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Fires and their key drivers in Mexico

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ABSTRACT

Background. Despite the regional and global effects of biomass burning at national and pantropical scales, little effort has focused on determining the influence of climate and socio-economic conditions on fire regimes in tropical regions. **Aims.** We explored the climate and human factors that explain remotely sensed burnt area and fire abundance in Mexico. **Methods.** We used MCD64A1 data and climate and socioeconomic metrics to understand factors explaining the variation in number of fires and burned area. **Key results.** The largest burned area (41.9% of the total) occurred in temperate forests, grasslands and hydrophilic vegetation, with numerous fire events of medium relative size. The next most extensive burned area (38%) was observed in croplands, with numerous small-size fires. The third group (17.8%) occurred in tropical forests, which had the smallest and most frequent fires. Finally, a fourth group (11.9%) was composed of shrublands, which showed the largest fire sizes and lowest-frequency events. The variability of burned area was related to variations in temperature and precipitation, poverty index, altitude, and distance to water bodies. **Conclusions and Implications.** Our analysis suggests that an assessment integrating climate, human and topo-graphic metrics predicts burned area and may improve fire forecasting in Mexico landscapes.

Keywords: biomass burning, burned area, climate, fires, fire frequency, human influences, key drivers, seasonal, spatial.

Introduction

Earth Observation satellites estimate that ~4 million km^2 are burned globally every year (Lizundia-Loiola *et al.* 2020), affecting mainly savannas and tropical dry forests (Yin *et al.* 2020; Zheng *et al.* 2021; Corona-Núñez and Campo 2023). Changes in the total burned area have recently been observed, raising serious concerns about how they will develop in response to projected future changes in climate and land uses (Bond *et al.* 2005; Pausas and Ribeiro 2017; Pausas and Keeley 2021; Haas *et al.* 2022). Despite the regional and global-scale effects of fires on the global carbon (C) cycle and biodiversity conservation, little effort has been dedicated to understanding the influence of climate and socio-economic conditions on fire regimes (Archibald *et al.* 2018; Kelley *et al.* 2019). Moreover, with increasing pressure on natural ecosystems from humans, global-scale studies suggest that these human factors could be among the dominant controls on fire dynamics in many regions (Haas *et al.* 2022; Wu *et al.* 2022).

Fire effects are very diverse, including on C emissions, vegetation dynamics and biodiversity and soil nutrients (Bruun *et al.* 2009; Lasslop *et al.* 2019; Pausas and Keeley 2019; McLauchlan *et al.* 2020; Agbeshie *et al.* 2022). For example, Akagi *et al.* (2011) estimated global emissions from biomass burning at 2.55 Pg C per year, with a tropical contribution of 1.27 Pg C (Randerson *et al.* 2012). Although fire is a natural factor in different ecosystems, helping to promote diversity and natural regeneration (Kelly and Brotons 2017; Archibald *et al.* 2018; Kelly *et al.* 2020), fire return intervals have been affected by human activities (Benali *et al.* 2017; Earl and Simmonds 2018). However, changes in the frequency and size of fires in recent decades have been also associated with exceptionally warm and dry conditions, and fire are then more probable as a result of climate change (Cochrane and Ryan 2009; Kirchmeier-Young *et al.* 2019;

Bowman *et al.* 2020; Collins *et al.* 2022), but their interactions with human activities are far from being comprehensively understood (Harrison *et al.* 2021). Although the most common factors that drive fires are climate conditions (particularly those affecting vegetation abundance and extent and intensity of water deficit as drought), contributions from demographic and socioeconomic changes, such as population growth, gross domestic product and cropland expansion play an important role in fire propagation (Archibald *et al.* 2009; Andela *et al.* 2017; Forkel *et al.* 2019; Corona-Núñez and Campo 2023). The combinations of all the previous factors drive a large variability in fire characteristics, which results in the creation of mosaics of different states of ecosystem regeneration and promote environmental heterogeneity (Turner 2005; McKenzie *et al.* 2011; Cardinale *et al.* 2012). Thus, knowledge of the environmental factors driving patterns of area burned is crucial for native ecosystem conservation where changing climate and fuel management practices are likely to drive shifts in fire regimes.

It is recognised that the tropics are involved in a high proportion of the global fires, including high fire density (Chuvieco *et al.* 2008; Corona-Núñez and Campo 2023). These fires are a serious ecological threat to tropical region biodiversity. For example, Mexico, with a total of 55 terrestrial ecoregions (Fig. S1), has the largest diversity of terrestrial ecoregions in the Americas and suffers a high density of fires (Corona-Núñez *et al.* 2020). The long dry season from November to May in Mexican forests, grasslands and shrublands and the high rate of fuel load accumulation during this rainless period favour extensive biomass burning (Myers and Rodríguez-Trejo 2009; CONAFOR 2020), C emissions (Corona-Núñez *et al.* 2020) and loss of biodiversity (Manson and Jardel Peláez 2009). Moreover, C emissions from fires in Mexico are responsible for 5% of the pantropical C emissions by fires with an significant increase in the last decade (Corona-Núñez *et al.* 2020). Moreover, Mexican C emissions from fires are accelerating over the global standard, probably owing to climate change in drylands (Krawchuk *et al.* 2009; Pechony and Shindell 2010), as is the case of the country. For example, Corona-Núñez *et al.* (2020) found that the national C fire emissions increased exceeded the global average increase in three times during. Consequently, understanding drivers of fires is a major keystone for fire-mitigation strategies, ecosystem services and biodiversity conservation in the country.

Although past studies of climate drivers of Mexican fire have focused mainly on the El Niño–Southern Oscillation (ENSO), identifying spatiotemporal heterogeneous responses in precipitation and the resulting fire activity and C emissions (Corona-Núñez *et al.* 2020), limited effort has been devoted to addressing the climate drivers and human influences on fire activity due to traditional uses of fire in slash-and-burn agriculture. Motivated by these gaps in our knowledge of climate and human influences on fires in Mexico, the aims of this study are to assess the spatiotemporal variability of fires in terms of number of fires and burned area in Mexico, and provide further insights into the state of knowledge of interactions between climate and human factors on Mexican fires. For that purpose, we use gridded environmental and social data in Mexico to examine trends and environmental and social drivers of burned area and the proportion of the main ecosystems that were impacted by fires from 2001 to 2020. We focus on fires $\geq 0.25\ km^2$ because they account for more than 95% of the area burnt across the country (CONAFOR 2020) and can have the greatest impact on the environment and society. Finally, this study shows the variability in drivers and severity of fires among different ecosystems, namely both tropical and temperate forests, grasslands, shrublands, croplands, and other vegetations (halophilic and hydrophilic vegetation, mangroves, riparian vegetation and coastal dune vegetation).

Materials and methods

Fire identification

We used Google Earth Engine (GEE) for fire data acquisition (Gorelick *et al.* 2017). The fire dataset consisted of the MCD64A1 product from MODIS (Giglio *et al.* 2021) included in the Earth Engine Data Catalogue in GEE. MCD64A1 returns fire boundaries with a spatial resolution of 500 m and employs MODIS surface reflectance imagery coupled with active fire observations. To address limitations of the MCD64A1 product, we tested the assumption that MCD64A1 data were representative of other fire products and not biased owing to omission errors: the distribution of MCD64A1 fire data was compared with those recorded in the field by CONAFOR (2020), and the spatial distribution was similar (similarity above 78% was observed for each year). In addition, validation of the MODIS burned area product relies mainly on the use of high-resolution Landsat scenes (Boschetti *et al.* 2019), and quality assurance dataset indicators discard persistent hot spots, too few training observations, or insufficient spectral separability between burned and unburned classes (Artés *et al.* 2019). The frequency of fire includes annual information in raster format considering 500-mburned pixels, for which the addition of raster layers was calculated by map algebra in a single layer with values from 0 (lack to fire) to 20 (at least one fire per year over the 20 years of the study period) and finally vectorised into polygons.

Almost all the fires on cropland are intentional (fire management) and even those that occur in native ecosystems are also usually attributable to humans; in >90% of cases, the fires result from human intervention (Balch *et al.* 2017; Bowman *et al.* 2020). As with the methodology used it is not possible to infer fire origin, prescribed burns and wildfires were treated without distinction. Thus, the number of fires refers to the fire events recorded every Julian day and grouped by month and year analysed. We performed a wall-to-wall monthly analysis of Mexico for the period 2001–2020. The study considers the terrestrial part of Mexico (1 932 524 km^2) at 500-m spatial resolution.

We related all the fire data to Mexico's most complete and detailed land-use/land-cover maps. These maps were developed by the National Institute of Statistics and Geography (INEGI) for the years 2002, 2005, 2009, 2015, and 2017 (INEGI 2003, 2005, 2009, 2013, 2017). All the maps were reclassified into seven land-use/cover types; these classes consisted of (i) temperate forests, (ii) tropical dry forests, (iii) tropical rainforests, (iv) shrublands, (v) grasslands, (vi) croplands, and (vii) other, which includes halophilic and hydrophilic vegetation, mangroves, riparian vegetation and coastal dune vegetation, similar classifications to others (Mendoza-Ponce *et al.* 2020).

Explanatory variables

To identify the main influences on fires, we related the site conditions of fires to local climate, topographic, and socioeconomic variables for each fire event (Table 1). We included a set of 32 explanatory variables (20 climatic, 5 topographic, and 7 socioeconomic variables).

Several studies have demonstrated the utility of large-scale climatic factors for regional fire prediction (Keeley 2004; Brey *et al.* 2021; Wang *et al.* 2021), while weather conditions are usually analysed as drivers that modulate variations in ignition efficiency (Andela *et al.* 2017; van der Werf *et al.* 2017). Climatic variables such as temperature and precipitation have been recognised as key drivers of moisture availability and fire propagation (Archibald *et al.* 2009), and fuel moisture has long been recognised as a major component of fire danger (Dupuy *et al.* 2020), because components of fire activity such as number of fires or burned area are known to respond positively to increasing fuel dryness (Flannigan *et al.* 2009; Turco *et al.* 2017). To evaluate the climatic influencers, we included the 19 bioclimatic variables (Bio 1–Bio 19) taken from WorldClim (Fick and Hijmans 2017); these variables consist of 11 variables related to temperature and 8 related to precipitation, and their seasonal changes. Additionally, we evaluated water deficiency based on the Lang aridity index (Trabucco and Zomer 2019) as the ratio of mean annual precipitation and mean annual temperature (mm per °C) as precipitation and temperature alone have been shown to be inadequate to measure hydrological conditions (Quan *et al.* 2013). This index suggests that the rise in temperature increases water deficiency and makes the air drier.

The topographic features include altitude, slope and the Euclidian distance to water bodies and rivers. The topographic data were derived from a digital terrain model with a spatial resolution of 90 m from the Shuttle Radar Topography Mission V.2.1 (Farr *et al.* 2007). From it, we derived the altitude and the slope at 500-m resolution. Finally, to evaluate the influence of human activities on fires, we evaluated different socioeconomic conditions such as the Euclidian distance to protected areas (CONANP 2014), roads (Meijer *et al.* 2018), and human settlements. Complementarily, we used the gross domestic product, population size and social marginalisation index at the municipality level (CONAPO 2011). All the spatial information was rescaled to a common grid cell of 1 km for further analysis. Table 1 provides a summary of all the variables used in this study, as well as their sources.

Statistical analysis

We used the Wilcoxon rank-sum test (*W* test) with continuity correction to test the statistical similarity between observations if the observations came from independent samples with different variances. Comparison of fire number and size and burned area across ecosystems (covers) involved one-way analysis of variance (ANOVA). We used Principal Component Analysis (PCA) to associate climatic and socioeconomic influences on the number of fires and burned area. The PCA analysis allows the dimensionality of interrelated variables to be reduced, providing insights about their interrelations, and suggesting simpler interpretations of the original data while retaining most of the variance of the original dataset (Afifi *et al.* 2019). However, PCA solves the multicollinearity problem by creation of the components among the original explanatory variables. PCA tests were performed with a 95% confidence level by means of the libraries *raster* (Hijmans *et al.* 2020), *pcaMethods* (Stacklies *et al.* 2007), and *factoextra* (Kassambara and Mundt 2020). All statistical tests were performed in R software version 3.5.2 (R Core Team 2018).

Results

Variability of fire number and burned area

The number of fires and burned area showed large variability across years (by a factor of three in the case of number of fires, and by a factor of six in the case of burned area) (Fig. 1; Tables S1, S2). The mean number of annual fire events was 12 424 ± 799 (mean ± 1 s.e.), with the lowest number registered in 2014 (5563) and the maximum in 2003 (18 617) (Fig. 1, Table S1). Fires affected a mean annual extent of 28 955 ± 2697 km^2. Overall, a strong positive relationship was observed between the annual number of fires and the annual burned area ($R^2 = 0.71$, $P < 0.001$) (Fig. S2). During the year 2011, after the strongest La Niña event during the study period, the largest total burned area was recorded; meanwhile, in 2015, after a weak El Niño year (2014–2015), the lowest burned area was observed.

The intra-annual variability of both the number of fires (Fig. 2*a*) and burned area (Fig. 2*b*) shows that the highest number of fires and burned areas were recorded in May

Table 1. Climatic, topographic and socioeconomic metrics selected.

Metric	Units	Abbreviation	Source
Climatic			
Annual mean temperature	°C	bio1	WorldClim
Annual precipitation	mm	bio12	WorldClim
Isothermality [(bio2/bio7) (×100)]	°C	bio3	WorldClim
Lang aridity index (bio12/bio1)	mm/°C	Lang	WorldClim
Maximum temperature of warmest month	°C	bio5	WorldClim
Mean diurnal range [mean monthly (max temp–min temp)]	°C	bio2	WorldClim
Mean temperature of coldest quarter	°C	bio11	WorldClim
Mean temperature of driest quarter	°C	bio9	WorldClim
Mean temperature of warmest quarter	°C	bio10	WorldClim
Mean temperature of wettest quarter	°C	bio8	WorldClim
Minimum temperature of coldest month	°C	bio6	WorldClim
Precipitation of coldest quarter	mm	bio19	WorldClim
Precipitation of driest month	mm	bio14	WorldClim
Precipitation of driest quarter	mm	bio17	WorldClim
Precipitation of warmest quarter	mm	bio18	WorldClim
Precipitation of wettest month	mm	bio13	WorldClim
Precipitation of wettest quarter	mm	bio16	WorldClim
Precipitation seasonality (coefficient of variation)	mm	bio15	WorldClim
Temperature annual range (bio5–bio6)	°C	bio7	WorldClim
Temperature seasonality (standard deviation × 100)	°C	bio4	WorldClim
Topographic and others			
Altitude	m	alt	NASA
Distance to rivers	m	riv	INEGI
Distance to protected natural areas	m	pna	CONANP
Distance to water bodies	m	bw	NASA
Slope	°	slp	NASA
Socioeconomic			
Distance to urban settlements	m	urb	INEGI
Distance to mud roads	m	trk	INEGI
Distance to paved roads	m	rd	INEGI
Distance to rural localities	m	rur	INEGI
Gross domestic product	Million Mexican pesos	gdp	INEGI
Population	Number of people	pop	INEGI
Poverty index	Ranked	pi	CONAPO

(40.0 ± 2.02 and 36.0 ± 1.58% of the total annual events and annual burned area, respectively). In contrast, the lowest were recorded from August to November (accounting for 3.2 ± 0.57% of the total annual number of events, and 3.2 ± 0.64% of the annual burned area).

On an annual basis, there is a large variability in the number of fires and burned area among ecosystems (Fig. 3, Tables S1, S2). The largest number of fires was observed in croplands (with an annual mean of 46.8 ± 1.53% of the total number of events), followed by

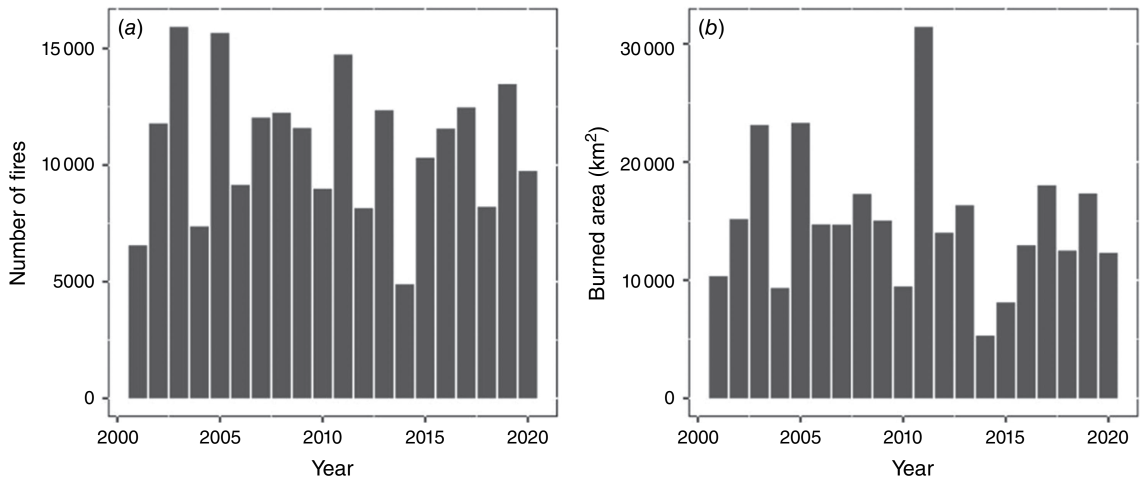

Fig. 1. Time series for total (*a*) number of fires, and (*b*) burned area from 2001 to 2020.

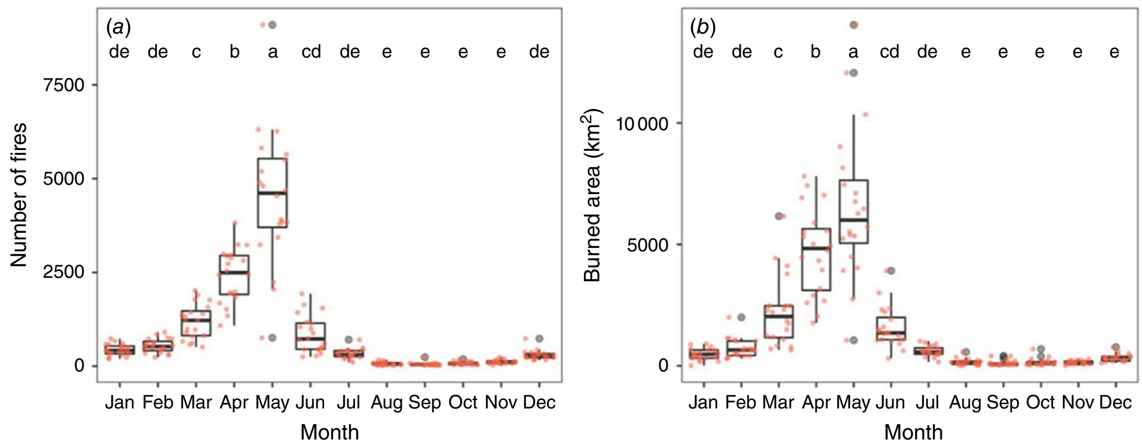

Fig. 2. Boxplot of monthly (*a*) number of fires, and (*b*) burned area from 2001 to 2020. Red dots represent monthly observations for each evaluated year. Outliers are represented with grey dots. Different letters represent different clusters ($P < 0.05$).

the forest ecosystems (i.e. tropical and temperate forests) that comprised ~44% of the total number of fire events (22.9 ± 1.08 in tropical forests and 20.6 ± 1.33% in temperate forests, respectively). Across tropical forests, tropical dry forests were more affected (59.0 ± 2.52% of the total fires in the tropical forest biome) than their humid counterpart (41.0 ± 2.47%) ($P < 0.05$). The remaining fire events occurred in other vegetations (i.e. halophilic and hydrophilic vegetation, mangroves, riparian vegetation and coastal dune vegetation), grasslands and shrublands (5.1 ± 0.10, 3.7 ± 0.14 and 0.8 ± 0.09%, respectively). Across native covers, the contribution of each ecosystem type to the total burned area decreased following the order temperate forests > tropical forests (tropical dry forest plus tropical rainforest) > other vegetation ≈ grassland (Fig. 3, Table S2).

Fire sizes also show large variability among covers (Fig. 4). Small-sized fires (<1.0 km^2) were the most common, and their contribution to the total burned area in each cover decreased following the order: tropical rainforests (71.6%) > tropical dry forests (68.9%) > croplands (68.8%) > temperate forests (60.3%) > grasslands (56.3%) > shrublands (50.0%) ($P < 0.05$). We found a decreasing gradient in the mean fire size in the direction shrublands > grasslands > temperate forests > other vegetation > tropical dry forests ≈ tropical rainforests ≈ croplands (Fig. S3, Table S3). On average, 2.7 ± 0.36% of the total temperate forest surface in the country was burned annually, 1.3 ± 0.20% of tropical dry forest, 2.2 ± 0.44% of the tropical rainforest, 0.1 ± 0.03% of shrubland, 1.0 ± 0.14% of grassland, 2.4 ± 0.20% of croplands, and 1.5 ± 0.19% of other vegetation (Fig. S4).

The fire return interval differed considerably across Mexico (Fig. 5). The corresponding ANOVA indicated that difference is highly significant across ecosystems ($P < 0.01$) and

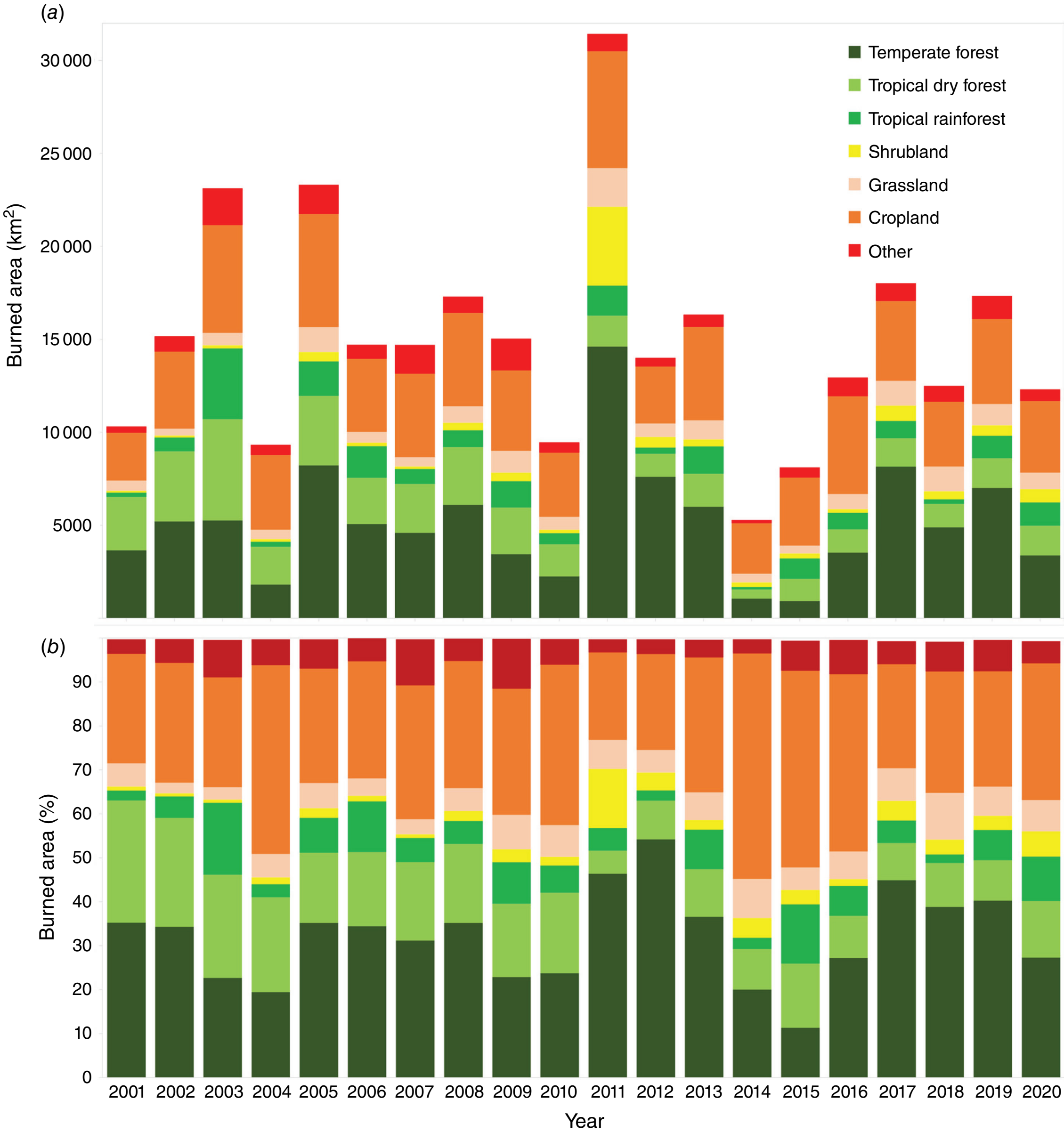

Fig. 3. Time series of the (*a*) total burned area from 2001 to 2020, and (*b*) its proportion by land cover.

paired comparisons using the Tukey–Kramer HSD (honestly significant difference) test show that plants in shrublands consistently suffered fewer fire events (fire return interval of 8.9 ± 0.44 year), while grasslands were the most frequently perturbed by fires (return interval of 6.5 ± 0.71 year). The remaining covers (tropical rainforests, 7.9 ± 0.55 year; tropical dry forests, 7.8 ± 0.60 year; temperate forests 7.6 ± 0.61 year; and croplands, 7.2 ± 0.65 year) constituted an intermediate, statistically homogeneous group ($P > 0.05$). Recurrent fires dominated the Pacific Coast and the Peninsula of Yucatan (Fig. 5), where tropical dry forest is the most abundant native vegetation. In contrast, less frequent fires were recorded in the north, where shrublands are the most representative ecosystem.

Factors of fire variability

The first three principal components (PCs) account for 58.0% of the total variability of the fire dataset (Fig. 6, Table S4). The PCA showed that burned area variability was related to climate variations in temperature (annual mean in the driest and in the coldest quarters, minimum in the coldest month and maximum in the warmest month) and precipitation amount (in the wettest month and the wettest quarter, i.e. in the three consecutive months that are wetter than any other set of three consecutive months). The PCA also indicated links of burned area with human factors (e.g. poverty index), altitude and distance to water bodies.

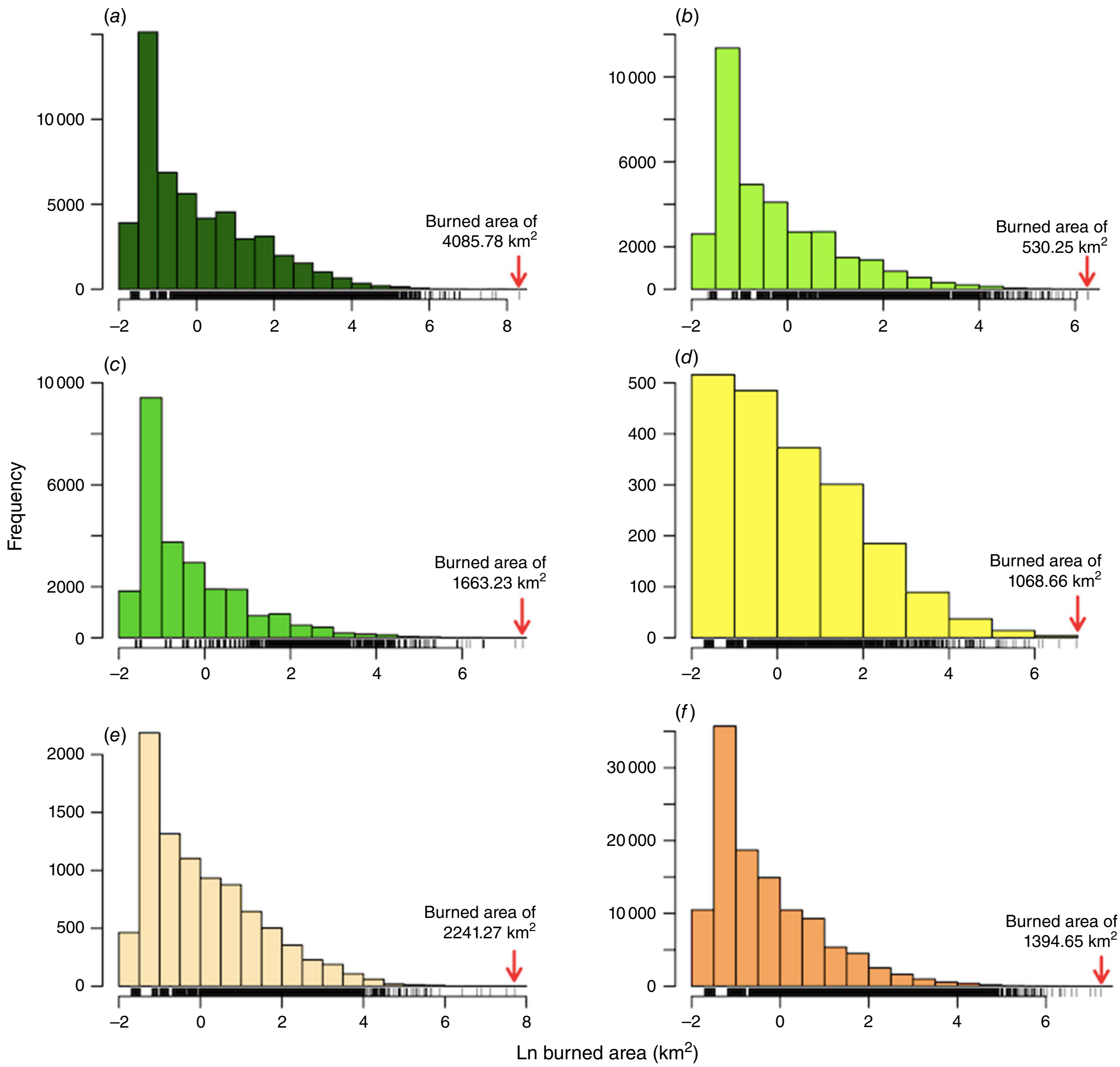

Fig. 4. Frequency of fire sizes by cover: (*a*) temperate forest, (*b*) tropical dry forest, (*c*) tropical rainforest, (*d*) shrubland, (*e*) grassland, and (*f*) cropland during the period from 2001 to 2020.

Climatic and human drivers influence fire frequency and the size of the burned area (Fig. 6*a*, *b*, Table S4). The frequency of fire includes annual information in raster format considering 500 m burned pixels, for which the addition of raster l ayers was calculated by map algebra in a single layer with values from 0 (lack to fire) to 20 (at least one fire per year over the 20 years of the study period) and finally vectorised into polygons. Polygons of burned area with low fire frequencies (less than 5 years with fire events recorded in the study period) were affected by all analysed climate, topographic and socioeconomic factors. More frequent fires across years (that occurred 5–15 years in the study period) showed influence of both precipitation amount and distribution. Finally, recurrent fires (more than 15 years with record of fire events) were influenced by slope, distance to water bodies and distance to urban and rural localities. Regarding fire size, small to medium-sized fires (less than 50 km^2) were influenced by many climate and socioeconomic factors. Larger fires (50–200 km^2) were influenced by seasonality in precipitation, topographic characteristics (altitude and slope) and humans. The largest fires ($\geq$200 km^2; megafires, as in Linley *et al.* 2022) were influenced by ranges in annual temperature, seasonality in precipitation and topographic factors (altitude and slope).

Drivers of fires differed considerably among ecosystems (Fig. 6*c*, Table S4). Fires in the temperate forest were driven by temperature (isothermality), topographic (slope) and human (all analysed metrics) factors. Fire drivers differed

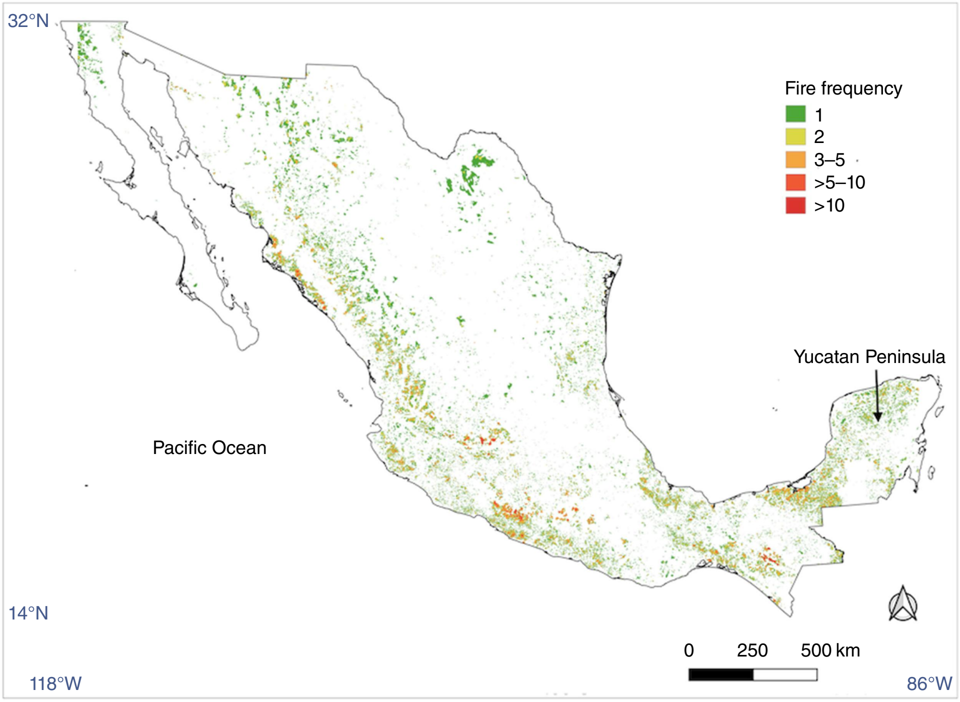

Fig. 5. Spatial distribution of fire frequencies (fire occurrence in each pixel) during the period 2001–2020. The fire frequencies varied from 0 (white, i.e. lack of fires) to 20 (at least one fire per year over the 20 years of the study period).

between tropical forest ecosystems. Fires in tropical dry forests were mainly influenced by human factors (distance to urban and rural localities and to roads), whereas in tropical rainforests, they were driven by temperature (isothermality) and extreme or limiting precipitation factors (precipitation in the driest month, in the driest quarter, in the warmest quarter and in the coldest quarter). Fires in shrublands were more influenced by the amplitude of temperature (mean diurnal range, temperature seasonality), the seasonality in precipitation and population density. Fires in croplands were influenced by temperature (isothermality and seasonality), extreme precipitation factors (precipitation of driest month, precipitation seasonality, precipitation of driest quarter, precipitation of coldest quarter) and human factors, while fires in grasslands were related to human factors and climate (mean diurnal range temperature, isothermality and seasonality in precipitation).

Discussion

Variability of fires in Mexico

Most of the Mexican ecosystems experience significant water limitation, with approximately 90% of the country's surface area experiencing an annual deficit of rainfall relative to evaporation demand (Díaz-Padilla *et al.* 2011), with 7 months of recurrent droughts (November to May). Correspondingly, plants experience a large period without water availability, except in the moist tropical rainforests and some areas with mountain temperate forests. Thus, the rainless period modulates both ecosystem function (Campo 2016) and C emissions by fires (Cruz-López and López-Saldaña 2011) that peak at the end of the dry season when the largest and driest wildland fuel accumulation occurs.

We show that small fires account for the largest proportion of burned area in the country. Furthermore, our data set of fire number and size (Tables S1–S3) allow us to identify four groups of burned area across ecosystems. The first, with the largest burned area (41.9% of the total burned area in the country) includes temperate forests, grasslands and hydrophilic vegetation, which show numerous fire events of relatively moderate size. The next most extensive burned area (38%) is observed in croplands, with abundant small-sized fires. A third group (17.8%) includes tropical forests (both dry forests and rainforests), with the smallest and most frequent fire events. Finally, the fourth group (11.9%) identified includes shrublands, which show the largest fire sizes and the least-frequent events. A remarkable observation from our results is the significant positive relationship of total burned area with fire frequency (Fig. S2), although a strong influence of climate was observed associated with the strongest La Niña event in 2011 when the largest burned area was recorded, suggesting a delayed positive effect of La Niña on fires probably owing to an increase in litter production. In

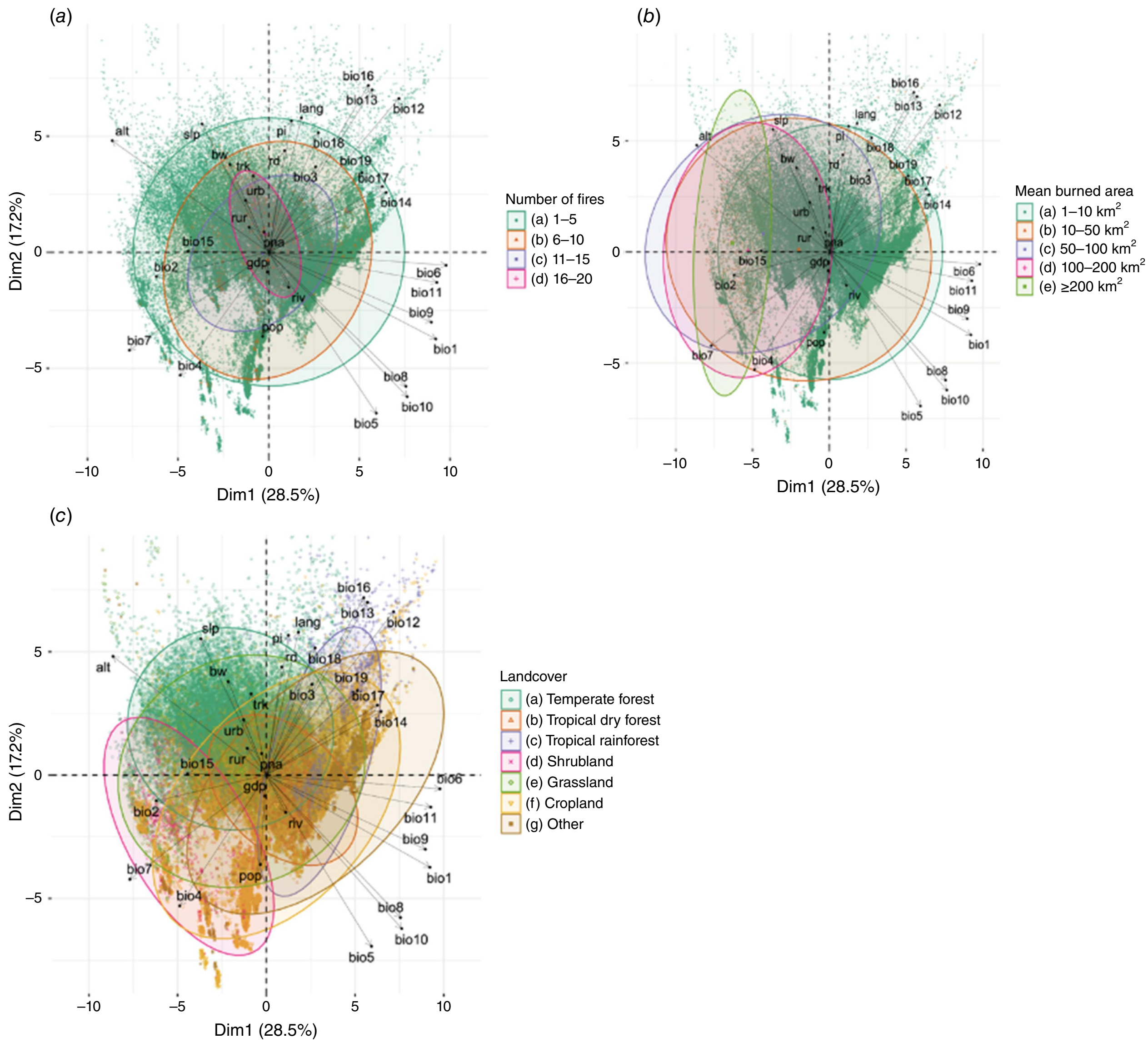

Fig. 6. Principal components analysis of (*a*) number of fires per year, (*b*) burned area (km^2 per year), and (*c*) land cover data. Details for variables codes are in Table 1.

contrast, after a weak El Niño year (2014–2015), the lowest burned area observed (year 2015 in Fig. S2) could be reflecting reduced litter accumulation. Our observations support those reported by others (Chen *et al.* 2017; Corona-Núñez *et al.* 2020).

We found that fire return interval (i.e. the prevailing period available for vegetation regeneration between fires) was highest in water-limited shrublands and lowest in grass fuel ecosystems with fast-growing plants (grasslands). The large and persistent C density in tropical forest ecosystems (Pan *et al.* 2011; Campo and Merino 2016) was burned every ~8 years irrespective of precipitation regime, a fire return interval similar to those observed in temperate forests. Although fast-growing trees suggest a rapid recovery of vegetation in tropical forests after burning, fires represent a threat to biological conservation in these remarkable endemic biodiverse ecosystems (Challenger and Soberón 2008), mainly in tropical rainforests where trees lack morphological and physiological adaptations to burning (Miller and Kauffman 1998; Rosell 2016). However, despite coniferous vegetation having developed strategies to cope with fire, C losses are expected from recently burned temperate forests owing to soil erosion (Saynes *et al.* 2012; Santín and Doerr 2019). Because of the long period required for plant regrowth in temperate forests and more frequent fires (Corona-Núñez *et al.* 2020), this ecosystem could experience a reduction of its C storage in biomass and soils. Aside from these short- and long-term scenarios, our study allows us to conclude that more forest fires without rapid recovery from natural regeneration or active restoration practices weaken the land C sink capacity in the following years.

To characterise the impact of fires across ecosystems, we estimated the fraction of vegetation cover that was burned each year. Our data indicate that the average burned surface is higher in temperate and tropical rainforests than in tropical dry forests. These results may contradict the hypothesis that the tropical dry forest biome is a fire-prone system (Corona-Núñez and Campo 2023) and demonstrate that fire disturbance in this forest ecosystem reflects direct (Fig. 6*c*) and indirect human influences owing to fire management in savannas located in tropical dry landscapes with forest savanna fringes (Galvin and Reid 2010; Zheng *et al.* 2021; de la Peña-Domene *et al.* 2022).

Drivers of fires in Mexico

Our analyses provide evidence of a climatically driven annual burned area and the proportion of native ecosystems that burnt in Mexico. Observed patterns in both fire number and burned area over the past two decades were driven primarily by extreme or limiting precipitation factors and temperature, mainly in temperate forests, tropical rainforests and grasslands. The currently identified ENSO influence, related to sea surface temperature anomalies, on the Mexican fires and burned area fraction in our study is largely consistent with previous conclusions that large fires are associated with anomalous drought (Canadell *et al.* 2021; Duane *et al.* 2021; Pausas and Keeley 2021). Drought affects the spatial connectivity of dry fine fuels and the frequency of surface weather conditions that promote rapid wildfire growth. The combination of dry fine fuels and fire weather conditions breaks down or reduces the influence of barriers to fire spread and facilitates the development of large wildfires (Nolan *et al.* 2016). However, prolonged and severe drought stress on plants reduces foliar moisture and increases forest canopy dieback and standing dead fuel biomass (Nolan *et al.* 2020; Hartmann *et al.* 2022). As the moisture content of canopy fuel decreases, the flammability of plant crowns increases, leading to greater flame height, and likelihood of canopy fire initiation (Molina *et al.* 2022). Thus, our findings indicate that if the climate becomes warmer and drier across Mexico over the coming decades (Conde *et al.* 2011), the exposure of native ecosystems to fires could exceed the fire resistance of vegetation (Parks and Abatzoglou 2020; Jiao *et al.* 2021; Collins *et al.* 2022). Targeted management of ecosystems aimed at increasing resistance and resilience will be required to mitigate the elevated risk of fires, as well as for the restoration of affected regions.

Our analysis suggests that human factors also drove the fires, consistent with official reports (CONAFOR 2020). Most of the land-use/land-cover changes that Mexico has experienced in the last decades involved fire as a useful tool for the elimination of vegetation (Dunbar-Irwin and Safford 2016; Rivera-Huerta *et al.* 2016), and socioeconomic factors such as gross domestic product and distance to rural localities were important key drivers of deforestation (Mendoza-Ponce *et al.* 2018). Interestingly, we estimated similar fire return intervals for temperate and tropical forest ecosystems as well as croplands. The similar return interval of fires in native vegetation and cropland probably reflect direct and indirect effects of traditional management of fires in slash-and-burn agriculture in tropical regions (Corona-Núñez *et al.* 2018; Mendoza-Ponce *et al.* 2018).

Deforestation and fires have been recognised as key factor that influences the C cycle (Houghton and Nassikas 2017; van der Werf *et al.* 2017). Mendoza-Ponce *et al.* (2018) have suggested that deforestation rates in Mexico have decreased in the last three decades, to a mean annual deforestation rate of 5027 km^2. In contrast, our results indicate that burned area has not decreased between 2001 and 2020. Thus, our study suggest that fires could be affecting native ecosystems more strongly than deforestation. For example, we found that annually ~2.0% of the temperate forest and tropical rainforests areas in the country were affected by fires; these estimates are considerably greater than the forest areas affected by deforestation reported by Mendoza-Ponce *et al.* (2018) (by a factor of 10 in the case of temperate forests, and by a factor of 5 in the case of tropical rainforests). Despite fires affecting a smaller proportion of tropical dry forest surface, the size is the double that of those affected by deforestation (Mendoza-Ponce *et al.* 2018). Overall, the impacts of fires on forest ecosystems have exceeded those from deforestation, suggesting that they not only influence the C stocks and emissions but could be a key factor in biodiversity loss, particularly of endemic species.

Conclusion

In conclusion, we explored the climate and human influences on fire dynamics, an understanding that is of interest for conserving natural capital in megadiverse countries where some types of vegetation, especially tropical rainforests, are very sensitive to fires. Our study allows an understanding of fire drivers either at countrywide or biome scales. Particularly, we illustrate that climate is the most influential factor on fire occurrence in Mexico, considering both average conditions and exceptional ones. Climate affects rainfall distribution within a year, and seasonal droughts impact fuel abundance through vegetation productivity and fuel water content. However, extreme fire seasons are related to exceptional climate conditions, such as those linked to La Niña events, or a combination of heatwaves and long droughts. In the face of climate change and the expected increase in drought risk, fire impacts on terrestrial ecosystems are expected to increase in the future (IPCC 2021). Our results also show that fire characteristics such as size and frequency proved to be influenced in different ways by climate and socioeconomic conditions that drive land-use and land-cover change. Understanding fire influences may enhance land-management practices and mitigate fire environmental impacts, including C emission and species loss in rich biodiversity hotspots (Myers *et al.* 2000).

Supplementary material

Supplementary material is available online.

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Data availability. The data that support this study will be shared on reasonable request to the corresponding author.

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