Natural and social factors influencing forest fire occurrence at a local spatial scale

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Abstract

Development of efficient forest fire policies requires an understanding of the underlying reasons behind forest fire ignitions. Globally, there is a close relationship between forest fires and human activities, i.e., fires understood as human events due to negligence (e.g., agricultural burning escapes), and deliberate actions (e.g., pyromania, revenge, land use change attempts). Wildfire occurrence even for human-ignited fires has also been shown to be dependent on biophysical variables (e.g., fuel conditions). Accordingly, this paper modelled the spatial risk of forest fire occurrence as a function of natural as well as socioeconomic variables. The study area is the region of Galicia (NW Spain). Our data include approximately 86,000 forest fires in nearly 3,800 Galician parishes, the unit of our study, during the ten years period 1999-2008, inclusive. The analysis combines spatial and non spatial econometric approaches to evaluate the consistency of the results and account for spatial autocorrelation in the fire ignitions data.

Keywords: intentional wildfires, fire occurrence, spatial autocorrelation

1. INTRODUCTION

In Spain, wildfires are a recurrent phenomenon, with an annual average of 15,000 forest fires and 173,000 ha burned between 1980 and 2010 (MARM 2010). A significant proportion of these fires, and in particular those intentionally ignited, occurred in the region of Galicia, northwest of Spain (APAS and IDEM 2006). Thus, during the period 1999-2008 an annual average of close to 8,600 forest fires burned about 40,000 ha in Galicia. Most fires are human-caused (99%), approximately 82% are set intentionally and 5% are either ignited accidentally or through negligence (Chas-Amil et al. 2010). However only a limited number of research has specifically evaluated how the human presence in this territory increase the risk of fire ignition (Martinez et al. 2009; Padilla and Vega-García 2011; Prestemon et al. *forthcoming*). This contrasts with the increasing literature on empirical assessments of the influence of socioeconomic aspects on forest fire risks, using variables such as population density, land cover changes associated with agriculture abandonment, distance to road or the density of human settlements (e.g., Brosofske et al. 2007; Maingi and Henry 2007; Moreira et al. 2011; Narayanaraj and Wimberly 2012).

In this study, the spatial pattern in the number of fires throughout Galicia is modelled to determine which topographic, meteorological, and socioeconomic variables best explained a decade-scale pattern of fire activity (1999-2008). However, the analysis of spatial data is complicated by the potential presence of spatial autocorrelation (SAC) (Dormann et al.

2007). SAC occurs when fire data from locations close to each other have more similar values than those farther apart. It may emerge because fire ignitions in a given area are strongly dependent on natural and human factors that are also themselves spatially structured, i.e., values in a given location are strongly influenced by those in their surroundings (Chou 1992). If this SAC still exits in the residuals of an econometric model of spatial data, this may lead to biased coefficients and limit hypothesis testing. We apply non-spatial and spatial models to evaluate the consistency of our results and the effect of spatial autocorrelation on estimated coefficients and inference.

2. MATERIALS AND METHODS

2.1. Study area

Galicia (NW of Spain) comprises a total area of 29,575 km^2, which corresponds to a 6% of the Spanish geographical area. Individual private ownership represents 68% of the forestland, while 30% is under collective private ownership. Forests cover nearly 70% of its territory and approximately 67% of this forestland is wooded. *Pinus pinaster, Eucalyptus globules, Quercus robur,* and *Quercus pyrenaica* are the main tree species.

2.2. Materials

In this work, we studied 1999-2008 wildfire data provided by the General Statistics of Forest Fires compiled by the Spanish Forest Service and the Rural Affairs Department of the Regional Government (Xunta de Galicia). This means a total of 85,784 wildland fires, which burnt 319,651 hectares. Recorded fire ignitions were assembled into a dataset of counts of wildfires for each of the 3,790 Galician parishes. We opted for the parishes as the geographical unit for the analysis because it is the smallest administrative unit that divides the territory. The parishes' mean size is 779 hectares with a standard deviation of 664 hectares.The potential explanatory variables studied in the model specification were based on an extensive literature review and can be divided in three broad types: topographic, meteorological, and socioeconomic. The variable definitions and their sources are summarised in Table 1.

2.3. Methods

We use Moran's Index to evaluate the degree of spatial autocorrelation of the Galician fire data over the studied decade (Moran 1950). Our modelled response variable is wildfire rate defined as the number of fire events per parish divided by the parish area, reported as fires per 100 hectares. Both Negative-binomial regression and OLS estimation were used to model fire ignitions as a function of the socioeconomic and natural covariates. A negative binomial model was chosen because of the overdispersion in the fire data per parish. Following Osgood (2000), we modified the basic Negative Binomial regression so that the analysis focuses on the fire rate per parish rather than counts of fire events. In addition, given the spatial character of fire data, the presence of spatial autocorrelation in the regression is examined using correlogram plots, which measure the similarity of the residuals as a function of geographical distances. A Generalised Least Squares (GLS) estimation, building a correlation structure that captures the fire's spatial patterning, was also applied to evaluate the consistency of estimation parameters and spatial correlation effects. An exponential spatial correlation structure was used, as these fit the variogram of residuals produced when using a simple GLS without a correlation structure (Dormann et al. 2007).

Table 1. Independent variables for modelling forest fire occurrence at the parish level

Variables	Data source	Description	Units
Physiography			
Slope	10 m Digital Elevation Model (1:5,000). SITGA.	Mean, minimum, maximum and standard deviation of the parish slope.	%
Elevation	10 m Digital Elevation Model (1:5,000). SITGA.	Mean and range elevation observed in the parish.	m
Meteorology			
Air temperature	Digital Climatic Atlas of the Iberian Peninsula- spatial resolution 200 m (Ninyerola et al. 2005). Monthly data.	Annual mean, maximum, mininum	ºC
Precipitation	Digital Climatic Atlas of the Iberian Peninsula- spatial resolution 200 m (Ninyerola et al. 2005). Monthly data.	Annual mean	l/m2
Forest use cover			
Forest area: - Wooded land - Other wooded land	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Land with tree crown cover, or equivalent stocking level of: -higher than 10% -lower than 10%	ha
Dominant forest vegetation: Eucalyptus, Conifers, Other broad-leaved species	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area	ha
Pure monoculture: Eucalyptus, Conifers, Other broad-leaved species	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Pure stands were considered with at least 80% of the area covered by a single species.	ha
Forest plantations	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area of planted forest consisting primarily of introduced species.	ha
Forest land tenure: Public, Private, Communal	Third Spanish Forest Inventory cartography (1:50,000). MARM.	Area by parish	ha
Protected natural area	Protected natural spaces coverage (1:25,000) Consellería do Medio Rural	Area of protected natural area by parish (dummy variable)	
Human factors			
Population density	Nomenclator (INE)	Mean of parish's population in the period divided by parish area	hab/ha
Road density (paved, path, forest path)	Base Topográfica Nacional (BTN25) (1: 25,000)	m of roads included in the parish divided by parish area	m/m^2
Accessibility index	Base Topográfica Nacional (BTN25) (1: 25,000)	$S_i = \sum_{i \neq j} \exp(-\alpha d_{ij}) A_j$ A is population size in parish j. α takes a value of 0.001 (average travelling distance is 10 km)	

3. RESULTS

The spatial representation of the total number of fires per parish illustrates that wildfires are mainly concentrated on the Atlantic coast and in the South. The global Moran's Index for wildfire occurrence was 0.404, indicating the presence of a statistically significant positive spatial autocorrelation in the parishes' fires (z-score=42.03, p-value: 0.000). OLS, Poisson and GLS estimates show consistent results in terms of the signs of the coefficients (Table 2).

Table 2. Model estimation results.

Explanatory variables	OLS log(rate+0.1)		Negative Binomial		Generalized least squares	
	Coef.	*P*	*Coef.*	*P*	*Coef.*	*P*
intercept	-2.179	0.0000 ***	-5.892	0.0000 ***	-1.3433	0.0228*
ln(Pop_density)	0.3186	0.0000 ***	0.3490	0.0000 ***	0.2450	0.0000 ***
% forestland	1.042	0.0000 ***	1.013	0.0000 ***	0.6326	0.0000 ***
ln(% plantation)	-0.1034	0.0074 **	-0.1246	0.0000 ***	-0.0625	0.1137
% wooded forest	-0.7535	0.0000 ***	-0.8943	0.0000 ***	-0.5053	0.0000 ***
DV protected land	-0.2015	0.0000 ***	-0.1736e	0.0000 ***	-0.099	0.0279*
% Communal forest	0.2643	0.0005 ***	0.2007	0.0036 **	0.2045	0.0209*
% Eucalyptus	--0.594	0.0000 ***	-0.6605	0.0000 ***	-0.194	0.2076
% Conifers	-0.435	0.0001 ***	-0.4348	0.0000 ***	-0.1814	0.1809
% Broadleaves Pure	0.7280	0.0000 ***	1.013	0.0000 ***	0.311	0.0729
Mean temp summer	0.1249	0.0000 ***	0.1511	0.0000 ***	0.1135	0.002**
Mean precip summer	-0.0118	0.0000 ***	-0.01267	0.0000 ***	-0.0126	0.0004***
Slope mean	-0.0077	0.0016**	-0.0064	0.0045 **	-0.0069	0.026*
Paved_density	149.5	0.0000 ***	153.7	0.0000 ***	100.82	0.0000 ***
Path_density	147.3	0.0000 ***	126.9	0.0000 ***	93.42	0.0000 ***
Forest_path density	25.20	0.1507	51.71	0.0013**	14.96	0.423
Access	6.1e-07	0.0000 ***	4.2e-07	0.0000 ***	0.00000	0.0000 ***
Ln(area_parish)	0.0844	0.0034**				
R^2	0.3		-2LL	28994		
			Residual deviance	4237 (1.037e-07)		

The variables explored have a significant effect on forest fire events in both the OLS and negative binomial models, except for forest path density. In addition, the regression coefficients for population density, percentage of forestland, and communal private forestlands were always positive and significant for all models. This means that, as expected, the higher the population pressure and the greater the share of forestland with respect other land uses in the parish, the greater the probability of fire occurrence. A negative relation is shown, however, with the percent of forest plantations and the percentage of forest area that is wooded. This result indicates that sparsely wooded landscapes are at lower risk of fire, while less densely wood landscapes are at greater risk, ceteris paribus. The high percentage of eucalyptus and conifers on forestry plantations may explain the negative effect of these two tree species on fire risk. Density of rural paved roads and paths as well as a higher accessibility index increase the probability of fire ignitions. We have also found that OLS and the negative binomial models do not completely explain the fire distribution, as they do not take into account the spatial structure of the dependent variable. Figure 1 shows that the negative binomial model's residuals display spatial autocorrelation up to 30 km.

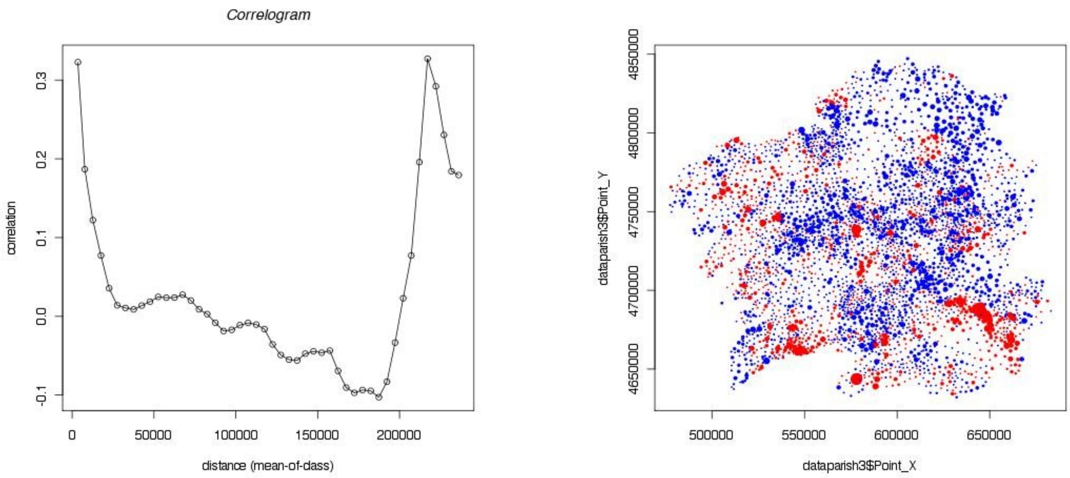

Figure 1. Correlogram plot and spatial representation of residuals from the estimated negative binomial model. Negative residuals (overpredictions) are represented as blue, positive residuals (underpredictions) as red.

4. CONCLUSIONS

Our models have identified variables that have significant relationships and signs to explain where forest fires are ignited in Galicia. Higher population pressure, communal ownership, and higher road and path accessibility to the forest increase the probability of fire, while increasing the productivity of forestlands through forest plantations decreases this probability. This econometric analysis, however, has so far failed to shed full light on the strong spatial pattern in the fire occurrence pattern, with significant clusters of fire events in the Atlantic coast and in the South of the region. The question remaining is how the number of fires reported at one location encourages/discourages occurrences at other nearby locations. Given the high proportion of deliberate fires in this region, this may be attributable to serial or copycat fire setting, with a relatively few individuals responsible for multiple fires over long time spans. It may also be related to the omission from our models of key covariates, still to be identified, whose spatial distributions closely align with the residual spatial patterns observed in our models.

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