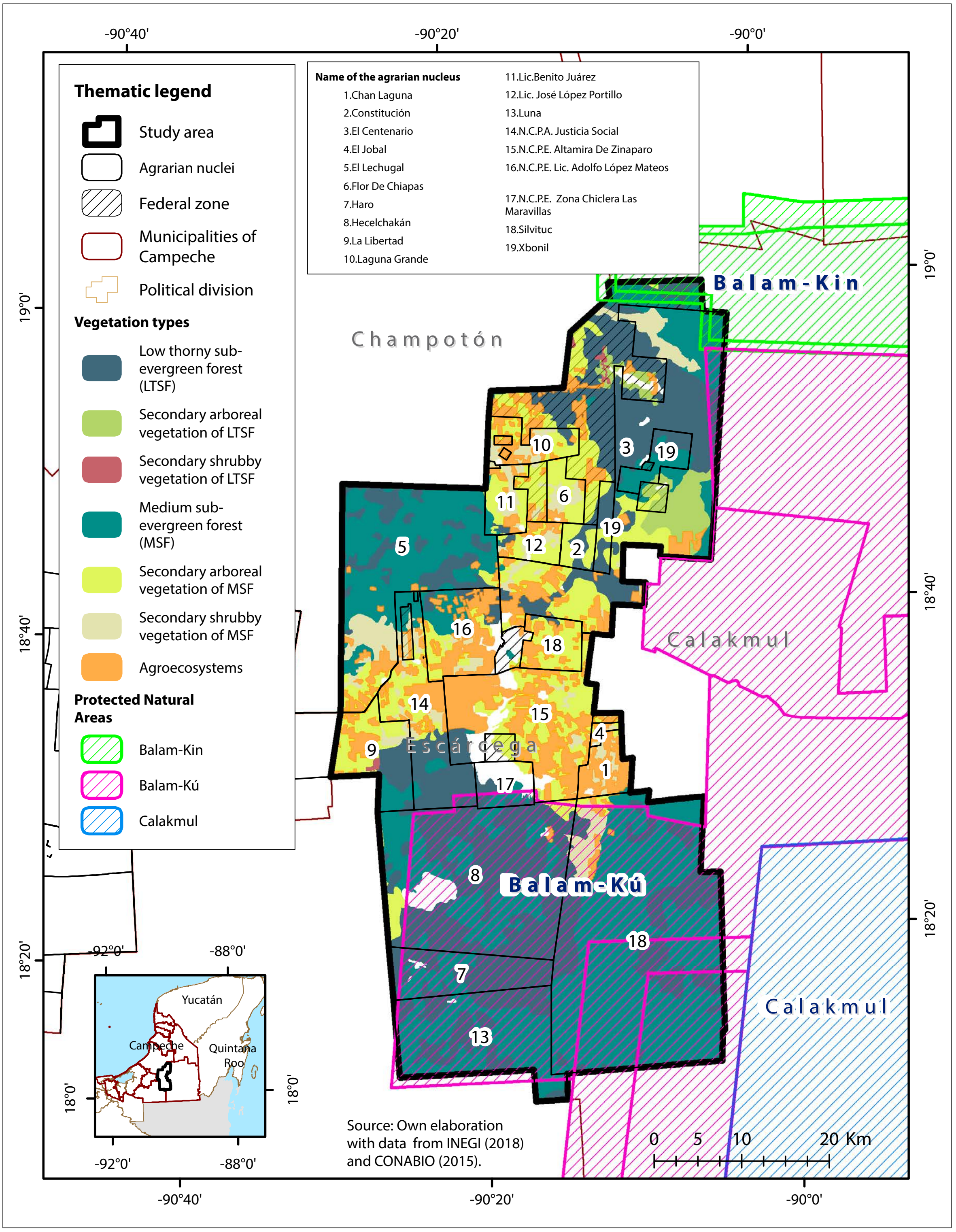

Figure 1. Location of the study area.

were used, corresponding to the dates (year, month, day) 20130729, 20140427, 20150617, 20160705, 20170606, 20180727, 20190425 and 20200513, in Geotiff format, geometrically and radiometrically (Level-1) corrected, in the UTM (Universal Transverse Mercator) projection. The images were radiometrically calibrated to obtain top-of-atmosphere (TOA) reflectance values of the optical bands; likewise, a mask of clouds and water bodies was constructed.

The distribution of vegetation and land uses in the study area was determined by interpretation of vegetation and land use maps (series VII) at a 1:250,000 scale for 2018 (INEGI, 2018). The vegetation types in the area are as follows: medium sub-evergreen forest (SMQ) and low thorny sub-evergreen forest (SBQ); the secondary vegetation includes arboreal secondary vegetation of medium sub-evergreen forest (VSA/SMQ), arboreal secondary vegetation of sub-evergreen thorny low forest (VSA/SBQ), scrub secondary vegetation of medium sub-evergreen forest (VSa/SMQ), and scrub secondary forest of low thorny sub-evergreen forest (VSa/SBQ).

Data on mean annual maximum temperature and annual cumulative precipitation for the state of Campeche from 2013 to 2020 were obtained from the National Meteorological Service (SMN, 2020). In addition, information on historical ENSO episodes was collected (Golden Gate Weather Services, 2024; NOAA, 2020) and data from the drought monitor in Mexico were recorded for the Escárcega municipality (SMN, 2021).

Detection and delimitation of burned areas

The analysis of spectral bands suitable for the detection of burned areas has been extensively used to develop several indices to facilitate perimeter delimitation, estimation of damage levels, characterization of affected vegetation, and analysis of spatial and temporal patterns (Manzo-Delgado & López-García, 2020; Valdez-Zavala et al., 2019). The indices most commonly used for these purposes are NBR and BAI (Flores-Rodríguez et al., 2021), which were selected for this study.

The NBR and BAI spectral indices were generated from the analysis of bands in Landsat 8 OLI satellite images to evaluate the vegetation affected by fire (Figure 2). *BAI* (Equation 1) uses ρ*NIR* (Near-Infrared) and ρ*Red* (Red) reflectance values (ρ). The bands used for calculating the BAI index are the 4 Red band (0.64–0.67 μm) and the 5 NIR band (0.85–0.88 μm). The thresholds for burned forest areas estimated with the *BAI* range from 1 to 847.

$$\text{BAI}=\frac{1}{(0.1\text{-}\rho\text{Red})\hat{}2+(0.06\text{-}\rho\text{NIR})\hat{}2} \tag{1}$$

The *NBR* index (Equation 2) considers the ρ*NIR* (Near Infrared) and ρ*SWIR* (Short-Wavelength Infrared) spectral reflectance regions. The bands used to calculate this index were the 5 NIR band (0.85–0.88 μm) and the 7 SWIR band (2.11–2.29 μm). The thresholds for burned forest areas estimated with the *NBR* range from 0 to 1.

$$\text{NBR}=\frac{\rho_{\text{NIR}}-\rho_{\text{SWIR}}}{\rho_{\text{NIR}}+\rho_{\text{SWIR}}} \tag{2}$$

Annual cartography of burned areas

Burned areas were spatially represented using the vector layers of the NBR and BAI polygons; those corresponding to the same year were grouped. Areas of less than 2 hectares were excluded due to the spatial resolution of the data, as including very small areas might be confounding and introduce noise into the analysis (Manzo-Delgado & López-García, 2020). Annual burned areas were classified according to vegetation type (tropical forests and secondary vegetation) and ejidos.

Assessing the Reliability of Burned Areas

The reliability of the cartography of burned areas was evaluated for the year 2019 because this year is representative of the study period, showing the highest number of hot spots. We used a Sentinel-2 image with a spatial resolution of 10 meters, higher than that of Landsat 8 OLI, which is 30 meters (Anaya & Chuvieco, 2012). The Sentinel-2 image was captured ten days later (May 5, 2019) than the Landsat 8 OLI image (April 25, 2019), which was used to delimit the burned area.

The polygons of the burned areas in the Sentinel-2 images were delimited by applying the NBR index. Subsequently, the burned areas were con-

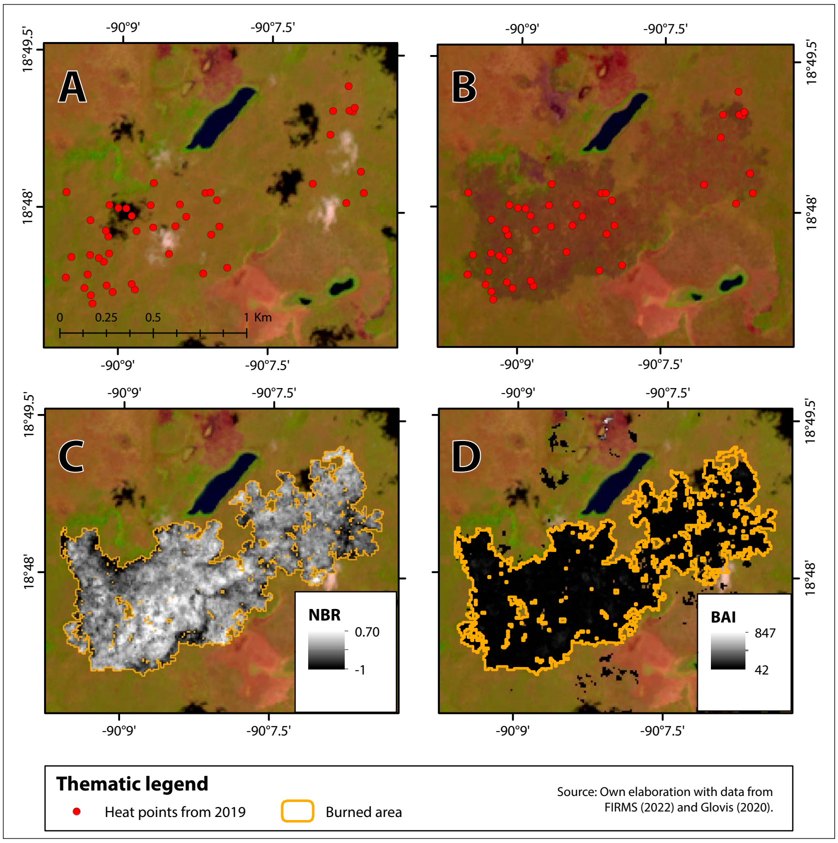

Figure 2. Processing of burned areas. Images A (pre-fire, March 24, 2019) and B (post-fire, April 25, 2019) show the false-color RGB 754 compounds in Landsat 8. Red shows the heat spots (VIIRS). Images C and D show the NBR and BAI indices generated with the post-fire image of April 25, 2019. The orange line marks the final perimeter of the burned area.

verted to vector format. The validation consisted of superimposing both polygons of burned areas derived from images and randomly selecting 31 regions in tropical forests with a burned area greater than 2 ha, representing a total area of 885.80 ha. In each region, the intercepted area and the differences between the two polygons were quantified. The results were organized into confounding matrices to estimate accuracy, omission errors, commission errors, and the Kappa coefficient (Manzo Delgado & López García, 2013).

Semi-Structured Interviews

Semi-structured interviews were conducted (Hammer & Wildavsky, 1990), focusing on local activities and habits potentially related to the ignition and spread of fires. These interviews were held between June 2022 and January 2023. Approaching the ejido authorities was key to communicating the purpose of the research and identifying the interviewees. Twenty-six interviews were held in 9 of the 19 selected agrarian nuclei: Justicia Social, Adolfo López Mateos, Silvituc, Constitución, Xbonil, El Lechugal, El Centenario, Laguna Grande, and Benito Juárez. The interviewees included ejidatarios (10), local authorities (commissioners) (9), and brigade members and volunteers who fight forest fires (7). The interview questions had an open format and were adjusted to reflect the varied experiences and points of view of the interviewees. Guidelines regarding free and informed consent were applied before interviews. The responses were transcribed and quantitatively analyzed. In this process, the responses were coded into key topics, and emerging patterns and trends in these responses were identified.

RESULTS

Validation of Burned Surface Area

The 31 areas used for validation covered an area of 885.80 hectares distributed in five types of forest:

five areas in SBQ, three in SMQ, three in VSA/SBQ, three in VSa/SMQ, and 17 in VSA/SMQ (Figure 3).

The mean Kappa index was 88.75 %, with a mean omission error of 1.72 % and a commis-

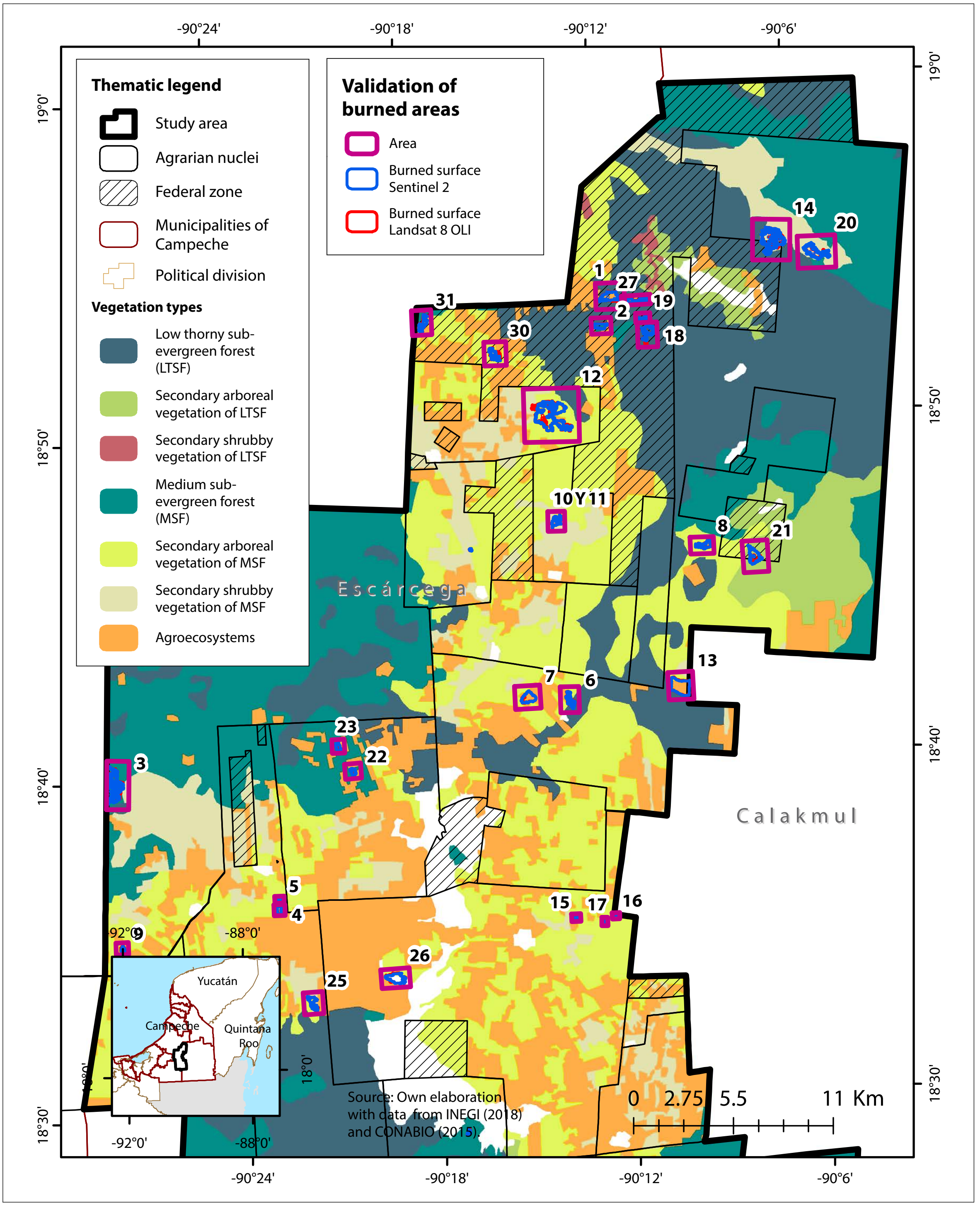

Figure 3. Spatial location of burned areas subjected to validation

sion error of 12.86 %. The mean accuracy of the burned areas detected from the Sentinel-2 and Landsat 8 OLI images was 95.91 % (Table 1). The main omission errors were due to the lag in the acquisition date of the Sentinel-2 image 10 days after the Landsat 8 OLI image, suggesting that the fires continued to advance, producing additional burned areas.

Table 1. Validation of the areas selected with the Sentinel-2 image

Area	Extension (ha) (Landsat 8 OLI)	Extension (ha) (Sentinel 2)	Overlap area (ha)	Type of tropical forest	Accuracy	Omission error %	Commission error %	Kappa index
1	36.09	33.65	31.43	SBQ	96.94	7.22	12.94	88.03
2	15.55	14.69	14.61	SBQ	98.26	5.25	5.74	93.47
3	113.04	101.89	94.74	SMQ	91.73	10.5	16.16	80.61
4	8.70	8.79	7.88	VSA/SMQ	98.02	-1.16	9.43	94.3
5	4.05	3.60	3.46	VSA/SMQ	95.27	10.36	13.5	85.1
6	17.69	17.02	16.17	VSA/SBQ	98.47	4.04	8.64	92.74
7	30.78	31.16	29.97	VSA/SBQ	99.73	-1.22	2.69	99.06
8	18.27	18.84	17.08	VSA/SMQ	99.42	-3.26	6.67	97.71
9	5.27	4.38	3.62	VSA/SMQ	94.39	20.26	31.7	70.46
10	8.64	8.01	7.69	VSA/SMQ	98.49	7.13	10.58	90.29
11	8.47	8.63	8.22	VSa/SMQ	99.85	-1.61	3.29	99.01
12	153.96	144.54	132.77	VSA/SBQ	96.62	6.65	13.79	87.62
13	74.52	72.20	70.95	SMQ	97.22	3.14	4.77	93.9
14	91.34	101.99	84.33	VSa/SMQ	100.83	-14.52	7.63	102.76
15	3.66	3.08	2.67	VSA/SMQ	92.53	18.84	27.84	71.98
16	3.69	3.45	3.12	VSA/SMQ	94.67	7.42	15.68	84.82
17	2.62	2.12	2.03	VSA/SMQ	93.35	19.12	21.92	75.49
18	30.06	27.56	24.75	SBQ	94.77	9.31	17.77	83.03
19	4.32	4.01	3.13	SBQ	96.6	8.48	27.21	79.25
20	34.38	47.78	14.33	VSa/SMQ	103.41	-68.2	4.07	123.88
21	32.09	36.57	11.98	VSA/SMQ	101.62	-16.63	2.34	107.23
22	7.64	7.90	7.60	VSA/SMQ	100.41	-4.11	0	102.24
23	5.95	7.96	5.70	VSA/SMQ	103.77	-56.59	3.39	121.45
24	49.21	36.33	35.29	VSA/SMQ	92.14	26.72	28.27	67.91
25	17.41	17.80	17.00	VSA/SMQ	100	-2.41	2.3	100
26	41.35	37.53	37.21	VSA/SMQ	94.03	9.42	10.12	85.93
27	16.38	16.43	14.21	SBQ	97.3	0	13.35	91.19
28	2.61	2.59	2.32	SMQ	98.57	0.43	10.77	93.31
29	13.95	12.32	11.12	VSA/SMQ	81.43	13.13	20.57	62.64
30	18.72	15.66	14.32	VSA/SMQ	80.17	17.51	23.42	60.34
31	15.41	12.75	12.00	VSA/SMQ	83.22	18.09	22.08	65.49
Total	885.80	861.22	741.71	Promedio	95.91	1.72	12.86	88.75

Distribution of burned areas

A total of 2,182 polygons of burned area were delimited for the period 2013–2020, covering a total area of 29,151.82 ha in the eastern region of the Escárcega municipality. The smallest affected area was found in 2013, with 926.75 ha, representing 0.77 % of tropical forests in the study area (241,720 ha). In contrast, 2019 accumulated the maximum burned area, with 11,027.91 ha (4.56 %), followed by 2020 and 2016, with 5,812.86 ha (2.40 %) and 5,120.16 ha (2.12 %), respectively. The largest burned area was recorded in 2019, with 2,203.14 ha (Table 2).

Burned Areas by Type of Forest Vegetation

In the study period, SMQ and its arboreal (VSA/SMQ) and scrub (VSa/SMQ) types accumulated a total of 23,958 ha of burned vegetation, representing 82.19 % of the total burned area. On the other hand, the Low Thorny Sub-Evergreen Forest (SBQ) and its arboreal (VSA/SBQ) and scrub (VSa/SBQ) types recorded 5,193 ha of burned vegetation, equivalent to 17.81 % of the total burned area (Table 3).

Analysis of Fires in Ejido Areas

The largest burned areas were recorded in the El Centenario (4,907 ha) and El Lechugal (9,409 ha)

Table 2. Annual distribution of burned areas in the eastern region of the Escárcega municipality, Campeche

Year	Polygons of burned areas	Total burned area (ha)	Mean burned area (ha)	Maximum burned area (ha)	Minimum burned area (ha)	% of tropical forest
2013	137	1,860.20	10.28	310.27	2.07	0.77
2014	187	1,191.70	4.97	104.4	2.04	0.49
2015	146	926.75	4.98	117.28	2.05	0.38
2016	316	5,120.16	12.74	987.92	2.00	2.12
2017	228	1,835.13	6.7	104.21	2.01	0.76
2018	281	1,377.11	3.98	86.74	2.01	0.57
2019	405	11,027.91	18.98	2,203.14	2.02	4.56
2020	482	5,812.86	9.29	312.25	2.01	2.40
Total	2,182	29,151.82	10.28	2,203.14	2	12.06

Table 3. Distribution of the total burned area by vegetation type

Vegetation type	Area (ha)	Burned area (ha)	Proportion of burned vegetation (%)
Medium sub-evergreen tropical forest (SMQ)	99,220	10,924	11
Low thorny sub-evergreen tropical forest (SBQ)	81,877	4,280	5
Arboreal secondary vegetation of medium sub-evergreen tropical forest (VSA/SMQ)	39,809	6,935	17
Arboreal secondary vegetation of low thorny sub-evergreen tropical forest (VSA/SBQ)	5,511	882	16
Scrub secondary vegetation of medium sub-evergreen tropical forest (VSa/SMQ)	14,868	6,099	41
Scrub secondary vegetation of low thorny sub-evergreen tropical forest (VSa/SBQ)	435	31	7
Total	241,720	29,151	

ejidos. On the other hand, the Silvituc ejido, with an area of 58,121.20 ha of tropical forest, showed a small burned area (522 ha). This may be because this ejido is part of the Balam-Kú Natural Protected Area, where the use of fire is restricted.

Xbonil, which is an extension of the Calakmul municipality, registered a burned area of 974 ha, out of a total of 1,046 ha. On the other hand, the Hecelchakán ejido, which also belongs to the same municipality, is in the last place with 871 hectares burned. In 2019, most ejidos showed the maximum burned area for the entire study period (Table 4), indicating that the burned areas have increased in recent years. It is worth mentioning that the study area includes an area classified as a Federal Zone, which has experienced an increase in the extension of the burned area in recent years. Field verification showed that this area is frequently burned for the establishment of human settlements.

In general, there appears to be an increasing trend in fires in 2019 and 2020 in all ejidos, regardless of population or forest area. This suggests that other factors, such as changes in fire management policies or weather conditions, could be affecting this trend.

Figure 4 shows the distribution of burned areas per year and the number of years an ejido has experienced a fire during the study period. We found evidence of ejidos affected by fires on a recurring basis, as well as small regions with no fires or with infrequent fires. The fire intervals vary between two and eight years (Figure 4). According to the analysis, the ejidos located in the northern region and the Federal Zone showed a constant incidence of fires throughout the study period.

Analysis of Meteorological Variables Associated with Fires

The analysis of the mean maximum temperature and burnearea (Figure 5) by year reveals that the years with the greatest burned area are 2016, 2019, and 2020, coinciding with an increase in the mean maximum temperature (SMN, 2021).

Furthermore, a decrease in cumulative precipitation was observed during the years 2016 and 2019, as shown in Figure 6. This decrease in rainfall could be related to strong (2015–2016) and weak (2018–2019) ENSO events and drought, which increases the probability of fires, as pointed out by Manzo-Delgado & López-García (2020). The drought monitor in Mexico indicates that the Escárcega municipality experienced its most severe drought from January to May, particularly in 2015, 2016, and 2019, when the drought fluctuated between abnormally dry and moderate (SMN, 2021). The years of the most severe drought were influenced by strong and weak ENSO events (Golden Gate Weather Services, 2024; NOAA, 2020).Haga clic o pulse aquí para escribir texto. In addition, in the study period, ten hurricanes affected the Gulf of Mexico and the Caribbean Sea, among which Barry (2013), Hanna (2014), and Cristóbal (2020) were notable for their proximity (NOAA, 2021). These phenomena may have contributed to the increase in the abundance of dry, flammable material due to the felling of trees, branches, and leaves.

Local Factors Influencing the Distribution of Fire

The interviews revealed that the main causes of fires are poaching (38 %), agricultural burning (38 %), and, to a lesser extent, changes in land use (24 %) (Figure 7). The interviewees who mentioned poaching indicated that this practice is carried out mainly for subsistence (77 %) and trade between ejido members (33 %).

In the case of agricultural burning, the fire can be started by local farmers (41 %) or by neighboring ejidos (59 %). This is mainly due to the lack of compliance with the burning calendar established by the state government and the lack of participation in awareness days.

Furthermore, some people burn tropical forests in the Federal Zone to take ownership of new areas for their own use. This was reported by 24 % of the interviewees. During the interviews held in 2022 and 2023, the inhabitants perceived a significant decrease in fires (90 %), which they attributed to the 'Sowing Life' program. However, they mentioned that in 2019, fires were set to incorporate plots into this program, and the largest area of tropical forest was burned this year. The downward trend in fires in 2020 can be attributed to the fact

Table 4 Distribution of burned areas by ejido.

Municipality	Ejido	Population size	Extension of the ejido (ha)	Area of tropical forest (ha)	Year (ha)							
					2013	2014	2015	2016	2017	2018	2019	2020
Calakmul	Constitución	1,386	1,947	1,923	0	0	3	4	8	5	5	48
	Xbonil	587	4,648	4,622	0	0	0	0	2	2	786	184
	Total				0	0	3	4	10	7	791	231
Escárcega	Chan Laguna	582	3,323	1,057	0	2	0	0	0	0	0	2
	El Centenario	1,038	35,148	32,067	117	57	99	276	363	575	2,034	1,386
	El Lechugal	635	27,690	25,814	1,411	773	181	2,256	282	75	3,392	1,039
	Flor De Chiapas	357	2,619	2,312	0	0	5	56	12	18	310	84
	Haro	1,231	8,197	8,054	0	0	3	10	26	15	0	0
	El Jobal	189	501	128	0	0	0	0	0	0	0	0
	La Libertad	1,469	7,520	12,065	0	0	8	202	7	2	12	179
	Laguna Grande	998	3,900	3,020	24	21	98	110	339	77	639	143
	Lic. Benito Juárez	304	3,460	2,931	27	7	19	4	48	21	195	216
	Lic. José López Portillo	363	2,733	1,823	8	0	7	0	6	160	101	115
	Luna	884	17,109	17,012	0	0	0	74	31	75	58	13
	N.C.P.A. Justicia Social	775	11,558	8,998	6	10	36	384	259	44	461	293
	N.C.P.E. Altamira De Zinaparo	1,167	18,359	8,113	0	4	21	284	11	62	204	222
	N.C.P.E. Lic. Adolfo López Mateos	371	8,403	4,569	8	28	34	475	166	53	440	432
	N.C.P.E. Zona Chiclera Las Maravillas	79	3,326	1,879	0	0	0	82	3	77	22	226
	Silvituc	985	58,121	56,294	8	2	72	141	12	25	190	72
	Total				1,610	905	582	4,354	1,565	1,278	8,059	4,422
Hecelchakán	Hecelchakán	9,974	34,244	32,320	0	0	5	334	2	4	64	462
	Total				0	0	5	334	2	4	64	462
Sin categoría (Zona Federal)	Sin categoría (Zona Federal)		27,532	23,601	250	286	337	428	258	88	2114	698
	Total				250	286	337	428	258	88	2114	698
	Total general				1,860	1,192	927	5,120	1,835	1,377	11,028	5,813

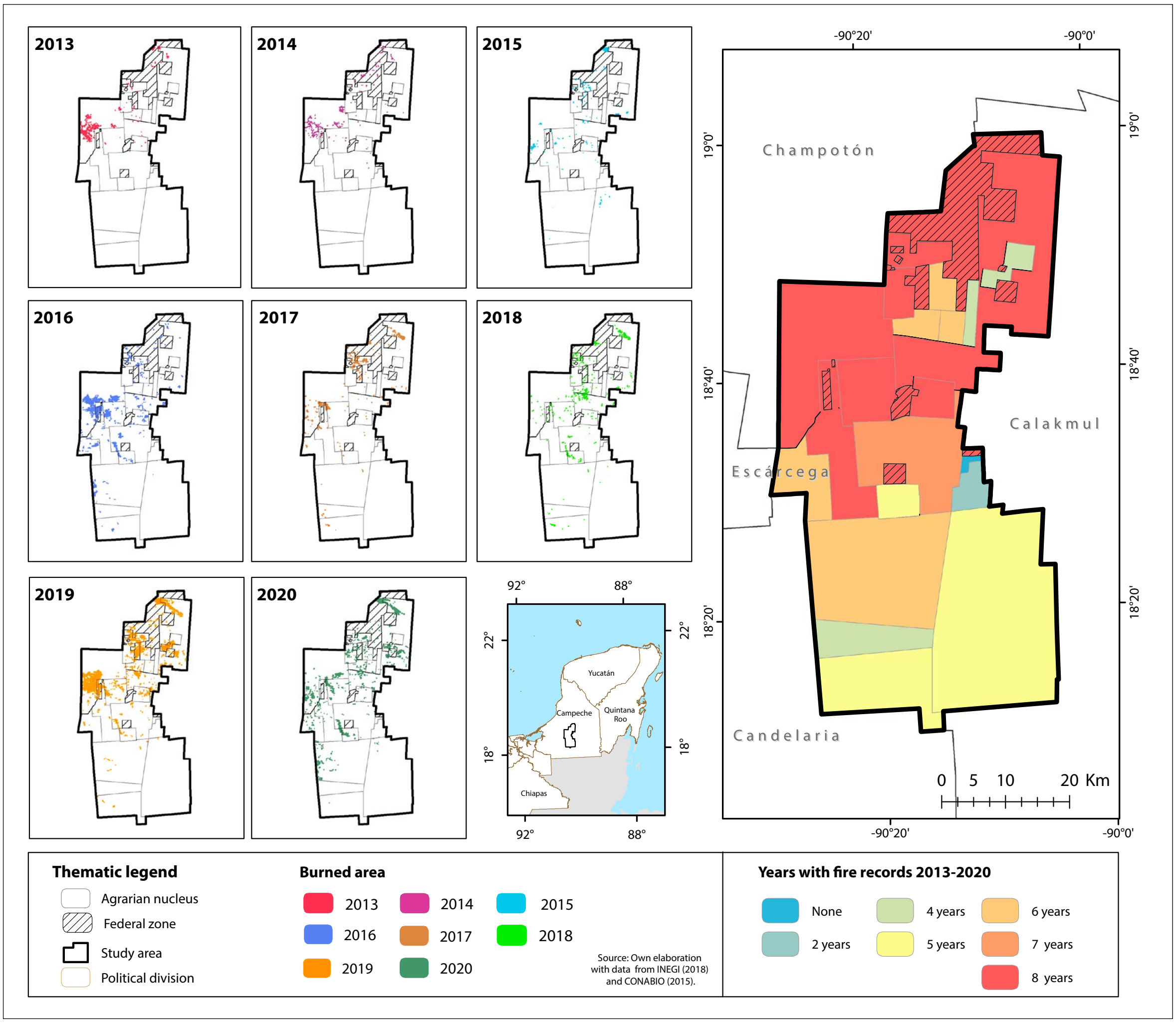

Figure 4. Records of fires.

that people who participate in the program are no longer allowed to use fire.

DISCUSSION

The BAI and NBR indices have proven to be useful and efficient tools in delimiting burned areas, as mentioned by Manzo-Delgado & López-García, (2020), especially in tropical regions. The heat spots detected with FIRMS have provided significant support for the detection and validation of burned areas. The results of the present study have confirmed that they are a reliable alternative to determine the spatial and temporal distribution of fires in the eastern region of Escárcega, Campeche.

Based on the validation results of the Sentinel-2 images, their reliability is acceptable, similar to that reported by Anaya & Chuvieco, (2012), with a mean Kappa value of 88.75 %, an omission error of 1.67 %, and a commission error of 12.86 %. The omission errors are attributed to the 10-day lag between the acquisition of Sentinel-2 and Landsat 8 OLI images.

The analysis of the fires revealed an increase in burned areas from 926.75 hectares in 2013 to

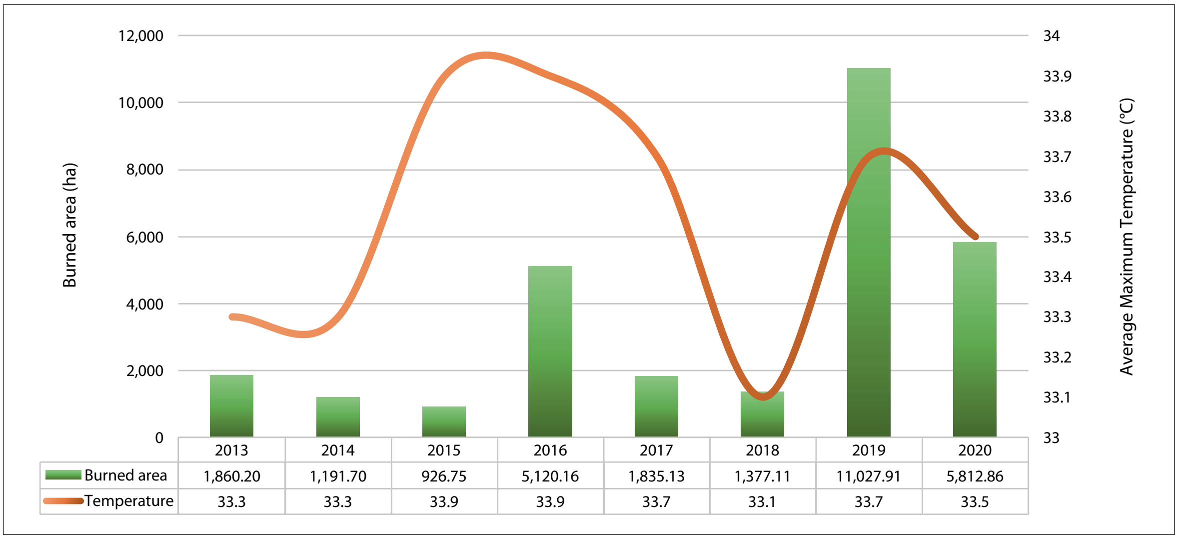

Figure 5. Relationship between burned area and annual mean maximum temperature for the period 2013-2020

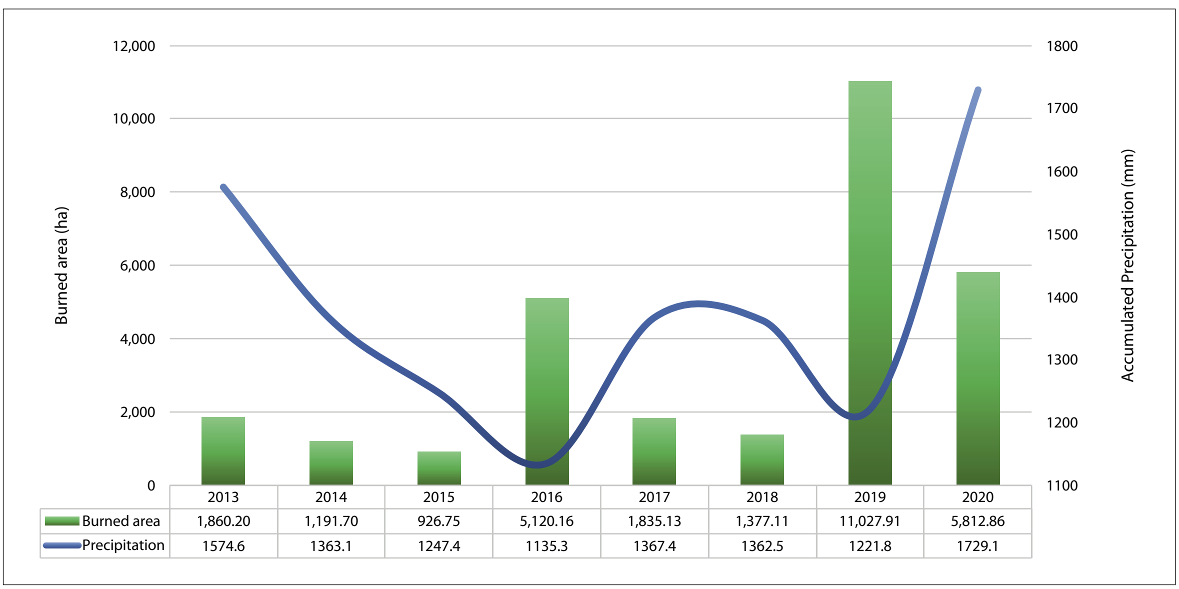

Figure 6. Relationship between burned area and annual cumulative precipitation for the period 2013-2020

11,027.91 hectares in 2019. The upward trend of burned areas in the tropical forests of southeastern Mexico, according to Manzo-Delgado & López-García (2020) and Pagan et al. (2021), results from multiple causes, including meteorological phenomena, the use of fire by farmers, and the lack of attention from government agencies.

Regarding the distribution of burned areas by vegetation type, most of them are in medium sub-evergreen forest (SMQ) and its arboreal (VSA/SMQ) and scrub (VSa/SMQ) types, representing 82.19 % of the total affected area and being the vegetation type that predominates in most ejidos. This suggests that tropical forests have been subjected

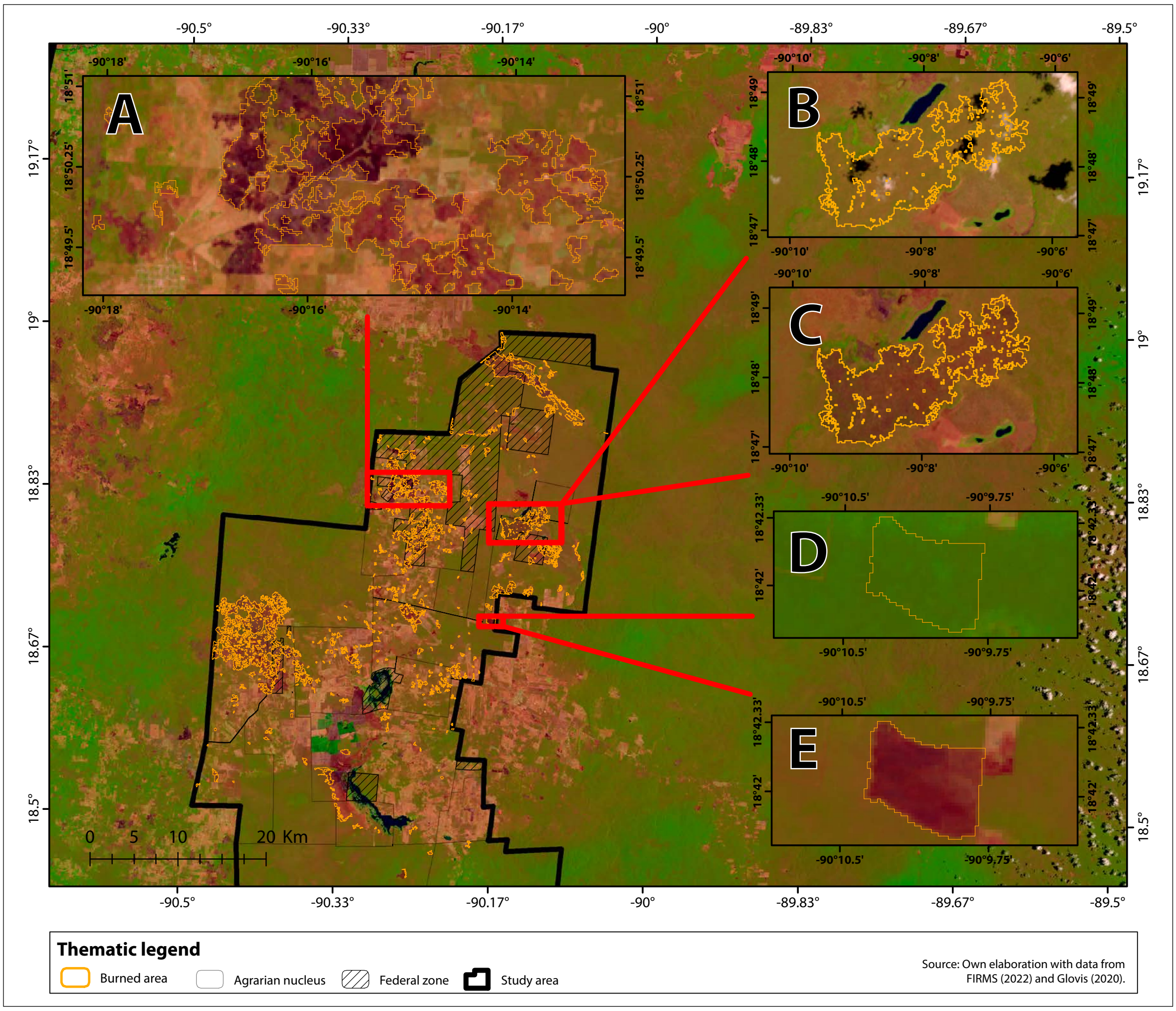

Figure 7. Classification of the fires identified in 2019: (A) Burns in tropical forests related to farming plots; (B and C) fires related to poaching; and (D and E) intentional fires related to changes in land use.

to constant anthropic pressures related to the traditional use of fire without adequate precautions, which has produced fires, as mentioned by Pagan et al. (2021). Likewise, this study confirmed that areas with secondary vegetation are more susceptible to fires due to the presence of herbaceous plants and the post-disturbance accumulation of biomass, proximity to agricultural areas, or conversion of forest land to agriculture, according to reports by Zamora-Crescencio et al. (2017).

The El Lechugal and El Centenario ejidos, which include extensive areas of tropical forest (25,814 ha and 32,067 ha, respectively) and crops (1,876 ha and 3,081 ha, respectively), recorded the greatest extension of the burned area during the study period. This finding may indicate intense fire-dependent agriculture with deficient techniques to prevent fire from spreading to adjacent tropical forests, non-compliance or ignorance of NOM-015, and a possible relationship with poaching, according to Pérez Rodríguez et al. (2018). This scenario is in contrast to the Silvituc ejido and its status as a Natural Protected Area, which restricts the use of fire in the southern part of the study area. This highlights the importance of monitoring, as illustrated in the analysis of the distribution of burned areas by ejido. This analysis shows that some ejidos have experienced fires throughout the study period, while others have been affected four times, twice, or none. The information reported in the present study is important and a valuable indicator for evaluating the incidence of fires in ejidos. It allows identifying those ejidos that demand closer attention regarding fire prevention and mitigation in tropical forests (Rodríguez Trejo, 2014). Furthermore, there is an apparent increasing trend in fires in 2019 and 2020 in all ejidos, regardless of population or forest area. This suggests that other factors, such as changes in fire management policies or weather conditions, could be influencing this trend (Pagan et al., 2021).

The years 2016, 2019, and 2020, which recorded the largest extension of burned area, coincided with the highest temperatures and the lowest rainfall volume in the period studied. These years were also characterized by the occurrence of El Niño-Southern Oscillation (ENSO) events, known for their impact on the rise in temperature and lower rainfall, which may have favored the spread of fires according to Manzo-Delgado & López-García (2020). The rise in temperature and the decrease in rainfall led to lower soil moisture, creating a favorable environment for the spread of fires, according to Withey et al. (2018).

In this context, the Escárcega municipality experienced its worst drought from January to May in 2015, 2016, and 2019 (SMN, 2021). These extreme weather conditions increased the region's vulnerability to wildfires, showing that a rise in temperature coupled with a decrease in rainfall can intensify fires (González et al., 2011; Pazmiño, 2019). However, a study by Monzón Alvarado (2018) found no evident correlation between cumulative precipitation and fire frequency, contradicting the common assumption that drier years lead to a higher occurrence of fires.

This leads us to consider other factors that can influence the frequency and intensity of fires. Human activities, particularly agricultural practices, can vary significantly from year to year. Agricultural and cultural policies and economic conditions can influence these variations. This is evidenced by the fact that, although 2015 was a dry year, it recorded the smallest extension of burned area (926 ha), most likely because fire was used less frequently, resulting in fewer agricultural burns. In contrast, 2019 was also a dry year, with weather conditions similar to those of 2015; however, it showed the largest burned area, associated with the marked increase in the use of agricultural fire documented by Pagan et al. (2021).

Additionally, despite the fact that the temperature peaked and rainfall recorded its minimum in 2016 during the period studied, the burned area was smaller than in 2019. This underscores the fact that weather conditions alone cannot accurately predict the frequency and intensity of fires. It is essential to acknowledge the complex interaction between weather conditions and human activities when seeking to understand and prevent fires (Monzón Alvarado, 2018; Pagan et al., 2021).

In this sense, the 'Sowing Life' government program initially encouraged the use of fire to clear land covered with vegetation, a recommendation that is non-compliant with NOM-015, which caused uncontrolled fires in 2019 and 2020 under weather conditions that favored the start and spread of wildfires in the tropical forest (Pagan et al., 2021). It can be concluded that human activities in those years influenced the increase in burned forest areas.

Interviews revealed that poaching (Pérez Rodríguez et al., 2018), agricultural fires, and changes in land use are the main causes of forest fires. These factors, together with the rise in temperature and prolonged drought due to ENSO, contribute to the larger extension of burned areas (Manzo-Delgado et al., 2009). The lack of knowledge, participation, and compliance with regulations highlights the urgent need to strengthen the dissemination and compliance with regulations to prevent forest fires. This is particularly important under adverse conditions of temperature and precipitation that affect the behavior and regime of fires (Monzón Alvarado, 2018). The interplay between human actions and meteorological variables influences the frequency of wildfires, where inappropriate fire management can lead to uncontrolled burns that can spread due to weather conditions.

CONCLUSIONS

We can conclude that the objective of this research has been met. The BAI and NBR indices have proven to be effective tools for analyzing the distribution of burned areas in the tropical forests of the eastern region of Escárcega, state of Campeche, during the period 2013–2020. Climatic factors, such as temperature and precipitation, have been essential to understanding the variability in burned area. Years of rising temperatures and low precipitation have coincided with an increase in fire-affected areas.

Additionally, periods of intense ENSO events, which favor drought, have also impacted the spread of fires, along with human activities involving the use of fires to clear agricultural land, changes in land use, or poaching.

This complex relationship underscores the importance of implementing fire prevention strategies that address both human actions and weather conditions. These strategies should allow sufficient flexibility to adapt to changes in forest wildfire regimes due to climate change. This knowledge lays the foundations for the development of effective strategies for the prevention and adaptation of the use of fire in the ejidos of the region, particularly those that require greater attention.

CONFLICT OF INTERESTS

The author declares no conflict of interest.

REFERENCES

Alonso Velasco, I., & Velázquez Torres, D. (2019). El contexto geopolítico de la explotación forestal en la Península de Yucatán, México. *Perspectiva Geográfica*. https://doi.org/10.19053/01233769.8427

Anaya, J. A., & Chuvieco, E. (2012). Accuracy Assessment of Burned area Products in the Orinoco Basin. *Photogrammetric Engineering & Remote Sensing, 78*(1), 53–60. https://gofcgold.umd.edu/sites/default/files/2020-01/anaya_chuvieco_pers_2012.pdf

Arellano, S., Vega, J. A., Rodríguez Y Silva, F., Fernández, C., Vega-Nieva, D., Álvarez-González, J. G., & Ruiz-González, A. D. (2017). Validación de los índices de teledetección dNBR y RdNBR para determinar la severidad del fuego en el incendio forestal de Oia-O Rosal (Pontevedra) en 2013. *Revista de Teledeteccion*, *2017*(49 Special Issue), 49–61. https://doi.org/10.4995/raet.2017.7137

Cuervo-Robayo, A. P., Téllez-Valdés, O., Gómez-Albores, M. A., Venegas-Barrera, C. S., Manjarrez, J., & Martínez-Meyer, E. (2014). *Precipitación anual en México (1910-2009)*. Catálogo de metadatos geográficos. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. http://geoportal.conabio.gob.mx/metadatos/doc/html/preanu13gw.html

Estrada, A., & Coates-Estrada, R. (2003). *Las selvas tropicales húmedas de México. Recurso poderoso, pero vulnerable*. La ciencia para todos. Fondo de Cultura Económica. https://fce.com.co/producto/las-selvas-tropicales-humedas-de-mexico-recurso-poderoso-pero-vulnerable/

FIRMS. (2022). *Fire Information for Resource Management System (FIRMS)*. FIRMS is part of NASA's Land, Atmosphere Near real-time Capability for EOS. https://firms.modaps.eosdis.nasa.gov/

Flores-Rodríguez, A. G., Flores-Garnica, J. G., González-Eguiarte, D. R., Gallegos-Rodríguez, A., Zarazúa-Villaseñor, P., & Mena-Munguía, S. (2021). Comparative analysis of spectral indices to locate and size levels of severity of forest fires. *Investigaciones Geograficas*, *106*. https://doi.org/10.14350/rig.60396

García, E., & CONABIO. (2001). *Climas, (clasificación de Koppen, modificado por García). Escala 1:1000000. México.* Catálogo de metadatos geográficos. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. http://www.conabio.gob.mx/informacion/gis/

Golden Gate Weather Services. (2024). *El Niño and La Niña Years and Intensities Based on Oceanic Niño Index (ONI)*. https://ggweather.com/enso/oni.htm

González, M. E., Lara, A., Urrutia, R., & Bosnich, J. (2011). Cambio climático y su impacto potencial en la ocurrencia de incendios forestales en la zona centro-sur de Chile (33° - 42°s). *Bosque*, *32*(3), 215–219. https://doi.org/10.4067/S0717-92002011000300002

Hammer, D., & Wildavsky, A. (1990). La entrevista semi-estructurada de final abierto. Aproximación a una guía operativa. *Historia, antropologia y fuentes orales* , 23–61. https://doi.org/10.2307/27753290

INEGI. (2001). *Conjunto de datos vectoriales Fisiográficos. Continuo Nacional serie I. Provincias fisiográficas*. Instituto Nacional de Estadística y Geografía (INEGI). https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=702825267575

INEGI. (2010). *Red Hidrográfica Escala 1:50,000 Edición 2.0*. Dirección General de Geografía y Medio Ambiente.

INEGI. (2018). *Conjunto de datos vectoriales de uso del suelo y vegetación. Escala 1:250 000. Serie VII. Conjunto Nacional*. Instituto Nacional de Estadística y Geografía (INEGI). https://www.inegi.org.mx/app/biblioteca/ficha.html?upc=889463842781

INIFAP, & CONABIO. (2008). *Edafología*. Catálogo de metadatos geográficos. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad. http://www.conabio.gob.mx/informacion/metadata/gis/eda251mgw.xml?_httpcache=yes&_xsl=/db/metadata/xsl/fgdc_html.xsl&_indent=no

IUSS Working Group WRB. (2015). *Base referencial mundial del recurso suelo 2014, Actualización 2015. Sistema internacional de clasificación de suelos para la nomenclatura de suelos y la creación de leyendas de mapas de suelos. Informes sobre recursos mundiales de suelos*. https://www.iec.cat/mapasols/DocuInteres/PDF/Llibre59.pdf

Manzo Delgado, L., & López García, J. (2013). Detección de áreas quemadas en el sureste de México, utilizando índices pre y post-incendio NBR y BAI, derivados de compuestos MODIS. *GeoFocus*, *2*(13), 66–83. https://www.geofocus.org/index.php/geofocus/article/view/288

Manzo-Delgado, L. L., & López-García, J. (2020). Spatial and temporal analyses of burned areas 1998, 2003 and 2015 in montes azules biosphere reserve, Chiapas, Mexico. *Bosque*, *41*(1), 11–24. https://doi.org/10.4067/S0717-92002020000100011

Manzo-Delgado, L., Sánchez-Colón, S., & Álvarez, R. (2009). Assessment of seasonal forest fire risk using NOAA-AVHRR: a case study in central Mexico. *International Journal of Remote Sensing*, *30*(19), 4991–5013. https://doi.org/10.1080/01431160902852796

Moghli, A., Santana, V. M., Jaime Baeza, M., Pastor, E., & Soliveres, S. (2021). Fire Recurrence and Time Since Last Fire Interact to Determine the Supply of Multiple Ecosystem Services by Mediterranean Forests. *Ecosystems*. https://doi.org/10.1007/s10021-021-0072

Monzón Alvarado, C. (2018). El manejo del fuego en Calakmul, Campeche: incendios forestales, gobernanza y variabilidad local de la precipitación. *CIENCIA ergo sum*, *25*(3), e23.1-e23.15. https://doi.org/10.30878/ces.v25n3a1

NOAA. (2020). *El Niño / Southern Oscillation (ENSO)*. Climate Predicction Center, National Weaher Service (NOAA). https://origin.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml#history

NOAA. (2021). *Central Pacific Hurricane Center (CPHC)*. US Dept of Commerce National Oceanic and Atmospheric Administration, Central Pacific Hurricane Center. https://www.nhc.noaa.gov/

Orantes-García, C., Ángel Pérez-Farrera, M., Rioja-Paradela, T. M., & Garrido-Ramírez, E. R. (2013). Viabilidad y germinación de semillas de tres especies arbóreas nativas de la selva tropical, Chiapas, México. *Polibotánica*, *36*, 117–127. https://www.scielo.org.mx/pdf/polib/n36/n36a8.pdf

Pagan, A., Rogan, J., Schmook, B., Christman, Z., & Sangermano, F. (2021). Understanding agricultural fire dynamics in the southern Yucatán Peninsular Region using the MODIS (C6) active fire product. *Remote Sensing Letters*, *12*(7), 715–726. https://doi.org/10.1080/2150704X.2021.1931530

Pazmiño, D. (2019). Peligro de incendios forestales asociado a factores climáticos en Ecuador. *FIGEMPA: Investigación y Desarrollo*, *1*(1), 10–18. https://doi.org/10.29166/revfig.v1i1.1800

Pérez, C. C., Olthoff, A. E., Hernández-Trejo, H., & Rullán-Silva, C. D. (2022). Evaluating the best spectral indices for burned areas in the tropical Pantanos de Centla Biosphere Reserve, Southeastern Mexico. *Remote Sensing Applications: Society and Environment*, *25*. https://doi.org/10.1016/j.rsase.2021.100664

Pérez Rodríguez, J. C., Guízar Vázquez, F., & Bello Baltazar, E. (2018). Conflicto territorial, ecoturismo y cacería no regulada: el traslape de territorialidades en el Área Natural Protegida de Balam-Kú. *Pasos. Revista de Turismo y Patrimonio Cultural*, *16*(4), 909–925. https://doi.org/10.25145/j.pasos.2018.16.064

Rodríguez Trejo, D. A. (2014). *Incendios de vegetación. Su Ecología, Manejo e Historia* (Vol. 1). Colegio de Postgraduados, Universidad Autónoma Chapingo, Semarnat, Programa de Prevención y Combate de Incendios Forestales, Conafor, Conanp, Parque Nacional Iztaccíhuatl-Popocatépetl, ANCF, AMPF.

Rodríguez Trejo, D. A., Muñoz, P. M., & Lara, P. J. M. (2019). Fire effects on the trees of a tropical pine forest and a tropical dry forest at villaflores, Chiapas, Mexico. *Ciencia Florestal*, *29*(3), 1033–1047. https://doi.org/10.5902/1980509833952

Rodríguez-Trejo, D. A., Martínez-Muñoz, P., Pulido-Luna, J. A., Martínez-Lara, P. J., & Cruz-López, J. D. (2019). *Instructivo de quemas prescritas para el manejo integral del fuego en el municipio de Villaflores y la Reserva de la Biosfera la Sepultura, Chiapas, México*. Fondo Mexicano para la Conservación de la Naturaleza, USDA FS, US AIDE, BIOMASA, A, C., Universidad Autónoma Chapingo, Ayuntamiento de Villaflores, SEMARNAT, CONAFOR, CONANP, Gobierno del Estado de Chiapas, ANCF. http://dicifo.chapingo.mx/pdf/publicaciones/Instructivo_de_quemas.pdf

Rodríguez-Trejo, D. A., Tchikoué, H., Cíntora-González, C., Contreras-Aguado, R., & Rosa-Vázquez Alfonso de la. (2011). Modelaje del peligro de incendio forestal en las zonas afectadas por el huracán Dean. *Agrociencia*, *45*, 593–608. http://www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S1405-31952011000500006&nrm=iso

Román-Cuesta, R. M., & Martínez-Vilalta, J. (2006). Effectiveness of protected areas in mitigating fire within their boundaries: Case study of Chiapas, Mexico. *Conservation Biology*, *20*(4), 1074–1086. https://doi.org/10.1111/j.1523-1739.2006.00478.x

SMN. (2020). *Resúmenes mensuales de temperatura y lluvia*. Servicio Meteorológico Nacional (SMN) de la Comisión Nacional del Agua (CONAGUA). https://smn.conagua.gob.mx/es/climatologia/temperaturas-y-lluvias/resumenes-mensuales-de-temperaturas-y-lluvias

SMN. (2021). *Archivos shapefiles del Monitor de Sequía en México (MSM) generados en el Servicio Meteorológico Nacional de México (SMN)*. Monitor de sequía de México. https://smn.conagua.gob.mx/es/climatologia/monitor-de-sequia/monitor-de-sequia-en-mexico

Valdez-Zavala, K. M., Bravo-Peña, L. C., & Manzo-Delgado, L. L. (2019). Áreas quemadas y cambio de uso del suelo en el suroeste de Chihuahua (México) durante el periodo 2013-2017: Identificación con el índice Normalized Burn Ratio (NBR). *Acta Universitaria*, *29*, 1–15. https://doi.org/http://doi.org/10.15174.au.2019.2418

Withey, K., Berenguer, E., Palmeira, A. F., Espírito-Santo, F. D. B., Lennox, G. D., Silva, C. V. J., Aragão, L. E. O. C., Ferreira, J., França, F., Malhi, Y., Rossi, L. C., & Barlow, J. (2018). Quantifying immediate carbon emissions from El Niño-mediated wildfires in humid tropical forests. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *373*(1760). https://doi.org/10.1098/rstb.2017.0312

Wu, B., Zheng, H., Xu, Z., Wu, Z., & Zhao, Y. (2022). Forest Burned area Detection Using a Novel Spectral Index Based on Multi-Objective Optimization. *Forests*, *13*(11). https://doi.org/10.3390/f13111787

Zamora-Crescencio, P., Rico-Gray, V., & Carlos Barrientos-Medina, R. (2017). Estructura y composición florística de la selva mediana subperennifolia en Bethania, Campeche, México. *Polibotánica*, *43*, 67–86. https://www.redalyc.org/articulo.oa?id=62150424003