Fire regime changes and major driving forces in Spain from 1968 to 2010

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ABSTRACT

Fire regimes play an important role in ecosystems and climate change, affecting the structure and composition of vegetation and influencing carbon dioxide (CO₂) emissions. Analyses of historical fire regimes have indicated that in many ecosystems, fire regime changes are linked to environmental and climatic changes, but these studies have often been both spatially and temporally limited. To determine whether there have been changes in the fire regime in Spain, we used a statistical change point approach to analyse the number of fires and the burned area since fire statistics were first recorded in 1968 for three pyrologically homogeneous regions over two fire seasons (vegetative season = May–November, non-vegetative season = December–April). Then, to assess the possible driving forces behind these changes, we related the significant change points for the number of fires and burned area to climate, land use and fire management variables. For the vegetative season, we observed upward and downward change points in all three regions. In the non-vegetative season, only upward change points were detected in all three regions, whereas downward changes only occurred in the Mediterranean region. Our analyses suggest that the fire regime changes have been driven by climate and land use and, more recently, have also been influenced by fire suppression policies. Our results may contribute to enhance fire management and future studies of fire ecology and climate change.

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1. Introduction

The term 'fire regime' refers to the characteristics of fires in a given place over a given period of time (Krebs et al., 2010). Since the early 1960s, there has been a growing interest in understanding fire regimes to enhance fire management measures and maintain the ecological integrity of ecosystems, given the ambiguous role of fire (Conedera et al., 2009; Gill, 1975). Given the current status of global change, it is important to understand the changes in fire regimes and the driving forces behind them (Turner, 2010).

Although it is widely recognised that current fire regimes are changing as a result of environmental and climatic changes (Marlon et al., 2008; Pausas and Keeley, 2009), there is much that remains to be clarified. Some authors have observed climate-linked changes in the frequency of fire, the burned area and the seasonality of fires in several regions, including boreal ecosystems (Kasischke and Turetsky, 2006), the western United States (Swetnam, 1993; Westerling et al.,...
human-driven change in Africa (Archibald et al., 2011), fire management changes in Africa (Ramona, 2009) and alpine ecosystems (Pezzatti et al., 2013).

In the Mediterranean ecosystem, several studies have indicated that the changes in fire regimes are mainly driven by fuel accumulation, which is caused by fire suppression policies (Minnich, 1983), climate (Pausas and Fernández-Muñoz, 2012) and human activities (Bal et al., 2011). However, some research suggests that future fire regimes will consist of larger fires (IPCC, 2007), which will reduce the importance of the human role in fire suppression (Loepfe et al., 2012), whereas other studies have highlighted the importance of humans in affecting fire regimes, such as those in Africa (Archibald et al., 2011).

In Spain, the study of historical fire regimes is challenging because the available data are limited (Lloret and Mari, 2001). Nevertheless, several local studies have been conducted using both qualitative and quantitative data (Bal et al., 2011; Kaal et al., 2011; Lloret and Mari, 2001). There are also studies of recent fire regimes, whether using descriptive approaches (Moreno and Chuvieco, 2013) or explicative ones (Vázquez et al., 2002; Vázquez de la Cueva et al., 2006).

Despite the difficulties in comparing different sources of data, there are studies that focus on the detection of fire regime changes (Lloret and Mari, 2001; Pausas, 2004; Pausas and Fernández-Muñoz, 2012), which highlight different aspects of fire regimes (e.g., frequency, seasonality, size and ignition sources) and how they may be triggered by different drivers (e.g., legislation, local agricultural habits, fire management, land use and climate). However, a comprehensive and long-term approach for the whole country is still lacking.

Based on the longest statistical data records currently available, i.e., the 42 years from 1968 to 2010, in this paper we investigate changes in the fire frequency and the burned area of three pyrologically homogeneous regions of Spain (the Northwest, Interior, and Mediterranean regions) and we discuss qualitatively the possible driving forces related to changes in climate, land use and fire management measures since 1968.

2. Methods

2.1. Study area

The study area includes all of the Autonomous Communities on the Spanish peninsula, covering a total surface area of 493,716 km², and includes mainly Oceanic and Mediterranean climatic conditions. Spain has experienced several environmental and social changes since the 1960s. For example, the human population density increased from 59 to 88 n/km² (Population Census 1960–2011).

The economy changed from agricultural to largely industrial and, more recently, to a reliance on the third-sector. The crisis in traditional agriculture has caused a huge exodus from rural areas, and those changes have, in turn, driven land use changes.

Much of the marginal agricultural land has been abandoned, and the natural management of the land through livestock grazing and wood gathering has declined, promoting a large accumulation of fuel in some areas. With these industrial changes, livestock rearing has become more intensive, promoted by EU agricultural policies, while the state’s reforestation policy of using fast-growing species for the paper industry (Seijo, 2005) has also contributed to an increase in woodlands. As a result, woodlands now cover about 37% of the study area, which represents an increase from 115,871 km² (First National Forest Inventory 1966–1975) to 182,582 km² (Third National Forest Inventory 1997–2007). Conversely, the livestock density decreased from 45 to 12 n/km² (Agricultural Census 1968–2009).

The transformation from a predominantly rural to urban society has promoted the growth of the forest–urban interface, and forest use has changed from providing resources to recreation (Martínez et al., 2009; Pausas, 2004).

Technological developments have greatly improved fire management practices, shifting from a focus on fire suppression to a more environmental approach that promotes prevention activities and the introduction of sylviculture (Vélez, 2000).

In addition to these changes, climatic variability, which has resulted in frequent droughts and warmer temperatures, may also have changed the fire regime.

2.2. Defining pyrologically homogeneous regions

Due to its heterogeneous climatic and environmental characteristics, Spain has different fire regimes in different regions. To select pyrologically homogeneous areas, we considered three regions, each consisting of several spatially contiguous provinces. These regions are used by the Spanish Department of Defense Against Forest Fires (ADCIF) in the Ministry of Agriculture, Food and Environment (MAGRAMA) in their forest fire statistical reports (Fig. 1). Furthermore, the study of these regions enabled us to make more extensive use of the dataset by analysing the fire reports without their locational details, which were addressed in previous studies (Moreno and Chuvieco, 2013; Moreno et al., 2011).

The Northwest region includes the Autonomous Communities of Galicia, Asturias, Cantabria and Basque Country, as well as the provinces of Leon and Zamora, covering a total surface area of 78,987 km². This region has oceanic climatic conditions, except for the provinces of Leon and Zamora, which have a continental Mediterranean climate. Most northern provinces are affected by the Foehn winds, which originate from southwest of the Iberian Peninsula during the spring season when traditional agricultural burning to maintain pastures occurred historically. This region had the highest human population density and the lowest population growth rate. Approximately 41% of the region is covered by woodlands, and it had the lowest woodland growth rate. The Northwest region has been most affected by fires that were caused by a conflict of interest between farmers and the previously mentioned reforestation policies (Seijo, 2005). These policies affect early consortium woodlands, which were previously used by farmers. However, the attempt to resolve the previous conflict in the 1980s resulted in a new law that assigned the allocation of communal woodlands and caused new conflicts between landowners over boundaries (Vélez, 1986). The livestock density had a lower reduction in its growth rate than the Interior or Mediterranean regions.
The Interior region, covering 260,336 km², includes all of the Autonomous Communities that lack a coastline, except for the provinces of Leon and Zamora, and has continental Mediterranean conditions, with frequent dry winds and heat waves that promote large fires in the summer. This region had the lowest human population density for the study period and the second highest population growth rate. Approximately 61% of its surface area is covered by woodland, and it had the highest woodland growth rate, probably due to the abandonment of agricultural activities and the reduction in the number of livestock. Livestock density had the highest reduction in growth rate.

The Mediterranean region has a surface area of 154,393 km² and includes all of the provinces in each of the Autonomous Communities that are located along the Mediterranean Sea. The region has a Mediterranean climate, and it is affected by Continental Foehn winds during the summer, when large fires used to occur. It had the highest human population density and the highest population growth rate during the study period, which was a consequence of the urbanisation processes and tourism activities that have encouraged most of the population to live along the coast. Approximately 22% of its surface area is covered by woodland, and the region had the second highest woodland growth rate as well as the second highest reduction in the livestock growth rate.

2.3. Forest Fire Statistics

We referred to the forest fires data that were collected by the Spanish ADCIF, using the reports that were produced by each Autonomous Community. These statistics comprise one of the oldest databases in Europe, with records going back to 1968 (Vélez, 2000).

The Forest Fire Statistics dataset was assessed to confirm the location of each report by conducting comparisons between different attributes of the fires. We checked that the assigned cell corresponded to the appropriate municipality, province and Autonomous Community, correcting erroneous information.

We then selected all the records for fires ≥ 1 ha to ensure that almost all of the recorded fires were included in our study and to avoid detecting changes arising from changes in the minimum size of fires recorded over the years. Finally, we considered two seasons because the distribution of fire during these seasons is clearly evident. The vegetative season was defined as May to November, and the non-vegetative season extended from December to April.

2.4. Climate, land use and fire management

We hypothesised that climate changes and changes in frequencies of weather extremes in particular, along with factors such as the abandonment of agricultural land in the 1960s, the subsequent reduction in economic activities involving forestry and livestock and fire management measures may have affected fire regimes. Consequently, we used existing forest fire weather indices as a proxy for possible climate changes during the study period, whereas woodland, livestock and population evolution were used as proxies for both land use and potential fire ignition activities.

Changes in livestock density could affect the fire regime both due to the presence of a rural population using fire and, therefore, constituting a potential source of ignition, and due to the regulation in fuel accumulation.

Similarly, because most fires are caused by humans, fire regime changes may be associated with changes in population density and economic activity. In Spain, society has shifted over the study period from being predominantly rural, with a population more involved in the use of fire, to being predominantly urban. Society’s use of forests has also changed, from a source of resources to a place for recreational activities.

Finally, fire prevention and suppression measures were used as a proxy for fire management activities. Improved fire management can decrease the number of fires and the burned
area through prevention, while fire suppression and quicker detection can reduce the size of the burnt area; nevertheless, fire suppression can also promote fuel accumulation.

Meteorological data were provided by the Spanish Meteorological Agency (AEMET). Because our goal was to ascertain whether the detected change points coincided with changes in climate, we selected one meteorological station for each region (Fig. 1). Furthermore, based on a previous study by Pausas (2004), who found a high correlation between the precipitation data from several stations across eastern Spain, Pausas and Fernández-Munoz (2012) indicated that wet or dry periods are synchronous in the entire eastern Mediterranean region.

We first estimated missing values in the meteorological data by averaging the values from the day before and the day after. We then used the Fire Weather Indices Calculator (http://wiki.fire.wsl.ch) application that was developed by the Swiss Federal Research Institute for Forest, Snow and Landscape Research WSL within the framework of the ALPFFIRS project (http://www.alpffirs.eu), to compute the following four fire weather indices:

- **Angström index**: this index was developed in Sweden and uses the relative humidity and temperature as input data; it is, thus, more appropriate for representing the non-vegetative season (Chandler et al., 1983; Pezzatti et al., 2013). This index does not consider the weather before the day predicted, unlike the rest of the indices that were used.
- **Nesterov ignition index**: this index is a cumulative index that is appropriate for measuring fine fuel moisture content and predicting fire ignition (Venevsky et al., 2002). It was developed in Russia and uses temperature, precipitation and dew point temperature as input data.
- **Keetch–Byram drought index (KBDI)**: this index was developed to measure the dryness in the upper layers of the soil (Keetch and Byram, 1968). It uses daily temperature and precipitation as well as annual precipitation as input data. We modified the start date parameter to avoid gaps in the results.
- **Canadian fire weather index (FWI)**: this index uses temperature, precipitation, relative humidity and wind speed as input data. Because it is the result of the combination of three moisture codes (the fine fuel moisture code, the Duff moisture code and the drought code) and two fire behaviour indices (the initial spread index and the buildup index), the FWI is appropriate for measuring fire activity in general (Van Wangner, 1987).

To render the indices comparable with regard to the number of fires and burned area per year, we counted the number of days above the 90th percentile, except in the case of the Angström index because its scale is inverse, and, therefore, we used the number of days in the 10th percentile.

Population density data were taken from the Population Census, compiled by the National Institute of Statistics (INE) for the period 1968–2011.

Woodland data were taken from the three currently available National Forest Inventories that were provided by the MAGRAMA. The first inventory was conducted from 1966 to 1975, the second from 1986 to 1996 and the third from 1997 to 2007.

Livestock density data (cattle, sheep and goats per km²) were obtained from the Agricultural Census that was produced by the INE for the period 1968–2009.

The laws and measures related to fire prevention policies and fire suppression were obtained from literature research (Vélez, 2000) and from the website of the Spanish ADCIF (http://www.magrama.gob.es/en/).

### 2.5. Data analysis

We defined a change point as the point in a temporal series at which a significant change occurs. An upward change point is the point after which the data change to an increasing trend, and a downward change point is the point after which data change to a decreasing trend. To detect these change points in our fire data series, we used a statistical change point analysis based on the non-parametric Pettitt test, as implemented by Pezzatti et al. (2013).

The Pettitt test can be used to test for significant differences in the number of fires and burned area under the null hypothesis (H₀) of no change vs. an alternative hypothesis (H₁) of change. It is defined in Eq. (1):

$$U_{i,T} = \sum_{t=1}^{T} \sum_{j=t}^{T} \text{sgn}(X_i - X_j)$$

where \(\text{sgn}(X) = 1\) for \(X > 0\), 0 for \(X = 0\) and \(-1\) for \(X < 0\). \(T\) is the number of years in the time period. The probability of a change occurring can be calculated using Eq. (2):

$$p(t) = 1 - \exp \left( -6 \times \frac{U_{i,T}^2}{T^3 + T} \right)$$

The advantage of this test is that it is not affected by extreme data values, unlike the cumulative sum of deviations (CUM-SUM) (Pezzatti et al., 2013) or other methods that require distributional information about the data (Pettitt, 1979).

Following Pezzatti et al. (2013), we first used a stepwise approach, splitting the data series into sub-periods after detecting the main change point. A second option consisted of calculating the Pettitt index value for the central point of an 11 year moving window over the original data series (i.e., a running Pettitt index). Change points with a p-value \(\geq 0.80\) were then tested for significant differences in rank order by applying the non-parametric Wilcoxon rank sum test, which tests the null hypothesis (H₀) that there is no difference in the fire frequency or burnt area between the periods preceding and succeeding the presumed change point. Finally, significant change points were compared to the temporal evolution of possible driving forces.

### 3. Results

#### 3.1. Change points detected

The results confirm the existence of significant upward and downward changes in the fire regime characteristics for the three regions that were analysed.

In the Northwest region, the number of fires during the vegetative season (Fig. 2) had significant upward change...
points in 1973 and 1977 and a downward change point in 1990, while the burned area had an upward change point in 1977 and a downward change point in 1991. During the non-vegetative season (Fig. 3), only upward change points were detected, in 1979 and 1988 for the number of fires and in 1972 and 1987 for the burned area.

In the Interior region, the number of fires for both seasons only had upward change points. During the vegetative season, there were upward change points for the number of fires in 1977 and 1984 and for the area in 1977. There was also a downward change point in 1991. During the non-vegetative season, the number of fires had upward change points in 1978 and 1988 and the burned area had an upward change point in 1979.

The Mediterranean area is the only region that had downward change points for both of the fire regime characteristics during both seasons. During the vegetative season, the number of fires had an upward change point in 1977 and downward change points in 1994 and 2005, while the burned area had an upward change point in 1973 and a downward change point in 1994. During the non-vegetative season, the number of fires had upward change points in 1972 and 1977 and a downward change point in 2000. The burned area had an upward change point in 1976 and a downward change point in 1986.

3.2. Evolution of major driving forces

During the vegetative season, the fire weather indices had a clear trend of increasing fire danger from the late 1970s to the early 1990s and since 2000 in the Northwest region, while in the Interior and Mediterranean regions, these indices peaked in the 1980s and 1990s. During the non-vegetative season, there was a clearly increasing trend in all three regions from the beginning of the period, which was even more notable since the 1990s.

The Northwest region had a gradual increase in population density from the beginning of 1970–1980 (Figs. 4 and 5). Subsequently, the density remained quite constant, decreasing slightly over the next several decades and increasing again in the last decade. This region is the second most populated region, after the Mediterranean region, which was the most populated region since the beginning of the study period. The Interior region has the lowest population density, with an increasing trend since the beginning of the study period.

The woodland data displayed an increasing trend for all three regions. In the Northwest region, it peaked in the late 1990s, while in the Interior region it increased gradually until the end of 1990s, as it did in the Mediterranean region. The Interior region had the highest increase, followed by the Mediterranean region (Figs. 4 and 5).

For all three regions, there was a peak in the livestock density at the beginning of the period, which was followed by a decrease that was particularly marked in the Interior and Mediterranean regions until the second half of the 1980s (Figs. 4 and 5). At this time, the livestock density increased again until the mid-1990s, after which it decreased strongly.

Table 1 lists the major State and European laws related to fire management in Spain. With the creation of the fire statistics database in 1968 and the introduction of forest fire legislation, Spain’s approaches to fire management have changed over the years; that effectively improved with the acquisition of resources to fire suppression through the 1990s. This shift, together with improved training, research and prevention measures and the incorporation of new technologies, has rendered fire management and suppression more effective. The importance of fuel management emerged in the 1980s, although this approach is still not fully implemented.

4. Discussion

Our results confirmed that there have been significant changes in fire regimes, both in the number of fires and the burned area, during both vegetative and non-vegetative seasons in all of the study regions.

Upward changes were detected in all regions and seasons in the 1970s, while downward changes were mostly observed from the 1990s to the present in the Mediterranean region and in the vegetative season of the Northwest and the Interior regions. In the 1980s different patterns were observed.

The increase in the number of fires has been already described by other authors (Pausas, 2004; Pausas and Fernández-Muñoz, 2012), specifically for the Mediterranean region. The upward change point in the 1970s in the Mediterranean region is consistent with Pausas and Fernández-Muñoz (2012), who also found an upward change in fire regimes for the province of Valencia in the Mediterranean region and suggested that the main driving force was an increase in the amount of accumulated fuel by the rural exodus. These authors concluded that fires were fuel limited before 1970 but are currently less fuel limited and more droughts driven than before because climate was poorly related to fire frequency before 1970. The latter conclusion was also reached by Pausas (2004) for the same region. Nonetheless, in a recent study, Pausas and Paula (2012) highlight the role of fuel in climate and fire regime interactions, suggesting that under a given climate condition, the level of flammability depends on the fuel structure. In contrast to our results, Pausas (2004) did not find a clear trend in the burned area, and Pausas and Fernández-Muñoz (2012) did not report downward changes in fire regimes, possibly due to the shorter period of time studied in both cases and differences in the datasets.

When comparing the detected changes of our study to climate and environmental changes, it became clear that the role of each driver might greatly vary by season and region.

The role of climate in driving upward changes in fire regimes is confirmed for all regions and for the vegetative season, as highlighted by the Nesterov and KBDI indices. This seasonal difference in index responses may be due to their better representation of summer conditions (Pezzatti et al., 2013). Climate may also have played a role in the downward change points of the Mediterranean (mid 1980s and mid 1990s) and the Northwest region (1990–1991), as highlighted by the KBDI index.

The early upward change points coincided with an increasing trend in population density in the three regions, when most of the population was rural and, thus, more involved in traditional activities using fire as a tool for agricultural purposes and livestock grazing. Moreover, an
Fig. 2 – Change point analysis for the period 1968–2010 for the vegetative season (May to November) in the Northwest region of Spain. The four upper graphs are related to the number of fires, while the lower four are related to the burned area. For each group, the two upper graphs in blue refer to the Pettitt index stepwise approach, while the lower graph in red refers to the Pettit 11 year moving window. Plain lines represent the Pettitt index, and dashed lines represent the significance probability (p-value) of a change point. Change points with a p-value ≥ 0.80 are represented by diagonal stripes (upwards are in red with diagonal stripes upward and downwards are in blue with diagonal stripes downward).
Fig. 3 – Change point analysis for the period 1968–2010 for the non-vegetative season (December to April) in the Northwest region of Spain. The four upper graphs are related to the number of fires, while the lower four are related to the burned area. For each group, the two upper graphs in blue refer to the Pettitt index stepwise approach, while the lower graph in red refers to the Pettit 11 year moving window. Plain lines represent the Pettit index, and dashed lines represent the significance probability (p-value) of a change point. Change points with a p-value ≥ 0.80 are represented by diagonal stripes (upwards are in red with diagonal stripes upward and downwards are in blue with diagonal stripes downward).
Fig. 4 – Climatic and environmental drivers possibly related to fire regime changes in the period 1968–2010 in the selected study regions. The fire regime characteristics and climate data refer to the vegetative season (May to November). The vertical red dotted lines represent the upward change points, and vertical blue dashed lines represent the downward change points that were detected for the number of fires or burned area.
Fig. 5 – Climatic and environmental drivers possibly related to fire regime changes in the period 1968–2010 in the selected study regions. The fire regime characteristics and climate data refer to the non-vegetative season (December to April). The vertical red dotted lines represent the upward change points, and vertical blue dashed lines represent the downward change points that were detected for the number of fires or burned area.
increase in intentional fires, which was related to a desire for revenge against the State’s reforestation policy in the Northwest region (Seijo, 2005), especially in Galicia, and the designation of protected areas (Vélez, 2009), may explain why the number of fires had an upward change before the burnt area. However, the opposite trend, which was detected in the latter years, suggests that the current cause of woodland fires is predominantly to negligence such as recreational human presence in the woodland (Martínez et al., 2009; Pausas and Vallejo, 1999) or accidental causes. The fire frequency may be higher under intermediate population densities, as in other Mediterranean areas (Syphard et al., 2007), because fire suppression is more efficient in areas with a high population density, as several authors (Guyette et al., 2002; Loepe et al., 2012; Martell and Sun, 2008; Pechony and Shindell, 2010) have suggested.
The number of fires during the non-vegetative season in the Northwest and Interior regions had the same upward change points, which indicate that the origin of the fires was similar, generally related to agricultural practices, while the difference in the burned area may be related to the fact that the vegetation type and climate were different. Moreover, neither region had downward change points, suggesting that traditional activities have decreased in these regions since the 1960s, although they still persist to a greater extent here than in the Mediterranean region, which was the only region that had downward change points for both the number of fires and the burned area for both seasons.

The effect of livestock density is clearer as an ignition source, especially in the Northwest and Interior regions during the non-vegetative season, than as a driver in the reduction of fuel. Earlier upward change points in the 1970s coincided with the stagnation of traditional livestock, and during the non-vegetative season the later upward change point in the 1980s for the Northwest and Interior regions coincided with an increase in livestock. However, this pattern was reversed for the vegetative season. One explanation may be that when Spain joined the European Community in 1986, it adopted new policies that promoted an intensification of industrial livestock practices. However, in the last decade, this effect may have been offset by a reduction in traditional human activities involving the use of fire as a tool in the Mediterranean region. Lloret and Mari (2001) reported that in the town of Tortosa, which is located in the Mediterranean region, the number of fires during the winter and autumn was higher under mediaeval fire regimes and suggested that this fact may be related to the abandonment of the traditional practice of burning pastures in winter.

The upward change during the vegetative season in the Interior and Mediterranean regions also coincided with an increase in woodland, similar to the Northwest region during the non-vegetative season. This may have resulted in a fuel accumulation caused by the abandonment of traditional agricultural activities and by the reforestation activities. Such land use evolution combined with a period of severe droughts as highlighted by the Nesterov index and produced a favourable environment for large fires throughout the 1980s.

Fire management may have caused changes in the fire regimes over the last decade, reducing both the numbers of fires and the burned area in the three regions, given the strong suppression policy. Nevertheless, as the results suggest, it should be noted that fire suppression may be effective with small fires but is not effective for large fires under extreme climate conditions (Piñol et al., 2005) that may counteract fuel management measures.

5. Conclusions

Statistical change point analysis can be used to improve our understanding of fire regimes at both regional and global scale. The proposed change point approach may also help in disentangling the main driving forces behind fire regime changes in the cases where two or more drivers occurred concurrently. Because detected change points can be considered as the final result of possible driving forces, the analysis helps broadening our understanding on specific fire regimes and can be used to improve fire management in the context of climate and land-use change.

Landscape and fuel management will be an important instrument to possibly manage increasing trends in fire regime driven by land use and climate. In particular, new planning policies should be developed focusing on the urban-forest interface and fire ecology studies will be crucial to determine the fire regime level that maintain the integrity of ecosystems. For example changes on fire regimes should be taken into account in climate change models and carbon dioxide (CO₂) emissions predictions.

Acknowledgements

We would like to thank the MAGRAMA and the AEMET for providing access to fire statistics and meteorological data. Support from Patrick Krebs and comments from Ricardo Vélez are much appreciated.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.envsci.2013.08.005.

References


