FOREST FIRE RECURRENCE IN CHIAPAS, MEXICO: ANALYSIS OF SPATIAL DISTRIBUTION, CAUSES AND CLIMATIC TRENDS †

[RECURRENCIA DE INCENDIOS FORESTALES EN CHIAPAS, MÉXICO: ANÁLISIS DE DISTRIBUCIÓN ESPACIAL, CAUSAS Y TENDENCIAS CLIMÁTICAS]

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SUMMARY

Background. Forest fires play an important role in ecosystems; however, uncontrolled wildfires can damage ecosystems and emit CO_2 into the atmosphere. The state of Chiapas ranks among the top ten places in Mexico in terms of the frequency of forest fires and the area damaged by them. The occurrence of fire and damage is the result of the complex interaction of social, climatic, and biophysical factors. **Objective.** To analyze the spatio-temporal dynamics of forest fires in the state of Chiapas during the period 2010-2024, as well as the leading causes of these events and their relationship with the trends of climate change. **Hypothesis:** The recurrence of forest fires can be explained by patterns of climate change. **Methodology.** The work was carried out by analyzing historical records of wildfires, as well as the trends of climatic variables, especially temperature and precipitation. The fire-prone areas were identified using the intersection of polygons across a temporal series in a Geographic Information System. The relationship between the recurrence of wildfire and climatic variables was determined by correlation and regression analysis. **Results.** The recurrent areas correspond, in great part, to the Sierra Madre of Chiapas, which, due to its physical-geographical characteristics, makes it prone to fire development. Likewise, during 2021-2024, the greatest fire damage was observed, mainly in areas where broadleaf and conifer vegetation predominates. **Conclusion.** The increase in the recurrence of forest fires in Chiapas is not entirely attributed to current climate trends; rather, part of these events is also related to anthropogenic causes and inadequate fire management, primarily due to agricultural activities. It is observed that these events are more frequent during the dry season, mainly between April and May. **Implication.** This type of research enables us to identify the primary conditions that favour wildfires and their relationship with climate change. The results will help in developing forest fire prevention and mitigation strategies.
Key words: Wildfire; climate change; anthropogenic activities; tropical forests; southeastern Mexico.

RESUMEN

Antecedentes. Los incendios forestales desempeñan un papel importante en los ecosistemas; sin embargo, los incendios incontrolados pueden dañar los ecosistemas y emitir CO_2 a la atmósfera. El estado de Chiapas se encuentra

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entre los diez primeros lugares de México en cuanto a ocurrencia de incendios forestales y superficie dañada por los mismos. La ocurrencia de incendios y daños son el resultado de la compleja interacción de factores sociales, climáticos y biofísicos. **Objetivo.** Analizar la dinámica espacio-temporal de los incendios forestales en el estado de Chiapas durante el periodo 2010-2024, así como las principales causas de estos eventos y su relación con las tendencias de cambio en el clima. **Hipótesis:** La recurrencia de incendios forestales puede explicarse en función de patrones de cambio en el clima. **Metodología**. El trabajo se llevó a cabo analizando los registros históricos de incendios forestales en la entidad, así como las tendencias climáticas, especialmente la temperatura y precipitación. Las zonas propensas a incendios se determinaron mediante la intersección de serie temporales de polígonos en Sistemas de Información Geográfica. La relación entre la recurrencia de incendios forestales y las variables climáticas se determinó mediante análisis de correlación y regresión. **Resultados.** Las zonas recurrentes corresponden, en gran parte, a la Sierra Madre de Chiapas, que por sus características físico-geográficas la hacen propensa al desarrollo de incendios. Asimismo, durante el periodo 2021-2024 se observaron los mayores daños por incendio, principalmente en las zonas donde predomina la vegetación latifoliada y de coníferas. **Conclusión.** El incremento en la recurrencia de incendios forestales en Chiapas no se atribuye en su totalidad a las tendencias climáticas actuales, sino que parte de estos eventos también se relacionan con causas de origen antropogénico y manejo del fuego, principalmente por actividades agropecuarias; a pesar de ello, se observa que estos eventos son más frecuentes durante la época seca, principalmente entre abril y mayo. **Implicación.** Este tipo de investigación permite identificar las principales condiciones que favorecen los incendios forestales y su relación con cambio climático. Los resultados ayudarán a desarrollar estrategias de prevención y mitigación de incendios forestales.
Palabras clave: Incendios forestales; cambio climático; actividades antropogénicas; selvas tropicales; sureste mexicano.

INTRODUCTION

Forest fires (FF) provide benefits to ecosystems, due to the natural processes that arise from their presence (González *et al*., 2020; Ávila *et al.,* 2014). However, uncontrolled FF, worldwide, can lead to detrimental ecological consequences (Schmoldt et al., 1999; Van Wees *et al*., 2021). In addition, these events significantly contribute to the emission of greenhouse gases into the atmosphere (Saha et al., 2023) and pose an economic, social, and environmental problem for the exposed socio-ecosystems (Cochrane, 2009). While fire escapes during land clearing are the leading cause of wildfire occurrence in rural landscapes, the long-term accumulation of surface litter and changing climate patterns make forest fires catastrophic and difficult to control (North *et al*., 2015; Zhao *et al*., 2024).

The occurrence of FF and the extent of the area affected by them are the result of the complex interaction of various factors, mainly social and biophysical. Climate is considered the primary shaper of forest ecosystems (Wells, 2007; Jones *et al*., 2024). In this sense, this factor can provide the necessary conditions for the development of FF (Piñol *et al.*, 1998); while, on short time scales, meteorological conditions such as temperature, precipitation, and humidity directly influence the availability of combustible material, which increases the probability of ignition of a fire in the ecosystem (Ortiz Mendoza *et al.,* 2024).

On the other hand, climatic variability influences the onset and duration of the fire season; At the same time, over long-time scales, climate can affect fire regimes by affecting the net primary productivity of ecosystems, the decomposition of organic matter, as well as the distribution and quantity of available forest fuel (Meyn *et al.*, 2007; Sánchez-Sliva *et al.*, 2018).

In Mexico, the incidence and distribution of forest fires are linked to specific meteorological and climatic characteristics, such as high temperatures and low precipitation, which, together with low humidity, promote a high availability of forest fuels in the environment. These conditions typically occur during a specific season of the year. In the southeastern states of the country, the fire season begins in January. It ends in June, marking the month when the first rains of the year are first perceived (Secretaría de Medio Ambiente y Recursos Naturales [SEMARNAT], 2018).

In recent decades, climate change and the expansion of the agricultural frontier have been mainly responsible for the increase in the extent and intensity of FF in tropical countries (Thompson *et al.*, 2013). Although wildfires are one of the primary problems affecting forest ecosystems in Mexico (Aryal et al., 2024), their effects can vary significantly depending on the environment in which they occur, their seasonality, and the site management (Yang *et al.*, 2007; Jardel *et al.*, 2009).

The tropical region of southeastern Mexico is home to enormous biodiversity (Mas and Sandoval, 2011). The state of Chiapas generates a large amount of forest fuel in a short period (Aryal *et al*., 2018; Ruiz-Corzo *et al*., 2023). This situation, combined with the inappropriate use of fire and the sensitivity of local ecosystems, makes the region vulnerable to the occurrence of FF (Rodríguez *et al.*, 2011; López-Cruz *et al*., 2022). This has positioned the state among the top ten nationally in terms of the occurrence of forest fires and the area damaged by fire (Comisión Nacional Forestal; CONAFOR, 2025). Identifying fire-prone regions in terms of fire recurrence and the extent of damage would help prevent and suppress wildfires before they become catastrophic.

Therefore, the objective of this study was to analyze the spatio-temporal dynamics of forest fires in the state of Chiapas during the period 2010-2024, as well as the leading causes of these events and their relationship with current climate trends.

MATERIALS AND METHODS

Study area

The state of Chiapas is located in southeastern Mexico. It is bordered to the north by the state of Tabasco; to the south by the Pacific Ocean; to the east by the Republic of Guatemala; and to the west by the states of Oaxaca and Veracruz. The entity has an area of 73 311 km^2 and has altitudes ranging from 0 m to 3 284 m above sea level. Its physiognomy is determined by two major mountain ranges: the Sierra Madre de Chiapas, which crosses the state parallel to the Pacific Ocean coast; and, the Cordillera Central, which extends in the central area of the state, parallel to the Sierra Madre de Chiapas, forming the Central Depression, and to the north of it, the region known as the Northern Mountains (Lorenzo *et al.*, 2017) (Figure 1).

Given the marked altitudinal difference, two major climatic groups predominate in the Chiapas territory: warm-humid (A) and temperate-humid (C), which contributes to the presence of various types of vegetation within the territory, including highland forests (pine, oak, mountain mesophyll), tropical forests (deciduous and evergreen), mangroves and grasslands (savannas, Savanoids) (Morales and Priego, 2020). Concerning the state's fauna, 9 of the 210 species of mammals recorded are endemic to the territory (Lorenzo *et al.* 2017); in the category of birds, 694 species have been recorded, of which 22 are considered endemic (Rangel *et al.*, 2013); as for reptiles, Chiapas has a total of 49 endemic species (Luna *et al.* 2013); while, in the group of amphibians, there are 17 endemic species registered, which makes Chiapas one of the states with the greatest biological diversity at the national level (Muñoz *et al.*, 2013).

Data processing and analysis

As part of the analysis, the annual forest fire records for the period from January 2010 to September 2024, provided by the State Center for Forest Fire Control of Chiapas (Centro Estatal de Control de Incendios Forestales de Chiapas, CECIF), were reviewed. This information was cleaned and organized in a new general database, which yielded 5 156 records for the study period (2010-2024), in which several capture errors were corrected, as well as incomplete data, which consisted mainly in the modification of some FF location coordinates since the values were incomplete due to the absence of one or two digits and recorded in the cell of the opposite coordinate. In addition, in the case of fires without location data, these were omitted because there was no certainty as to their location. It should be noted that the omission of this data was not representative of this study, since there were fewer than

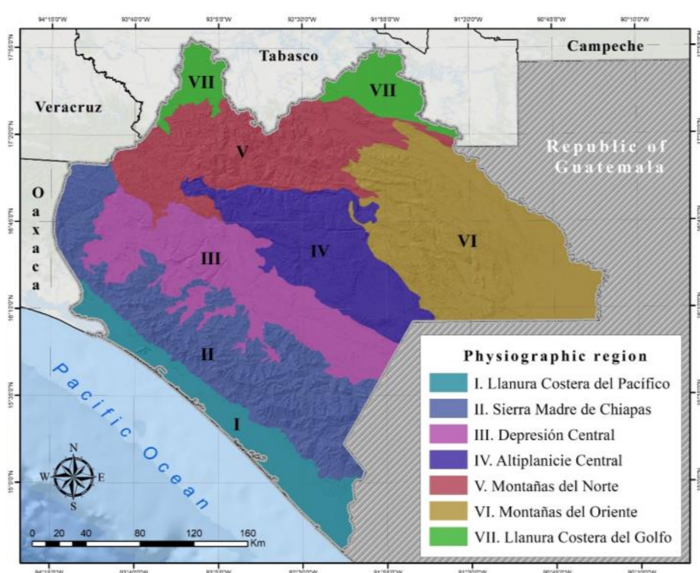

Figure 1. Physiographic regions of the state of Chiapas. Source: Own elaboration with data from the Geographic Chart of the state of Chiapas, 2001.

10 fires. Likewise, information on average monthly and annual temperature data, as well as monthly and yearly precipitation (accumulated rainfall), was used, all of which is available in the monthly temperature and precipitation summaries of the National Water Commission (Comisión Nacional del Agua, CONAGUA).

The database generated included the following variables: Fire key, Municipality, Coordinates, Year, Month, Cause, affected surface, Precipitation (mm), Average Temperature (°C), Average Maximum Temperature (°C), and Average Minimum Temperature (°C), which were statistically processed through the calculation of descriptive statistics and graphic analysis, allowing the identification of seasonal patterns (monthly and annual).

The SPSS Statistics statistical package was used for data processing, while the analysis and elaboration of cartography were carried out with the help of Geographic Information Systems (ArcMap 10.8).

Recurrence of FF

The recurrence of FF can be described as the frequency of occurrence of FF at the same site. The areas of greatest FF recurrence within the state were determined by processing the polygons corresponding to regions affected by these events during the last 15 years, which were obtained from the National Forest Information System (Sistema Nacional de Información Forestal, SNIF), as well as from CECIF records. For this, a geometric process was performed using the vector data known as "union," in which polygons are joined, allowing areas to be identified that inherit the attributes of one or more of these spatial entities (Olaya, 2014). Based on this, each polygon was assigned a value of 1; subsequently, the geometric attribute calculator was used to calculate the sum of these values, which enabled the identification of areas where the fire phenomenon occurs frequently (Figure 2). The information was classified into four categories using the natural breaks (Jenks) method, as the data distribution was not uniform, and this method yielded better results (Chen *et al.*, 2013a).

The forest fire density, expressed as the "forest fire-to-area ratio (forest fires/ha), was calculated by dividing the sum of each of the events that occurred by the average area affected by these events (Conafor, 2025), every month, during the analysis period.

Analysis of the climate trends in rainfall and temperature

For the analysis of climatic trends, 30 years was considered, as it is internationally accepted that this duration is sufficient for calculating climatic averages and detecting significant trends, as it helps smooth out short-term variations and reflects stable climatic patterns (World Meteorological Organisation, 2017). This period spanned from 1995 to 2024. The following climatic variables were used: annual accumulated precipitation (mm), average annual temperature (°C), average annual maximum temperature (°C), and average annual minimum temperature (°C). The Mann-Kendall non-parametric test and Sen´s slope methods were applied for climatic trend analysis. To estimate the total change over the 30 years, the Sen´s slope was multiplied by the number of years in the series (1995-2024) (Mann, 1945; Sen, 1968).

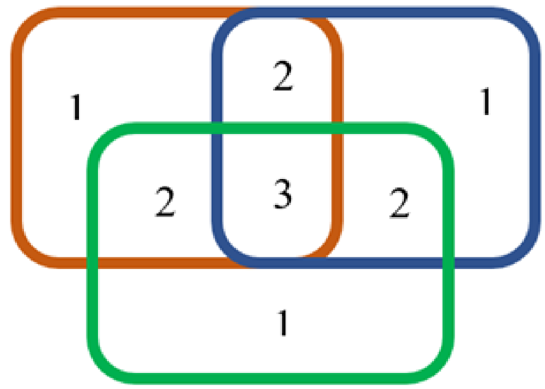

Figure 2. Determination of fire recurrence values through the spatial joining process.

Analysis of the relationship between the recurrence of FF and climatic variables

The identification of the relationship between the recurrence of forest fire events and the climatic trends of temperature and precipitation in the entity was carried out using a linear correlation analysis (Pearson), which first made it possible to quantify the strength and direction of the interaction between the prediction variables (precipitation, mean temperature, maximum temperature, and minimum temperature) and the response variables: a) number of forest fire events and, b) area affected (ha). Subsequently, a simple linear regression analysis was performed for each combination of the prediction and response variables.

Analysis of the causes of FF

The FF records were analyzed year by year, and the data were standardized in a single table since the description of these events was not the same in some years. The cause of these events was determined by the brigade chief, *in situ*, who applied what was established by the course: "Determination of evidence and causes in forest fires and elaboration of forest restoration projects" (Conafor, 2018).

Vegetation affected by fire

To determine the type of vegetation affected by the fire, the land use and vegetation type (USyV) charts were cut out from series V, VI, and VII of the National Statistics and Geography Institute (Instituto Nacional Estadística y Geografía, INEGI). Within the forest fire polygons, the vegetation types were grouped as follows: mountain mesophyll forest vegetation, humid tropical forests, conifer and highland forests, mangrove vegetation, Popal and Tular vegetation, riparian vegetation, and grasslands. It should be noted that the use of different USyV charts is because we tried to represent the existing cover during each year to get a little closer to the conditions present during the period of analysis. On the other hand, the analysis of average forest mass loss was carried out for three periods, which were determined as follows: the first category considers the total analysis period (2010-2024); on the other hand, the second category, was taken from 2014 to 2020, due to the reliability of the data, since at the beginning of this period, the forest fires polygons in the entity began to be regularly registered, therefore, such cut, would show surfaces more attached to reality; while, the last period was taken from 2021 to 2024, due to a remarkable increase in the data. This calculation was carried out using the following equation (Quezada *et al.*, 2022):

$$R = \frac{A_1 - A_2}{t_2 - t_1}$$

Where:
R = Loss of average forest mass
A_1= Initial land surface area
A_2 = Final surface area
t_1 = Initial year of the period
t_2 = Final year of period

RESULTS

Recurrence of FF

The areas with the highest recurrence of forest fires (≥ 3 events in the same site) cover different regions of the state (Figure 3). Such is the case of Frailesca, where the municipalities of Villaflores, Villa Corzo, La Concordia and El Parral are the most affected by fire. On the other hand, in the Valle Zoque region, the affected areas correspond to the municipalities of Cintalapa and Jiquipilas. Meanwhile, in Soconusco, the municipalities of Villa Comaltitlán, Mazatán, and Acapetahua are the most affected. Villa Comaltitlán, Mazatán, and Acapetahua are among the municipalities with the greatest recurrence, mainly in mangrove areas. It is worth mentioning that Tonalá and Arriaga, belonging to the Istmo Costa region, present greater effects in mountain areas. What is common among the aforementioned municipalities, except Villa Comaltitlán, Mazatán, and Acapetahua, is that the identified areas are distributed throughout a large part of the Sierra Madre de Chiapas.

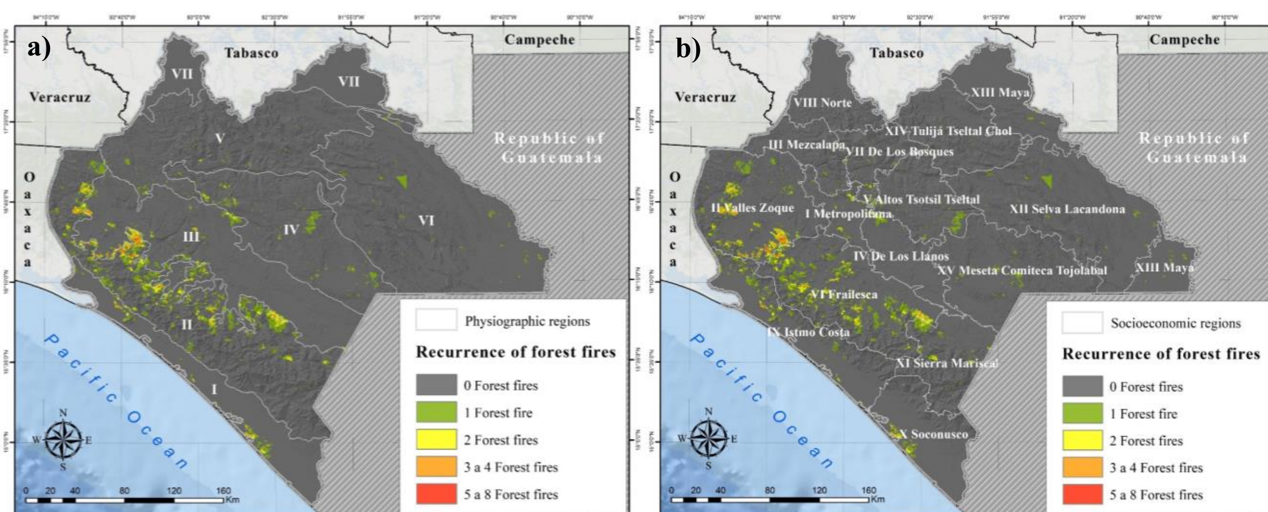

Figure 3. Recurrence of forest fires in the state of Chiapas: a). recurrence by physiographic regions and b). recurrence by socioeconomic regions. Source: Own elaboration.

Analysis of the climate trends in rainfall and temperature

The analysis of climate trends using Sen´s non-parametric test for the period 1995-2024 revealed significant results for both precipitation and temperature (Table 1). The annual rainfall showed a negative trend, with a Sen´s slope of -39.9 mm/year, and a 95% confidence interval that excluded zero. However, the Mann-Kendall test did not detect a significant trend, which may be due to its sensitivity to interannual variability or the presence of outliers. In contrast, all temperature variables presented consistent positive trends. The average annual temperature increased at a rate of 0.07 °C per year, while the maximum and minimum temperatures increased at rates of 0.04 °C per year and 0.1 °C per year, respectively. The confidence intervals for these slopes did not include zero, which confirms statistical significance. Furthermore, the Mann-Kendall test for temperature variables revealed highly significant trends, supporting the existence of a warming pattern over the last three decades (Figure 4). These rates correspond to total increases of approximately 2.1°C in average and maximum temperatures, and 3°C in minimum temperatures over the 30 years.

Seasonal and annual patterns

During the period 2010-2024, a total of 5221 FF occurred in the state of Chiapas, with an annual average of 348 FF events. Fire during the period affected an area of 498 147 ha, which represents 6.8% of the total land surface of the state. There was an increase in the number of FF as well as in the area affected by fire, towards the year 2024. Although an increase in the number of FF events was observed from 2010 to 2019, the greatest increase in the data, in terms of surface area, begins from 2021 to 2024 (Figure 5); years in which the area affected exceeds the annual average of the data, registering, for the last year, an approximate of 451 FF, with an area affected of more than 185 thousand hectares per year.

Table 1. Results of the climate trend analysis (1995-2024) using the Mann-Kendall test and Sen´s slope method.

Variable	Z (Mann-Kendall)	*p*-value	Sen´s Slope	95% Confidence Interval	30-Year Change
Annual accumulated precipitation (mm)	-0.41	0.682	-39.9 mm/year	(-54.65, -29.57) mm/year	-1195.5 mm
Average annual temperature (°C)	4.91	0.000	0.071 °C/year	(0.05, 0.09) °C/year	2.1 °C
Average annual maximum temperature (°C)	2.69	0.007	0.040 °C/year	(0.014, 0.063) °C/year	2.1 °C
Average annual minimum temperature (°C)	5.26	0.000	0.1 °C/year	(0.078, 0.12) °C/year	3 °C

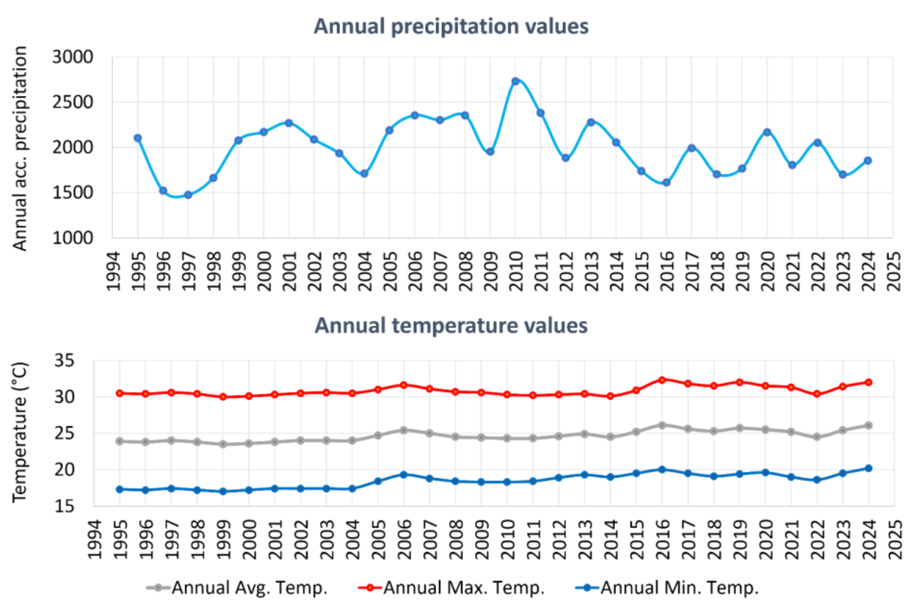

Figure 4. Monthly behavior of precipitation and temperature from 1995 to 2025 in Chiapas, Mexico.

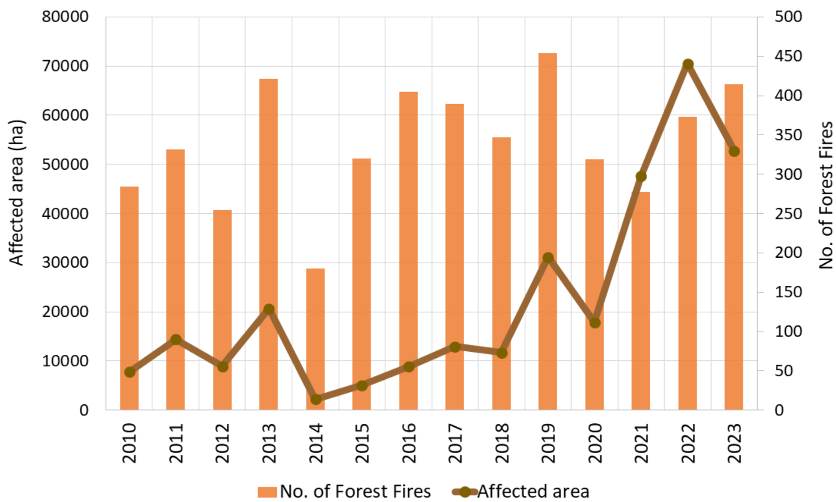

Figure 5. Number of forest fires and area affected in Chiapas during the period 2010-2024.

From the analysis of the seasonal patterns of the study period as a whole, the months of April and May were identified as those in which the number of FF occurred and the area affected exceed the average behavior of the global set of data, with maximum values above 100 FF events in April and more than 67,800 ha affected in May, when grouping the annual data every month (Figure 6). At the same time, the recurrence of FF presents its maximum value in April (2019) with 223 events, while the affected area obtains its maximum value in May (2024) with a total of 79 559 ha.

Although the monthly sum of the number of fires and the area affected by fire is much higher in April than in other months, the forest fire-to-area ratio is much higher in May, which indicates that during these months the presence of fire is more critical in the state, since it exceeds the annual mean ratio (51.24 forest fires/ha) (Table 2).

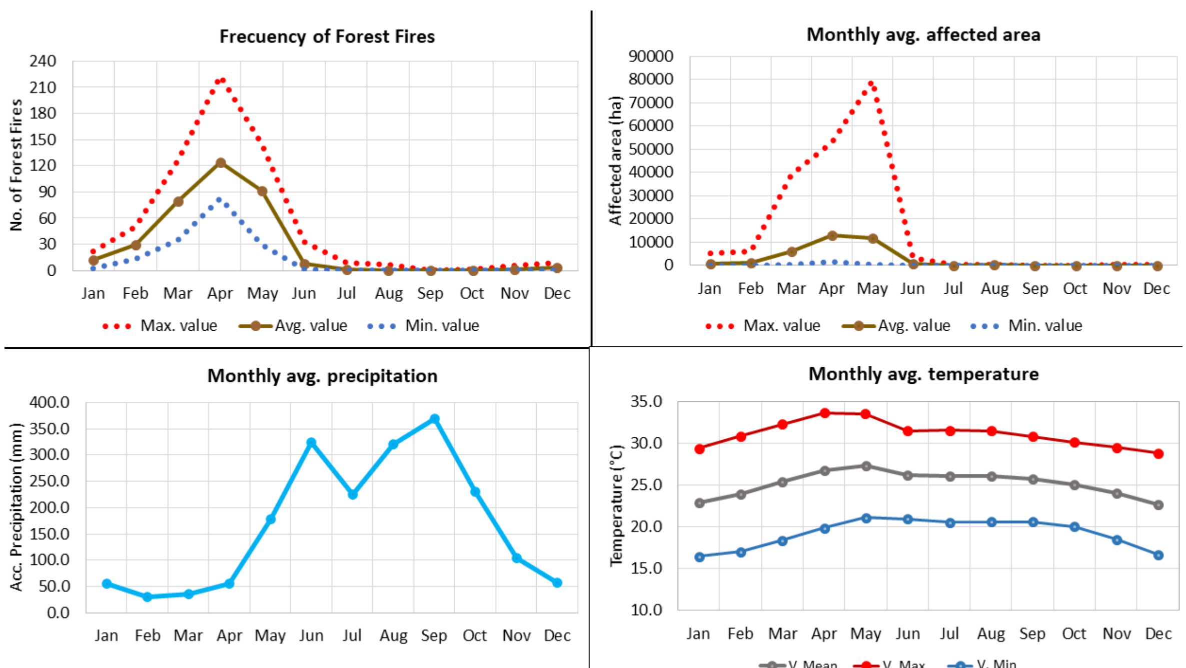

Figure 6. Maximum and minimum values of the variables analyzed (frequency of forest fires, area affected by forest fires, average monthly precipitation, and average monthly temperature)

Table 2. Monthly forest fire records in Chiapas for the period 2010-2024 and fire event to area ratio.

Month	Number of forest fires	Affected area (ha)	Forest fire-to-area ratio (ha/fire event)
January	173	9280.18	53.64
February	428	18 478.57	43.17
March	1192	90 968.47	76.32
April	1855	192 712.80	103.89
May	1372	176 219.47	128.44
June	127	8280.98	65.20
July	15	658.6	43.91
August	7	145	20.71
September	0	0	0.00
October	3	87	29.00
November	13	286.1	22.01
December	36	1029.9	28.61
Total	**5521**	**498 147.07**	**51.24 (mean)**

In terms of meteorological conditions, during the season of highest FF recurrence, maximum temperatures above 33°C and precipitation regimes ranging between 50 and 180 mm were observed in April and May. At the same time, annual patterns show that after a period of rain, in the dry season, maximum temperatures increase, while a greater number of FF are recorded in those months. In general, it is important to highlight several points from Figure 7. Firstly, the extreme climatic conditions (hot and dry) of 2016 could indicate a period of high susceptibility for the development of FF in the entity. This year was characterized by a total of 405 FF events with a loss of 84 446.5 ha area. Secondly, the climatic conditions of 2019. Although they were not the maximum reached in the analyzed period, they were above average. It was this same year that recorded the highest recurrence of FF in the analyzed period (454 events with 31 197.28 ha lost). Finally, the year 2024, with more than 185 222 ha and 451 events up to June, followed by 2022, with 70 486.51 ha and 373 events, were the years in which the largest area affected by forest fire was recorded, even though the latter year presented less warm and dry conditions, with values close to and below the average, compared to the years mentioned above.

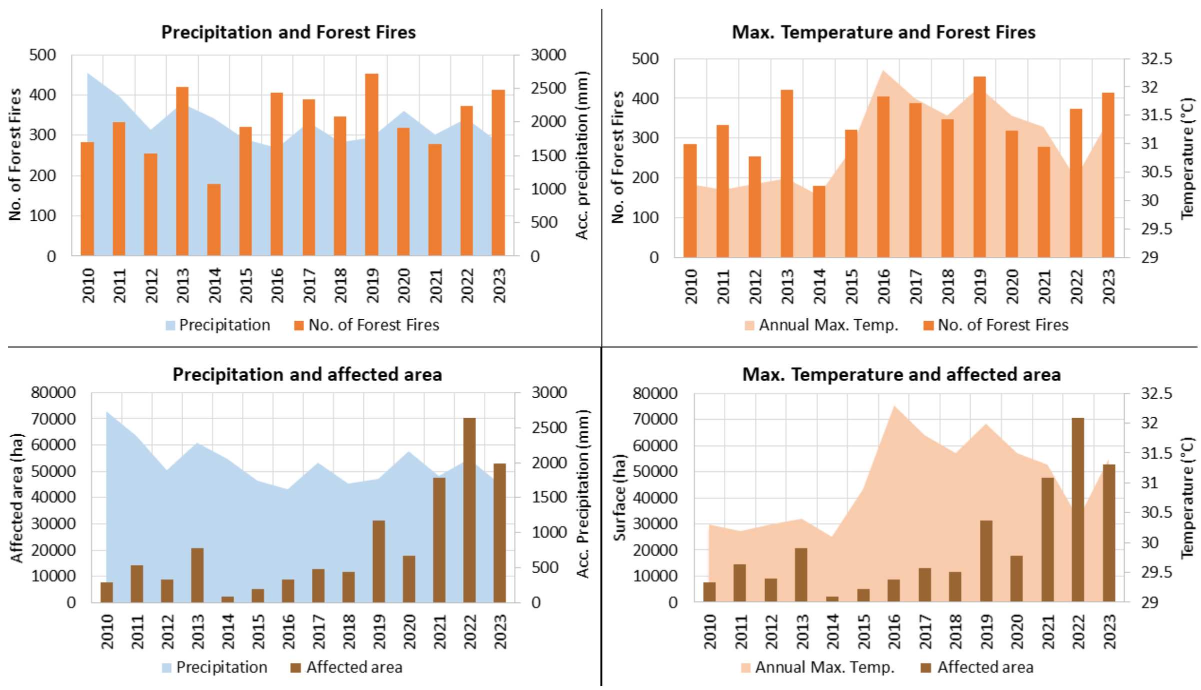

Figure 7. Relationship between climatic variables (precipitation and maximum temperature) and the occurrence of forest fires in Chiapas (2010-2024).

Analysis of the relationship between FF recurrence and climatic variables

The correlation and linear regression models demonstrated statistical significance, with correlation coefficients (R) indicating a significant and predictable relationship for most variables studied, particularly in the case of maximum temperature and the occurrence of FF (46.84%) and the area affected (24.36%). On the other hand, for the variable precipitation, a negative or inverse relationship was observed for both cases. At the same time, the results indicate a strong positive relationship between the occurrence of forest fires and the area affected; however, this variable only explains 37.04% of the variability of the data (Table 3).

Analysis of the causes of FF

According to the interpretation of the records, it was found that most of the FF events in Chiapas originate mainly from the misuse of fire in the agricultural sector (47.62%), especially land clearing and preparation during the dry season. However, poaching (12.23%), vandalism (8.91%), burning of waste (1.61%), improper disposal of cigarette butts (4.97%), among other natural causes (1.27%), as well as illegal activities (2.45%), also play a role. In addition, 20.94% of the ignition causes in the analyzed period are considered to be of unknown origin. This coincides with the weekly reports published by CONAFOR.

Vegetation affected by fire

During the analysis period, there was a significant variation in the area affected by wildfire (Table 4). The highland forests and humid tropical forests were the canopies with the greatest area affected by fire, in terms of the total affected area (69% and 16% respectively). In the case of mountain mesophyll forest, the affected area corresponds to 3.08%, while mangrove, Popal, and Tular vegetation, with an area equivalent to 6.06%, and grasslands, with 6.72% of the total area affected by fire during the period of analysis.

Regarding the calculation of the average forest mass loss, it was observed that the greatest vegetation loss corresponds to the 2021-2024 period, which is much higher compared to the 2014-2020 period. Unlike the other vegetation types, mangrove, Popal, and Tular were the least damaged from 2021 onwards, reducing 14.42 ha and 614.64 ha, respectively (Table 5).

DISCUSSION

Recurrence of forest fire

The areas with the highest recurrence of FF in the state extend over a large part of the Sierra Madre de Chiapas. This is a complex geological formation characterized by its high relevance for biodiversity in the country (Vidal *et al.*, 2014; Morales and Riechers, 2005) and its representative topography, in which its moderately steep to steep slopes (9 - >40%) stand out in most of the region (Martínez, 2023), which determines the rapid heating of forest fuel, given that the flame has greater contact with the resulting surface (Flores *et al.*, 2016). This coincides with the findings of Pacheco *et al.* (2024), who determined that the topographic factor of slopes greater than 55% in the micro-watershed “La Unión, Chiapas” constitutes the areas of greatest danger to FF. In addition, the type of vegetation present in the Sierra Madre de Chiapas plays

Table 3. Values of the correlation and linear regression models for the response variable: a) No. of forest fire events and b) Affected area (ha) and climatic variables as predictors.

	Regression analysis values			Correlation analysis values			
a) Fire recurrence							
Independent variables	**R-cuad**	**F**	**T**	**R**	**95% CI for R**	**P**	**RELATION**
Precipitation (mm)	16.32%	34.12	-5.84	-0.404	(-0.520, -0.273)	0.000	Moderate negative
Average temperature (°C)	18.63%	40.06	6.33	0.432	(0.303, 0.544)	0.000	Moderate positive
Maximum temperature (°C)	46.84%	154.2	12.42	0.684	(0.597, 0.756)	0.000	Strong positive
Minimum temperature (°C)	1.17%	2.08	1.44	0.108	(-0.040, 0.252)	0.151	Not significant
b) Area affected by fire							
No. of forest fires	37.04%	102.95	10.15	0.609	(0.507, 0.694)	0.000	Strong positive
Precipitation (mm)	4.87%	8.96	-2.99	-0.221	(-0.357, -0.076)	0.003	Weak negative
Average temperature (°C)	13.78%	27.96	5.29	0.371	(0.237, 0.492)	0.000	Moderate positive
Maximum temperature (°C)	24.26%	56.05	7.49	0.493	(0.372, 0.597)	0.000	Moderate positive
Minimum temperature (°C)	3.56%	6.46	2.54	0.189	(0.042, 0.327)	0.012	Weak positive

Table 4. Type of vegetation affected by forest fire in Chiapas during 2010-2024.

Year	Area affected (ha)						
	Mesophilic mountain forests	Humid tropical forests	Mangrove	Highland forests	Popal and Tular	Riparian Vegetation	Grasslands
2010	0	0	0	2985.70	0	0	65.54
2011	656.05	0	0	0	0	0	171.99
2012	0	0.00	16.47	0	0	0	0
2013	N/D	N/D	N/D	N/D	N/D	N/D	N/D
2014	34.62	90.42	0	0	0	0	69.26
2015	115.88	245.47	3.35	0	9.20	0	380.40
2016	2,265.98	2,698.17	13.59	0	211.33	0	398.14
2017	232.86	821.18	46.19	7,357.50	2,375.54	42.62	1,682.29
2018	306.13	295.02	10.98	7,997.52	1,107.26	8.71	606.99
2019	1,139.93	2,526.40	42.02	24,030.35	2,739.09	1.11	972.17
2020	550.02	1,379.75	10.85	12,598.84	2,030.39	12.36	1,186.69
2021	1,989.61	6,909.51	63.02	30,899.35	4,418.58	1.88	2,284.75
2022	1,004.38	12,337.69	19.67	48,157.87	2,057.65	64.09	5,302.09
2023	703.18	3,539.21	100.42	41,693.91	2,629.84	14.72	3,288.96
2024	3,012.35	31,251.58	19.75	93,818.83	2,574.66	12.45	9,817.66

N/D = no data available.

Table 5. Average loss of vegetation cover (ha/year) due to wildfire in Chiapas (2010-2024).

Period	Total affected vegetation	Mountain mesophyll forests	Tropical humid forests	Mangrove	Highland forests	Popal and Tular	Riparian vegetation	Grasslands
2010-2024	-9818.29	-215.17	-2232.26	-1.41	-6488.08	-183.90	-0.89	-696.58
2014-2020	-2929.10	-85.90	-214.89	-1.81	-2099.81	-338.40	-2.06	-186.24
2021-2024	-31313.53	-340.91	-8114.03	14.42	-20973.16	614.64	-3.52	-2510.97

a fundamental role in the availability of combustible material, which, together with the conditions of high temperatures and low precipitation, constitutes an ideal environment for fire propagation (Ruiz-Corzo *et al*., 2022). The variety of vegetation in the fire-prone areas includes humid tropical forests, pine, oak, and cloud forests (Vidal *et al*., 2014). There is a record of a high incidence of FF within natural protected areas in the state (Román and Martínez, 2006; Maldonado *et al.*, 2019). The Sierra Madre de Chiapas is home to several important areas for biodiversity conservation, including La Sepultura Biosphere Reserve, La Frailescana Natural Resources Protection Area, El Triunfo Biosphere Reserve, Pico El Loro-Paxtal Ecological Conservation Area, Tacaná Volcano Biosphere Reserve, and the Sierra Madre del Sur Biological Corridor (Morales and Riechers, 2005). On the other hand, there are small polygons in some areas of the Central Depression and the Northern Mountains, on the Chiapas Coast, as well as in the area that includes the Selva Lacandona.

Climate trends and seasonal patterns

A trend has been observed in the increase of FF events, as well as in the areas affected by them. This may be related to various environmental factors, including climatic factors that promote the availability of forest fuels, as well as social factors related to the use and management of fire. In turn, the trends in the increase of temperatures, especially the maximum temperatures, are similar to those found by Zamora *et al.* (2022) in Las Tunas, Cuba, by Campos (2015a) in Zacatecas, and by Zarazúa *et al.* (2014) in the Southern Gulf Coastal Plains region in Mexico. Similarly, Peralta (2009) notes the increase in maximum temperature and a higher frequency of warm days in southeastern Mexico, while Mora *et al.* (2016) and Figueroa (2017) report significant upward trends for maximum and minimum temperatures in Chiapas. In turn, Escalante and Amores (2014) suggest a generalized trend in the increase of maximum temperature along the entire Chiapas Coast, likewise, they report negative trends in rainfall regimes in Soconusco, Chiapas, similar to that reported by Campos (2015b) for the state of Zacatecas. In this regard, Arellano and Ruíz (2019), in an analysis of the Zanatenco River basin, Chiapas, report, for the region, a strong relationship between dry and rainy years for the presence of El Niño and La Niña periods, at the same time that events of maximum temperatures linked to drought are observed with greater frequency and intensity. This means an increase in favorable climatic conditions for the occurrence of FF in the entity.

Several studies at regional (Perez *et al.*, 2014; Antonio and Ellis, 2015; Pompa *et al.*, 2018) and global scales (Groot *et al.*, 2012; Doerr and Santín, 2016), document that the increase in temperature, combined with drought conditions enhanced by climate change, increases the risk of FF. This would translate into a greater number of FF per year, as well as the area affected by them and the damage caused to exposed systems. This is because atmospheric conditions play a crucial role in all stages of FF, and can influence fire behavior, determining its intensity and speed of spread. However, it is important to mention that FF will occur as long as forest fuel is available (Pacheco *et al.*, 2024; Flores *et al.*, 2016). From the annual patterns, it is observed that, after a period of rain, in the dry season, maximum temperatures increase, while a greater number of FF are registered in the entity in March, April, and May.

In this regard, Galván and Magaña (2020) have studied that, in Mexico, the fire season corresponds to the period of minimum rainfall and when the highest maximum temperatures are observed. This coincides with the spring months, mainly April and May, and with the beginning of the spring-summer seasonal agricultural cycle, when the use of fire in agricultural activities becomes more common in the region. They have also observed that, at the beginning of the rainy season, the number of FF tends to decrease, which seems to be consistent with our findings. In April, the number of fire events and the area affected by the fire were much higher than in other months; however, in May, the ratio between the area affected by each fire event was much higher than in April. Therefore, it is important to consider these two months as a priority, given that, for each event in the territory, there is a much higher surface area/fire event ratio than the annual average. This pattern, although it does not explain the cause of fire origin, highlights the influence of meteorological conditions on the development of FF, underlining the importance of atmospheric monitoring for FF risk management in the territory. Likewise, years with similar weather patterns are visualized, but with considerable differences in the number of FF, as well as in the area affected by them.

Analysis of the relationship between FF recurrence and climatic variables

From the results, it is possible to suggest that, as temperature increases and precipitation decreases, FF events in the entity will be greater, as well as the area affected by these events. Likewise, maximum temperature is identified as the climatic variable that best explains the occurrence of FF in the entity (47% of variance explained). Similar to the study conducted by Manzo et al. (2004), where the temperature variable significantly explained the occurrence of FF in Mexico; while Zamora *et al.* (2022) obtained low correlation coefficients between the area affected and the meteorological variables, such as: mean and maximum temperature, dew point, relative humidity and wind speed in Cuba. For their part, Carrasco *et al.* (2017) obtained very low and low correlation coefficients for the case of relative humidity, to the occurrence of FF, while observing an inversely proportional relationship between precipitation and the occurrence of FF over time. Furthermore, in Mexico, including some regions of southern Chiapas, Cisneros *et al.* (2018) determined that drought, including variables such as precipitation and evapotranspiration, is related to the occurrence and intensity of FF (32% variance explained), as well as with the fire-affected area (38% variance explained). In this work, it was observed that the variable precipitation is inversely related to the occurrence of FF in the entity (with 16.32% of variance explained). Meanwhile, climate change scenarios anticipate warmer conditions and predict a 12.5% reduction in annual precipitation for the state of Chiapas (Montero *et al.*, 2013), which could be related to an increase in the occurrence of FF in the state, a phenomenon that, due to the emission of Greenhouse Gases into the atmosphere, would feedback positive conditions of radiative forcing at local scales, modifying the local microclimate and enhancing global climate change scenarios.

However, even though the meteorological conditions of maximum temperatures and the scarcity of precipitation influence the increase in the occurrence of FF in the state, it is not possible, based on the results obtained here, to attribute the increase in the areas affected solely to current climate trends. This is because less than 50% of the variance of the data was explained by this variable. This is similar to what was found by Antonio and Ellis (2015), who used maximum temperature in May and total precipitation in winter as variables in the state of Mexico; determining, from the correlation analysis, that, despite being consistent, the climatic variables were not sufficient to predict the extent of the areas affected by FF, attributing this result to the complexity of FF. Galván and Magaña (2020) conclude that the increase in the occurrence of FF in Mexico, especially in the central-southern part, is mainly due to anthropogenic effects and is intertwined with environmental variables. This implies the existence of other factors that may influence the trends observed in the number of FF and the area affected by them, such as topographic conditions, the type of ecosystem and vegetation cover, as well as anthropogenic causes related to changes in land use and fire management in the territory.

At the same time, the influence of the ocean-atmospheric phenomenon El Niño-Southern Oscillation has been studied worldwide as one of the main factors for fire regimes, because it generates unusually warm and dry conditions in many regions of the world, as in the case of Mexico (Pompa and Sensibaugh, 2014; Burton *et al.*, 2020). Under these conditions, an increase in the occurrence of FF has been observed (Cerano *et al.* 2016; Cerano *et al.*, 2021). In this regard, Román *et al.* (2004) mention that, in Chiapas, FF are more recurrent in years with El Niño; the most influential factors in the occurrence of FF during these years are low precipitation and the presence of dry vegetation biomass. However, other studies, such as Bravo *et al.* (2017), found that the year after the Niño, the probability of the occurrence of an FF is reduced by 40%. This is because the effect associated with the Niño produces, in the case of Mexico, greater precipitation in winter, which results in less forest fuel available during the following spring.

Analysis of the causes of forest fire

This study revealed that the primary origin of FF in the state of Chiapas was the escape of fire during land clearing for agriculture. Several studies suggest that most FF events in Mexico have anthropogenic causes, both accidental and intentional, or related to the uses and customs that communities have linked to fire (Huffman, 2013), especially in those regions where livestock and agriculture are the main economic activity (Zamora et a., 2022; Rodríguez *et al.*, 2011; Martínez and Pérez, 2018). The traditional use of fire in Chiapas, Mexico, has been frequently documented, mainly in activities related to the cultivation of corn, sugarcane, and pasture, as well as in the milpa system (Huerta and Ibarra, 2014; Cheng *et al.*, 2013; Martínez Pérez, 2018). Likewise, it has been observed that the use of fire is a frequent phenomenon in the neighborhood of the natural protected areas in mountainous regions of Mexico, such as Sierra de Manantlán Biosphere Reserve in Jalisco and La Sepultura Biosphere Reserve in Chiapas (Jardel *et al.*, 2006), an area in which Gutiérrez *et al.* (2017) describe the use of fire as a traditional peasant practice, fundamental to the corn production cycle, used mainly, to save work time, control pests and fertilize the soil. This is also observed in different countries, where fire is used as an ingrained habit, as a tool in the management and preparation of soil for agricultural purposes (Müller *et al.*, 2013; Huffman, 2013), mainly in the elimination of crop residues, weeds and pests (Martínez *et al.*, 2016), as well as to maintain and expand the agricultural frontier; a phenomenon considered among the main causes of the increase in the extension and intensity of FF in tropical countries (Thompson *et al.*, 2013).

Particularly, in Chiapas, where agriculture and livestock are highly relevant economic activities in a large part of the territory (Sagarpa, 2016), the use of fire in the agricultural sector has been constituted as a triggering factor in the change of land use to expand the agricultural frontier, being, at the same time, the main cause of FF (Huerta and Ibarra, 2014; Martínez *et al.*, 2018). An example of this is reported by Román *et al.* (2004) and García *et al.* (2009), who documented the slash-and-burn technique, commonly used in the state to expand the agricultural frontier. The aforementioned supports the findings of this research, where the use of fire in the agricultural sector has been the main cause of the origin of FF in the entity. Similar to the findings of Pacheco *et al.* (2024), who determined that agricultural and livestock land use has a considerable influence on the initiation and spread of fire in certain areas within Chiapas.

On the other hand, causes such as poaching and vandalism, among other illegal activities, are observed in the territory, particularly in forest areas subject to conservation, and are strongly related to the extraction and exploitation of natural resources, the change of land use for productive uses, or for the expansion of urban areas. These phenomena have also been documented in the Amazon Forest, where fire, including illegal burning, has been the main tool for deforestation, timber extraction, expansion of the agricultural frontier, expansion of the urban area, and the creation of roads (Condé *et al.*, 2019; Krawchuk *et al.*, 2009). However, in Chiapas there are also cases, as in Neger *et al.* (2022), in which the origin of FF is due to social factors related to solid waste management, especially cigarette butts and burning of garbage dumps; problems of inequality and land ownership; criminal acts and vandalism, as well as negligent acts related to the use of bonfires and fireworks; lack of knowledge about fire management; lack or ambiguity of government policies, among others. Natural causes are rarely associated with the occurrence of lightning strikes, or are not specified in most of the records, which adds to the 20.94% of FF causes that are reported as unknown.

Vegetation affected by fire

The vegetation cover affected by fire has shown the same trend observed in the increase of the area affected by FF in the state, where the period 2021-2024 accumulates the highest values of affected vegetation. Considering that the total area of polygons of vegetation affected by FF totals 390 530 ha, the amount of forest affected in the analyzed period is alarming, reaching a total of 269 560 ha, of which 214 570 ha were burned in 4 years, starting in 2021. However, the above comparison is a bit ambiguous, considering the lack of records, specifically, for this type of vegetation, during the years 2011 to 2017. Nevertheless, the largest area of affected forest was recorded in 2024, with a total of 93,800 ha. Similar patterns are observed for tropical forests and grassland vegetation, and slightly for mountain mesophyll forest vegetation. Mangrove, Popal, and Tular vegetation have shown a decrease in the area that has been burned or affected. Although forest vegetation has the largest area affected by fire in the state, this type of cover has a low severity of forest fires, compared to forests, which take longer to regenerate post-fire. Likewise, mesophilic mountain forests and mangroves, although they are not affected much in the state, are considered sensitive to these events (Rodríguez, 2006).

Fire is recognized for its important role as a modeling agent in many natural ecosystems (Chen *et al.*, 2013b). In this regard, it is known that FF has a direct impact on biomass reserves and landscape fragmentation while affecting various ecosystem functions and processes, including biodiversity, species distribution and abundance, and the hydrological cycle (Bizama *et al.*, 2011; Nasi *et al.*, 2002; Chia *et al.*, 2016; Müller *et al.*, 2013). On the other hand, in some tropical ecosystems, fire has positive impacts, since it allows the expression of the seed bank of some species, through different ecological mechanisms (Parr and Chown, 2003; Chen *et al.*, 2020). An example of this occurs in the pine-oak forest, where fire intervenes in the dispersion of pine seeds, in addition to promoting the regrowth of oak trees (Flores, 2021; Aquino *et al.*, 2024). However, to know the magnitude of the effects caused by FF on these ecosystems, it is necessary to integrate other types of studies that address, in addition to frequency, their intensity and severity (Elliot and Vose, 2010; López-Cruz *et al*., 2022). It is worth mentioning that the total area of the vegetation polygons observed here differs from the total area reported by CECIF, with an approximate difference of 107,617 ha. This is because not all the polygons of the FF that occur in Chiapas are reported to the National Forest System, since in most cases, a single coordinate that reflects their location is attached, but no polygon visually demonstrates the area affected by the fire. This could be because the fires occur in inaccessible locations or because the coordinates are not completely recorded during field verification.

CONCLUSIONS

Although there have always been areas with ideal characteristics for the initiation and development of forest fires in the state of Chiapas, the recurrence of these events has increased alarmingly in the last 14 years. Fire recurrence was mainly observed within the Sierra Madre de Chiapas region, especially in the municipalities of Cintalapa, Jiquipilas, Villaflores, Villa Corzo, and La Concordia, where the presence of wildfires in the same place was more frequent than in other regions of Chiapas. The observed climate trends, particularly the increase in temperature and the decrease in annual precipitation, partially explain the elevated risk of forest fire recurrence and the land area affected by wildfire. However, the increase in the occurrence and area affected by forest fires is not entirely attributable to the changes in current climate trends, but also to anthropogenic factors such as land-use change, agricultural activities, and fire management practices. Nevertheless, forest fire events were more frequent during the dry season, particularly in April and May, when maximum temperatures tend to reach their peak, which suggests a seasonal climatic influence on fire occurrence. This study also suggests the existence of other anthropogenic factors, such as waste management, pest control, lack of local fire management capacity, and policy shortcomings, that influence the increase in forest fire recurrence and the area affected by wildfire observed in Chiapas, México.

Therefore, it is vital to implement forest fire prevention and management actions that include climate monitoring and citizen training, as well as strengthening the technical capacities of the institutions involved. Interinstitutional coordination and the correct execution of strategies embodied in the state and regional fire management programs are essential. Our study has highlighted the critical zones, as well as the amount of surface area affected by forest fire, which can be useful for the construction of indicators to identify and delimit areas of priority attention, that could be helpful to optimize resource allocation, improve fire management, and minimize future impacts. Furthermore, improving the accessibility and quality of information, particularly by standardizing and enhancing institutional data recording practices, and promoting scientific research, is essential to enhance understanding and support evidence-based decision-making for fire management in the region.

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