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Research article

Incendios en Michoacán a partir de series *MODIS* (2015-2022) y su relación con el clima

Fires in *Michoacán* State from MODIS series (2015-2022) and their relation with climate

María Luisa España Boquera[1]*, Omar Champo Jiménez[1], María Dolores Uribe Salas[1]

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[1]Instituto de Investigaciones Agropecuarias y Forestales, Universidad Michoacana de San Nicolás de Hidalgo. México.

*Autora para correspondencia; correo-e: maria.uribe@umich.mx
*Corresponding author; e-mail: maria.uribe@umich.mx

Abstract

Fires affect more natural surfaces than any other disturbance factor on the planet. They result from the interaction of fuel, dry environmental conditions, and an ignition source. In the state of *Michoacán* conditions are conducive for the annual occurrence of numerous fires. Remote sensing offers global, consistent and objective information on fires, with the generation of series of burned areas, such as the 500m MCD64A1 generated from MODIS data. The objective of this work was to analyze this series to know the fires that occurred in the entity between 2015 and 2022, considering vegetation covers affected (INEGI Series VII) precipitation and temperature. An average of 3 340.87 pixels with fires were recorded annually; 2021, during confinement due to the Covid-19 pandemic, was the year with the most fires (5 269 pixels) and 2022 with the fewest (2 398). The fires are concentrated in the driest and hottest months, mainly May (1551.00 pixels on average) and April (958.38 pixels); the highest number was recorded in April 2021 (2 347 pixels), and the second month with the most detections was May 2020 (2 094 pixels). Most events are associated with agricultural burning (48.41%), mainly in irrigated land, in spring and winter. Forest fires significantly affect temperate forests and associated secondary vegetation (32.85%); in tropical deciduous forest areas (17.14%), fires occur mostly in secondary vegetation. In years with an early onset of rains (2015 and 2018), fewer fires accumulated.

Key words: Temperate forest, tropical decidous forest, precipitation, agricultural burning, time series, temperature.

Resumen

Los incendios afectan a más superficies naturales que cualquier otro factor de disturbio en el Planeta. Resultan de la coincidencia de combustible, condiciones ambientales secas y una fuente de ignición. En el estado de Michoacán existen las condiciones propicias para la ocurrencia anual de numerosas conflagraciones. La teledetección ofrece información global, consistente y objetiva sobre los incendios, con la generación de series de áreas quemadas, como MCD64A1 de 500m, generada con datos *MODIS*. El objetivo de este trabajo fue analizar esta serie para conocer los incendios ocurridos en la entidad entre 2015 y 2022, considerando las coberturas afectadas (Serie VII de INEGI), la precipitación y la temperatura. Se contabilizaron al año, en promedio 3 340.87 pixeles con incendios; 2021, durante la pandemia de Covid-19, fue el año con el mayor número de registros (5 269 pixeles) y 2022 con menos (2 398). Los incendios se concentraron en mayo (1551.00 pixeles en promedio) y abril (958.38 pixeles); el máximo número de incendios se detectó en abril de 2021 (2 347 pixeles), seguido de mayo de 2020 (2 094 pixeles). La mayoría de los eventos se asocian a quemas agrícolas (48.41%) en terrenos de riego, en primavera e invierno; los incendios forestales afectan sobre todo a bosques templados y a la vegetación secundaria asociada (32.85%); en zonas de bosque tropical caducifolio (17.14%), los incendios ocurren, en su mayoría, en vegetación secundaria. En los años con un inicio temprano de la temporada de lluvias (2015 y 2018) se acumularon menos incendios.

Palabras clave: Bosque templado, bosque tropical caducifolio, precipitación, quemas agrícolas, series de tiempo, temperatura.

Introduction

Around 3 to 5 million square kilometers of natural cover burn each year around the world (Jones *et al.*, 2022). The impact of fires on wildlife and ecosystems can be deep and have implications for biodiversity, the development of plant communities, carbon storage (Justice *et al.*, 2006; Jones *et al.*, 2022), soil erosion and hydrological cycles (Chuvieco *et al.*, 2019). More than 90 % of fires in most biomes are of anthropogenic origin (Chuvieco *et al.*, 2019; Neger *et al.*, 2022a), with the aim of changing land use or land management, to carry out agricultural practices, due to accident or negligence (Jones *et al.*, 2022). Fires affect climate and air quality, which is why they have been identified as Essential Climate Variables (ECVs) by the Global Climate Observing System (GCOS) (Justice *et al.*, 2006).

Climate change is increasing the incidence of fires (Jones *et al.*, 2022) and the effects of fire are expected to increase in the future, although their consequences will vary regionally, based on changes in precipitation patterns (Chuvieco *et al.*, 2019).

Fire is the result of the simultaneous occurrence of three factors: (I) An ignition source, human or natural, (II) Fuel reserve, and (III) Environmental conditions (precipitation, temperature, wind, air and soil humidity) sufficiently dry (Jones *et* *al.*, 2022; Neger *et al.*, 2022a), which is known as the fire triangle (Jardel *et al.*, 2014). Climate conditions double the potential for fires, since, on the one hand, it determines the accumulation of biomass, as a result of the ecosystem processes of primary productivity and decomposition, and on the other, the seasonality of rain and drought defines the state of humidity of fuels and their availability to maintain the spread of fire (Jardel *et al.*, 2014). A long moisture deficit during the months preceding the fire season can reduce soil moisture reserves and make vegetation less resilient to conditions conducive to fire initiation (Jones *et al.*, 2022). This is particularly the case in areas of high vegetation production, where fire activity is associated with high temperatures and periods of drought (Chuvieco *et al.*, 2019; Neger *et al.*, 2022a). These are regions with intermediate (or alternating) availability of humidity, productive enough to accumulate biomass, but with dry conditions frequent enough to intermittently dry the available vegetation (Jardel *et al.*, 2014; Jones *et al.*, 2022).

This is the case of pine or oak forests in humid temperate climates, but with a long dry season (Jardel *et al.*, 2014), as well as savannahs and tropical deciduous forests (Chuvieco *et al.*, 2019), mainly in America of South, Southeast Asia and Sub-Saharan Africa, where deforestation and management practices must be added to natural fires (Justice *et al.*, 2006).

A large part of the territory in Mexico is located in the tropical and subtropical zone and the physiographic characteristics, climate and types of vegetation are conducive to the occurrence of fires. According to the National Forest Commission (Conafor), in the 2015-2022 period, nearly 500 000 hectares of forest were burned throughout the country (without accounting for agricultural burning), an average of close to 7 000 fires per year. The state of *Michoacán*, with significant areas of temperate and tropical deciduous forests, experiences numerous fires every year, and contributes about 10 % to national statistics (Conafor, 2024). These data, which come directly from field reports, have been used to carry out some cartographic work (Pompa-García *et al.*, 2018); however, there are deficiencies in Conafor's capture system, so they are not reliable in all cases (González-Gutiérrez *et al.*, 2020).

This problem is common in many national or regional inventories, which tend to include only some types of fires, resulting in incomplete and fragmented databases (Chuvieco *et al.*, 2019; Jones *et al.*, 2022), therefore that could be used in combination with other data sources (Zúñiga-Vásquez *et al.*, 2017); furthermore, the locations of the burned areas are often made after the fact and in an approximate manner, which generates errors in georeferencing (González-Gutiérrez *et al.*, 2019).

One of the most important advances in the study of fires in recent decades has been the development of satellite products for detecting fires and burned areas, which have allowed us to build a global panorama of fire activity (Szpakowski and Jensen, 2019; Jones *et al.*, 2022). Although the series have lower spatial resolution, their analysis is simpler than the estimation of burned areas from satellite images such as Landsat or Sentinel-2, used for the validation of the series (Giglio *et al.*, 2020), as well as for the study of particular cases and the precise analysis of the affected surface, the level of involvement and subsequent recovery (Llorens *et al.*, 2021).

Among the global series available, the MCD64A1 product stands out, built by NASA (National Aeronautics and Space Administration) using data from the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor from the *Terra* and *Aqua* satellites (Giglio *et al.*, 2018). This monthly series corresponds to collection 6, the latest version of the algorithm with which the complete data file since 2000 has been recalculated (Giglio *et al.*, 2020). MODIS sensor detections are based on the identification of thermal anomalies, allowing the detection of active fires, as well as the estimation of the power emitted by the fire and the burned area (Giglio *et al.,* 2021).

The MCD64A1 series has proven to be more accurate for the identification of fires and burned areas in the state of *Michoacán* than other available products, such as the PROBA-V 300 m series from *Copernicus* (Champo *et al.*, 2023). There are also global satellite data series of climate variables, such as those provided by NASA's Global Land Data Assimilation System (GLDAS), which contribute to the understanding of the fire problem and its implications (Rui and Beaudoing, 2022).

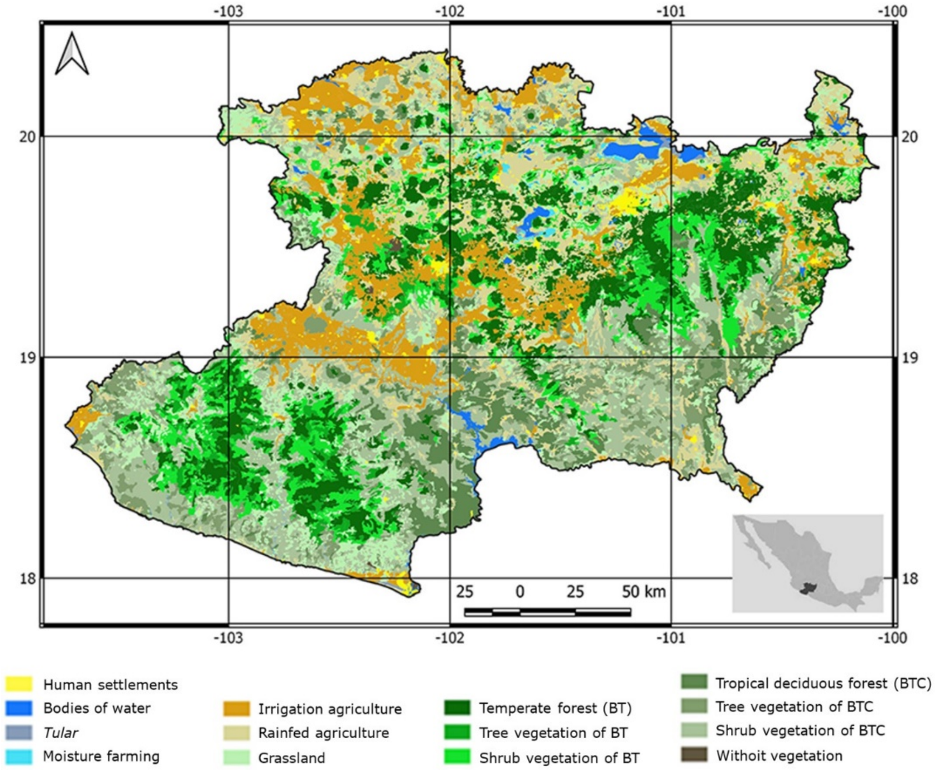
Interest in the use of remote sensing data to study fires has been increasing in Mexico in recent years, as shown by the growing number of publications on this topic (Neger *et al.*, 2022b). From the series of burned areas MCD45A1, prior to MCD64A1, large forest fires that occurred in Mexico between 2000 and 2014 were evaluated; in this period, 389 454 hectares burned in Michoacán were identified, which corresponds to an average of 25 963.6 hectares year^{-1} (Manzo, 2016). Other studies use MODIS data to explore the relationship between fires and climate with a prediction (González *et al.*, 2023) or causality (Villar-Hernández *et al.*, 2022) approach; Pompa-García *et al.* (2018) used the aridity index, and obtained that in the northern part of the country natural causes prevail, while in the center and south (where *Michoacán* is located), the high population density and agricultural activities would explain the most fires.

The objective of this work was to analyze the occurrence of fires in the state of *Michoacán*, for the period between 2015 and 2022, based on the MCD64A1 series with different vegetable covers and the climatic variables average temperature and precipitation. It is based on the hypothesis that the fires in *Michoacán* have mostly human causes.

Materials and Methods

Study area

The study area corresponds to the state of *Michoacán*, in the Central West of Mexico, between 18° and 21° N and 100° and 104° W. The territory is crossed from east to west by two mountain structures: the Transversal Volcanic Axis and the *Sierra* Mother of the South. The predominant climates are: rainy tropical Aw with summer rains, dry steppe BS and temperate Cw with summer rains. The altitudinal range is from 0 m to about 4 000 m. Different types of temperate forest coexist (pine, oak, fir and mesophyllous), with associated secondary arboreal and shrubby vegetation; the tropical deciduous forest and its secondary tree and shrub vegetation are also developed; agriculture is both irrigated and seasonal, with areas of moisture farming; there are also grasslands and bushes; the rest of the coverage (such as *tulares*, mangroves and hydrophilic vegetation), along with human settlements, areas without vegetation and bodies of water, are not very susceptible to fires (Durán and Sevilla, 2003; Rzedowski, 2006). Figure 1 shows the coverage map of the state of *Michoacán*.



Source: Inegi, 2019.

Figure 1. Coverage map of *Michoacán*, derived from the land use and vegetation map Series VII.

Data

The MODIS MCD64A1 fire date series (day of burn), January 2015 to October 2022, was downloaded from the official website of the University of Maryland (Giglio *et al.*, 2021), in a monthly reprojected version, in format GeoTIFF, with 500 m resolution. The date of detection is coded as a Julian day (1 to 366).

On the other hand, global GLDAS data on average surface temperature (AvgSurfT_inst: Average Surface skin temperature, changed from degrees Kelvin to centigrade) and precipitation (Rainf_f_tavg: Total precipitation rate, expressed in amount of water per square meter and per square meter second, kg m^{-2} s^{-1}, which is equivalent to mm s^{-1}), were downloaded for the 2015 to 2022 period, from the NASA page https://giovanni.gsfc.nasa.gov/giovanni/. The values are monthly, with a spatial resolution of 0.25°×0.25°.

Methods

Each pixel with a burn date (day of burn different from 0) was counted as a detection; only one event per pixel per month is considered. It is not possible to directly convert the pixels to the burn area, since this could correspond to the entire pixel (25 ha) or only a part of it (the surface is provided in the MCD64A1 burn area series).

The number of pixels identified with fires was counted per month and year, in each type of coverage: agriculture (in its irrigation and rainfed modalities, including grasslands), temperate forest and tropical deciduous forest (with their respective secondary arboreal and shrubby vegetation), for which the coverage map, obtained from the land use and vegetation map, Series VII, of Inegi, was superimposed. The corresponding statistics were obtained by date and coverage.

The average and standard deviation of precipitation and average temperature were calculated, by month and year, in the state of *Michoacán*, as well as for the temperate forest, tropical deciduous forest and agriculture zones; in this case, the types of agriculture or secondary vegetation were not considered separately, given the low spatial resolution of the climate data (approximately 27.7 km) with respect to the fire data (500 m).

The Snap 8.0 (ESA) (Snap, 2024) programs were used to obtain statistics on fire detections and climate data by vegetable covers, and QGIS 3.22 (QGIS, 2024) to construct the maps.

Results

The temperatures and precipitation by month and year are shown in Figure 2. The average temperature in the period 2015-2022 in *Michoacán* was 22.66 °C; 2015, 2018, 2019 and 2020 were above the average and 2016, 2017, 2021 and 2022 below. Temperatures increase annually from January to May (the latter being the warmest month, with averages of up to 29 °C) and gradually decrease until December (and may be below 19 °C). Precipitation occurs between June and October, which are within the rainy season.

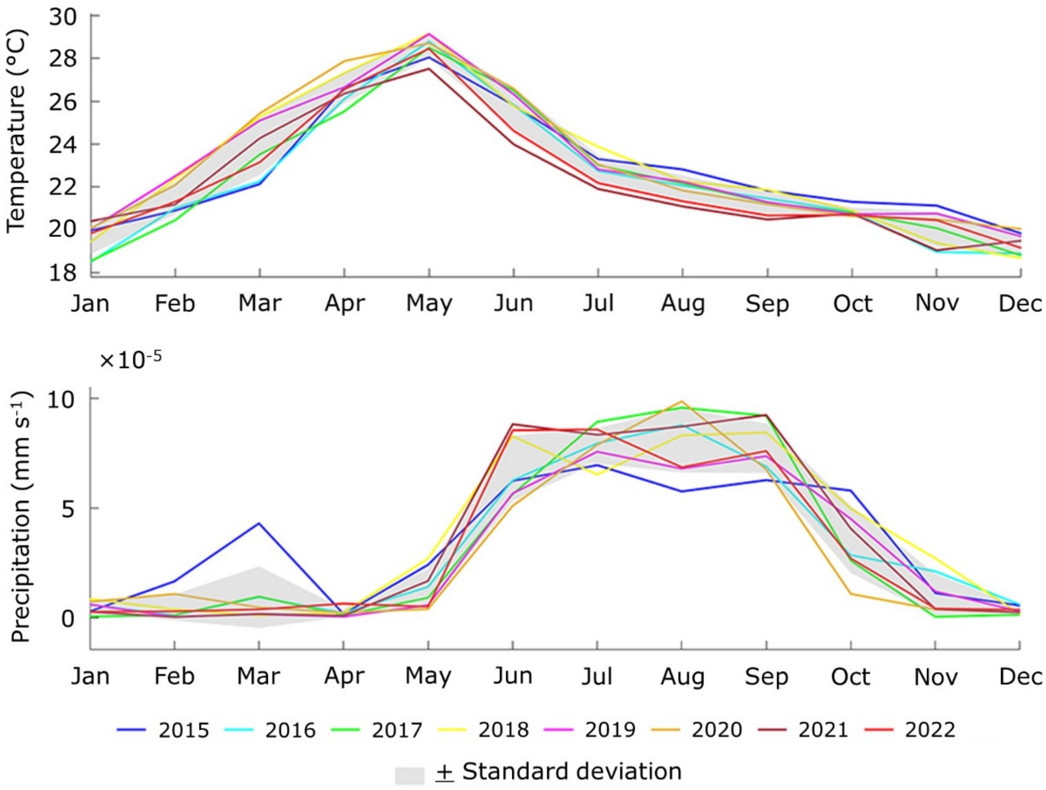


Figure 2. Average temperature and precipitation in *Michoacán* by month and year from 2015 to 2022 (GLDAS data).

The map in Figure 3 show fire detections in the state of *Michoacán* each year between 2015 and 2022. 26 727 pixels in total were counted with fire detection (3 340.87 annual detections on average); 2021 was the year with the highest number of detections (5 269) and 2022 the year with the lowest (2 398).

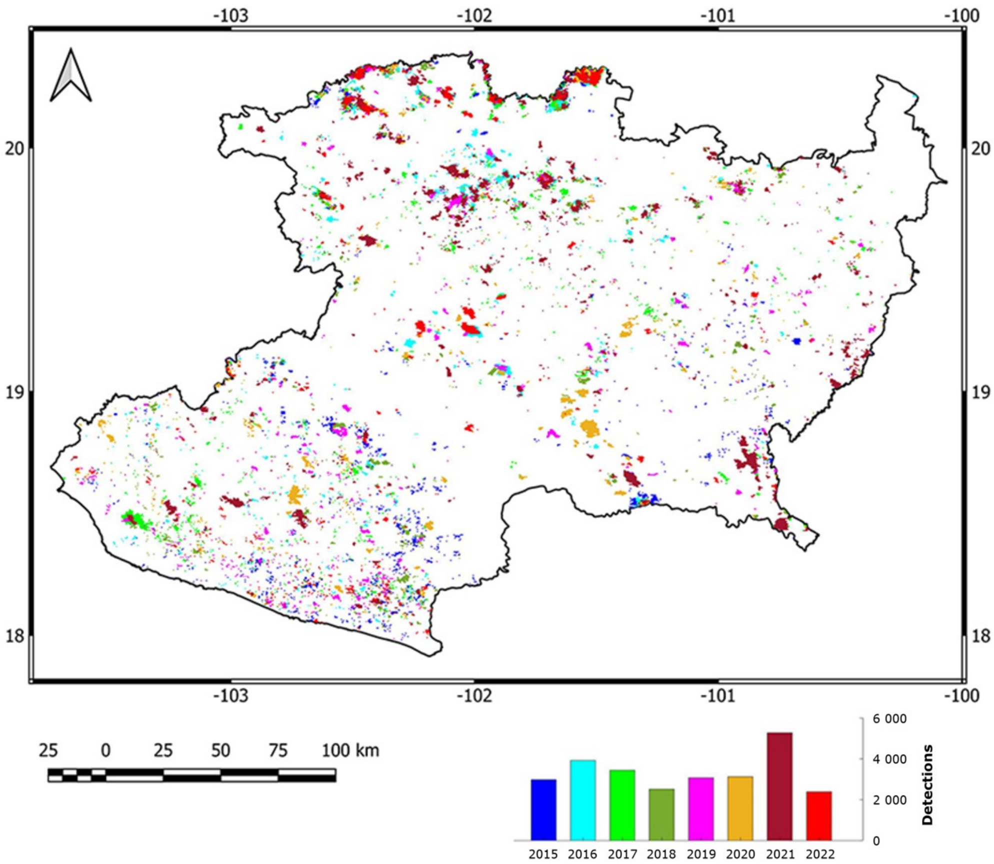


Figure 3. Map of fire detections in *Michoacán* from 2015 to 2022 (MCD64A1 data).

Throughout the year, fires are concentrated in the driest and hottest months, mainly in May, with an average of 1 551.00 detections, and April with 958.38; the maximum number of detections corresponds to April 2021, with 2 347, followed by May 2020, with 2 094. In the rainy season, fires are rare or even non-existent (Figure 4).

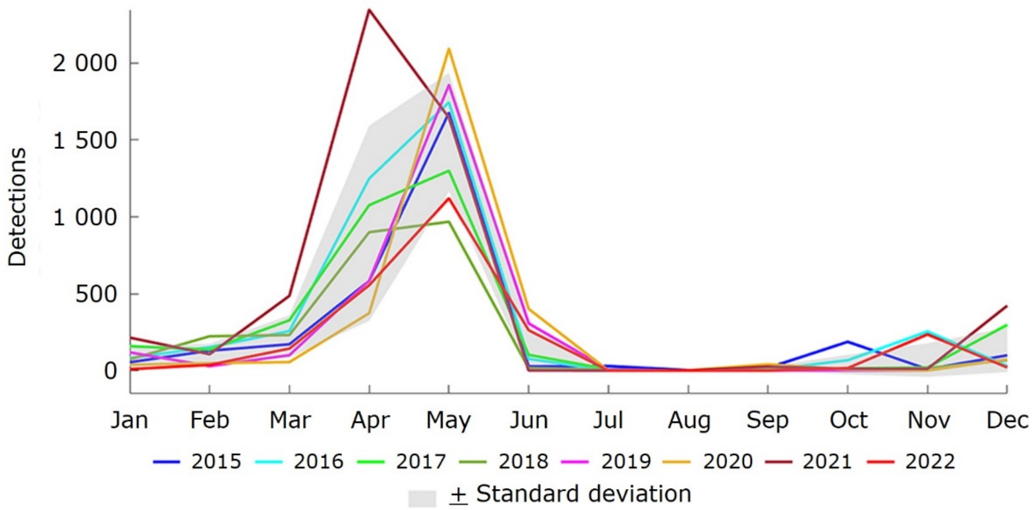


Figure 4. Fire detections in *Michoacán* by month and year (MCD64A1 data).

Agricultural burning represents 48.41 % of detections. Most of them are burns in irrigated agriculture (31.36 %), in two seasons: the most important in spring (May, with events in April) and another in winter (November and December); there are also grassland burnings (8.72 %) in spring (April and May) and some at the beginning of summer (June); in rainfed agriculture (8.33 %), burning is carried out from January to May.

Forest fires (32.85 %) mainly affect temperate forests (19.18 %) and also secondary shrub vegetation (8.72 %) and trees (4.96 %) of this association; they occur from March to June, in April and May in particular. In areas of tropical deciduous forest (17.14 %), fires occur in April and May, being more numerous in areas of secondary arboreal (5.02 %) and shrub vegetation (9.65 %), where they last until June, than in tropical deciduous forest itself (2.48 %) (Figure 5). This general trend presents some variations for each coverage in the years studied (Figure 6).

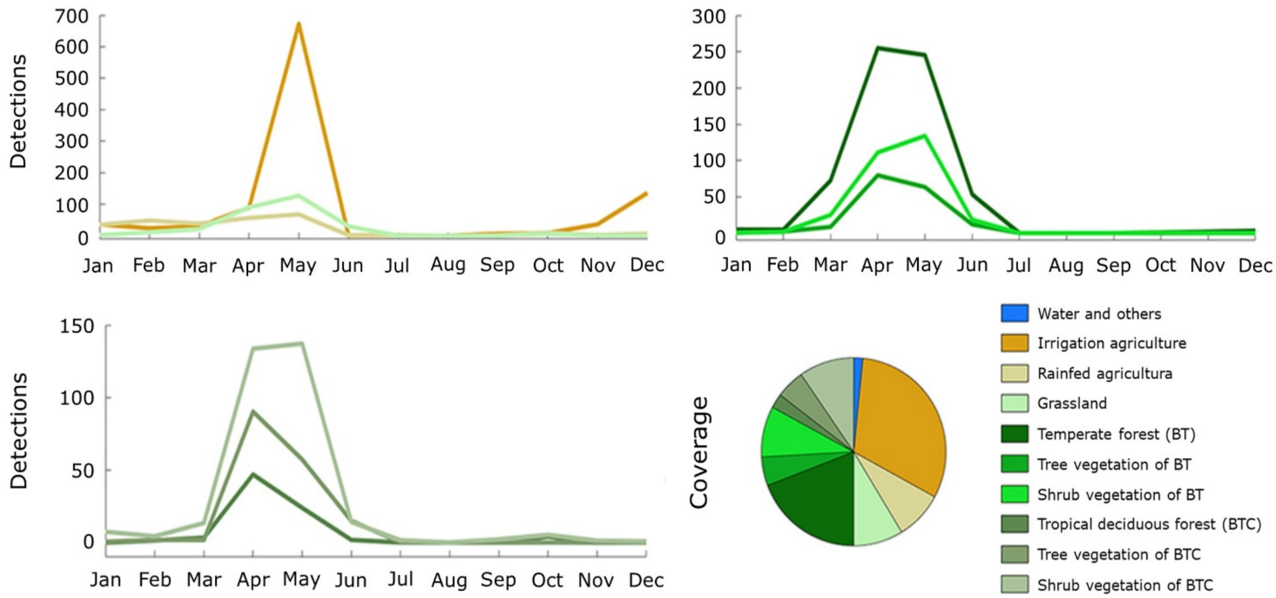
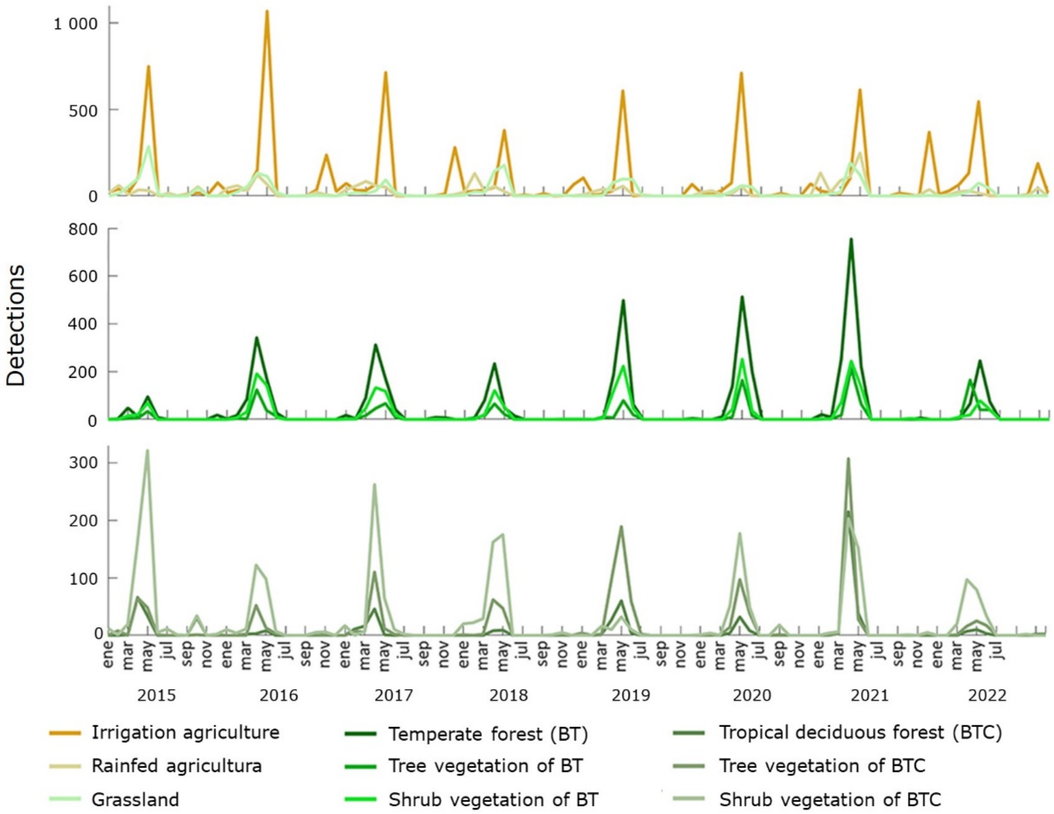


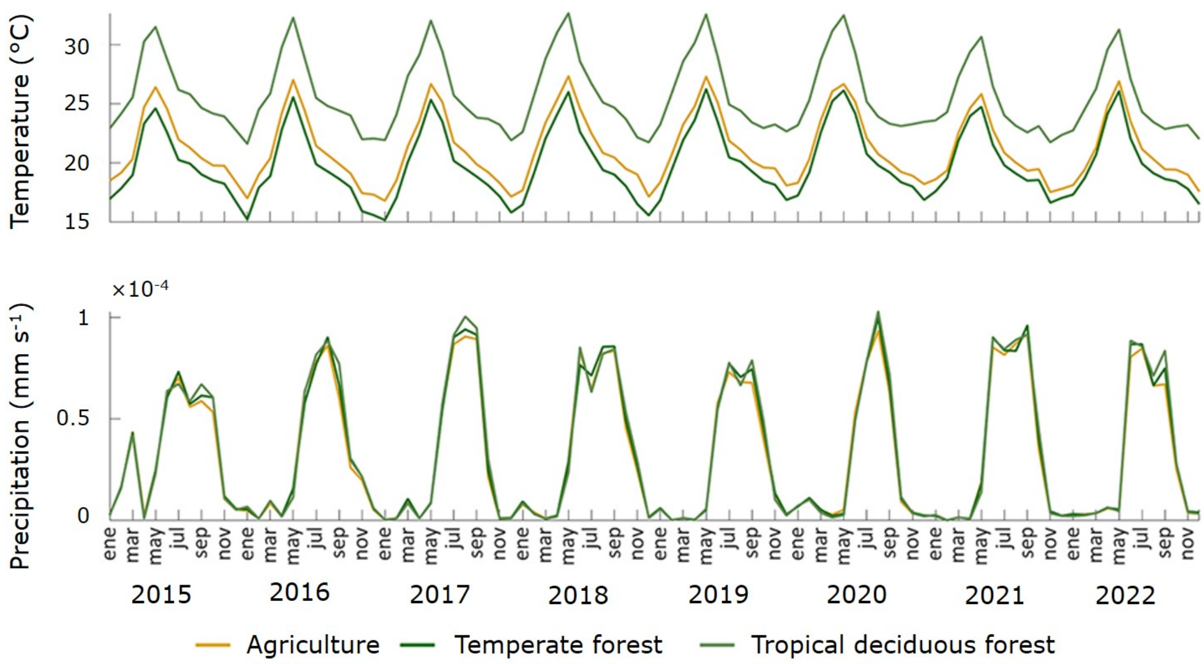
Figure 5. Monthly variation of the average fire detections in the main coverages of *Michoacán* and its distribution by coverage, in the period 2015 to 2022 (MCD64A1 data).



Ene = January; *Mar* = March; *May* = May; *Jul* = July; *Sep* = September; *Nov* = November.

Figure 6. Fire detections in the main coverage areas by month and year in *Michoacán* between 2015 and 2022 (MCD64A1 data).

Figure 7 shows the variation by month and year of the analyzed climatic variables corresponding to the vegetable covers of agriculture, temperate forest and tropical deciduous forest, with their respective secondary vegetation. Agriculture and the temperate forest are located in similar climatic zones, with annual averages in the period of 21.17 °C and 19.92 °C, respectively, while in the tropical deciduous forest the temperatures are higher, with a general average of 25.64 °C. Precipitation is similar throughout the territory, with small differences between coverage at the peaks of the rainiest months.



Ene = January; *Mar* = March; *May* = May; *Jul* = July; *Sep* = September; *Nov* = November.

Figure 7. Average temperature and precipitation by month and year from 2015 to 2022 for the main vegetable covers (GLDAS data).

Analysis by year

The year 2015 started cold and rainy; temperatures were relatively low until June, particularly in March and May; however, starting in July they were higher than in the other years studied, with a particularly mild autumn. There was exceptionally heavy rain in March, and May was also a wetter-than-normal month, which favored a longer, though less intense, rainy season that lasted into October. These climatic conditions helped limit the number of forest fires. The main events correspond to burning in irrigated agriculture, in *José Sixto Verduzco*, *Angamacutiro*, *Vista Hermosa*, *Briseñas*, *Pajacuarán*, *Venustiano Carranza*, *Tepalcatepec*, *Huetamo*, *Tuzantla* and *Coeneo* municipalities. There were fires in tropical deciduous forests, some in October, in *Apatzingán*, *Arteaga* and *Lázaro Cárdenas*.

In 2016, temperatures were cold in general (compared to the studied years), particularly in November which was also a relatively rainy month. The fire season began in April and ended in June. It is the year in which most burnings were carried out in irrigated agriculture, which in winter were brought forward to November, specifically in *José Sixto Verduzco*, *Angamacutiro*, *Vista Hermosa*, *Pajacuarán* and *Cotija* municipalities. Major forest fires were detected in *Tocumbo*, *Purépero*, *Cherán*, *Chilchota*, *Zacapu*, *Tlazazalca*, *Penjamillo*, *Nuevo Urecho* and *Gabriel Zamora*.

In 2017, temperatures were similar to those of previous years, although March and November were less cold. Rains began in June and were intense from July to September, with a dry November. The first fires occurred in April, and in May they were less numerous than the other years, except 2018 and 2022. Agricultural fires in irrigation lands were detected in *José Sixto Verduzco*, *Angamacutiro* and *Ecuandureo*; fires in tropical deciduous forest in *Aquila* and *San Lucas*; and fires in temperate forests in *Huetamo*, *Madero* and *Coeneo*.

The year 2018 was warmer than previous years, particularly from January to April, and in July. After some particularly dry months of March and April, the rainy season began in May and was the longest of those analyzed, lasting until November; the month of June was very rainy; in contrast, in July it rained less than other years. After some events in February (burns in rainfed agriculture and fires in secondary vegetation of tropical deciduous forest), there were fires in April and May in all coverage; however, it was the month of May with the fewest fires among the years studied and there were no more for the rest of the year, which resulted, in general, in the year with the fewest events in the period, except for 2022. Areas of forest burned tropical deciduous in *Aquila* and *Arteaga*; burns were detected in rainfed agriculture in *Zacapu*, in addition to temperate forest fires in *Cherán*, *Zacapu*, *Tiquicheo*, *Zinapécuaro*, *Coeneo* and *Turicato*.

In the first half of 2019, temperatures were relatively high and rains began in June, and although they were not particularly abundant, they lasted until November. Fires started in April, and were less numerous this month than in previous years, increasing in May and continuing in June. Burns were carried out in irrigated agriculture in *José Sixto Verduzco*, *Vista Hermosa*, *Ecuandureo* and *Ixtlán*; more forest fires occurred than in previous years, specifically in *Chilchota*, *Madero*, *Huetamo*, *Nuevo Urecho* and *Apatzingán*.

As in the previous two years, in 2020 the temperatures were high from January to June, in April and June in particular, the latter being the least rainy of the period studied, and the same can be said of October; in contrast, February was rainy and August was the wettest of the entire series. The fires started in April, but were less numerous than other years; on the contrary, May and June reached the maximum number of fires of the period. Burning in irrigated agriculture was detected in *José Sixto Verduzco*, *Vista Hermosa*, *Pajacuarán* and *Ixtlán*; and forest fires in *Aguililla*, *Turicato* and *Tacámbaro*.

The year 2021 was very dry until April; after some rainfall in May, the rainy season was verified with a very rainy month of June; the rains continued heavy until September and ended in October. Temperatures were moderate until April, and from May to November they were the lowest of the years studied. This year the highest total number of fires of the period analyzed occurred. In particular, in the month of March there were more fires than in other years and mainly in April the fire record was broken; there were also events in May, but they ceased from June until December, when agricultural burnings were carried out in *José Sixto Verduzco*, *Vista Hermosa*, *Pajacuarán*, *Ixtlán* and *Zamora.* It is the year with the highest number of fires in temperate and tropical deciduous forests, as well as in secondary shrub/tree vegetation of tropical deciduous forests. Specifically, there were important fires in *Coalcomán*, *Tumbiscatío*, *Huetamo*, *Morelia*, *Coeneo*, *Zacapu*, *Cherán*, *Paracho*, *Chilchota*, *Purépero*, *Ziracuaretiro*, *San Lucas* and *Huetamo*. More than temperatures or precipitation, it may have been due to an effect of confinement due to the Covid-19 pandemic (MacCarthy *et al.*, 2023), which led to impunity and made surveillance and extinction efforts difficult (Chávez-Ortiz and Morón-Cruz, 2023).

In 2022 temperatures were moderate until May; however, starting in June they remained relatively low, similar to those of 2021. The first rainfall took place in June, which was a fairly rainy month, as was July; August and September were less rainy than other years. In contrast to 2021, it was the period with the fewest fires in the period studied. In particular, there were fewer fires in temperate and tropical deciduous forests, as well as in secondary shrub/tree vegetation of tropical deciduous forest. Burning in irrigated agriculture was detected in *José Sixto Verduzco*, *Vista Hermosa*, *Ixtlán* and *Pajacuarán*; forest fires in temperate forests of *Uruapan*, *Gabriel Zamora*, *Tancítaro* and *Tzintzuntzan*.

Discussion

In the state of *Michoacán*, the fire season corresponds to the dry season, in spring, when temperatures are high and the rainy season has not yet begun. This is naturally the case in subtropical zones, where the conditions conducive to the occurrence of this type of events occur annually: precipitation deficit, positive thermal anomalies and hydrologically stressed vegetation (Galván and Magaña, 2020). The frequency of fires is related to the seasonality of rainfall and drought, and more specifically, to the duration of the period of the year with a moisture deficit, in which there is available fuel and conditions for the spread of fire (Jardel *et al.*, 2014). However, these conditions by themselves are not sufficient to explain the high number of detections in the state: an average of 3 340.87 per year. The participation of a human factor is evident as the cause of direct ignition (Neger *et al.*, 2022a), associated with agricultural or forestry management practices, or the intention to make a change in land use (Chuvieco *et al.*, 2019).

The observed differences in mean temperature, and in particular changes in precipitation patterns (Neger *et al.*, 2022a), only partially explain the interannual variability of fires. For example, no negative ENSO anomalies (*El Niño* phenomenon) are observed, such as those in 2003, 2005 and 2011, which are related to huge fires that occurred in different parts of the country (Neger *et al.*, 2022a). The only notable climatic anomaly in the period studied was the atypical rain in March 2015, which could limit the number of forest fires that year. Another factor that may explain the lower incidence of fires in 2015 as well as in 2018 is the early start (March-April) of the rainy season in those years; however, this is an argument in a negative sense: it does not explain the occurrence of more fires in years with favorable conditions, but rather their limitation when these were not; in other words, since it started to rain, the producers had to stop burning.

Based on the analyzed data, 48 % of the events detected in *Michoacán* between 2015 and 2022 corresponded to agricultural burning. In the country, it is estimated that agricultural activities induce at least 40 % of fires, due to the traditional practice of slash and burn (Galván and Magaña, 2020). In particular, most of the fires that occur in Central and Southern Mexico have anthropogenic causes, mainly related to agricultural activities and socioeconomic factors, which concentrate in the most densely populated areas (Pompa-García *et al.*, 2018).

Likewise, the results obtained show that fires in rainfed agriculture begin in January and in irrigated agriculture in December, which confirms that the seasonality of fires in agricultural areas has an earlier start than the spring fire season, which coincides with the start of the dryland agricultural cycle (Pompa-García *et al.*, 2018; Galván and Magaña, 2020). In *Michoacán*, most of the burning associated with agriculture occurs in the North of the state, in the *Lerma-Santiago* depression, on the border with the states of *Jalisco* and *Guanajuato*, where fire is used as a "peasant tool" to eliminate weeds, encourage the regrowth of pasture for livestock, clean the plot of agricultural debris and/or kill pests (Farfán *et al.*, 2020).

As for forests, vulnerability to abnormally dry and warm climatic conditions, especially in periods of drought, depends on factors such as the proximity of agriculture and other human activities, or the accessibility to forest ecosystems (Galván and Magaña, 2020). Often, intentional logging for agricultural purposes results in forest fires, to some extent accidental; however, it is evident that most forest fires in *Michoacán* in recent years have been intentional, in order to change land use and expand areas for the production of crops, such as avocado (Bravo-Espinosa *et al.*, 2014; Galván and Magaña, 2020; Olivares, 2020).

The tropical deciduous forest, which occupies many natural areas of *Michoacán*, is a highly vulnerable type of vegetation, since, during the dry season from March to May, it tends to be highly flammable (Galván and Magaña, 2020). The data analyzed show that the fires detected in this coverage essentially correspond to secondary vegetation, which indicates that there is recurrence in disturbed areas.

Conclusions

In order to know the incidence of fires in the state of *Michoacán* and its relationship with the climate, the MODIS MCD65A1 series was analyzed, together with the GLDAS temperature and precipitation series corresponding to the period 2015 to 2022, through the Inegi Series VII to distinguish the types of coverage affected. In general, climatic conditions do not explain the high number of fires, with an annual average of 3 340.87 detections, although an early start of the rainy season coincides with the years that accumulate fewer incidents (2015 and 2018). In 2021, the maximum number of detections was recorded, with 5 269, especially in April, which could have been caused by a particularly dry environment, which coincides with the confinement due to the Covid-19 pandemic; in contrast, the minimum is recorded in 2022, with 2 398.

The participation of a human factor is evident, in particular due to the use of fire for agricultural practices, mainly irrigated agriculture, which represent almost half of the detections, in particular in the *Lerma-Santiago* depression, North of the state.

Detections in temperate forests account for a third of the total and affect forests more than secondary vegetation; in areas of tropical deciduous forest, fires occur more in secondary vegetation, which indicates the recurrence of disturbances.

Time series derived from satellite data, together with climate data and types of coverage, allow global and objective monitoring of fires, and achieve an understanding of the general panorama of this problem. On the other hand, high-resolution satellite images contribute to a more detailed analysis of particular cases.

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Conflict of interests

The authors declare no conflict of interest.

Contribution by author

María Luisa España Boquera: analysis and interpretation of data and writing of the manuscript; Omar Champo Jiménez: downloading and processing data and building graphs; María Dolores Uribe Salas: interpretation of the results and revision of the manuscript.

References

Bravo-Espinosa, M., M. E. Mendoza, T. Carlón A., L. Medina, J. T. Sáenz-Reyes and R. Páez. 2014. Effects of converting forest to avocado orchards on topsoil properties in the Trans-Mexican volcanic system, Mexico. Land Degradation & Development 25(5):452-467. Doi: 10.1002/ldr.2163.

Champo J., O., M. D. Uribe S. y M. L. España B. 2023. Validación comparativa de detección de áreas quemadas PROBA-V/MODIS/Sentinel-2 en Michoacán, México (2015-2020). Investigaciones Geográficas 112:e60774. Doi: 10.14350/rig.60774.

Chávez-Ortiz, P. y J. A. Morón-Cruz. 2023. Efectos de la pandemia por COVID-19 en la contaminación ambiental. *In*: Oyama, K. y F. García-Oliva (Coords.). La década COVID en México: los desafíos de la pandemia desde las ciencias sociales y las humanidades. Tomo 14: Ecología, medio ambiente y sustentabilidad. Escuela Nacional de Estudios Superiores Unidad Morelia de la Universidad Nacional Autónoma de México. Coyoacán, Cd. Mx., México. pp. 343-365. https://decadacovid.humanidades.unam.mx/wp-content/uploads/DCM_tomo-14_ecolog-medio-ambiente-sustentabilidad.pdf. (6 de diciembre de 2023).

Chuvieco, E., F. Mouillot, G. R. van der Werf, J. San Miguel, … and L. Giglio. 2019. Historical background and current developments for mapping burned area from satellite Earth observation. Remote Sensing of Environment 225:45-64. Doi: 10.1016/j.rse.2019.02.013.

Comisión Nacional Forestal (Conafor). 2024. Historial de incendios forestales. https://monitor_incendios.cnf.gob.mx/incendios-graficos-animados-barra. (12 de mayo de 2024).

Durán C., V. y F. Sevilla P. (Coords.). 2003. Atlas geográfico del Estado de Michoacán. Secretaría de Educación del Estado de Michoacán, Universidad Michoacana de San Nicolás de Hidalgo y EDDISSA. Morelia, Mich., México. 308 p.

Farfán G., M., A. Flamenco S., C. R. Rodríguez P., L. Rodrigues de Sousa S., I. González G. y Y. Gao. 2020. Cartografía de la probabilidad de ocurrencia a incendios forestales para el estado de Guanajuato: Una aproximación antrópica de sus fuentes de ignición. Acta Universitaria 30:1-15. Doi: 10.15174/au.2020.2953.

Galván, L. and V. Magaña. 2020. Forest fires in Mexico: An approach to estimate fire probabilities. International Journal of Wildland Fire 29(9):753-763. Doi: 10.1071/WF19057.

Giglio, L., L. Boschetti, D. P. Roy, M. L. Humber and C. O. Justice. 2018. The Collection 6 MODIS burned area mapping algorithm and product. Remote Sensing of Environment 217:72-85. Doi: 10.1016/j.rse.2018.08.005.

Giglio, L., L. Boschetti, D. Roy, A. A. Hoffmann, M. Humber and J. V. Hall. 2020. Collection 6 MODIS Burned area product user´s guide. Version 1.3. National Aeronautics and Space Administration (NASA). Washington, D. C., United States of America. 34 p. https://lpdaac.usgs.gov/documents/875/MCD64_User_Guide_V6.pdf. (6 de diciembre de 2023).

Giglio, L., W. Schroeder, J. V. Hall and C. O. Justice. 2021. MODIS Collection 6 and Collection 6.1 Active fire product user´s guide. Version 1.0. National Aeronautics and Space Administration (NASA). Washington, D. C., United States of America. 64 p. https://modis-fire.umd.edu/files/MODIS_C6_C6.1_Fire_User_Guide_1.0.pdf. (27 de marzo de 2023).

González G., I., M. Farfán G., L. M. Morales M., D. R. Pérez S., J. J. Garza S. y A. Medina P. 2023. Índices y modelos para la predicción de la ocurrencia de incendios forestales: una revisión para México. Revista Geográfica de América Central 2(71):193-219. Doi: 10.15359/rgac.71-2.7.

González-Gutiérrez, I., J. F. Mas-Caussel, L. M. Morales-Manilla and K. A. Oceguera-Salazar. 2020. Thematic accuracy of hotspots and wildfires in Michoacán, Mexico. Revista Chapingo Serie Ciencias Forestales y del Ambiente 26(1):17-35. Doi: 10.5154/r.rchscfa.2019.01.011.

Instituto Nacional de Estadística y Geografía (Inegi). 2019. Carta de uso de suelo y vegetación de México, Serie VII, Escala 1:250 000. Inegi. https://www.inegi.org.mx/temas/usosuelo/#Descargas. (12 de mayo de 2024).

Jardel P., E. J., D. Pérez S., E. Alvarado y J. E. Morfín R. 2014. Principios y criterios para el manejo del fuego en ecosistemas forestales: guía de campo. Comisión Nacional Forestal (Conafor). Zapopan, Jal., México. 59 p. https://www.researchgate.net/publication/288827174_Principios_y_criterios_para_el_manejo_del_fuego_en_ecosistemas_forestales. (6 de diciembre de 2023).

Jones, M. W., J. T. Abatzoglou, S. Veraverbeke, N. Andela, … and C. Le Quéré. 2022. Global and regional trends and drivers of fire under climate change. Reviews of Geophysics 60(3):e2020RG000726. Doi: 10.1029/2020RG000726.

Justice, C., L. Giglio, L. Boschetti, D. Roy, … and Y. Kaufman. 2006. Algorithm technical background document. MODIS fire products. National Aeronautics and Space Administration. Washington, D. C., United States of America. 34 p. https://modis.gsfc.nasa.gov/data/atbd/atbd_mod14.pdf. (10 de junio de 2023).

Llorens, R., J. A. Sobrino, C. Fernández, J. M. Fernández-Alonso and J. A. Vega. 2021. A methodology to estimate forest fires burned areas and burn severity degrees using Sentinel-2 data. Application to the October 2017 fires in the Iberian Peninsula. International Journal of Applied Earth Observation and Geoinformation 95:102243. Doi: 10.1016/j.jag.2020.102243.

MacCarthy, J., J. Richter, S. Tyukavina, M. Weisse and N. Harris. 2023. *The Latest Data Confirms: Forest Fires Are Getting Worse*. https://www.wri.org/insights/global-trends-forest-fires. (6 de diciembre de 2023).

Manzo D., L. de L. 2016. Incendios forestales de gran relevancia: algoritmos y sensor MODIS para su detección y monitoreo. *In*: Moncada M., O. y Á. López L. (Coords.). Geografía de México. Una reflexión espacial contemporánea. Instituto de Geografía de la Universidad Nacional Autónoma de México. Coyoacán, Cd. Mx., Mexico. pp. 334-349. http://www.publicaciones.igg.unam.mx/index.php/ig/catalog/book/105. (12 de mayo de 2024).

Neger, C., J. F. León-Cruz, L. Galicia S. y L. de L. Manzo-Delgado. 2022a. Dinámica espaciotemporal, causas y efectos de los megaincendios forestales en México. Madera y Bosques 28(2):1-21. Doi: 10.21829/myb.2022.2822453.

Neger, C., L. de L. Manzo D. y L. Galicia S. 2022b. La investigación geográfica de los incendios forestales en México: una perspectiva bibliométrica y territorial. Investigaciones Geográficas 108:e60488. Doi: 10.14350/rig.60488.

Olivares M., L. D. 2020. Regímenes de incendios y sus efectos en suelos forestales de la franja aguacatera. Tesis de Maestría en Ecología Integrativa. Instituto de Investigaciones sobre los Recursos Naturales. Universidad Michoacana de San Nicolás de Hidalgo. Morelia, Mich., México. 142 p.

Pompa-García, M., J. J. Camarero, D. A. Rodríguez-Trejo and D. J. Vega-Nieva. 2018. Drought and spatiotemporal variability of forest fires across Mexico. Chinese Geographical Science 28(1):25-37. Doi: 10.1007/s11769-017-0928-0.

Quantum Geographical Information System (QGIS). 2024. QGIS 3.22. Santa Cruz, CA, United States of America. QGIS. https://www.qgis.org/en/site/forusers/download.html. (12 de mayo de 2024).

Rui, H. and H. Beaudoing. 2022. README Document for NASA GLDAS Version 2 Data Products. NASA Goddard Space Flight Center. Greenbelt, MD, United States of America. 34 p. https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/GLDAS_NOAH025_M.2.1/doc/README_GLDAS2.pdf. (4 de diciembre de 2023).

Rzedowski, J. 2006. Vegetación de México. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (Conabio). Tlalpan, D. F., México. 504 p.

Sentinel Application Platform (Snap). 2024. Copernicus Data Space Ecosystem (Snap v. 8.0). Paris, Par., France. European Space Agency. https://step.esa.int/main/download/snap-download/. (12 de mayo de 2024).

Szpakowski, D. M. and J. L. R. Jensen. 2019. A review of the applications of remote sensing in fire ecology. Remote Sensing 11(22):2638. Doi: 10.3390/rs11222638.

Villar-Hernández, B. de J., S. Pérez-Elizalde, D. A. Rodríguez-Trejo and P. Pérez-Rodríguez. 2022. Spatio-temporal analysis of wildfires occurrence in the Mexican State of *Oaxaca*. Revista Mexicana de Ciencias Forestales 13(74):120-144. Doi: 10.29298/rmcf.v13i74.1274.

Zúñiga-Vásquez, J. M., D. Cisneros-González, M. Pompa-García, D. A. Rodríguez-Trejo and G. Pérez-Verdín. 2017. Spatial modeling of forest fires in Mexico: an integration of two data sources. Bosque 38(3):563-574. Doi: 10.4067/S0717-92002017000300014.