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Exploring the spatial patterns of fire density in Southern Europe using Geographically Weighted Regression

Sandra Oliveira [a,b,*], José M.C. Pereira [a], Jesús San-Miguel-Ayanz [c], Luciano Lourenço [b]

[a] Forest Research Centre, School of Agriculture, University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal
[b] Centre for Scientific Research on Forest Fires, University of Coimbra, Aeródromo da Lousã, Chã do Freixo, 3200-395 Lousã, Portugal
[c] Institute for Environment and Sustainability, Joint Research Centre, European Commission, Via E. Fermi 2749, 21027 Ispra, VA, Italy

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A B S T R A C T

The spatial patterns of fire occurrence were analyzed in two regions of Southern Europe, focusing on the long-term factors that influence fire distribution. The relationship between fire occurrence and the physical and anthropogenic variables collected was investigated with Geographically Weighted Regression (GWR) and the results were compared with Ordinary Least Squares (OLS). Local patterns of the significant variables were explored and a strong spatial variability of their explanatory power was revealed. Climate (precipitation), livestock and land cover (shrubland) were found to be significant in both regions, although in particular areas and to different extents. Regarding model performance, GWR showed an improvement over OLS in both regions.

The investigation of the spatial variation in the importance of the main drivers over a broad study area, gives a valuable contribution to the improvement of fire management and prevention strategies, adjusted to the particular conditions of different areas.

Introduction

Wildland fire is a widespread event that affects many regions of the world (Bowman et al., 2009; Dwyer, Pinnock, Gregoire, & Pereira, 2000; FAO, 2010; Flannigan, Krawchuk, de Groot, Wotton, & Gowman, 2009; Pechony & Shindell, 2010). Although the occurrence of fires largely depends on local factors, such as vegetation cover and land use (Dwyer et al., 2000; Sebastián-López, Salvador-Civil, Gonzalo-Jiménez, & San-Miguel-Ayanz, 2008), their impacts are evident also at global scale, when considering atmospheric emissions, land cover change or ecosystem functions and services (Carvalho et al., 2010; Pechony & Shindell, 2010; Sebastián-López et al., 2008). This global dimension of fires and the need to understand the complex interaction between factors that are not confined to a restricted geographical area, require the assessment of fire occurrence also at regional, continental or global scales (Chuvieco, Giglio, & Justice, 2008; Sá et al., 2011; Sebastián-López et al., 2008).

From a long-term perspective, fire occurrence is assessed considering the average conditions during a certain period of time, in relation to those factors which remain stable for at least one fire season, such as topography and roads (Jappiot, Gonzalez-Olabarria, Lampin-Maillet, & Borgniet, 2009; San-Miguel-Ayanz et al., 2003). The long-term assessment is suitable to investigate the structural factors that affect the fire proneness of an area, assisting in the definition of prevention strategies and the allocation of fire resources prior to the start of the main fire season (Oliveira, Oehler, San-Miguel-Ayanz, Camia, & Pereira, 2012; San-Miguel-Ayanz et al., 2003).

At the European level, an extraordinary effort has been made in the last decades to compile reliable information on the fire events that affect many countries (Camia, Houston, & San-Miguel-Ayanz, 2010; San-Miguel-Ayanz et al., 2012), to assist in fire prevention and in support of policy-making. Statistics reveal that more than 80,000 fires occur on average a year in Europe, which burn over 500,000 ha of land (European Commission [EC], 2012) and cause extensive damage. The factors that influence fire occurrence differ among European countries and regions, as a result of the diversity of biogeographical features, the physical and anthropogenic conditions across the continent, and due to the fire prevention policies and fire suppression techniques applied at national or local levels (Ganteaume et al., 2013; Montiel & San-Miguel-Ayanz, 2009; Montiel-Molina, 2012; Roekaerts, 2002). Southern Europe, particularly the western countries, where Mediterranean-type climate and vegetation prevail, is the most affected region (Konstantinidis, Tsiourlis, & Galatsidas, 2005; San-Miguel-Ayanz & Camia, 2009; San-Miguel-Ayanz et al., 2009). Furthermore, these trends in fire

* Corresponding author. Centre for Scientific Research on Forest Fires, University of Coimbra, Aeródromo da Lousã, Chã do Freixo, 3200-395 Lousã, Portugal. Tel.: +351 912 856 744.
E-mail address: sisoliveira@gmail.com (S. Oliveira).

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occurrence are expected to be amplified due to ongoing land use and climatic changes, which could cause a substantial increase in the fire-proneness of certain areas and in fire severity, even where fires are currently less relevant (Flannigan et al., 2013; Flannigan, Krawchuk, de Groot, Wotton, & Gowman, 2009; Lindner et al., 2010; Moreira et al., 2011).

Understanding the spatial distribution of fires, its causes and impacts in relation to the specific characteristics of the places where they occur, is crucial for the implementation of efficient strategies of fire prevention and wildland management. The main purpose of this study is, therefore, to contribute to the investigation of the spatial patterns of fire distribution (number of fires) in Southern Europe and uncover the influence of the most important structural factors that drive fire occurrence in the region, with the following objectives:

i) Analyze the spatial variability of fire occurrence in Southern Europe
ii) Identify the main factors that influence fire occurrence across Southern European countries
iii) Assess the consistency of the explanatory power of the variables throughout the study area, exploring the local and regional variations of their significance

Several methods exist to explore the interactions between spatial drivers and fire occurrence; regression methods have been widely used, such as linear and logistic regression (Chuvieco et al., 2010; Oliveira et al., 2012; Sebastián-López et al., 2008) and classification and regression trees (Amatulli, Rodrigues, Trombetti, & Lovreglio, 2006; Archibald, Roy, van Wilgen, & Scholes, 2009; Oliveira et al., 2012). These methods focus on the global picture and follow the assumption of spatial stationarity, which is often violated in real-world situations (Koutsias, Martínez-Fernández, & Allgöwer, 2010; Sá et al., 2011). In broad areas, the level of importance of the variables in explaining fire occurrence is, most likely, not homogeneous throughout the entire study domain (Archibald et al., 2009; Ganteaume et al., 2013). Previous studies suggest that fire assessment models can greatly benefit from the use of analytical methods that capture the spatial attributes of the phenomenon being studied (Koutsias, Martínez, Chuvieco, & Allgöwer, 2005; Koutsias et al., 2010; Kupfer & Farris, 2006; Sá et al., 2011). Geographically Weighted Regression (GWR) (Fotheringham, Brunsdon, & Charlton, 2002) has been applied in the investigation of fire activity at large scale, namely in Mediterranean Europe (Koutsias et al., 2005, 2010) and in sub-Saharan Africa (Sá et al., 2011). GWR allows for regression coefficients to vary for individual locations, capturing the effects of non-stationarity and revealing variations in the importance of the variables across the study area, focusing particularly on data analysis and interpretation, rather than prediction.

Considering the variety of fire data collection structures among countries and the difficulty in obtaining a robust model for the whole of Southern Europe, the study area was further divided in two regions, as described in the following section. OLS and GWR were applied separately in each region and the results compared. The resulting maps are expected to give an overview of the spatial patterns of fire occurrence and its main drivers throughout both regions, providing indications of the variations in the importance of the explanatory variables according to their spatial location.

Material and methods

Study area

This study was carried out for the countries of Southern Europe which are part of the European Forest Fire Information System (EFFIS) network (Camia, Houston, & San-Miguel-Ayanz, 2010; San-Miguel-Ayanz et al., 2012) with a minimum period of data available (at least 6 years). In spite of the harmonized standards already in place, the data collection structures differ among countries (San-Miguel-Ayanz et al., 2012); country data is gathered by the national fire or civil protection services and the information collected depends, to a certain extent, on the resources available in the countries, which vary widely within the European territory. Thus, although European countries have been gathering fire data for several decades, an inclusive transnational coordination on data collection and harmonization is an ongoing effort. For this reason, and after an exploratory analysis of the data, the available countries were grouped in 2 regions: Southwestern Europe (SW Europe) and Southeastern Europe (SE Europe) (Fig. 1). Greece is usually considered part of Southwestern Europe, however our exploratory analysis showed that Greece evidenced similar patterns to the countries of Southeastern Europe regarding fire density and frequency, hence it was included in this region instead; for the same reason, the Balkan countries with available data were included in Southeastern Europe, despite the geographical gap. For France, only the southern provinces, where fire frequency is similar to the remaining countries, were included in Southwestern Europe.

Data collection and processing

Response variable

The probability of fire occurrence results from the joint combination of an ignition source and the conditions for fire to spread (Jappiot et al., 2009; Oliveira et al., 2012); to represent ignitions, we obtained the number of fires recorded in the European Fire Database for each country (Camia, Durrant-Houston, & San-Miguel-Ayanz, 2010; European Commission, 2012). This database compiles and harmonizes fire records from the participating countries since the 80's, the starting year varying according to country; for each individual fire event, specific information is added by the Forest Department and Civil Protection Services of the Member-States, such as the date of the fire, the type of land cover affected, the burned area size, and the administrative region where it occurred, usually a descriptive location at NUTS3 level (corresponding in most countries to the level of provinces), whereas accurate geo-referencing of the fires is lacking for the most part. The number of fires recorded was aggregated at NUTS3 level for each country, for the period 1996–2010 when available, or the longest time-series of the country (at least 6 years). In view of the geolocation uncertainty associated with the fire records, fire density (number of fires/area km^2) was used as a proxy of fire ignition. The calculation of fire density follows a similar procedure to the one used by Oliveira et al. (2012), thus only a brief explanation is presented here.

The fire events with accurate geo-referencing available in the database, for several countries, were used for an exploratory analysis of the proportion of fires occurring in different land cover types, as defined by the Corine Land Cover 2000 map (EEA-ETC/TE, Joint Research Centre [JRC], 2002). From this analysis, the land cover types associated with fire occurrence were aggregated in 2 main categories: wildland and non-wildland areas. Wildland areas include those land cover categories where fires are more likely to occur due to their typical vegetation cover, such as forests, shrublands and grasslands. Non-wildland areas, on the other hand, are those land cover types where a proportion of the fires can occur (or at least start), although their conditions are not typically related to the occurrence of wildland fire, such as agro-forestry areas. The land cover categories with a negligible contribution to fire occurrence, such as water bodies and continuous urban surfaces, as well as areas with elevation above 2000 m, were excluded. It was found