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Forest fires in Mexico: an approach to estimate fire probabilities

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Abstract. The probabilities of forest fires in Mexico are estimated using information on precipitation and temperature, along with data on type of vegetation, human activities near forests and fire prevention policies. The proposed model addresses the factors that account for extreme wildfire hazard, and may provide a basis for fire prevention actions, reducing vulnerability factors.

Additional keywords: climate, drought, natural hazard, vulnerability.

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Introduction

Forests provide important ecosystem services, such as climate regulation, recharge of aquifers, food production and greenhouse gas sequestration (e.g. Krieger 2001). For these services to continue, these ecosystems should be conserved or recovered, particularly in areas affected by human activities (Food and Agriculture Organization (FAO) 2014). In many parts of the world, forest fires frequently have negative impacts in the short and long term, because the recovery of the associated ecosystem services may take several years. It is estimated that each year, ~350 million ha of natural areas suffers fire damage around the world (FAO 2007). The resulting CO_2 emissions are almost 50% of those produced by burning fossil fuels (Jolly *et al.* 2015). At times, forest fires may have positive effects in ecosystems (Ressl and Cruz 2012), as maintaining appropriate burning helps to reduce fuel hazard and to maintain the nutrient cycle in pine forests (e.g. Rodríguez-Trejo and Fulé 2003).

In several countries in the tropics, the main cause of forest fires is human activities related to land-use change or agriculture (Nobre and De Simone 2009; Costafreda-Aumedes *et al.* 2017). Various studies have used the term risk of forest fire to refer to the probability of anthropic and natural fires. However, fire effects in a risk analysis should consider the likelihood of a fire burning and the variety of values susceptible to wildland fire (Finney 2005).

Every year numerous forest fires in Mexico are reported, and preventive actions are still insufficient (Zúñiga-Vásquez *et al.* 2017*a*). Although there has been progress in actions to detect and control forest fires, there is still significant work to be done to prevent human-induced forest fires. Prevention requires appropriate climate information and complete analyses of vulnerability to adverse climatic conditions in order to have better estimates of fire probabilities, particularly during dry and hot years (Anderson *et al.* 2019). Forest fires in Mexico are estimated to be between 40 and 99% related to human activities (Comisión Nacional Forestal (CONAFOR) 2001; Pompa-Garcia *et al.* 2018). Meteorological droughts increase the chances of forest fires, as in 1998 and in 2011 (Magaña 1999; Vose *et al.* 2016). During an El Niño year, rainfall may be below normal in the central and southern parts of the country and, at times, this may turn into a severe meteorological drought. In 1997, the rainfall deficit associated with El Niño caused an extreme drought that contributed to a record number of fires in the tropical forests of Mexico during the spring of 1998 (CONAFOR 2009). In 2011, a prolonged extreme drought took place in northern Mexico, and anomalously high temperatures exceeded 40°C for several days during the spring months. Lightning activity in northern Mexico appears to have led to several forest fires that devastated large areas of coniferous forests in the state of Coahuila (Magaña and Neri 2012; Zúñiga-Vásquez *et al.* 2017*b*).

The frequency of forest fires in Mexico is partially related to climate anomalies and frequently to human activities that involve the use of fire. The vulnerability of forests to anomalously dry and hot climatic conditions depends, among other things, on the proximity of agricultural activities to forests. It is estimated that agricultural activities induce at least 40% of forest fires in Mexico (CONAFOR 2001), owing to the traditional practice of slash and burn. Intentional burning for agricultural purposes also results in forest fires (Bravo-Espinosa *et al.* 2014), particularly during the dry season or periods of meteorological drought. Vulnerability also depends on accessibility to forest ecosystems, the distance of forests to other human activities (e.g. road traffic), or practices aimed at land-use change (Pérez *et al.*

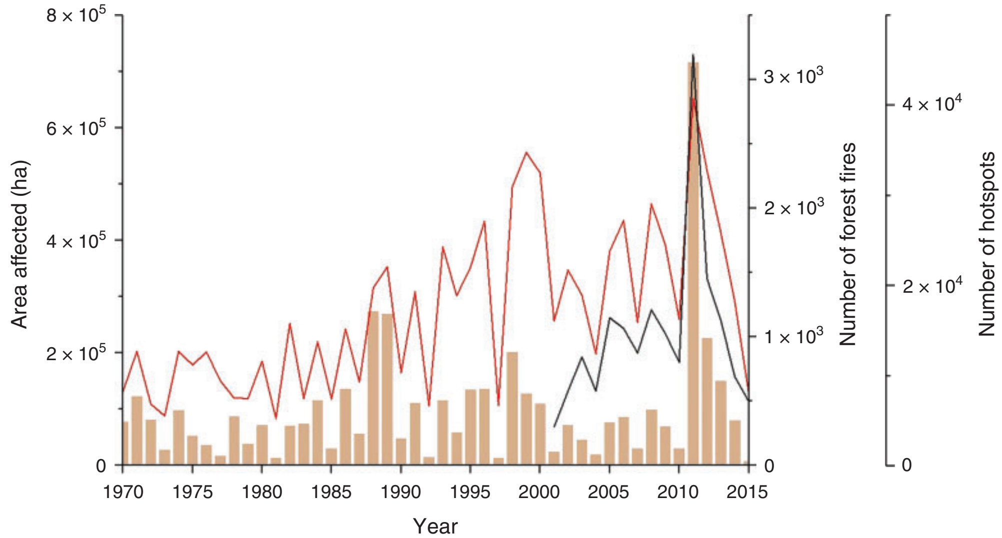

Fig. 1. Annual number of forest fires in Mexico, as reported by the National Forestry Commission of Mexico (CONAFOR) (red line); area affected (ha) by fire (brown bars); and hotspots associated with number of fires, as monitored by FIRMS-NASA (black line).

2013). Consequently, the probabilities of forest fires come from a climatic hazard related to meteorological droughts (precipitation deficit, positive temperature anomalies and hydrologically stressed vegetation), in a vulnerability context, mainly associated with human activities (e.g. agriculture). This approach to estimate climatic risk has been followed in several studies that analyse the potential impacts of climate change (Intergovernmental Panel on Climate Change (IPCC) 2012).

In general, climatic risk is given in terms of the probabilities of natural hazard times vulnerability, as an index that reflects social, economic and environmental conditions, and the exposure of the system that may be affected (IPCC 2012; Neri and Magaña 2016). Finney (2005) states that fire risk analysis depends on characterising and combining fire behaviour probabilities and effects, i.e. the consequences. Meteorological droughts are considered one of the most serious climatic hazards that increase forest fire probabilities. McKee *et al.* (1993) determined that moderate drought occurs 9.2% of the time, severe drought 4.4% and extreme drought 2.3% worldwide. Therefore, the probability of a meteorological drought (moderate to extreme), characterised with a Standardised Precipitation Index (SPI-3) less than –1, is ~16%. Actual manifestations of this type of climatic hazard have occurred in 1998 in central southern México, during an El Niño event, and in 2011 in northern Mexico, conditions that are referred to as hazardous events. The chances of positive temperature anomalies are 50%, assuming a normal distribution of the variable. Similarly, the probability for a negative anomaly of the Normalized Difference Vegetation Index (NDVI) is 50%, assuming a normal distribution of this variable. Consequently, the joint probability for a natural hazard that may lead to forest fires is of the order of 4%, i.e. a hazardous climatic condition of this kind may approximately occur once every 25 years. However, forest fires in Mexico occur much more frequently than that. This implies that probabilities of forest fires should include the vulnerability of the natural system, mainly related to human factors (Avila-Flores *et al.* 2010; Pompa-Garcia *et al.* 2018).

In Mexico, response and recovery actions after natural disasters are more common than prevention. The capacity to control forest fires appears to have improved more than the capacity to prevent them. The number of forest fires during the last 45 years has increased at a more rapid rate than affected area (Fig. 1). Dry conditions, like the severe meteorological drought in 2011 in central northern Mexico, are the most important climatic factor that leads to a record area affected by fire. However, forest fires in the central and southern regions appear to depend mostly on human factors (Pompa-Garcia *et al.* 2018).

There is interest within the Mexican government to prevent forest fires, but this effort requires a diagnosis of the factors (natural and human) that induce fires, and risk management strategies through the reduction of vulnerability to drought, for instance. The main objective of the present paper is to develop a method for the quantification of the probabilities of forest fire in Mexico that helps to promote forest fire prevention strategies, identifying the importance of natural and human factors.

Data and methodology

An evaluation of probabilities of forest fire requires characterisation of the climatic conditions and the corresponding physical, economic and social vulnerability factors. Climatic hazards are usually expressed in terms of probability based on historical records. Meteorological drought (i.e. the natural hazard) is a recurrent condition that may be represented in terms of indices, such as the SPI (McKee *et al.* 1993, 1995). This factor serves to describe adverse climatic conditions related to drought. In the present study, the climatic hazard corresponds to a combination of factors, including:

(i) Three-month SPI-3 data (Chen *et al.* 2002) to describe meteorological drought conditions in 0.5° × 0.5° grids, for the 1970–2015 period. Fernandes *et al.* (2011) and Galván (2011) found a strong correlation between SPI-3 and forest fires;

(ii) Monthly surface maximum temperature anomalies from the North American Regional Reanalysis (NARR 2004), in a 0.3° × 0.3° mesh, for the 1979–2015 period; and

(iii) Bi-weekly anomalies of the NDVI (Rouse *et al.* 1974), obtained from the US Geological Survey (Huete *et al.* 2002), in 250 × 250-m grids, for the 2001–15 period.

To combine hazard data into a single grid, coarse-resolution data were linearly interpolated into a 250 × 250-m grid, corresponding to the high spatial resolution of the NDVI data. In each grid cell, SPI-3, temperature anomalies and NDVI data were normalised between 0 and 1 using the relationship:

$$V_r(t) = \frac{\alpha(t) - \min(\alpha)}{\max(\alpha) - \min(\alpha)}$$

where V_r refers to the normalised value of the climate variable, $\alpha(t)$ is a climate variable and max (α) and min (α) correspond to its maximum and minimum values. The linear combination of the normalised climate variables results in a climatic hazard index.

Vulnerability may be estimated using information that relates to physical, environmental and socioeconomic factors. In this way, qualitative information is translated into quantitative data of vulnerability using official agencies' data for recent years. The various vulnerability indicators vary in time to reflect the dynamic nature of vulnerability.

According to CONAFOR (2010), the main causes of forest fires are related to the use of fire in agricultural or cattle ranching activities. Vulnerability of natural ecosystems to dry periods also increases from other human activities related to land-use change, illegal forest activities, rights of way, burning of garbage or fire for poaching. These factors can be represented directly or indirectly with data from official sources. For instance, data on the density of the rural population in Mexico and their activities, along with data on built-up areas, roads, railroads, shorelines, land use and cover, and night-time lighting have been used to construct vulnerability indicators. These factors, along with data on the Mexican population, were used to construct a Human Influence Index (HII) (Wildlife Conservation Society Center for International Earth Science Information Network (WCS-CIESIN) 2005). The HII provides information on the direct influence of humans on ecosystems over North America. Its scale ranges from 0 to 100, where 0 represents no human influence and 100 represents maximum human influence.

Regional or local public policies aimed at preventing the occurrence of forest fires are also a key element in the reduction of vulnerability, and therefore, the probability of forest fires. Data on the number of forest fires indicate that in Natural Protected Areas (NPAs), fire prevention practices are more efficient than in the outside rural regions. This makes NPAs less vulnerable to meteorological droughts, which can be represented as an indicator of vulnerability between 0 and 1 (CONAFOR 2012; Comisión Nacional de Áreas Naturales Protegidas (CONANP) 2013).

Table 1. Susceptibility of vegetation to fire (source: CONABIO 1998)

Value	Type of vegetation
1	Residual moisture agriculture, seasonal agriculture, semi-deciduous rainforest, irrigation agriculture, low deciduous rainforest
0.9	Natural grassland, pine forest, ayarin forest, high mountain meadow, sabanoide, savanna, subtropical shrubland, scrubland, pine–oak forest, medium-sized deciduous rainforest, coniferous scrub, tascate forest, natural palmar, induced palm grove
0.8	Medium semideciduous rainforest, cultivated grassland
0.7	Halophile vegetation, popal, cattail vegetation, cedar forest, oyamel forest, cultivated forest, gallery forest, tall semi-evergreen forest, hydrophilic halophile vegetation, mangrove, semi-evergreen thorn lowland rainforest, mountain mesophile forest, coastal rosette-like scrubland, lowland evergreen rainforest, tall evergreen rainforest, sarco-crasicaule scrub, induced forest, peten vegetation, rosette-like desert scrub, sarco-crasicaule cloud scrub, deciduous thorn lowland rainforest, coastal dune vegetation, sandy desert vegetation, gallery forest, crasicaule scrubland, oak forest, microfilo desert scrub, oak–pine forest, submontane scrub, sarcocaule scrub
0.6	Medium-sized evergreen rainforest, tropical mesquital, medium-sized semi-evergreen rainforest
0.5	Induced grassland
0.4	Tamaulipas thorny scrub, xerophilous halophilic vegetation, gypsophile grassland, gypsophile vegetation, desert mesquite, mesquite forest, halophilic vegetation, halophilic grassland
0.3	Human settlements
0.2	Aquaculture
0.1	Urban area, without apparent vegetation
0	Water bodies, devoid of vegetation

Various studies have been developed to characterise the sensitivity of vegetation to fire (e.g. Pyrke and Marsden 2005). In Mexico, this type of characterisation of vulnerability based on the susceptibility of forests and rainforests to fire has been developed by the National Commission on Biodiversity (CONABIO 1998). Certain types of vegetation are more likely to catch fire than others (Table 1). These data have been converted into an indicator of vulnerability between 0 and 1.

An index of vulnerability to meteorological drought is constructed by averaging a normalised version (between 0 and 1) of the three indicators listed above. For instance, in northern Coahuila (102°W, 29°N), the human influence index is between 0.2 and 0.3 (low vulnerability), the susceptibility of the vegetation is between 0.6 and 0.8 (high vulnerability), and the protected area condition corresponds to ~0.1 (low vulnerability). The average normalised vulnerability index is ~0.3–0.4, which corresponds to low vulnerability. The vulnerability index is evaluated in a 250 × 250-m grid. It is clear the vulnerability factors are dynamic and should be updated periodically. Using the hazardous event data and vulnerability index, an estimate of the probability of forest fires is obtained to develop a case study for the spring of 2011, when a severe prolonged meteorological drought affected northern Mexico.

A measure of forest fire activity was obtained using hotspots detected by satellite (MODIS (Moderate-Resolution Imaging Spectroradiometer) Collection 6), defined with an 80% or above confidence level. This information was obtained from the National Aeronautics and Space Administration (NASA)-Fire

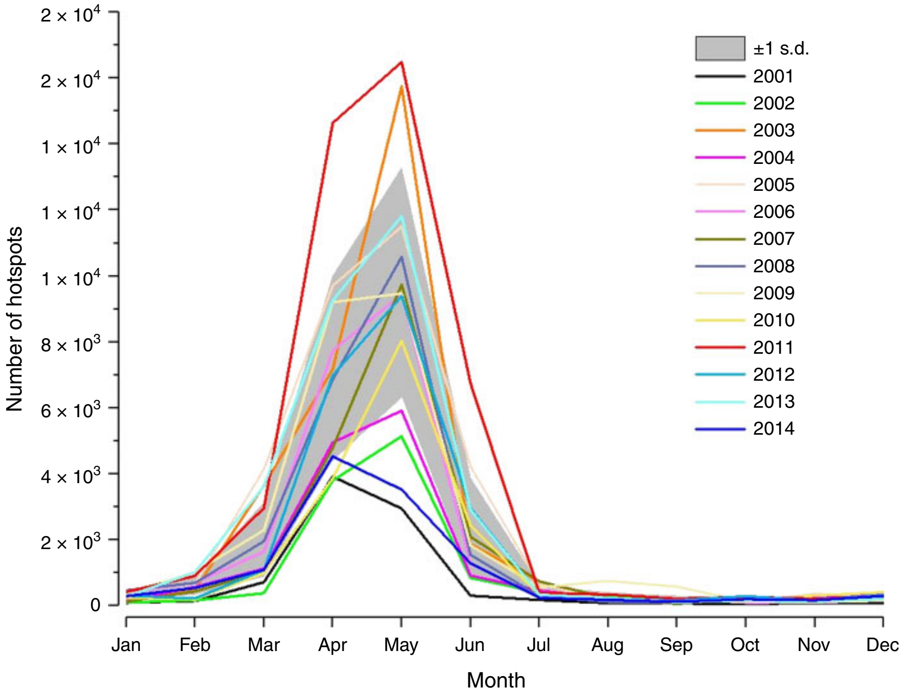

Fig. 2. Number of hotspots of forest fires per month in Mexico between 2001 and 2014. The grey band corresponds to ±1 s.d. in the number of events detected.

Information for Resource Management System (FIRMS) for the 2001–15 period. The accuracy of the forest fires estimates for the 2011 episode was determined by comparing the ranks of probabilities of forest fires with the density of observed hotspots. The number and location of hotspots were also compared with climate information only to establish the advantage of using vulnerability information for the probabilities of forest fires.

Results

Forest fires in Mexico: temporal behaviour

In Mexico, the number of forest fires shows a maximum during the spring months (April to May) (Fig. 2), i.e. during the period of minimum precipitation, when the highest maximum temperatures are observed (Magaña 1999). After the onset of the rainy season, between June and July, few forest fires are detected. Therefore, most of the analysis focuses on forest fire activity during the first half of the year. The seasonality in forest fires also coincides with the beginning of the spring–summer rain-fed agricultural cycle, when slash and burn practices are common over most of the country.

The years 2003 and 2011 correspond to periods of prolonged (2 to 3 years) and intense (SPI-3 <-2) meteorological droughts in northern Mexico. The periods with minimum forest fire activity were related to normal or wet winter–spring conditions, as in 2014. A large number of forest fires may occur even in wet years (e.g. 1986), suggesting the importance of human activity in the occurrence of these events. As the rural population increases, more human activities raise the probability of forest burns (Fig. 3). The rural population has increased approximately at a rate of 0.5% per year, from ~33 million in 1970 to more 58 million in 2015 (World Bank 2017). As there is no clear trend in dry or wet periods in Mexico in recent decades, the tendency for more forest fires may be related to more rural population and human activities. A preliminary (spatially averaged) estimate of probabilities of forest fires may be obtained by combining information on the increase in rural population and the spatial average of SPI-3. In some years, droughts tend to favour a significant increase in the number of fires, particularly in northern México (Pompa-Garcia *et al.* 2018). The correlation between preliminary approximation of the chances of forest fire activity and actual number of fires is 0.85 for northern Mexico, and 0.54 for southern Mexico. In this preliminary approximation, which combines rural population and SPI-3 data (as a precipitation hazard index between 0 and 1), the correlation mostly reflects the coherence in high-frequency variations regulated by climate variability, whereas the positive long-term trend in forest fires appears to be associated with the increase in human activities of the rural population.

Forest fire prevention policies reduce the vulnerability to drought. In NPAs, there are forest fire prevention policies that make these regions less vulnerable during dry and hot conditions (CONANP 2014). These preventive policies include clearing paths in the forests, removal of fuel, and skill creation for the personnel in charge of forest surveillance.

The chances of forest fire may also depend on the type of exposed vegetation, which may determine fire spread.

The previous vulnerability factors may be quantified in terms of indicators that in turn may be averaged into a consolidated vulnerability index. In the present analysis, a larger weight (0.5) was empirically given to the HII, considering it plays a major role in the number of forest fires. Public

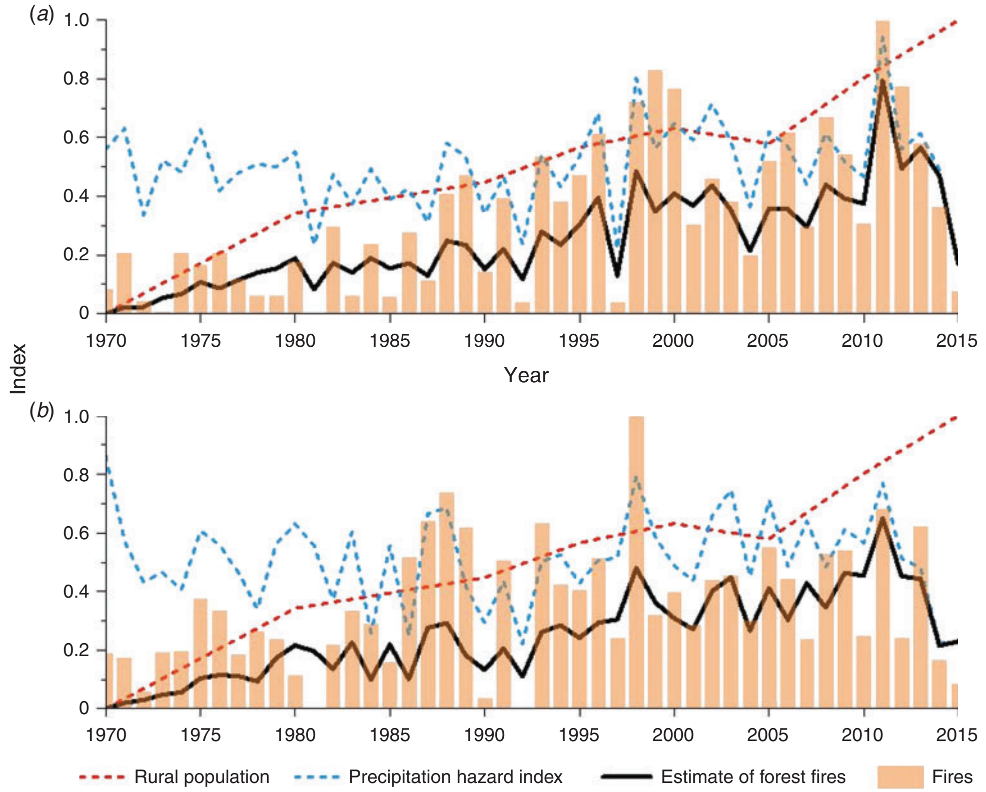

Fig. 3. Time series March–May: a precipitation hazard index obtained from the inverse value of SPI-3 (Standardised Precipitation Index), normalised between 0 (low) and 1 (high) between 1970 and 2015 (blue dashed line) for (*a*) northern Mexico; (*b*) southern Mexico. Red dashed line corresponds to the Mexican rural population normalised between 0 and 1; a preliminary estimate of forest fire activity (black solid line); and reported number of fires from CONAFOR (2016) (coral bars).

policies related to the level of protection or ecosystem management, as well as the characteristics of the exposed vegetation, were given a weight of 0.25 each in the averaging process to obtain the vulnerability index. When this index was used in combination with climatic hazardous event data, an estimate of the probabilities of forest fires was obtained. The estimate of forest fires was used to evaluate the specific case of the spring of 2011, a particularly dry year.

Case study: the drought of 2011

The natural hazard

To analyse spatial contrasts in the occurrence of forest fires in Mexico, the conditions during the severe drought of 2011 were analysed. A large area (~300 000 ha) of pastures, forests and rainforests burned, mainly in northern Mexico during that year (Zúñiga-Vásquez *et al.* 2017*b*). The SPI-3 during April 2011 reached values below –2, which is considered an extreme drought (Fig. 4*a*). The maximum temperature anomalies in the northern and central regions of Mexico were between +2 and +3°C above average (Fig. 4*b*). These conditions combined with negative NDVI anomalies that correspond to severe water stress in the vegetation, mostly over north-western and north-eastern Mexico (Fig. 4*c*). Water stress in the vegetation along the Gulf of Mexico and over the Yucatan peninsula was also large. When these factors were combined into a climate hazard index, north-eastern Mexico faced an important hazardous event, and the region was at high risk of forest fires (Fig. 4*d*).

The spatial pattern of the 2011 drought in northern Mexico included areas severely affected by forest fires, but a closer look at the distribution of hotspots shows that these events also occurred in regions not affected by drought, such as the western-central part of Mexico (Fig. 4*d*).

Vulnerability

The HII is an important factor in the probability of forest fires. In order to determine the origin of recurrent burn activity in some parts of Mexico, this factor should be examined at the regional and local level. Most of southern and central Mexico forests are particularly vulnerable given that more than 60% of the Mexican population is concentrated there (Fig. 5*a*). Agricultural practices frequently make use of slash and burn (Gómez *et al.* 1993) and further, some fires in recent years have been intentional, in order to expand the areas for avocado production and other crops, particularly in western Mexico (Bravo-Espinosa *et al.* 2014). The type of vegetation is also a factor in vulnerability. For instance, during the dry season from March to May, low deciduous forest tends to be highly flammable (Table 1), as in the western Yucatan Peninsula (Fig. 5*b*). Finally, ecosystem management policies appear to make NPAs (Fig. 5*c*) less vulnerable during dry and hot climatic episodes. The

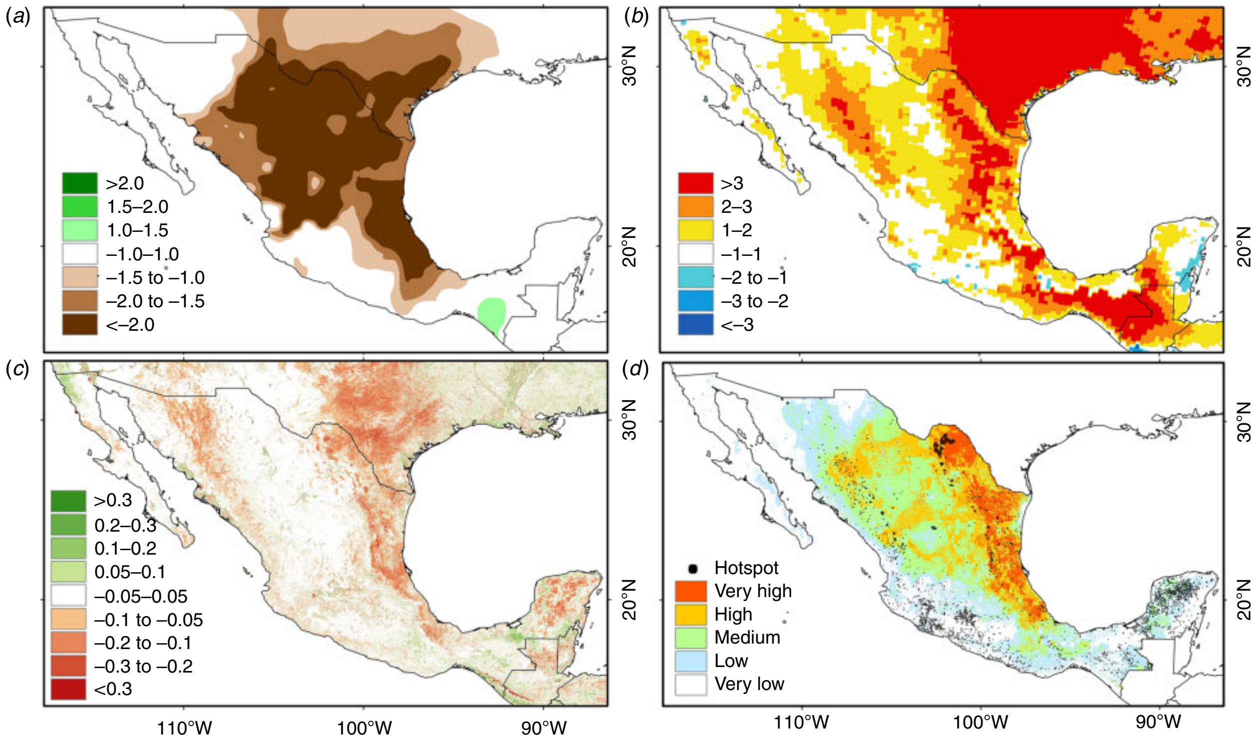

Fig. 4. Climatic hazards during April 2011: (*a*) SPI-3; (*b*) surface temperature anomaly (°C); (*c*) Normalized Difference Vegetation Index (NDVI) anomaly; and (*d*) ranks of the resulting climate hazard index. Black dots indicate fires detected by satellite.

weighted average of the normalised indicators results in a consolidated vulnerability index (Fig. 5*d*), showing areas of high vulnerability mostly where the HII is large. The regions of high forest fire activity are mainly located in southern and central Mexico, which are in turn areas of high vulnerability.

The highest climatic vulnerability is located in the southern and coastal parts of western Mexico and the Gulf of Mexico. In the Yucatan peninsula for instance, the western part is more vulnerable than the eastern part, corresponding with the type of vegetation and its flammability. The western part of Yucatan, as well as the western-central part of Mexico, are two regions that are severely affected by forest fires year after year, almost independently of climatic conditions (Fig. 5*d*). When the hazard index was combined with the vulnerability index, an estimate of probabilities of forest fires was obtained, which can be represented in an informal ranking as very high, high, medium, low and very low probabilities.

Probabilities of forest fires in spring 2011

During the spring of 2011, the number of forest fires significantly exceeded the seasonal average (Neri and Magaña 2016), and most hotspots were located in regions of very high and high burn probabilities (Fig. 6). In the northern part of the state of Coahuila, forest fires mainly occurred in regions of very high and high risk, outside NPAs. However, some forest fires were also detected within NPAs with low and very low probability values that resulted from the propagation of fires from neighbouring zones. High and very high forest fire probabilities were observed in some parts of the Yucatan Peninsula or in western central Mexico, mainly related to high and very high vulnerability. Nevertheless, numerous forest fires occurred in regions of medium, low and very low probability of fire, because the number of induced fires was difficult to estimate.

A simple evaluation of the forest fire (estimate) model was conducted using the number of hotspots in the areas of very low to very high probabilities. Results show that most forest fires (72%) occur when probabilities are very high, high and medium (Fig. 7*a*). When only climatic hazard information is used, results tend to be less accurate (Fig. 7*b*). Therefore, the analysis that combines climatic hazards and vulnerability factors is more accurate than the climatic information (hazardous condition for April 2011) to estimate forest fire probabilities. Areas with a low level of fire probability also include a large number of hotspots. This is mainly related to a significant number of fires, of medium and low fire probability ranking, in the western state of Michoacan and in the Yucatan peninsula. In the former, the large number of hotspots reflects a vulnerability level higher than estimated, because intentional burning of natural forests to expand area for avocado orchards (Barsimantov and Antezana 2012; Bravo-Espinosa *et al.* 2014) was not considered. This effect was not well captured by the HII used in the present analysis. In the Yucatan peninsula, a similar tendency to a large number of forest fires exists in relation to forest clearing activities for agricultural and cattle ranching expansion purposes (Cheng *et al.* 2013). The evaluation tends to be more biased towards higher ranks of probability of fire when Michoacan and Yucatan are not included in the evaluation. This implies that the HII should be modified in these regions considering the exacerbated use of fire.

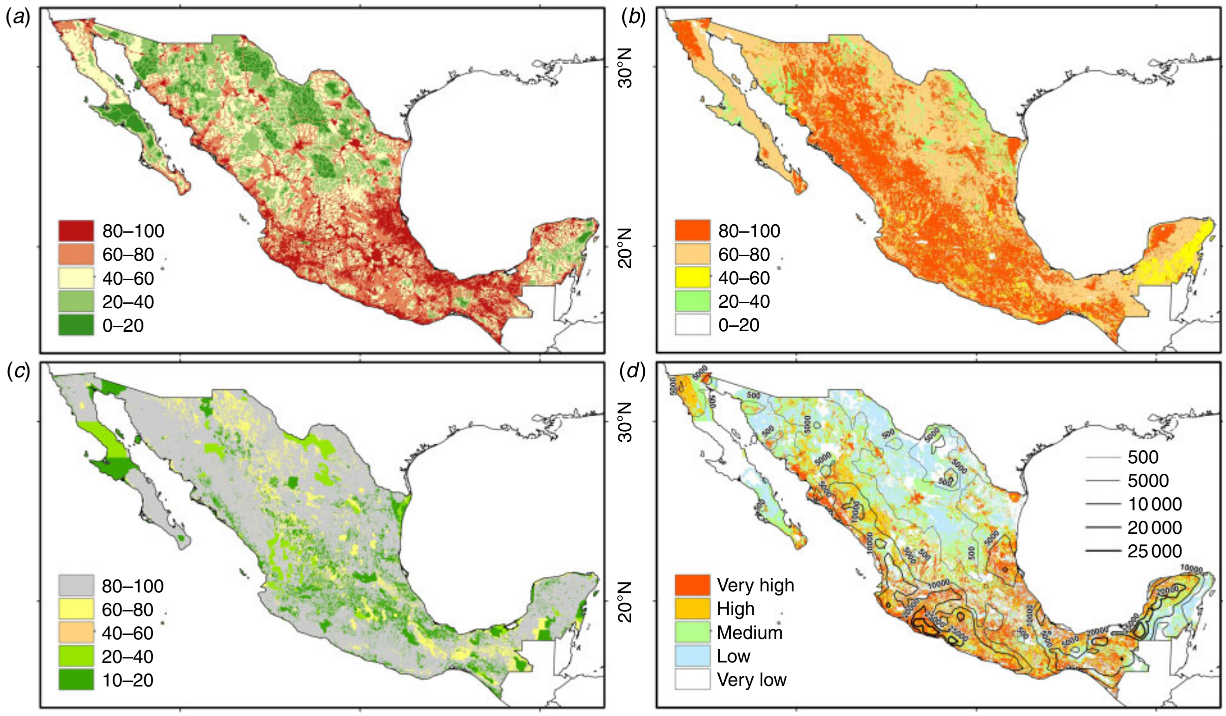

Fig. 5. Vulnerability indicators related to: (*a*) human influence index (HII); (*b*) susceptibility to fire by type of vegetation; (*c*) natural protected areas (NPAs). (*d*) Consolidated index of vulnerability. As a reference, the number of accumulated hotspots during 2001–15 is presented as black solid lines in (*d*).

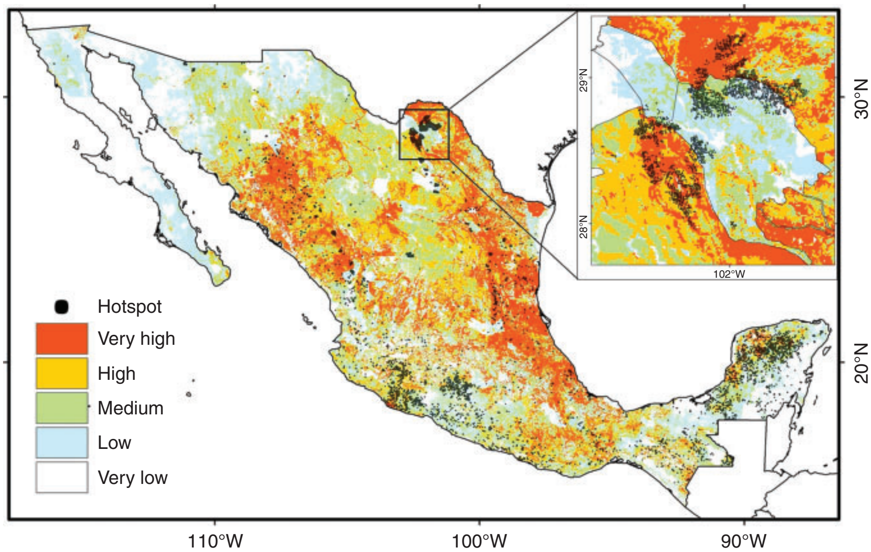

Fig. 6. Informal ranking of the probabilities of forest fires for April 2011. Detected hotspots for the same period are denoted by black dots. The box corresponds to the northern part of Coahuila state, severely affected by forest fires during that period.

Predicting the probabilities of forest fires

One of the goals of environmental policies in Mexico is to reduce the number of forest fires. For this purpose, the use of climate information is important for climate risk management with preventive actions. Seasonal climate forecasts, regularly issued, and vulnerability estimates may be combined to produce predictions of probabilities of forest fires. For instance, the meteorological drought of spring 2011 constitutes a good

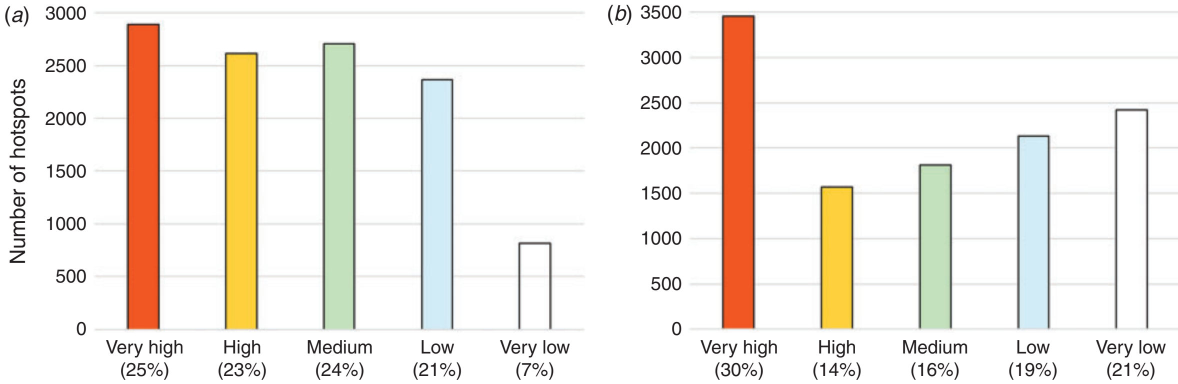

Fig. 7. Percentage of hotspots in (*a*) the ranks of probabilities of forest fires, and (*b*) the ranks using climatic information only.

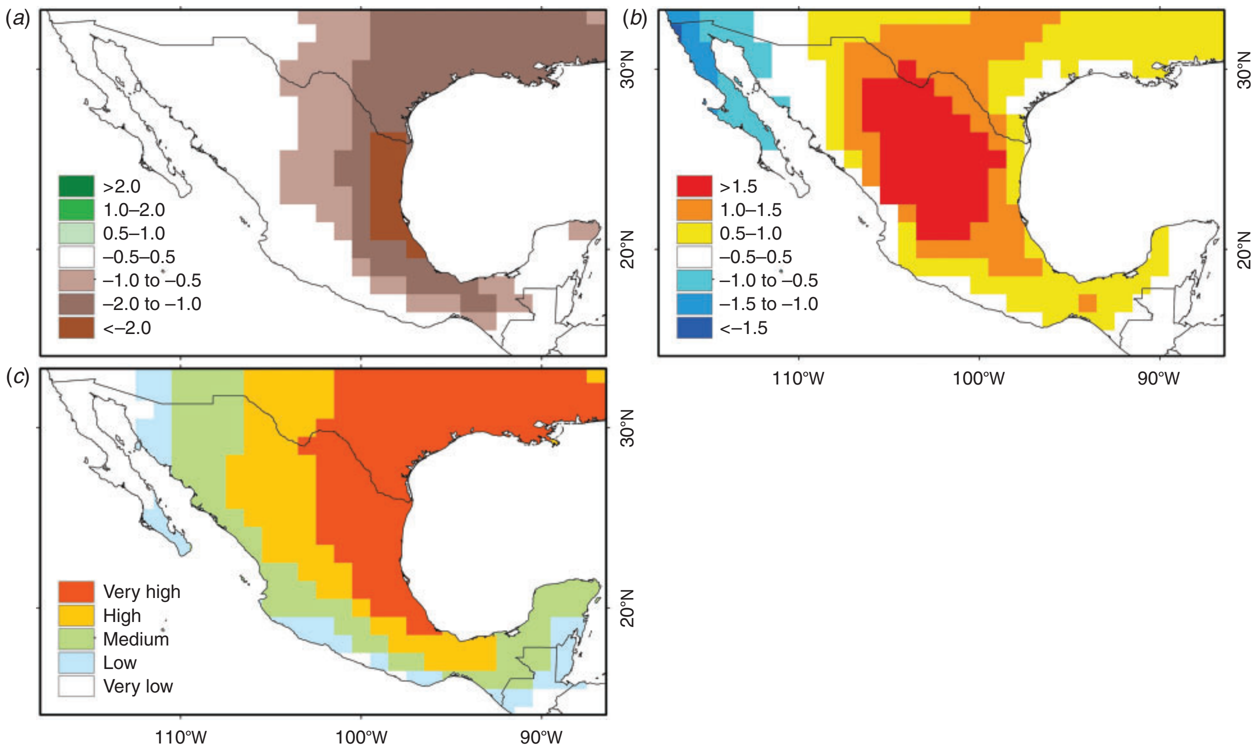

Fig. 8. Climate forecast for April 2011 with initial condition for March 2011 using the Geophysical Fluid Dynamics Laboratory (GFDL) model for (*a*) precipitation anomalies; (*b*) temperature anomalies; and (*c*) climatic hazard index.

example on how this type of information may be constructed. The 1-month climate forecast, such as that prepared by the Geophysical Fluid Dynamics Laboratory (GFDL) in March 2011 (Kirtman *et al.* 2014; NOAA-GFDL 2014), indicated that the meteorological drought would continue during April 2011, mainly in the states adjacent to the Gulf of Mexico, with precipitation anomalies close to –2 (Fig. 8*a*). Temperature anomalies between +1 and +1.5°C were also predicted, mainly in northern Mexico (Fig. 8*b*). Such conditions would lead to severe water stress in the vegetation. However, forecasts of NDVI anomalies were not available, so the hazardous event index was calculated with precipitation and temperature anomalies only. The combination of these elements resulted in high and very high hazardous climatic conditions in north-eastern Mexico, and medium, low and very low climatic hazard in the rest of the country (Fig. 8*c*).

When the information on the predicted climatic hazard was combined with a recent estimate of vulnerability, a forecast of forest fire probabilities was obtained, for instance, 1 month in advance (Fig. 9). The climate forecast for April 2011 indicated that areas of forests and rainforests in north-eastern Mexico and the Gulf of Mexico states could be affected by fire. A comparison of this forecast with the hotspots observed in April 2011 indicates that forest fire occurrence was approximately

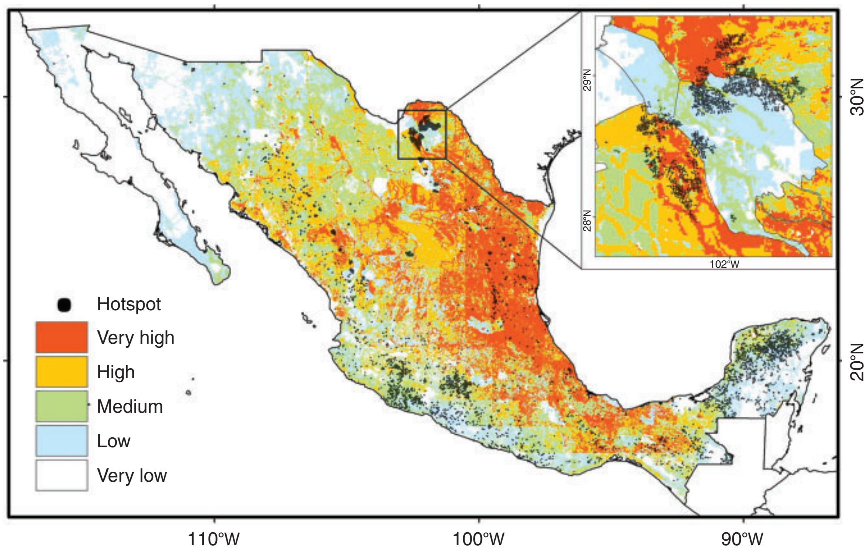

Fig. 9. Forecast of ranking of forest fire probabilities for April 2011 using Geophysical Fluid Dynamics Laboratory GFDL-CM2p1 predictions based on conditions during March 2011.

predicted in north-eastern Mexico in a better way than could have been predicted with the climate forecast only. However, in the western part of the Yucatan peninsula and western central Mexico (Michoacan state), where medium levels of burn probabilities were predicted, numerous hotspots were observed. These regions have been identified as zones of recurrent and intense forest fire activity, well above the rest of the country. This result suggests a more regional analysis should be conducted in these locations, considering that most forest fires are mainly due to negligence or lit on purpose.

Conclusions

The number of forest fires in Mexico has increased in recent decades and their environmental, economic and social costs are significant. The present study estimates the probabilities of forest fires in terms of climatic anomalies and vulnerability conditions mainly related to human activities. There are no universally accepted methods to quantify vulnerability, but it may be estimated based on indicators related to human activities, the characteristics of vegetation and public policies aimed at preventing forest fires. The combination of these factors and hazard data results in a model that better explains probabilities of forest fires than the approach based on climate information only. Vulnerability explains the trends and low-frequency (decadal) variability in the number of forest fires, while climate information modulates the interannual variations.

Some regions of Mexico experience forest fires even when no significant climatic anomalies are observed, as in the western central part of Mexico or the Yucatan peninsula. It has been determined that these fires are intentionally caused to clear forest for agriculture, to remove residual crop biomass and to maintain already modified land (*milpa*, sugarcane and pasture) (Cheng *et al.* 2013). The present analysis suggests that, in terms of the probabilities of forest fires, climate anomalies are more important in the northern part of Mexico, while vulnerability factors (mainly human activity) are more relevant in the central southern part.

Identification of the factors that result in vulnerability is a key step in risk management. The present analysis scheme consists essentially of translating qualitative diagnosis of vulnerability into quantifications that lead to an index of vulnerability under meteorological drought. Results indicate that the weight given to vulnerability should vary from one region to another. It should be larger in regions where forest fires are intentionally caused by human activities owing to negligence or intentionally during the dry season, as in Michoacan or Yucatan. In these regions, public policies should be improved to reduce or eliminate practices such as slash and burn. Other policies such as an early warning system are particularly relevant when meteorological droughts are predicted in highly vulnerable areas.

Evaluation of the forest fire probability model of the present study requires a recurrent update of vulnerability factors. Unfortunately, the HII factor or vegetation susceptibility to fire is not always easy to evaluate in a yearly manner. Thus, the uncertainty in the predictions of probabilities of forest fires should be examined. Constructing actual time series of vulnerability, at least every 5 years, and then developing an evaluation of the model for a period such as 1980–2015 would improve the model.

A more accurate approach of predicting probabilities of forest fires should consider an ensemble of climate predictions and the consequences of such events (Finney 2005). This would serve to determine the level of critical risk considered as the threshold, for instance, for the implementation of an early warning system.

One of the major challenges that tropical and subtropical regions will face under climate change is the prevention of forest fires. Identification of the causes of such type of events opens the possibility of implementing more efficient adaptation measures in the long term. The adequate management of climatic risk may be crucial in the conservation of the planet's natural resources.

Conflicts of interest

The authors declare no conflicts of interest.

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