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# Driving Factors for Forest Fire Occurrence in Durango State of Mexico: A Geospatial Perspective

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**Abstract:** Forest fire is one of the major causes of forest loss and therefore one of the main constraints for sustainable forest management worldwide. Identifying the driving factors and understanding the contribution of each factor are essential for the management of forest fire occurrence. The objective of this study is to identify variables that are spatially related to the occurrence and incidence of the forest fire in the State of Durango, Mexico. For this purpose, data from forest fire records for a five-year period were analyzed. The spatial correlations between forest fire occurrence and intensity of land use, susceptibility of vegetation, temperature, precipitation and slope were tested by Geographically Weighted Regression (GWR) method, under an Ordinary Least Square estimator. Results show that the spatial pattern of the forest fire in the study area is closely correlated with the intensity of land use, and land use change is one of the main explanatory variables. In addition, vegetation type and precipitation are also the main driving factors. The fitting model indicates obvious link between the variables. Forest fire was found to be the consequence of a particular combination of the environmental factors, and when these factors coexist with human activities, there is high probability of forest fire occurrence. Mandatory regulation of human activities is a key strategy for forest fire prevention.

**Keywords:** forest fire; Geographically Weighted Regression (GWR); land use; forest management; Durango State; Mexico

## 1 Introduction

The spatial pattern of forest fire occurrence is a key factor in understanding forest fire dynamics, and presence of a forest fire is determined by several biotic and non biotic factors, however, the effects of each factor vary between ecosystems and within spatial and temporal scales (Yang *et al*., 2007). Although the availability of combustible bed is one of the most frequently addressed factors in forest fire prevention programs, anthropogenic activities strongly influence the frequency and spatial patterns of the forest fire. Thus, understanding both the anthropogenic and biophysical factors that explain forest fire patterns could help to define where these events are most likely to occur (Syphard *et al*., 2008). In order to design suitable strategies and actions for forest fire management, robust information regarding the nature of forest fire is required, especially with regard to the causal agents and conditions that favour fire. Researches on causal agents are of prime importance because the design and operation of prevention programmes, based on the awareness on risk and danger factors, require strong background knowledge (Castillo *et al*., 2002). Several relevant studies have been carried out in this respect. Martinez (2004) found that 20%–50% of the forest fire in Spain was associated with negligent and intentional burnings related to agricultural practices. Rodriguez *et al.* (2008) suggested that in Mexico, a combination of factors such as maximum wind speed, number of producers and their educational levels are the factors most frequently associated with the forest fire. Roman and Martinez (2006) found signifi-

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cant relationships between road density, agricultural land extension and forest fire in the biosphere reserves located in Chiapas, Mexico.

Researches on the spatial pattern of the forest fire occurrence at Las Bayas Forest Reserve in the State of Durango, Mexico showed that the occurrence of forest fire is related to extreme variations of the weather (Drury and Veblen, 2008). Renteria (2004) developed digital models for forest fire risk in the community of Pueblo Nuevo in Durango, and this model was devised as a support tool for decision-making in the plan for forest combustible management. Furthermore, Avila *et al.* (2010) analyzed the spatial patterns of forest fire occurrence in Durango State, Mexico, indicating that the occurrence of forest fire is a function of the variables that are not constant in space. This spatial influence was better analyzed by the Geographical Weighted Regression (GWR) method, which assumes the existence of local variations in the estimated parameters, and at the same time includes a geographical weighted system according to the geographical localization. The variable selection was considered in the studies of spatial patterns of the forest fire (Krishna *et al.*, 2006; Han-Bin *et al.*, 2007; Yang *et al.*, 2007; Syphard *et al.*, 2008). The analysis on the spatial patterns of the forest fire occurrence as well as the relationships between the forest fire occurrence and physical, environmental and social factors indicated that social factors are the most important one and the combination of intensive land use, topographical treatments and climatic variations increases the probability of ignition.

The complex physiographical composition of Durango, due to its location in the Sierra Madre Occidental, makes it a highly diverse region in which almost all types of vegetation found in Mexico occur, with the exception of rainforest (Gonzalez *et al.*, 2007). However, few studies on the causes of ecosystem degradation from a geographical perspective were conducted. The GWR method is a useful tool to analyze the causes and identify the spatial variations in regions. Therefore, this method was employed in this paper since forest fire occurs frequently in Durango due to physiographical diversity.

The objective of this study was to identify the variables that are spatially related to the presence and incidence of the forest fire in Durango, taking as the hypothesis that the spatial pattern of the forest fire occurrence is closely related to the presence of anthropogenic activities.

## 2 Materials and Methods

### 2.1 Study area

The State of Durango is located in the northwest of Mexico (22°16′–26°53′N, 102°29′–107°16′W) (Fig. 1) and covers a forest area of $9\times10^4$ km$^2$ (Federal Agency for Environmental Protection, 2009), with a high diversity of forest communities. Temperate forests are mainly composed of several species of pine and oak, which are important for commercial exploitation.

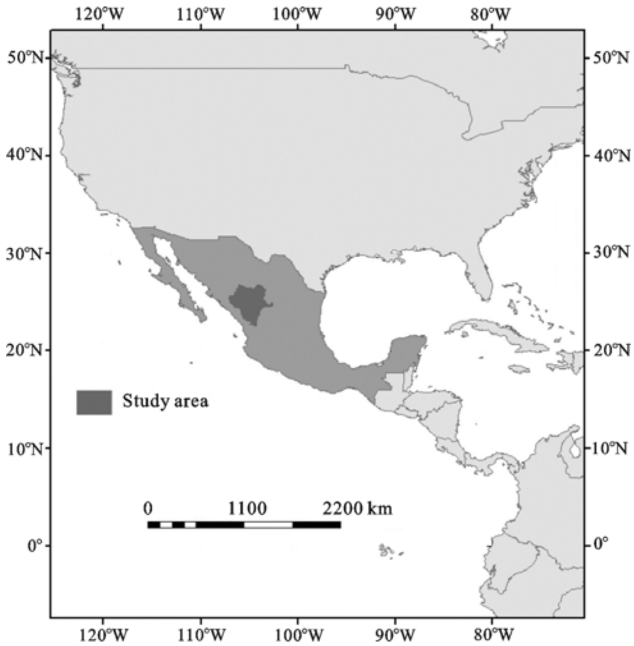


Fig. 1 Location sketch of study area in Mexico

### 2.2 Data sources

Data were obtained from the report of *Evaluation of Soil Degradation Caused by Man in the Mexican Republic, 2001–2002* (Ministry of Enviroment and Natural Resources and Post Graduate College, 2001). The database from field collection and the corresponding physiographical digital map (1∶250 000) were used. Physiographical units (referred to as terrestrial systems) were deployed from the digital cartography, and then linked to the field database in order to provide information regarding the location, slope, rock type, land use, vegetation type and intensity of land use change. Climatic information, including mean annual temperature (℃) and average annual precipitation (mm), was also considered for the period of 2004–2008. A forest-fire database, with information on Durango, collected in the field by the National Commission for Forestry from 2004 to 2008, was considered along with the terrestrial systems data, to provide a complete dataset for each system, including the physical properties of the system and the frequency of forest fire.

Although the time of physiographical data and forest-fire database used were not consistent, there is no statistical impact on the results, since the terrestrial systems do not suffer modifications of natural form throughout the time, and the study area was defined at a smaller scale. Therefore, the heterogeneity of the study area was negligible.

### 2.3 Statistical analysis

Linear regression is a useful tool to analyze if two or more variables are related in a linear fashion. In this study, slope, susceptibility of vegetation, intensity of land use change, temperature and precipitation were selected in the spatial correlation analysis, and GWR was used to select variables. In order to estimate the parameters of a model for any place $u$, greater weight must be given to those observations that are closest to $u$, over those observations further away. We use $u$ to indicate some general location in the study area. Typically $u$ will be a vector of coordinates measured in either a projected coordinate system (such as Universal Transverse Mercator) or a geodetic system such as WGS84 (Charlton and Fotheringham, 2009).

The underlying idea of GWR is that parameters may be estimated anywhere in the study area given a dependent variable and a set of one or more independent variables which have been measured at places whose location is known. Taking Tobler's observation about nearness and similarity into account it is expected that if parameters for a model at location $u$ were estimated, then observations which are nearer to the location $u$ will have a greater weight in the estimation.

We assume that the analysis has a dataset consisting of a dependent variable $y$ and a set of independent variable(s) $m$ ($x_k$, $k = 1, \ldots, m$), and for each of the observations in the dataset, a measurement of its position is available in a suitable coordinate system.

The equation for a typical GWR version of the Ordinary Least Squares (OLS) regression model is as the following:

$$y_i(u) = \beta_{0i}(u) + \beta_{1i}(u)x_{1i} + \beta_{2i}(u)x_{2i} + \ldots + \beta_{mi}(u)x_{mi}$$

where $y_i$ is the dependent variable; $\beta_{0i}$ to $\beta_{mi}$ indicate the parameters that describe the relationship around the coordinates ($u$) of the $i$th point in space (site-specific); and $x_{mi}$ is the $m$th variable in the $i$th point.

In this model, the number of forest fire in each unit of terrestrial system was considered as the dependent variable, at the same time, the descriptive characteristics for each unit: slope (%), temperature (℃), precipitation (mm), intensity of land use change (persons/km$^2$), and susceptibility of vegetation to fire (%), according to National Commission for Knowledge and Use of Biodiversity (1998), were selected as independent variables. For example, if it was necessary to assign quantitative value to the dominant vegetation variables and intensity of anthropogenic effects on land use change, we would weigh the information contained in these fields by assigning high values to those classifications that had more to do with the presence of fire, i.e., in the case of the dominant vegetation, a greater value was assigned to the vegetation depended on the fire. In the case of intense change of land use resulting from anthropogenic activities, the highest value was assigned to the type of land use unit with the largest number of forest fire. For the independent category, an intermediate value was assigned to the category which is identified as sensitive and influenced by the fire. To plot the local influence of each unit characteristics on forest fire, an adaptive kernel of GWR was applied. Tests and plotting were performed with ArcGIS 9.3.

## 3 Results

The results based on the scatter plot matrix show that the number of forest fire occurrence is significantly correlated to susceptibility of vegetation, intensity of land use change and precipitation (Fig. 2). It highlights anthropogenic effect on the concentrations of forest fire, which is reflected by the variables of intensity of the change in land use such as farming, forestry and recreation.

The regression model reveals that the above mentioned variables are statistically significant (Table 1). The coefficients of variables are the following ranking: intensity of land use change > susceptibility of vegetation > precipitation. Furthermore, low Variance Inflation Factor (VIF) values (< 7.5) demonstrate that there is no multiple co-linearity between the variables.

The adjusted model confirms that the explanatory variables are closely related to the dependent variable

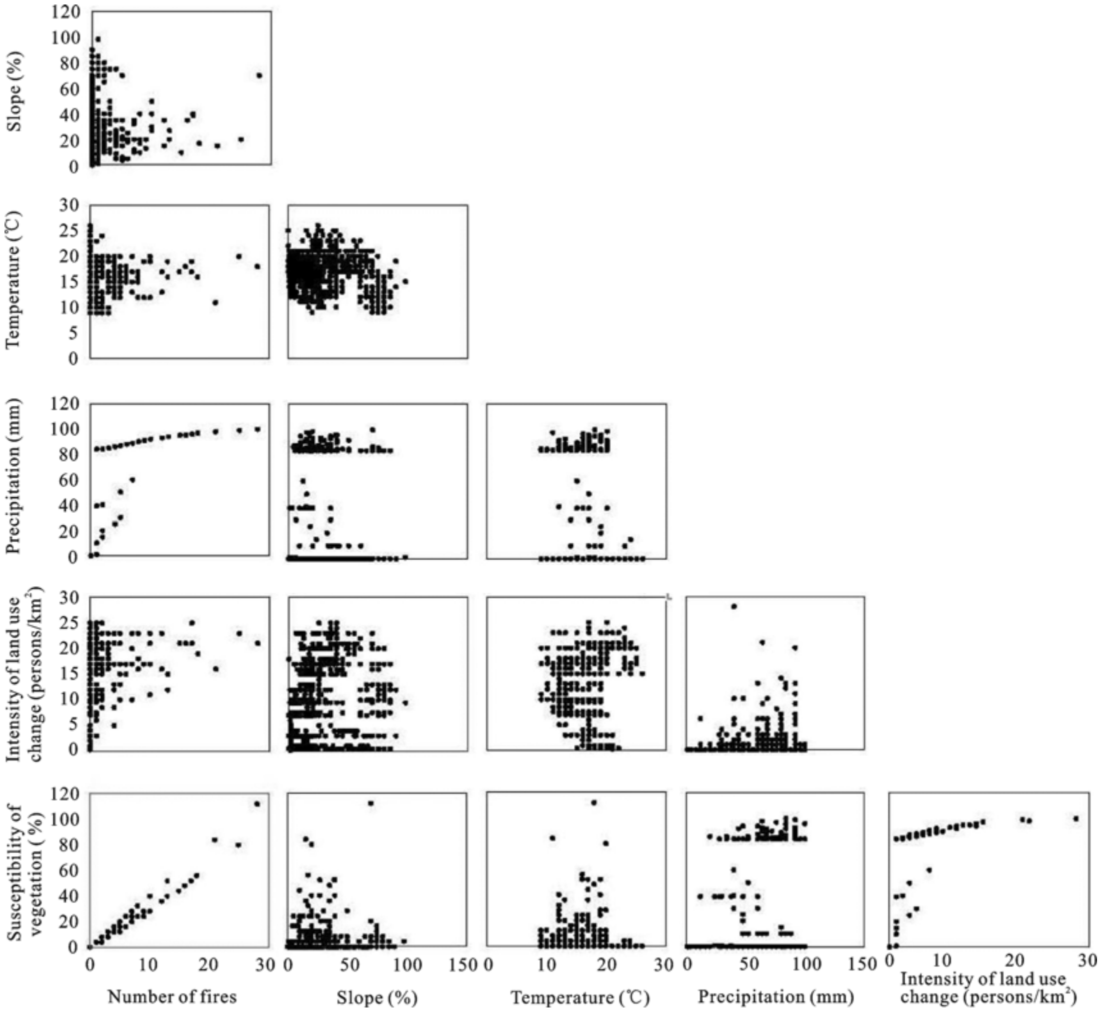


Fig. 2 Correlation between number of forest fire occurrence and variables

Table 1 Statistics results of significant variables

| Variable | Coefficient | Probability | VIF |
|---|---|---|---|
| Susceptibility of vegetation | 0.0035 | 0.0000* | 1.9750 |
| Precipitation | 0.0008 | 0.0244* | 1.2677 |
| Intensity of land use change | 1.1274 | 0.0000* | 1.7332 |

Notes: * denotes statistically significant at 0.05 level; VIF is Variance Inflation Factor

($R^2$ = 0.9762); Akike Information Criterion (AIC = 757.28) indicates that the model is the best in terms of describing the relationship between variables (Table 2). Similarly, statistics results of Joint F and Joint Wald show high significance for the model, and that of the Jarque-Bera presents that the residuals are normally distributed. The Moran Index measures the level of spatial autocorrelation among the residuals, and in this case the value (0.083) indicates that there is no spatial autocorrelation. All variables are statistically significant because the Koenker (BP) values are relatively higher. If the result of BP test is significant, it means that GWR can be performed on the data.

Table 2 Statistics results obtained from Ordinary Least Squares indicator

| | Joint F | Joint Wald | Jarque-Bera | Koenker (BP) |
|---|---|---|---|---|
| Value | 18382.8594 | 3510.8829 | 75922.0276 | 1113.1824 |
| Probability (> $F$) | 0.0000* | 0.0000* | 0.0000* | 0.0000* |

Note: * denotes statistically significant at 0.05 level

The standardized residuals from the GWR predictions can be mapped in order to identify any prediction outliers. Figure 3 describes the highest and lowest predictions for the spatially distributed explanatory variables in each terrestrial unit evaluated. These terrestrial units

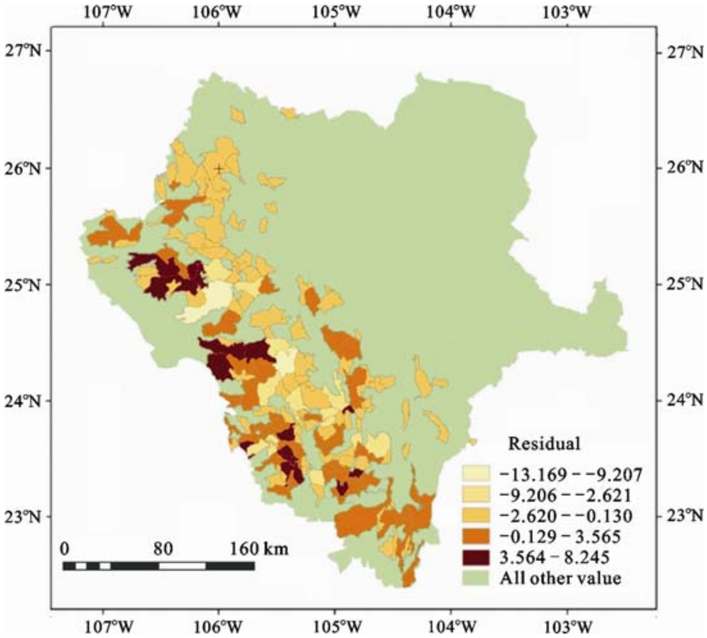


Fig. 3 Residuals′ distribution in study area

could be examined to ascertain if there are any special characteristics of these cases that might explain the large residuals. Any spatial dependency which might have been presented in the residuals for the global model have been removed with the geographical weighting in the local model.

## 4 Discussion

There are a few studies focused on the causes of forest fire occurrence from the geographical perspective in Durango, and previous researches found that intensity of land use change, vegetation type and precipitation are main factors that determine spatial patterns of forest fire. The forest consisting of Pine and Oak provides fuel for the fire, this fire regime is variable and significant according to the land use intensity because the areas with agriculture and tourism are susceptible to fire, particularly in early summer when the fuel conditions are highly flammable (Sepulveda *et al.*, 2001). The results of the present study are consistent with those reported by Badia *et al*. (2000), whose research showed that the spatial distribution of forest fire in Spain responds to behavior patterns, which in turn are linked to typology and functioning of the territory. Cardille *et al.* (2001) analyzed the social and environmental factors that influence the occurrence of forest fire in Minnesota, Wisconsin and Michigan (USA). According to their researches, the variations in forest cover, soil type, density of human settlement and land management strategies can influence the spatial pattern of forest fire. The results indicate that the spatial distribution of forest fire in this area is the result of a combination of environmental and social factors.

Still some results emphasized the crucial role of anthropogenic activities in the spatial distribution of forest fire. Roman and Martinez (2006) found that the high density of forest fire recorded in Biosphere Reserves in Chiapas was linked to the areas devoted to agricultural activities and the areas with high densities of roads. Similarly, Maingi and Henry (2007) found that the distance to roads and human settlements are the factors influencing the occurrence of forest fire in Kentucky. Catry *et al.* (2007) reported that in Portugal, most forest fire occurred close to densely populated areas.

In this study, four physical factors were considered (slope, susceptibility of vegetation, temperature and precipitation), but only precipitation and susceptibility of vegetation were highly significant. It might because physical factors change over space and time, so they cannot be considered as the best factors to explain the concentration of forest fire in certain areas. The result of this study is consistent with the conclusion in previous research. Romero *et al.* (2008) pointed out that spatial patterns of forest fire are strongly associated with human's access to natural landscape, so that the proximity to urban areas and roads is clearly a determining factor in forest fire occurrence. Researches suggest the need to consider human activities in the models of assessing forest fire risk.

Based on the analysis of the geographical space perspective, it is evident that causes are not homogeneous in this study because the results indicate that the relationship between the causal factors is not spatially stationary. The heterogeneity condition could be resolved by using the geographically weighted regression where the statistical estimators obtained. The level of explaining forest fire occurrence was improved through this study, and this method could evaluate the geographic conditions of each individual location of a forest fire incident.

Strategic planning of fire suppression requires detailed understanding of the combined factors of current fire and geographical conditions. Understanding the factors involved in forest fire occurrence is of key importance in the development of prevention strategies and preparedness planning. Only the principal causes of forest fire presence were considered in this study. It is important to have more information on climatic condition and forest fire risk maps. In addition, dynamic and flexible characteristic from a geographical perspective will be studied if the nature of the spatial data can be obtained.

## 5 Conclusions

Human activities are the main factor determining the occurrence of forest fire, followed by vegetation type and precipitation, which should be considered as fundamental elements in the design of forest fire prevention programmes. Mandatory regulation and surveillance of activities are also key strategies for forest fire prevention, especially in regions where fire utilization is part of the productive cycle.

The model applied in this study proved useful since it was statistically significant with regard to explaining the spatial correlation between forest fire and their location, and thus it can be used with necessary adaptations. Indeed, the need to elaborate a risk index for Durango was highlighted in this study, actually, the high ecosystem diversity and complex physiographical structure of the region, and also those factors related to the nature and context of management practices in the forest and agricultural sectors should be considered.

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