

"I think you should be more explicit here in step two."

Chapter 2

Role of environmental and human-related variables on wildfire patterns in ENSO and non-ENSO years in tropical Mexico.

Abstract

Tropical and subtropical areas present the vast majority of contemporary global fires. Despite the human origin of most of these fires, little is known of how environmental and socio-economic variables contribute to the spatial patterns of fire incidence and burned areas. The tropical Mexican State of Chiapas represents a good case study to analyze these interactions, due to the availability of official data, and its similarities to other tropical countries, in terms of environmental and socio-economic characteristics. This study evaluates the relative importance of human-related and environmental variables in determining the distribution of the number of fires and area burned in the tropical State of Chiapas, in years of normal and extreme climatic conditions (Non-El Niño versus El Niño). We have searched for causal relationships among fire, environmental, and socio-economic variables in Chiapas using path analysis.

Results of this study have reported a major importance of environmental variables in non-El Niño years, suggesting that the status of the vegetation was the main cause determining fire ignition and fire spread in these years. Contrarily, the observed trends in the El Niño period indicate that fire trends were mainly determined by the presence of ignition agents. In these El Niño years, vegetation is so severely water-stressed that, when fire starts, all vegetation types burn independently of their flammability properties. The main vegetation types affected by fire in non-El Niño years were the most flammable ones, such as pine-oak communities, while rain forests burned the most in El Niño years. Altitude, pine-oak communities and poverty levels played major roles in the arboreal fire incidence in non- El Niño years, whereas the distribution of pastures appeared as an important variable determining arboreal fire incidence in El Niño years. When all fires were considered (affecting any vegetation layer), almost identical trends were observed, with the incorporation of a new variable influencing the area burned, the density of infrastructures. The results of this study strengthen the importance of El Niño years in the conservation of rain forest ecosystems and suggest the existence of synergistic effects between fires, fragmentation and certain elements of the landscape, such as cattle pastures, in tropical areas.

Key words: fire distribution, fire incidence, El Niño, Chiapas, tropical rainforest, human-related variables, causal relations

INTRODUCTION

Natural and anthropogenic fires play an important role in the structure and functioning of many ecosystems (Johnson 1992, Naveh 1994). In recent decades, however, climatic and socioeconomic changes have modified the geography and dynamics of fire, so that fire regimes have been altered practically everywhere (Pyne 1995). Although there is great variability of fire characteristics, it is possible, as well as important, to determine the main spatial and temporal patterns of fire, in order to evaluate its economic, ecological and social damage (Johnson and Gutsell 1994). Nowadays, there exist a large number of studies attempting to model fire occurrence and fire behavior to improve fire management (see reviews in Chuvieco et al. 1997). Variables considered in these studies depend on their temporal and spatial scales. In general, studies dealing with short temporal scales mainly strengthen dynamic variables, such as meteorology (e.g. air temperature or precipitation) and their consequences on fuel status (e.g. moisture contents) (see review in Bovio and Camia 1997). Fire studies focusing on longer temporal scales usually combine static and dynamic variables (Chuvieco and Salas 1996, Castro and Chuvieco 1998): synoptic climatic data, topography and fuel characteristics (such as vegetation structure and composition, or fuel loads).

Notwithstanding the importance of environmental variables, in some places they are not the ultimate factor determining fire regime, and more importance should be given to human-related variables such as socioeconomic and cultural conditions that affect landscape patterns and fire management. Thus, Vélez (1991) analyzes the situation in the southern and northern Mediterranean Basin countries, and suggests that differences in the number and surface burned by forest fires are more related to socioeconomic characteristics than to geographical differences in climate, as southern countries have more extreme conditions but fewer fires with smaller burned areas. Similarly, Minnich (1983,1998) and Minnich et al. (1995) emphasize the importance of fire management policies (fire suppression versus absence of fire-control) in determining differences in fire regime between Southern California and Northern Baja California. He suggests that some of the differences in the fire regimes of these areas may be the consequence of fire control rather than differences in climate. In spite of these results, human-related variables are rarely included in fire prediction models (Chuvieco and Salas 1996). A possible reason for their absence might be partially related to the difficulties in obtaining high-quality information on the motivation of human-caused fires (Vélez 2000), and on the precise location of the various fire-related human activities (Vega-García et al. 1993, Salas et al. 1994). When human-related variables are considered, they are frequently taken into account in three main different ways: (i) the analysis of the spatial distribution of certain human infrastructures (roads, recreation areas, camping sites, etc) as areas of higher fire risk (Chou 1992, Vega-García et al. 1995, Pew and Larsen 2001); (ii) the elaboration of fire occurrence maps (or fire history maps), which are a spatial representation of historical fire incidence and causes of ignition (with emphasis on human-caused fires) in a given area (Salas et al. 1994, Gouma and Chronopoulou-Sereli 1998); (iii) the search for underlying causes related to fire occurrence, by the analysis of several socioeconomic variables: population density, unemployment rates, mean salaries, activity sectors, etc (Vélez 1986).

In tropical areas, the consideration of human-related variables is even more important, because human

causality is responsible for almost 90% of the ignitions (Goldammer 1993, Rodríguez 1996, SEMARNAT 1999) and ecosystems are more fragile and less resilient to human pressures (Taylor et al. 1999). Over the past several decades, the vast majority of fires worldwide have occurred in the tropics and subtropics (Goldammer 1990, Dwyer et al. 1999). Even in tropical rainforests, where humid understory conditions normally preclude burning, forest fires have become a common event (Kauffman et al. 1988, Uhl and Kauffman 1990, Cochrane et al. 1999). This is because timber harvesting, road building, slash-and-burned agriculture, and pasture conversion for livestock have greatly increased the flammability of forests, especially during El Niño droughts (Malingreau et al. 1985, Goldammer 1993, Laurance and Williamson 2001, Nepstad et al. 2001). An interesting case study is the tropical Mexican state of Chiapas, which has a large number of fires influenced both by environmental and human-related factors (see Román-Cuesta 2000). From the point of view of human-related factors, fire is influenced by a complex socio-economic situation, where sixty percent of the population is directly related to land, combined with a variety of land tenures (INEGI 1997). In terms of environmental factors, fire activity results from a particular seasonal distribution of rainfall, which exclusively concentrates fires in the dry season (November to May), and a varied climate and topography, which give a diverse array of vegetation types. An added environmental feature of the State is the major role played by El Niño-Southern Oscillation (ENSO) episodes. As in other tropical areas, this climatic phenomenon produces extreme drought conditions that are associated with severe fire seasons, such as those of the 1986-1987 and 1997-1998 ENSO episodes (SEMARNAT 1999, Setzer and Pereira 1991, Román-Cuesta 2000). In the case of Chiapas, forest affectation during the peaks of El Niño 1987 and 1998 corresponded to 47% of the total forest area affected in this State during the period 1984-1999. These high values suggest the need to consider separately fire effects during ENSO and non-ENSO years, in order to contrast the ways in which socio-economic and environmental variables affect fire patterns.

The purpose of this study is to evaluate the relative importance of human-related and environmental variables in determining the distribution of the number of fires and area burned in the tropical State of Chiapas, during the period 1993-1999. Since the Mexican climatic conditions of 1998, an ENSO year, were reported as the worst in the last 70 years in terms of drought and high temperatures (SEMARNAT 1999), this study will compare the relative importance of environmental and human-related variables on fire distribution in years of normal and extreme climatic conditions (Non-ENSO versus ENSO). We believe that human variables have a major importance in Chiapas, because the majority of fires are related to negligence and deliberate burning (SEMARNAT 1999, Román-Cuesta 2000). However, we hypothesize that in ENSO years environmental variables will play a major role because of the severe drought conditions. To analyze this hypothesis, we will search for causal relationships among fire, environmental, and socioeconomic variables in Chiapas using path analysis.

STUDY AREA

Climate, vegetation and population in Chiapas

The state of Chiapas is located in the southeast of the Mexican Republic ($14^{\circ} 32'$ to $17^{\circ} 59'$ N; $90^{\circ} 22'$ to $94^{\circ} 14'$ W; elevation range: 0 m to 4093 m above sea level on the Tacaná volcano (Figure 1). It has an

area of 75635 km² (3.8% of the Mexican territory). When this study was conducted, Chiapas was composed by 111 municipalities grouped into nine economical regions. Due to its location in the tropical area, Chiapas is characterized by climates corresponding to the warm and semi-warm groups (climate A following the Köppen climatic classification), with different degrees of humidity, but temperate and semi-cold climates are also frequent (climate type C following the Köppen climatic classification) in areas higher than 2000 m. Mean annual precipitation in Chiapas is 1982 mm (range: 1000->4500 mm; series: 1941-1996; WWW1). Precipitation is quite seasonal: there is a wet season from May to October, and a dry season from November to April. Under the ENSO phenomenon, however, rainfall patterns vary, increasing the number of months of the dry season -until June or even July-, and decreasing the amounts of rain in certain months (mainly April and May) (Román-Cuesta, unpublished data).

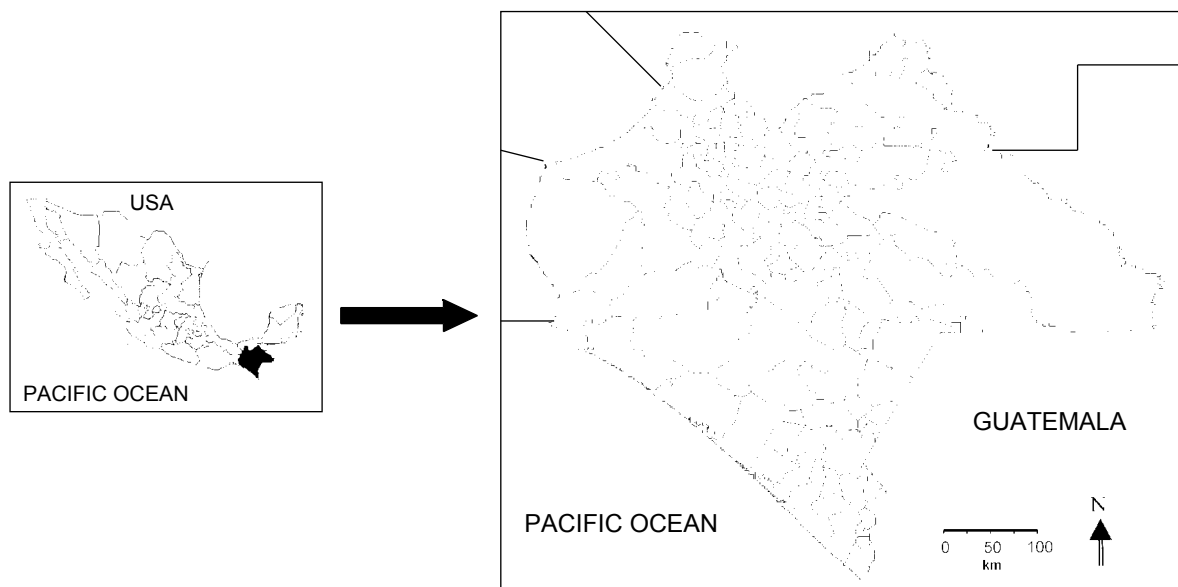


Figure 1. Geographic location and administrative division of Chiapas

Sixty-eight percent of the State is forested, mainly covered by temperate forests (22%) and rain forests (42%) (Valera-Hernández 1994). During recent decades, human pressures have increased the number of fragmented forests, with a progressive substitution of species-rich forests by species-poor and more flammable types, and, therefore, fire risk (as described in other tropical areas by Cochrane et al. 1999, Cochrane and Schulze 1999, Laurence et al. 1998). Moreover, in several regions, extensive areas of rain forests have been replaced by pastures for cattle production (Villafuerte et al. 1997), increasing the probability of fire propagation to the adjacent forest fragments. The main disturbance agents described by the National Forest Inventory were: land use changes, logging activities and fire.

The population in Chiapas in 2000 was almost 4 million inhabitants (INEGI 2000). Economic regions with higher population densities are located in the central plateau of Los Altos (115 persons/km²) and in the south-west of the State, on the border with Guatemala. The Frailesca region (west-center), represents the lowest values, with 25 persons/km². Mean annual growth rate in Chiapas was one of the highest of the

Mexican Republic in 1997 (INEGI 1997). More than 60% of the population is rural, most of them related to subsistence. Concerning its secondary sector, the main factories are related to farming and agriculture services. In spite of the lack of a developed industry sector, Chiapas has a powerful petrol and gas sector, being the third producer in the national ranking (INEGI 1997).

Fire regime in Chiapas in the period 1993-1999

Forest fires present a strong seasonal pattern in Chiapas. The fire season is exclusively concentrated in the dry season, from November to April. No fire records have been recorded outside of these months (Román-Cuesta, unpublished data). These seasonal trends, together with the traditional use of fire, the presence of a steep topography, and a peculiar socio-economic framework, produce complex fire patterns in the State.

In the Non-ENSO period (years 1993, 1994, 1995, 1996, 1997, and 1999), 47% of the municipalities recorded forest fires, while 39% were affected by fires that reached the arboreal layers. In these six years, the mean annual number of fires was 159, and the mean total area burned per year was 21454 ha, mainly affecting non-arboreal layers (grasslands, shrublands and regeneration). Thus, 86% of the incidences were surface fires. Pine-oak was the most affected community. There were ten large forest fires. During the period considered, 50% of the incidents were associated to negligence (Román-Cuesta, unpublished data).

During El Niño-1998 period, 47% of the municipalities were affected by fires, with 37% suffering fires that reached the arboreal layers at some point. The total number of forest fires during this year was 405, which burned a total area of 198808 ha. 23% of the total area burned corresponded to arboreal layers, with rainforest communities as the most affected vegetation type (55%). During this year, there were 76 large forest fires that were responsible for 75% of the total burned area. 67% of the incidents corresponded to surface fires. Negligence was responsible for 56% of the incidences (Román-Cuesta 2000).

METHODS

Data sets

The analysis concentrates on the 111 municipalities of Chiapas during the 1993-1999 period (the two extreme years included), as detailed information about fires was only available for these years. In order to determine the relative importance of environmental and human-related disturbances, three main groups of variables were selected: fire, environmental, and socioeconomic variables. Originally, there were 94 variables that were reduced to 17 through several steps: elimination of variables with missing data, selection of variables of each group with correlation coefficients higher than 0.8, and multi-collineality analysis and elimination of redundant variables with VIF (variance inflation factor) values higher than 10. The application of these steps allowed us to reduce the variables to four fire variables, seven environmental variables, and

six anthropogenic variables. In the case of fire variables, mean annual values were used for Non-ENSO and ENSO years separately. For the environmental variables, structural data -the same mean value for both ENSO and non-ENSO episodes-, were used, for each municipality (i.e. historical climatic means for the period 1985-1998). Regarding the socio-economic variables, data used for the different municipalities referred to the results of the 1990 Census.

Fire-related variables. This study considers forest fires according to the definition in POE (1999). This definition excludes all intentional burnings related to land practices that use fire, excepting those where fire spreads out of the established field area, due to the absence or inefficiency of security measures. Fire data were based on SEMARNAT (Mexican Secretary of Environment and Natural Resources) original fire field reports. Regarding the interest of Chiapas forests and considering the differences in severity of fires which reach crowns as compared to all other fires, this study distinguishes between arboreal fires, i.e. those that affected the arboreal layers at some point, and all-layers fires, i.e. those that take into account all fires, independently of the layers affected (arboreal, and/or herbaceous and/or shrubland layers). Of the original 30 fire-related variables, there were four final ones:

- (1) Arboreal fire incidence: mean number of fires that affected the arboreal layers at some point (>0.5 ha), rated by the municipal area (number fires ha^{-1}).
- (2) All-layers fire incidence: mean number of total fires (>0.5 ha) (independently of the affected layer) rated by the municipal area (number fires ha^{-1}).
- (3) Arboreal burned area: mean area burned of those fires affecting arboreal layers rated by the municipal area ($\text{ha ha}^{-1} \times 100$).
- (4) All-layers burned area: total mean area burned (including all fires) rated by the municipal area ($\text{ha ha}^{-1} \times 100$).

Environmental variables. They are abiotic (climate and topography) and biotic (vegetation) variables. Most of them were achieved in a digital form, from LAIGE (Laboratory of Image Analysis) in El Colegio de la Frontera Sur (ECOSUR)-San Cristóbal.

Climatic data were obtained from LAIGE (ECOSUR) in a digital form. These data were originally based on meteorological variables obtained in several State weather stations managed by the National Water Commission (CNA) (historical period of 1985-1998). The six original climatic variables were reduced to two, which were applied for both ENSO and non-ENSO years:

- (5) Maximum temperature in the dry season. Originally it was a digital vector layer, at 1:250.000 scale.

Temperatures were shown in eight categories: from $0-18$ °C (the first one) to more than 33 °C (the last one). This categorical variable was transformed into a continuous mean value for each municipality, following this procedure: 1) each category was reduced to the mean value of its interval; 2) by means of a GIS system (Pons 2000) we calculated the percent of total municipal area under each category; 3) the

temperature of each municipality was calculated by averaging with area adjustment, the values of temperature within each geographic unit:

$$T_m = 1/S_m \sum_{i=1}^n s_j t_j$$

where T_m is the mean temperature of each municipality, S_m represents the total municipal area in hectares, and s_j refers to the municipal area with a mean temperature t_j .

- (6) Total precipitation in the dry season. This variable was originally a digital vector layer, at a 1:250000 scale, with 19 categories: from 0-25 mm for the first one to 1700-2000 mm for the last one. This categorical variable was transformed into a continuous variable for each municipality, following the same procedure applied to the previous variable.

Topographic data include slope and elevation. Slope was a digital raster layer obtained from a digital elevation model of 1 km pixel resolution (WWW2), while elevation data were a list of altitudes above sea level obtained in a statistical review (INEGI 1997).

- (7) Altitude. These values were obtained from INEGI (Mexican National Institute of Statistics, Geography and Computer Science) statistical information. They represent the altitude above sea level of the city capital of each municipality.
- (8) Percent of flat slope. This variable was the percent of surface with a slope ranging from 0 to 10%. To calculate it, the information included in the digital elevation model was transformed into percents of slope using a GIS system. Then, the percent of each municipality that presented less than 10% of slope was computed.
- (9) Percent of steep slope. Similarly, this variable was the percent of surface with a slope higher than 35%.

Biotic variables include vegetation data. Vegetation variables were obtained from the National Periodical Forestry Inventory map of 1994, at a 1:250000 scale. It was a digital vector layer obtained from LAIGE. There were 6 original variables that were reduced to two:

- (10) Percent of rainforests: percent of each municipality that was covered by rainforests (i.e. montane, deciduous and lower montane rain forests, sensu Miranda 1975), but also non-disturbed oak communities, evergreen cloud forests and oyamel forests. In terms of fire flammability, this variable related to potentially non-flammable fuels in usual climatic conditions.
- (11) Percent of pine-oaks: percent of each municipality that was covered by pine communities and disturbed pine-oak communities. In terms of fire flammability, they are fire-prone communities.

A third category of vegetation, pastures, was included in the socioeconomic variables, because the distribution of these pastures is strongly determined by humans.

Socioeconomic variables. Variables of this section were obtained from SIMBAD (Municipal DataBase System), which is a service offered by INEGI. It contains socioeconomic data obtained from several Mexican General Censuses, which must be used with some caution, as there is a part of the population that is not registered. Originally, there were 52 variables that were reduced to 6 final variables:

- (12) Density of people related to the primary sector: its units are inhabitants per hectare, and it was calculated as the active population working in the primary sector (12 years-old or older) in each municipality, rated by the municipal surface. Data used to compute this variable were obtained from the XI Population and Housing General Census, held in 1990.
- (13) Poverty levels: it was calculated as the percent of the active population (12 years-old or older) in each municipality that earn less than a minimum salary; minimum salary is considered by INEGI as the reference value to analyze poverty levels in the Mexican Republic.
- (14) Ejidos with farming activities: this variable was calculated as the percent of the total number of ejidos that had farming activities in each municipality. The ejido is the minimum Mexican agrarian and farming administrative unit.
- (15) Immigration: it was calculated as the percent of people of each municipality coming from other States.
- (16) Density of infrastructures: it was originally a digital vector layer at a 1:250000 scale, obtained from LAIGE; it measured the abundance of roads and the degree of fragmentation associated to communication routes in each municipality; this variable was obtained following this procedure: 1) the State was divided into a net of 100 m-side pixels by means of a GIS system; 2) the variable was calculated as the proportion of cells in each municipality that were crossed by a road.
- (17) Percent of pastures. It represented the percent of each municipality that was covered by pastures. This variable was based both on the National Periodical Forestry Inventory (1994).

Table 1 shows the ranges and mean values of the original variables considered in this study. Values of these variables were log transformed as required to improve the normality of distributions.

Mathematical model applied: path analysis

Path analysis was selected for its ability to examine causal relationships between two or more variables, using a linear equation system. It is a combination of multiple regression and exploratory factor analysis, that requires a hypothetical causal model (Li 1986). Path analysis has been described as an accurate method of evaluating alternative structural hypothesis and predicting direct and indirect interactions and trends among variables (Schemske and Horvitz 1988, Herrera et al. 1994, Wotton 1994). An important difference compared to other methods is that path analysis also describes interactions among independent variables themselves. Path results include direct, indirect and effect coefficients, which are standardized partial-regression coefficients obtained from a multiple regression of standardized variables for each dependent variable in the diagram (Shipley 1999). The effect coefficient is the sum of the effects exerted along direct and indirect paths. Path coefficients are coefficients of determination (R^2) calculated for those variables affected by one or more interactions, in order to know the explained variability. Since none of the models fully explain the variability of the described variables, paths from residual variables U, that include the effects related to unknown causes, are also included in the models.

The program used for path analysis was Piste, included in the R Package ver.3.02 (Casgrain and Legendre 2001). The agreement between the model and the original data was assessed by the Chi-squared

test (Wotton 1994) and the adjusted goodness of fit index (AGFI), which ranges from 0 (null fit) to 1 (perfect fit). These statistics measured the ability of the model to predict the data, and were calculated using the SAS system v.8.1 for Windows (SAS Institute Inc.1998).

Table 1: Descriptive statistics for the considered variables in the path models. Mean values are given in a municipal, yearly scale (N=111). In the case of fire variables, their means are divided into ENSO and non-ENSO years.

Variables	Min	Max	Mean	Std.deviation
All-layers fire incidence in ENSO years (number fires.ha ⁻¹)	0	0.002	0.0001	0.0003
All-layers burned area in ENSO years (ha.ha ⁻¹ .100)	0	16.7	1.8	3.6
Arboreal fire incidence in ENSO years (number fires.ha ⁻¹)	0	0.0006	0.00004	0.0001
Arboreal burned area in ENSO years (ha.ha ⁻¹ .100)	0	9.4	0.36	1.18
All-layers fire incidence in non ENSO years (number fires.ha ⁻¹)	0	0.004	0.0004	0.0007
All-layers burned area in non ENSO years (ha.ha ⁻¹ .100)	0	18.2	1.1	3.1
Arboreal fire incidence in non ENSO years (number fires. ha ⁻¹)	0	0.004	0.0002	0.0005
Arboreal burned area in non ENSO years (ha.ha ⁻¹ .100)	0	6.3	0.34	1.04
Density of people related to the primary sector (persons.ha ⁻¹)	0.006	1	0.15	0.17
Percent of pastures (%)	3.7	100	39.7	23.9
Poverty levels (%)	0.6	39.3	12.5	9.4
Altitude (m)	10	2850	859.7	697.2
Percent of steep slopes (%)	0	12.9	1.0	2.28
Percent of flat slopes (%)	9.1	100	59.3	27.9
Percent of Pine-oak (%)	0	96.1	17.2	24.6
Percent of Rainforests (%)	0	79.5	17	18.90
Total precipitation in the dry season (mm)	47	1799	442	425
Maximum temperature in the dry season (T°)	15.4	35	26.1	4.4
Percent of ejidos with farming activities (%)	0	100	10.6	21.9
Immigration (%)	0.01	37.4	2.8	4.5
Density of infrastructures (%)	0	4.8	2.1	0.9

Models

Path models developed in this study were based on a statistical review of Chiapas fire trends (Román-Cuesta 2000), on SEMARNAT's fire-fighters' expert knowledge, and on classical factors affecting fire ignition and fire spread (Rothermel 1983). As a point of difference with other studies, our analysis searched for possible causes affecting the extent of area burned, instead of exclusively focusing on the causes associated with fire incidence. Thus, burned area causality, as well as socioeconomic variables, are frequently excluded in fire studies. However, different studies in tropical areas reinforce the importance of

human-related variables influencing fire regimes (Goldammer 1990, Nepstad et al. 1999).

Due to the known effect of El Niño on the number of fires and burned areas (Malingreau et al. 1985, Román-Cuesta 2000, Nepstad et al. 2001), path models were applied separately for the ENSO and Non-ENSO years. The ENSO fire dataset included data from 1998, while the Non-ENSO dataset included the mean annual fire values from the remaining years, on a municipal basis. An environmental and a human-related causal model were established for both ENSO and Non-ENSO years, and for arboreal and all layers. Both environmental and human-related variables were joined in a mixed model to determine the combined influence of all these variables on fire distribution (considered as the combination of both fire incidence and burned areas) (Figure 2). Since path coefficients are standardized regression coefficients (Li 1986), the results of these mixed models offer an idea of the relative weight of each variable in the distribution of fire patterns in the State. Burned areas were the final dependent variables, because they were affected by fire ignitions.

Considering the environmental variables, we determined, based on our fire knowledge of the State, that altitude had a direct effect on fire distribution (incidence and burned areas), as well as on rainfall and maximum temperature in the dry season (Figure 2). Temperature and rainfall directly affected the distribution of fire and, at the same time, were also considered to influence the location of pine-oak and rainforest ecosystems. The distribution of these vegetation communities was considered to directly influence fire incidence and burned areas, due to their flammability characteristics and their amounts of fuel loads. Topography, in terms of slope percent, was related to the distribution of pine-oak and rainforest communities (Figure 2), and it was also considered to affect the area burned.

Concerning the human-related variables, fire causality is mainly associated to agrarian and farming activities, as has been shown for other tropical areas (Goldammer 1990, 1993, Cochrane et al. 1999, Nepstad et al. 2001). Therefore, density of people in the primary sector, poverty levels, location of pastures, and the density of infrastructures (roads, railways, paths, etc) were directly related to fire variables (incidence and area burned) (Figure 2). Density of infrastructures is considered to be influenced by the density of people working in the primary sector, as fifty percent of the total number of infrastructures corresponded to small paths made by peasants to communicate with other villages, or to get to their fields. On the other hand, considering the characteristics of people re-distribution in Chiapas (Villafuerte et al. 1997, Ramírez-Marcial et al. 2000), immigration rates were also included as a direct effect on fire variables (Figure 2).

Final models were the path models resulting after pruning non-significant variables ($p > 0.15$), for each considered period. Therefore, these final models were exclusively created with those variables and those relationships among variables that resulted in a significant adjustment of predicted and observed values, with a probability threshold of $p = 0.15$. The final resulting models for both the arboreal layers and all-layers were displayed in path diagrams, and the relationships were broken down into direct, indirect and effect coefficients (additive values of both direct and indirect coefficients).

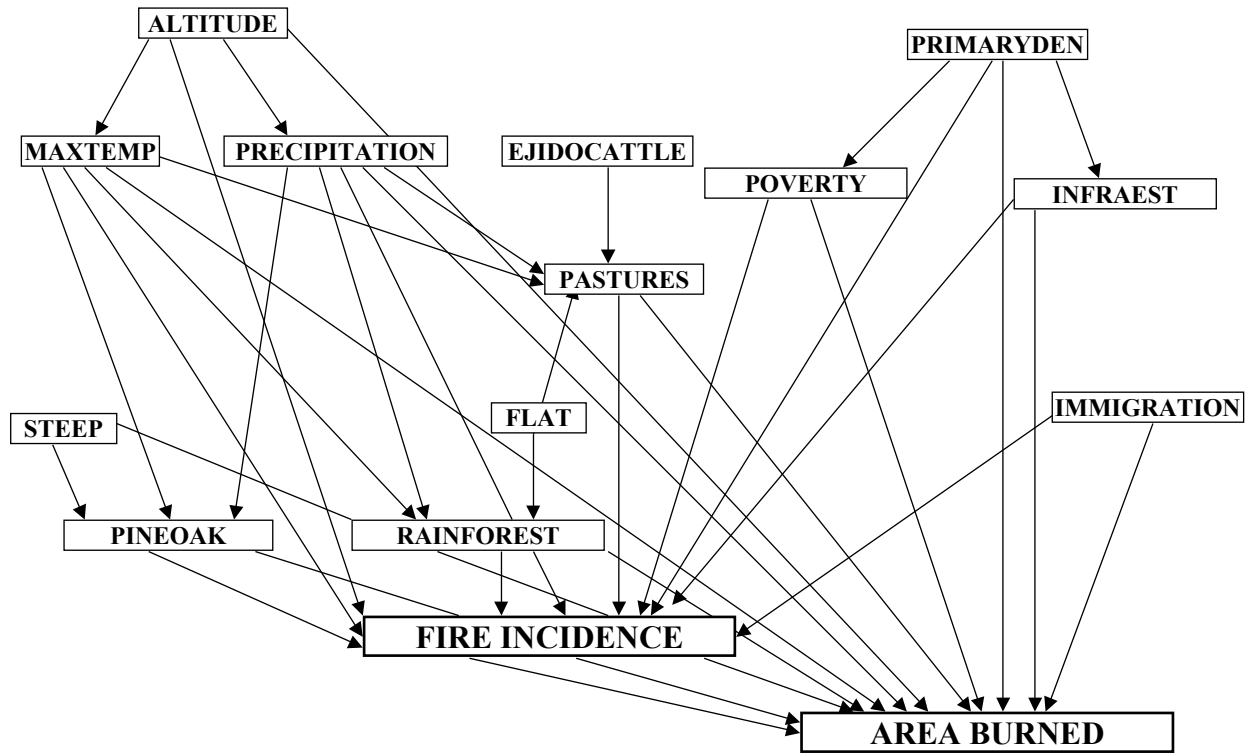


Figure 2. Mixed model with environmental and human-related variables and interactions among them, both for the arboreal and all-layers models, and the ENSO and non-ENSO periods. Final models were obtained from these mixed models, by pruning non-significant relationships. Abbreviations of variables are as follows: ALTITUDE, altitude above sea level of city capitals; EJIDOCATTLE, % ejidos with farming activities; FLAT, % flat slope; IMMIGRATION, % immigrants; INFRAEST, density of infrastructures; MAXTEMP, maximum temperature in the dry season; PASTURES, % pastures; PINEOAK, % pine-oak communities; POVERTY, poverty levels; PRECIPITATION, total precipitation in the dry season; PRIMARYDEN, density of people related to the primary sector; RAINFORESTS, % rain forests STEEP, % steep slope.

RESULTS

Fire incidence

The proportion of variation explained by the final models regarding fire incidence on arboreal layers was almost identical for both ENSO and non-ENSO episodes ($R^2=0.26$, $R^2=0.27$, respectively) (Table 2).

However, variables explaining this variability were quite different. The actual values of the direct, indirect and total effect of each variable are shown in Table 3. In Non-ENSO years (Figure 3A, Table 3A), significant variables affecting fire incidence were mainly environmental ones. Positive direct effects corresponded to the percent of pine-oak communities and altitude ($b=0.43$, $b=0.16$, respectively), while poverty levels displayed a

negative direct effect ($b=-0.25$). In the path for the ENSO year (Figure 3B, Table 3B), human-related variables played a key role in arboreal fire incidence, mainly caused by the direct positive effect of the percent of pastures and the density of people related to the primary sector ($b=0.32$, $b=0.16$, respectively). In this ENSO year, altitude ($b=0.33$) and the total precipitation in the dry season ($b=-0.23$) directly affected arboreal fire incidence. The percent of pastures was positively affected by the total precipitation and maximum temperature in the dry season ($b=0.26$, $b=0.24$ respectively), mainly indicating its location in ancient rainforest areas.

Regarding all-layers, trends displayed by the final path for fire incidence were different depending on the period considered. For the Non-ENSO period (Figure 4A, Table 4), all-layers fire incidence was explained similarly to arboreal fire incidence ($R^2=0.27$), and by the same variables (pine-oak communities: $b=0.43$; altitude: $b=0.18$; and poverty levels: $b=-0.27$). For the ENSO year, different trends were observed. The explained variability for all-layers fire incidence was nearly twice that of the arboreal fire incidence ($R^2=0.48$ versus $R^2=0.27$, Table 2). Variables with significant direct effects were similar to those of the arboreal fire incidence (Table 3), although in the all-layers fire incidence case, total precipitation in the dry season was not included, while the percent of pine-oak communities and poverty level were included (Table 4). The percent of pine-oak communities presented the main direct effect ($b=0.46$) (Table 4).

Table 2. Coefficients of determination (R^2), Chi-square validation test, and the adjusted goodness of fit index (AGFI), for the path analysis of the final models. n.s implies non-significant models. ** represent models that fit the data well. R^2 values are displayed for both fire incidence and area burned.

Climatic episode	Dependent variable	Arboreal layers			All layers		
		R^2	p<Chi-sq	AGFI	R^2	p<Chi-sq	AGFI
Non-El Niño years	Fire incidence	0.26	0.44**	0.93	0.27	0.51**	0.98
	Burned area	0.79			0.58		
1998 El Niño year	Fire incidence	0.27	0.19**	0.90	0.48	0.60**	0.93
	Burned area	0.20			0.50		

Area burned

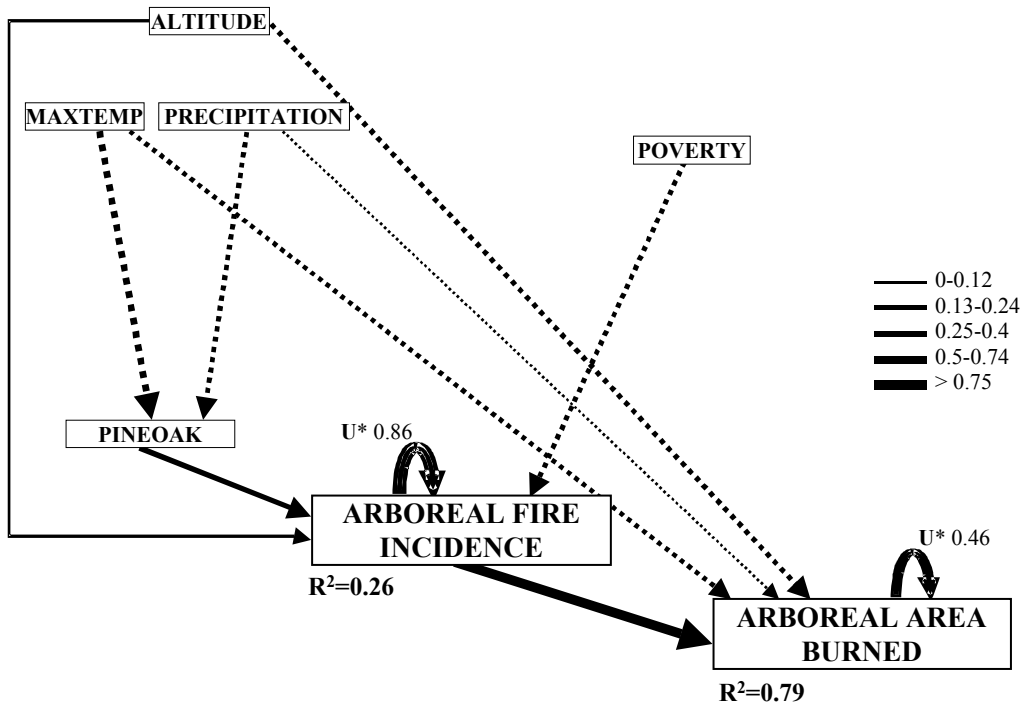
The proportion of variation explained in the distribution of the arboreal burned area was very different in non-ENSO and ENSO periods ($R^2=0.79$ and $R^2=0.20$ respectively, (Table 2). There was a high value for the non-ENSO period, but the main variable influencing this result was the arboreal fire incidence (Table 3A, Figure 3A). The direct effect of the arboreal fire incidence in the non-ENSO period ($b=0.87$) doubled the value of the ENSO year ($b=0.42$) (Table 3, Figure 3). In the non-ENSO period, the other variables that significantly affected the arboreal burned area were mainly environmental ones. Altitude, total precipitation in the dry season and maximum temperature in the dry season presented negative direct effects (Table 3, Figure 3), while the effect coefficient of elevation showed a positive relationship ($b=0.25$) (Table 3A, Figure 3A). In the ENSO year, the arboreal burned area was related to an environmental variable, the percent of rainforests, which showed a positive direct effect ($b=0.19$) (Table 3B).

The explained variability of the all-layers burned area did not follow the trends observed for the arboreal burned area. In Non-ENSO years, the all-layers burned area presented a lower percent of explained variability for burned areas than in the arboreal mixed model ($R^2=0.58$ versus $R^2=0.79$, Table 2). In this case, two additional variables were included in the model of the Non-ENSO years: density of infrastructures and the percent of pine-oak communities (Figure 4A and Table 4). In the ENSO period, the value of R^2 explained by the all-layers burned area doubled that of the arboreal burned area ($R^2=0.50$ versus $R^2=0.2$, Table 2). This was mainly related to the fact that the all-layers fire incidence presented a stronger direct effect ($b=0.54$ versus $b=0.42$, Figure 4B and Table 4). Interestingly, in the case of the all-layers burned area for the ENSO period, the percent of pine-oak communities was included while the percent of rainforests was excluded.

Table 3. Breakdown of the correlations with fire incidence and arboreal burned surface, into direct and indirect effects, for both (A) non-ENSO and (B) ENSO periods, for the arboreal layers. The effect coefficient is the sum of direct and indirect coefficients. *, $p<0.15$; **, $p<0.5$; ***, $p<0.05$.

(A) Final model for the non-ENSO period	Direct effect	Indirect effect	Effect coefficient
<i>Towards ARBOREAL FIRE INCIDENCE</i>			
Altitude	0.16*	0.22	0.38
Percent of Pine-oak communities	0.43***	0	0.43
Poverty levels	-0.25***	0	-0.25
<i>Towards ARBOREAL BURNED AREA</i>			
Altitude	-0.28***	0.53	0.25
Arboreal fire incidence	0.87***	0	0.87
Maximum temperature in the dry season	-0.26***	-0.25	-0.51
Total precipitation in the dry season	-0.18***	-0.13	-0.31
(B) Final model for the ENSO period	Direct effect	Indirect effect	Effect coefficient
<i>Towards ARBOREAL FIRE INCIDENCE</i>			
Altitude	0.33***	0	0.32
Density of people related to the primary sector	0.16**	0	0.16
Percent of pastures	0.32***	0	0.32
Total precipitation in the dry season	-0.23***	0	-0.23
<i>Towards ARBOREAL BURNED AREA</i>			
Arboreal fire incidence	0.42***	0	0.42
Percent of rainforests	0.19***	0	0.19

A- NON-ENSO years, arboreal layer



B-ENSO year, arboreal layer

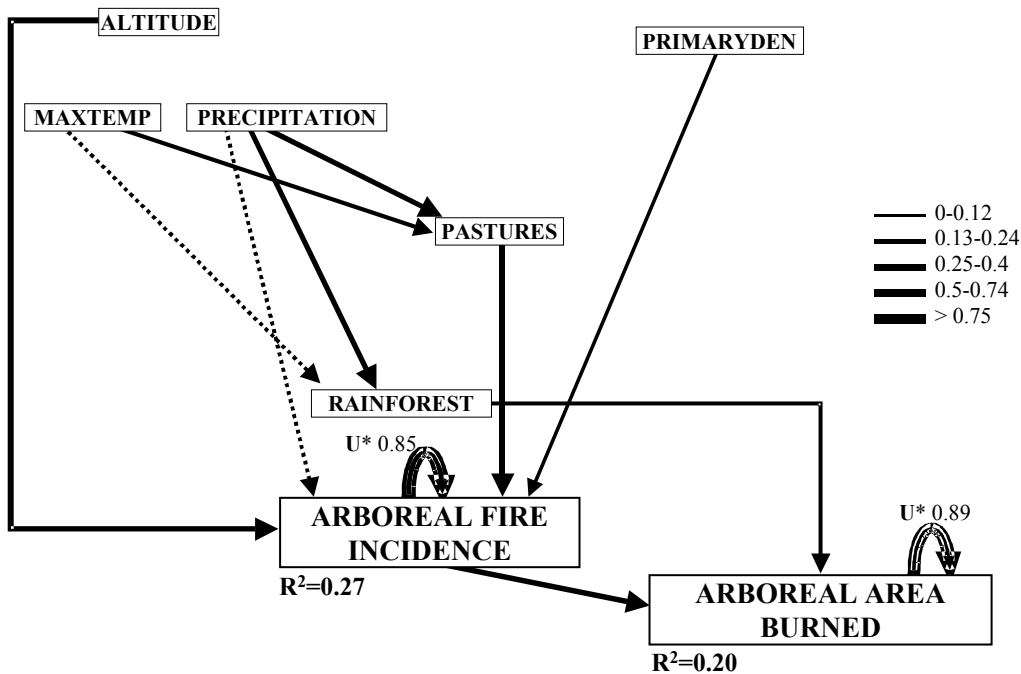


Figure 3. Final models for the arboreal layers, displaying significant ($p < 0.15$) relationships, for the non- ENSO (A) and the ENSO (B) periods. Dashed lines indicate negative relationships. The thickness of each line is related to the absolute value of each direct path coefficient, as indicated in the figure. See abbreviations in the legend of Figure 2.

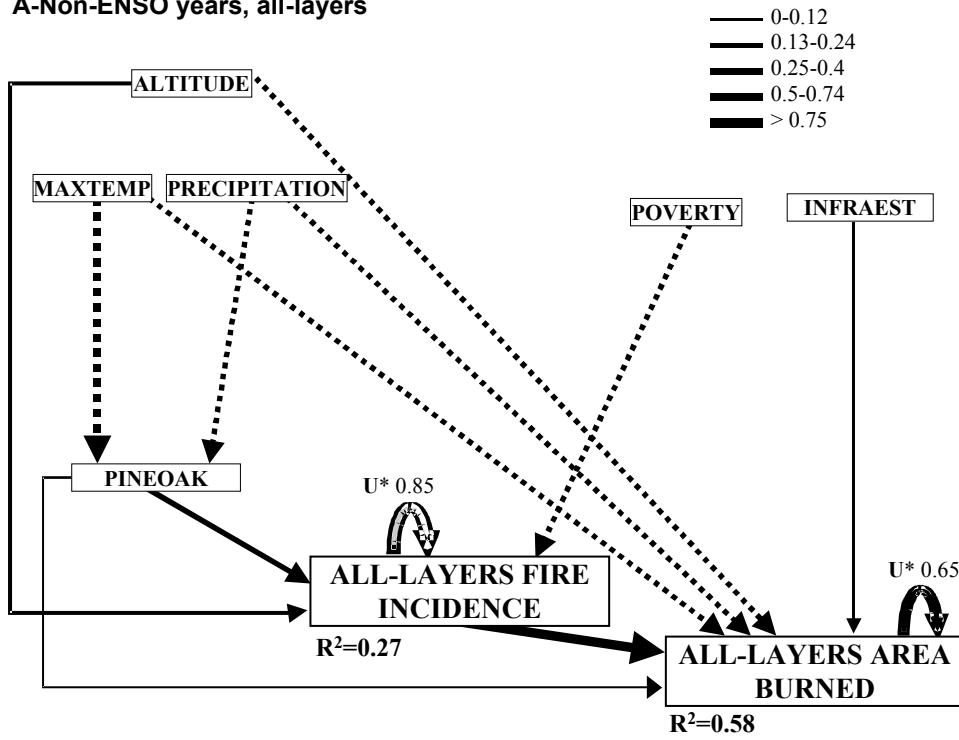
Table 4. Breakdown of the correlations with fire incidence and arboreal burned surface, into direct and indirect effects, for both (A) the non-ENSO and (B) the ENSO period, for fires affecting all layers. The effect coefficient is the sum of both direct and indirect coefficients. * $p < 0.15$ ** $p < 0.5$ *** $p < 0.05$.

(A) Final model for the non-ENSO period	Direct effect	Indirect effect	Effect coefficient
<i>Towards ALL-LAYERS FIRE INCIDENCE</i>			
Altitude	0.18*	0.22	0.40
Percent of Pine-oak	0.43***	0	0.43
Poverty levels	-0.27***	0	-0.27
<i>Towards ALL-LAYERS BURNED AREA</i>			
Altitude	-0.38***	0.54	0.16
All-layers fire incidence	0.65***	0	0.65
Density of infrastructures	-0.13**	0	-0.13
Maximum temperature in the dry season	-0.27**	-0.27	-0.54
Percent of Pine-oak	0.13*	0.28	0.41
Total precipitation in the dry season	-0.27**	-0.14	-0.41
(B) Final model for the ENSO period	Direct effect	Indirect effect	Effect coefficient
<i>Towards ALL-LAYERS FIRE INCIDENCE</i>			
Altitude	0.3***	0.24	0.54
Density of people related to the primary sector	0.15**	-0.03	0.12
Percent of pastures	0.24***	0	0.24
Percent of Pine-oaks	0.46***	0	0.46
Poverty levels	-0.24***	0	-0.24
<i>Towards ALL-LAYERS BURNED AREA</i>			
All-layers fire incidence	0.54***	0	0.54
Percent of Pine-oaks	0.24***	0.25	0.49

DISCUSSION

Several authors have remarked on the importance of fire as a disturbing agent in Chiapas (Valera-Hernández 1994, Miranda 1975), and the State was identified in 1987 as one of the warmest places on Earth because of its fire activity (Villafuerte et al. 1997). However, it was not until the severe fire season of the 1998 El Niño that there was any real awareness of the magnitude of the problem. When considering some of the consequences of that fire season (SEMARNAT 1999), it seems clear that modelling the contribution of variables affecting fire incidence and burned area is an urgent task.

A-Non-ENSO years, all-layers



B-ENSO year, all-layers

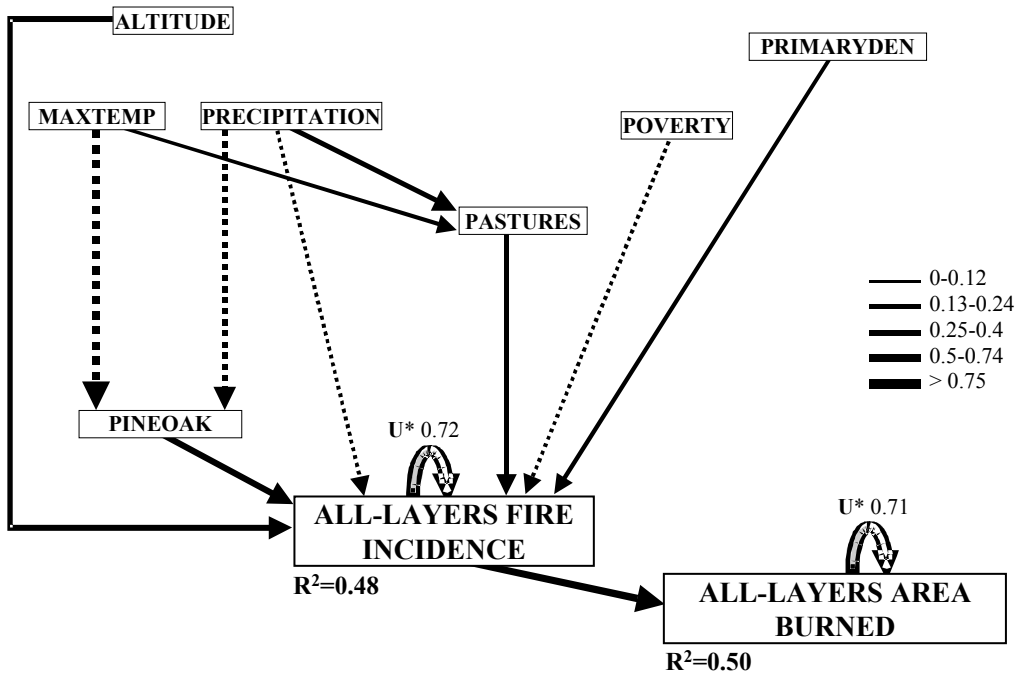


Figure 4. Final models for all layers, displaying significant ($p < 0.15$) relationships, for the non-ENSO (A) and the ENSO (B) periods. Dashed lines indicate negative relationships. The thickness of each line is related to the absolute value of each direct path coefficient, as indicated in the figure. See abbreviations in the legend of Figure 2.

Variables affecting fire regime in Non-ENSO years

Environmental variables played a decisive role in non-ENSO years, suggesting that the status of the vegetation is the main cause determining fire ignition and fire spread in these years. Corroborating this idea, Lawson et al. 1993 (in Pew and Larsen 2001) stated that the great importance of climate indicates that the occurrence of sustained ignition of a fire is more dependent on the ability of fuel to be ignited than on the presence of an ignition agent. Several studies analyzing human-caused wildfires (Martell et al. 1987, Chou et al. 1993, Pew and Larsen 2001) also find that climate has the greatest potential to predict fire incidence. Among the significant environmental variables for the arboreal layers in Non-ENSO years, altitude played an important role, indicating that elevated areas presented higher incidence than lower areas. In tropical areas, altitude has been found to affect fire regimes in two ways, either by determining the existence of cooler, less rainy and more fire-prone ecosystems, such as pine-oak communities, or by modifying the microclimatic conditions of rainforest trees over ridges or moderately high summits. In this last case, trees lose the surrounding protection of the remaining trees, altering their temperature and moisture content (Ennos 1997), as it has also been reported on the edges of fragmented rainforests (Uhl and Kauffman 1990, Laurance et al. 1997, 1998). In the case of Chiapas, these high areas correspond to Los Altos de Chiapas, where colder, less rainy and more fire-prone ecosystems are located (pine-oaks), together with one of the highest population densities (125 inhabitants/km²). According to Rodríguez and Sierra (1995), pine-oak forests present high fuel loads (more than 76 ton/ha), and frequently grow close to easily flammable fuels (pastures, litter, logging residues) which, combined with pine resins, contribute to fire spreading. This was confirmed by the major importance of pine-oak communities in the arboreal area burned.

Concerning socio-economic variables in Non-ENSO years, the negative relationship displayed by poverty levels towards the arboreal fire incidence (i.e. the poorest areas have lower fire incidence), requires further analysis. This relationship might be related to the way this variable was calculated (areas where people have low salaries might concentrate a large number of people younger than 12 years). A review of the poorest municipalities shows that 25% of them correspond to the region of Los Altos. We hypothesize that the importance of forests in the life-style of many indigenous ethnic groups of Los Altos, who generally have low incomes, might be a determinant aspect in the conservation of their forest resources.

A similar explanation of the model of arboreal-layers could be offered for the model of all-layers, because the same variables and the same trends were observed. In the case of the area burned, the density of infrastructures displayed an interesting negative trend in the all-layers model. This result suggests that areas with a higher number of paths and roads are easier to access, resulting in fires being more rapidly extinguished. It should be observed that half of the road system consisted of dirt tracks and small trails, which were mainly concentrated in highly populated areas, explaining in part the will to preserve land possessions. Interestingly, density of infrastructures was not a significant variable determining the all-layers fire incidence, which indicates that the number of fires is not related to the proximity and number of roads. This trend is in contradiction with almost all fire causality studies that incorporate road systems in the analysis, either in temperate or boreal forests (Chou et al. 1992, Vega-García et al. 1995, Pew and Larsen

2001), or in tropical rainforests (Nepstad et al. 2001). All these studies refer to the importance of the proximity of roads to the origin of fire. As this variable is not significant in the arboreal model (neither in fire incidence nor area burned), indicating that these burnings mainly affect non-arboreal layers. Considering this, we suggest that these fires mainly relate to cattle pastures, which occupy large extensions of private tenure with lower development of road systems, thus explaining a negative trend in the infrastructure variable.

Variables affecting fire regime in ENSO years

The observed trends in the ENSO year agreed with studies carried out in other tropical areas (Malingreau et al. 1985, Setzer and Pereira 1991, Laurance and Williamson 2001). Thus, our analysis suggests that human-related variables play a major role in the ENSO year, indicating that for this year the presence of ignition agents mainly determines fire trends, as the vegetation is so stressed that, when fire starts, everything burns independently of its flammability properties. In Chiapas, this implied major participation of rainforests in the final area burned. Nepstad et al. (2001) reported that, in the 1998 fire season in Brazil, there were 1.5 million km² of susceptible rainforests that did not burn because of a shortage of ignition sources. In the present study, the importance of ignition sources in ENSO years was confirmed by the significant positive trend of the density of people in the primary sector, towards fire incidence; which was not significant in non-ENSO years. Thus, the higher the number of people in the forests, the higher the number of fires. This phenomenon is not associated to higher fire-negligence in this year, which remains fairly constant (Román-Cuesta, unpublished data), but rather to the pointed stressed status of the vegetation.

The arboreal fire incidence in the ENSO year was also strongly influenced by the presence of pastures, which were not important in Non-ENSO years. In tropical areas, fire frequency in grasslands is frequently high, due to human-related ignitions for regeneration purposes, and also because grasslands are easy to burn, as they become flammable after just one rainless day (Uhl and Kauffman 1990). Moreover, pastures frequently substitute rainforests and establish synergistic relations with the surrounding fragment edges (Holdsworth and Uhl 1997, Sorrensen 2000, Cochrane 2001). These edges are submitted to changes in microclimatic conditions that alter the rainforest's ecological dynamics, resulting in a loss of biomass and provoking changes in species composition. All these processes lead to the appearance of more fire-prone edges, where fortuitous fires can advance (Cochrane 2001, Cochrane and Laurance 2002). This synergistic interaction between pastures and the surrounding rainforest fragments resulted on the importance of the percent of rainforests in the arboreal burned area in this ENSO year and contrasts with the role of pine-oak communities in Non-ENSO years. When rainforests burn under normal climatic conditions, fires are usually superficial and cause relatively little small damage in a long-term basis (Uhl *et al.* 1988). However, when rainforests burn, they create positive feedbacks in future fire susceptibility and fire intensity (Cochrane et al. 1999, Cochrane and Schulze 1999). This leads to changes in structural and functional dynamics (Uhl and Kauffman 1990, Holdsworth and Uhl 1997), to the substitution of species-rich rainforests by relatively species-poor forests (Cochrane and Schulze 1999, Laurance et al. 1998, 2001), and to the invasion of weeds, grasses and open canopy species, with the transformation of closed tropical rainforests into

savannas as the final step towards degradation (Goldammer 1999). Unusual severe episodes occur when extreme drought conditions (e.g. El Niño years) allow fire to spread in these communities (Goldammer 1993, Taylor et al. 1999, SEMARNAT 1999), where large fuel loads and vertical and horizontal continuity burn large extensions that are impossible to attack. Therefore, special attention should be given to rainforests in these years, because they are the communities that suffer the most destructive fires.

The positive fire feedback found in ENSO years in tropical forests in Chiapas, has also been reported for temperate and Mediterranean forests that have an understory grass cover. An increased fire risk and forest damage are the consequences of this positive feedback (Weatherspoon and Skinner 1995; Vilà et al. 2001).

The arboreal burned area in the ENSO year was poorly explained by the variables considered (20% of explained variability), the arboreal fire incidence being the one that contributed the most. Thus, it can be suggested that reducing the number of fires would not guarantee the preservation of forest resources. Moreover, because of the special climatic conditions of these years, reported synergistic relations between fire and pastures, logged forests, and fragmented rainforests are likely to strengthen, making the lineal effects difficult to model.

In the all-layers model, the area burned was influenced by the percent of pine-oak communities, in contrast to the role of rainforests in the arboreal model. This result suggests that non-arboreal layers (pastures, shrublands) also suffer from extensive fires in this ENSO year. Compared to the arboreal fire incidence, all-layers fire incidence displays a new human-related variable: poverty levels, which presents a negative sign. Thus, among other variables, the affectation of the all-layers fire incidence is positively influenced by the density of people in the primary sector and negatively affected by the distribution of the poorest people. These latter results are difficult to interpret and require further research about the characteristics of the areas where these people live.

Implications on fire management in Chiapas

Contrary to our initial hypothesis, this study reveals that human-related variables are key factors in ENSO years, while environmental variables are more important in non-ENSO years. In non-ENSO years, the limitation of the number of fires would have an effect to preserve forest resources, due to the strong relationship between fire incidence and burned areas. However, some research should be done to improve knowledge of the role of fire in these communities, as fire suppression might not be a good alternative in cold ecosystems. Thus, studies made in other Mexican pine-oak communities discuss how fire suppression changes fire regimes compared to non fire-managed forests (Minnich et al. 1995). In terms of fire management, to reduce burned areas and to regulate ignitions, efforts should be concentrated in areas with low rainfall and cold temperatures. A review of the statistical analysis of the affected vegetation during the period 1993-1999 confirms this importance, as 61% of the total burned surface, 71% of the incidents and 41% of the arboreal affectation corresponded to these areas (Román-Cuesta, unpublished data).

In ENSO years, rainforests are the major concern. In these ecosystems, the negative effects of environmental and human-related pressures on forest preservation gain importance, not only because they are known to interact among themselves, but also because their levels of positive feedback, synergism and hysteresis are poorly understood and are difficult to predict (Taylor et al. 1999). The low relationship between fire incidence and burned areas suggests that controlling incidence is important but will not have the same effect as in Non-ENSO years. In this case, the research should focus on the distribution of pastures, which is one of the main stressor agents. Restricting pasture-burning in these years might be an important measure, although not easy to put into practice. To reduce negative effects on forest resources (especially referring to rainforests), preventive campaigns should focus on the reinforcement of the application of security measures around the fields to be burned, in order to avoid fires spreading to adjacent forest resources. The application of effective strategies to prevent accidental forest fires or the discontinuation of fire in land practices, is a common demand in other studies of tropical areas (Nepstad et al. 1999, Taylor et al. 1999). However, fire is the agrarian tool that fits best in the tropical socioeconomic and environmental framework (Vélez 1991), whereas only non-realistic alternatives have been suggested. This lack of alternatives, and a long history of fire use, are held to be responsible for the failure of fire suppression initiatives in Chiapas, despite a history of official opposition to wildfire, dating back to pre-Columbian times (Fule and Covington 1997).

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