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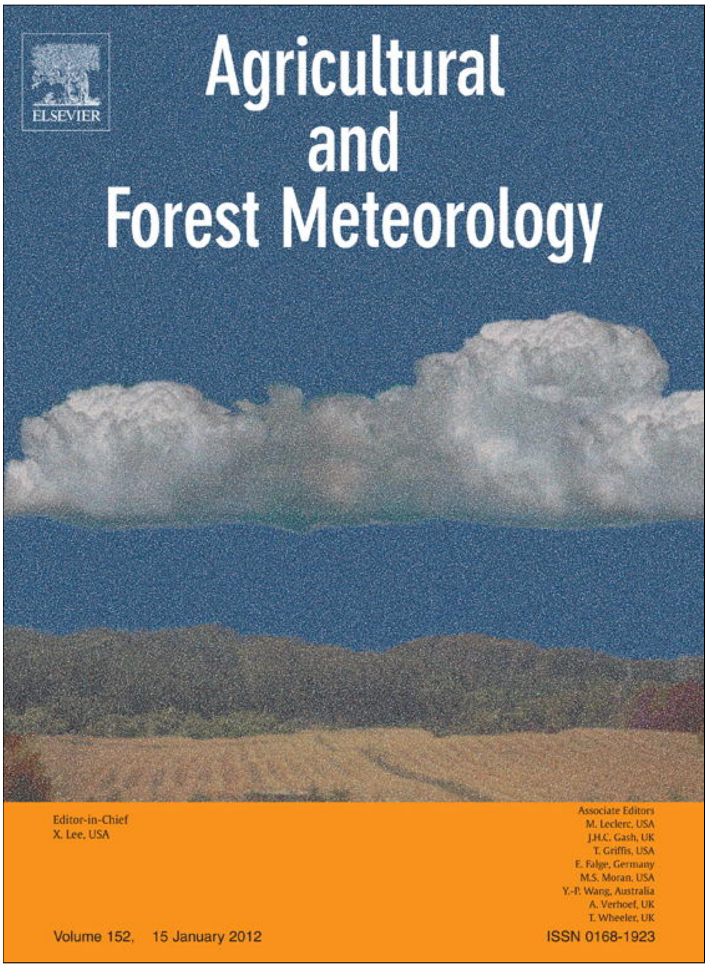
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Lightning-caused fires in Central Spain: Development of a probability model of occurrence for two Spanish regions

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ABSTRACT

Lightning-caused fire occurrence has been modelled for two different Spanish regions, Madrid and Aragon, based on meteorological, terrain, and vegetation variables. The model was built on two very contrasting regions, one presenting low number of lightning-caused fires whereas the other presented a high occurrence. The research was conducted between May and September, which happens to be the most lightning-fire prone period in Spain, for a three year interval starting in 2002 up to 2004.

A time-invariant model for lightning-caused fire occurrence was developed for each region at a spatial resolution of 3 km ×3 km. The probabilistic models were based on the logistic regression, aiming to explain the probability of having at least a lightning-fire during the three year period.

Results showed that the number of thunderstorms during the three-year period was the most significant variable in the model, where an increasing number of thunderstorms leads to a higher probability of occurrence. Validation was assessed through the Receiver Operator Characteristic, showing a good agreement between the modelled probabilities and the reported lightning-caused fires, with an Area Under the Curve around 0.7 in Aragon. However, the model in Madrid showed a poor AOC performance, showing therefore insights that the study period should be larger due to the low occurrence of lightning-fires in that region.

1. Introduction

Assessing fire danger is one of the most important issues for the management of Mediterranean ecosystems (Pausas and Vallejo, 1999). A critical component of fire danger is a better understanding of different fire ignition factors. Although most fires on the Mediterranean are human-caused, lightning fires are also very relevant. For instance, in Spain, these fires only account for a 3.9% of the reported fires (Área de Defensa Contra Incendios Forestales, 1991–2004) but they tend to burn relatively large areas compared to human-ignited fires, being responsible of 10.7% of the total burned area. The reason is twofold: firstly, they usually occur in remote areas, where the detection and first attack take longer (Wotton and Martell, 2005), and secondly, they are frequently associated to extreme meteorological conditions with dry thunderstorms and strong winds, which makes difficult the use of aerial extinction resources (Vélez, 2000; García-Ortega et al., 2011).

This study is part of the FIREMAP project (Integrated analysis of forest fire risk using Remote Sensing data and Geographical Information Systems), which aimed to develop methods for mapping a synthetic fire risk index at 1 km^2, based on a wide range of risk factors (Chuvieco et al., 2010). The risk index includes, not only the estimation of fire ignition or propagation danger, but also the potential damages derived from fire. Therefore, the index takes into consideration variables associated to the fuel moisture content (both live and dead fuels), as well as human factors, rate of spread and fire intensity, potential damages to the ecosystem, and socio-economic values. This study is focused on the lightning-caused fires.

Most of the thunderstorms in the Iberian Peninsula occur between May and September, where the temperatures favour the conditions for the development of convection processes (Rivas Soriano et al., 2005). In consequence, most of the lightning-caused fires in Spain are registered during the referred months. The occurrence of lightning is strongly related to topography (Dissing and Verbyla, 2003; Rivas Soriano et al., 2005) and the proximity to the coast (Rivas Soriano et al., 2005). Also vegetation type may affect the occurrence of lightning since the surface albedo and roughness can influence on convection (Dissing and Verbyla, 2003). Previous

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studies have identified a number of key factors that can characterize lightning-caused fires. Theses factors include the terrain (Díaz-Avalos et al., 2001; Wierzchowski et al., 2002; Podur, 2003), lightning characteristics such as the presence of a long enough continuing current or the polarity (Latham and Schlieter, 1989; Kourtz and Todd, 1991; Latham and Williams, 2001; Anderson, 2002; Wotton and Martell, 2005), the amount of rainfall (Rorig and Ferguson, 1999; Álvarez Lamata, 2005), or the moisture content of fuels lying on the ground (Kourtz and Todd, 1991; Nash and Johnson, 1996; Díaz-Avalos et al., 2001; Rorig and Ferguson, 2002; Wierzchowski et al., 2002; Podur, 2003; Álvarez Lamata, 2005; Wotton and Martell, 2005).

The objective of this study is to elaborate an operational cartography of lightning ignition probability within the framework of the FIREMAP project. This product should be integrated with other factors of fire danger, such as human-caused probability of ignition (Chuvieco et al., 2010; Vilar et al., 2010). Therefore, the model has several constraints in terms of spatial and temporal resolution and range of values. We have developed a time-invariant probability of lightning-caused fires, at a spatial resolution of 3 km ×3 km, which is the finest resolution with the currently available data. Similar spatial resolutions have been proposed by Nieto et al. (2006), Vilar et al. (2010) and Castedo-Dorado et al. (2011). The study period covers spring and summer (May–September), when most of the thunderstorms and lightning-caused fires occur in Spain. The availability of meteorological data restricted the analysis to a three year period: 2002–2004.

2. Study area and data

2.1. Study area

Two study regions, Madrid and Aragon (Fig. 1), were selected for this study. These regions present a contrasting occurrence of lightning-caused fires. Madrid has a total forested area of 420,093 ha, accounting for a 52.3% of the total area of the region (Dirección General de Conservación de la Naturaleza, Subdirección General de Montes, 2004). Most of this surface is located in the Central Range. The most common species in woodlands are *Pinus sylvestris* L. and *Quercus pyrenaica* Willd. at higher ranges, whereas *Quercus ilex* L. dominates the lower ranges. Madrid is the region with the highest population density of Spain, and most of the wildfires are hence human-caused. Only 2% of the total reported wildfires in the region are lightning-caused over the 1991–2004 period (Área de Defensa Contra Incendios Forestales, 1991–2004). Moreover, Madrid has a notorious altitudinal gradient form Northwest to Southeast, and therefore there is barely a variation in exposures to dominant winds.

Aragon, on the other hand, has a total forested area of 2,608,312 ha, accounting for 54.7% of the total region (Dirección General de Conservación de la Naturaleza, 1996). Three different geomorphologic units can be depicted in Fig. 1. The North is dominated by the Pyrenees Range, with extensive forest cover composed mainly by Alpine vegetation (*Pinus uncinata* Ramond ex DC., *Abies alba* Mill., and *P. sylvestris* L.) and a strong altitudinal gradient. The Iberian Range is located in the south of the region. This area has one of the lowest population densities of Spain, with an important presence of Mediterranean vegetation at its different bioclimatic stages (*Q. ilex* L., *Juniperus thurifera* L., *Pinus pinaster* Aiton, and *Pinus nigra* J.F. Arnold). Finally, between both mountainous regions, the Ebro Valley is mainly composed by crops and hence has a low proportion of forest areas. These socioeconomic and biophysical differences among the three units cause the lightning-fires to be more frequent in the Iberian and Pyrenees Ranges than in the Ebro Valley.

2.2. Data

2.2.1. Lightning strikes

Data concerning the lightning strikes were provided by the State Meteorological Agency (AEMET, former National Meteorological Institute) of Spain. The AEMET has a lightning detection network with 14 magnetic direction finders installed over the Iberian Peninsula. They provide information about estimated location, detection time, precision (χ^2 and ellipse error (Paradowski, 1995)) and stroke intensity. This data is available from 1992, but since year 2001 the system efficiency has been improved (Rivas Soriano et al., 2005). Due to precision requirements of our final output model, we discarded all lightning detected with a poor precision ($\chi^2 \leq 2$) and an semi-axis ellipse error ≤1.5 km (Martín León, 1996).

2.2.2. Topography

Altitude measurements were taken from the Digital Terrain Model (DTM) of the National Cartographic Database. This database has a 1:200,000 scale and a corresponding pixel resolution of 250 m. Slope and aspect were derived from the DTM using standard algorithms (Burrough and McDonell, 1998).

2.2.3. Vegetation

Vegetation categories were derived from the Spanish Forest Map by the General Biodiversity Directorate of the Ministry of Environment. This map provides information about species composition in both the overstory and understory layers at a scale of 1:50,000. The forest map was classified into six main forest cover types according to canopy structure and albedo: conifer woodlands, broadleaved woodlands, mixed forests, shrublands, grasslands and other forest surfaces (arid areas, sparse vegetation areas and agricultural-forest mosaics).

2.2.4. Meteorological data

Daily meteorological records of temperature, relative humidity, 24 h rainfall and wind speed were supplied by Meteológica, a Spanish company specialized in meteorological forecasting and analysis. This company provided interpolated data in a 3 km ×3 km UTM grid from the European Centre for Medium range Weather Forecast (ECMWF) outputs (Aguado et al., 2007) for the period 2002–2004. We have calculated several moisture codes of the National Fire Danger Rating System (NFDRS) and the Canadian Forest Fire Weather Index (CFFWI): the 1-H and 10-H timelag fuel moisture content from the NFDRS (Bradshaw and Deeming, 1983), and the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC) and the Drought Code (DC) from the CFFWI (Van Wagner, 1987). These components have shown a good agreement with moisture content in Mediterranean environments (Rodríguez y Silva, 2002; Aguado et al., 2007).

2.2.5. Fire reports

Fire-occurrence data was obtained from the national database of fire reports, which is compiled by the General Biodiversity Directorate of the Ministry of Environment. This database has normalized registries since 1968 (Vélez, 2000). In our case, only data spanning years 2002–2004 were analyzed in order to match the availability of meteorological data. This database provides a complete description of every reported fire in Spain. For our purpose, information about detection time, point of ignition and starting cause were extracted. Most of these registries do not have the exact ignition location in terms of *X* and *Y* coordinates. They are coded instead by municipality (average municipality surface of 44.57 km^2 and 65.20 km^2, respectively for Madrid and Aragon), and by a 10 km ×10 km UTM reference grid. In order to reduce this spatial uncertainty, both fields (municipalities and 10 km ×10 km UTM grid)

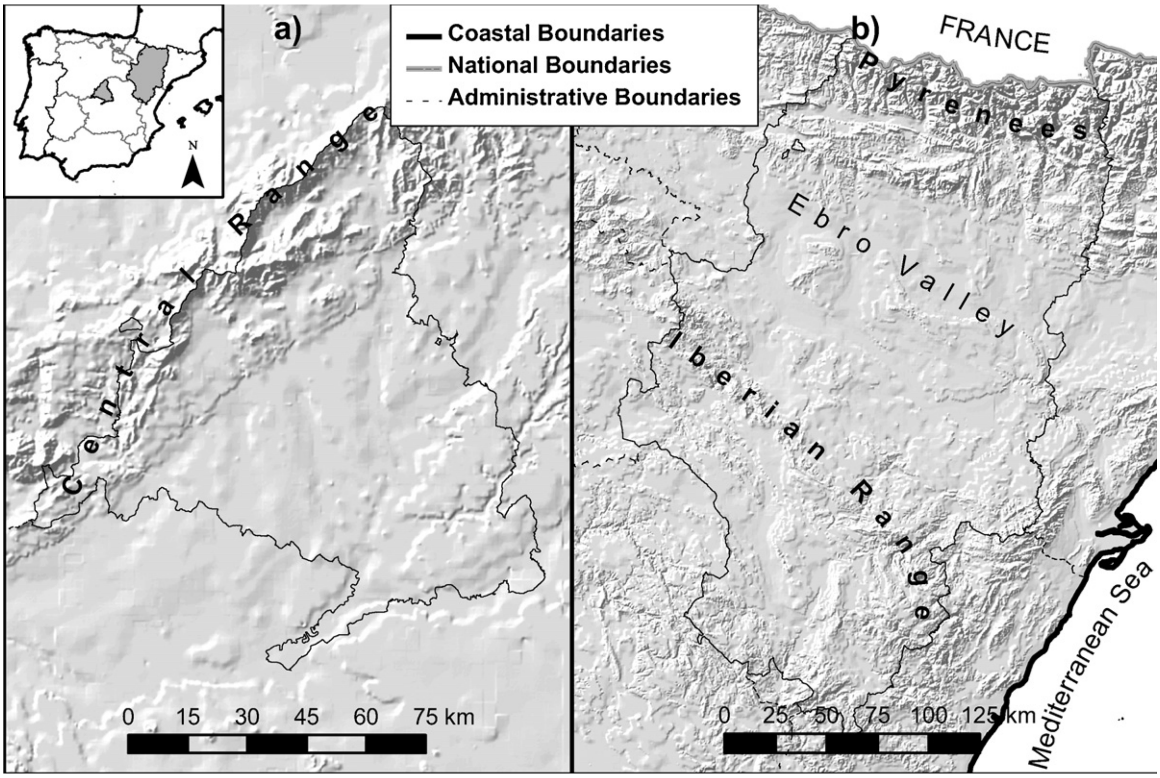

Fig. 1. Location and topography of both study areas: (a) Madrid and (b) Aragon.

were cross-tabulated in a dedicated GIS, creating thus an intersection of polygons that improved the location of fire ignitions. Additionally, it was assumed that this type of fires have their origin over natural areas. Therefore, the previous set of polygons were masked out with natural areas (including woodlands, shrublands, grasslands and sparse vegetation). The final average size of the target polygons to locate the ignitions was 13.64 km^2 and 15.18 km^2 in Madrid and Aragon, respectively. Besides of this dataset, another dataset that contains actual ignition points for years 2005–2007 was used for validation of the models.

3. Methodology

Before calibrating the model, the spatial uncertainty of ignitions must be reduced from the target polygons to the desired 3 km ×3 km UTM grid output. For each fire registry, a 3 km ×3 km cell was randomly selected within the target polygon (intersection between municipalities and 10 km ×10 km UTM grid) where the fire occurred. A constrain for the ignition point is that the cell must have reported at least one lightning strike over a natural area the day that the fire was reported (Fig. 2).

Two different set of variables were analyzed. The first set is what we have called "time-invariant variables", which are related to spatial variations of topography, vegetation and lightning data: These variables are shown in Table 1 and represent summaries at the level of the target polygons (intersections between municipalities and the 10 km ×10 km UTM grid).

The second set of variables is related to what we have called "Thunderstorm events". We define a thunderstorm event as the occurrence, on a daily basis, of at least one lightning strike within each grid cell (see Fig. 2 for a visual explanation). In order to characterize the meteorological and fuel moisture conditions that are more likely to produce an ignition, we analyzed the histogram of these thunderstorm events that caused ignitions. We have thus selected the values for precipitation and fuel moisture codes that

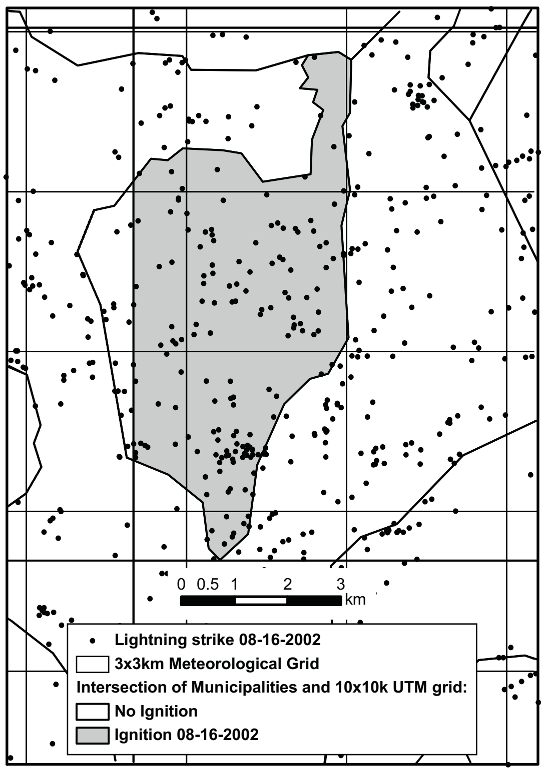

Fig. 2. Detail of resulting municipality-10 km ×10 km UTM intersections (thick lines) and 3 km ×3 km UTM meteorological grid (thin lines). The greyed polygon highlights a reported lightning ignition the 16th August 2002. Points represent the strokes that were detected the day the fire was reported. According to the definition of a thunderstorm event, one can deduce that the 16th August 2002 there was one event that caused one ignition (greyed polygon) and several events that did not (the rest of the polygons that show at least one stroke within).

Table 1
List of variables computed for each 3 km ×3 km UTM grid cell. Mean and standard deviation (STD) values are shown for each region.

Source	Variable	Description	Mean (STD)	
			Madrid	Aragon
Lightning data	N strikes	Total number of strikes over natural areas	8.35 (8.93)	39.30 (40.48)
	N positive	Total number of positive strikes over natural areas	0.32 (0.62)	0.73 (1.05)
	Mean Intensity	Mean intensity of strikes over natural areas (kA)	−16.63 (15.23)	−16.10 (6.14)
	Maximum intensity	Maximum intensity of strikes over natural areas (kA)	0.62 (30.10)	15.09 (36.33)
	Minimum intensity	Minimum intensity of strikes over forest areas (maximum negative intensity, kA)	−34.99 (28.70)	−49.24 (27.93)
Terrain	Altitude	Mean altitude of natural areas (m)	845.21 (323.62)	841.39 (459.41)
	Slope	Mean slope of natural areas (%)	6.04 (7.04)	8.92 (10.00)
	% No aspect	% of natural areas with no aspect	10.81 (22.12)	7.74 (17.12)
	% N	% of natural areas exposed to North	6.07 (11.64)	10.69 (15.20)
	% NE	% of natural areas exposed to Northeast	6.11 (11.54)	14.58 (18.38)
	% E	% of natural areas exposed to East	12.48 (18.56)	12.16 (15.49)
	% SE	% of natural areas exposed to Southeast	17.98 (21.60)	10.77 (14.27)
	% S	% of natural areas exposed to South	13.36 (17.23)	11.58 (15.45)
	% SW	% of natural areas exposed to Southwest	10.34 (15.62)	13.03 (17.44)
	% W	% of natural areas exposed to West	12.08 (18.55)	10.59 (15.50)
	% NW	% of forest surface exposed to Northwest	10.77 (18.50)	8.85 (12.82)
Vegetation	% Forest Surface	% of total natural areas	54.00 (35.23)	52.87 (34.84)
	% Conifers	% of conifers woodlands	10.63 (20.99)	19.83 (29.66)
	% Broadleaved	% of broadleaved woodlands	37.50 (32.91)	14.27 (25.38)
	% Mixed forest	% of mixed woodlands	1.77 (5.42)	2.39 (8.21)
	% Shrublands	% of shrublands	38.11 (37.40)	33.39 (35.27)
	% Grasslands	% of grasslands	5.66 (15.01)	12.40 (24.28)
	% Others	% of other forest surfaces	7.30 (16.82)	19.35 (26.65)

include the 90% percent of the cases with ignitions as critical values for an ignition following Krawchuk et al. (2006). From these thresholds we have created new time-invariant variables related to the thuderstorm events. These new variables are described in Table 2.

The model to be developed aims to locate the cells where it was more likely to have any lightning-caused fire during the full record period (2002–2004). This model is therefore defined as a "time-invariant" probability of occurrence, meaning that it is not time-dependent. The probabilistic model was built using logistic regression. A different logistic model was developed for each region, Madrid and Aragon. The binary response variable is defined as the occurrence of at least one lightning-fire during the 2002–2004 period within each 3 km ×3 km UTM cell. The independent variables were those variables described in Tables 1 and 2. A previous exploratory analysis (Nieto et al., 2006) helped to flag out from the model those variables that were not found significant in the occurrence of lightning-fires.

The criterion for variable selection was the forward stepwise method based on the significance of Wald statistic. The significance criterion to enter in the model was 0.05. A 60% of each dataset was used for calibrating the model while the remaining 40% was left for model testing. Two tests were applied to test and validate the model: (1) the Hosmer and Lemeshow test (Loftsgaarden and Andrews, 1992) using the 40% test dataset, and (2) the Receiver Operator Characteristic (ROC) Area Under the Curve (Fawcett, 2006) using the ignition points for 2005–2007. The first test evaluates the goodness of fit between the observed ignitions/non-ignitions and the estimated ones from the model. Each case is assigned to one group depending on its predicted probability. These groups are formed by partitioning the predicted probabilities using the percentiles of the predicted event probability. The latter test, on the other hand, is a plot that evaluates the performance of a binary classifier. It compares the fraction of true positives versus the fraction of false positives at varying discriminating thresholds. The Area Under the Curve (AUC) computes the area below the ROC curve. It varies between 0 and 1, where a value of 0.5 means that the classifier does not perform better than a random classification, a value of 1 indicates a perfect classification, and a value below 0.5 represents that the result is opposite than the desired value.

Table 2
List of additional variables computed for each 3 km ×3 km cell characterizing the meteorological and fuel conditions. Also shown the mean and standard deviation (STD) values for each region.

Source	Variable	Description	Mean (STD)	
			Madrid	Aragon
Lightning data	N storms	Total number of thunderstorms within each cell along the period study	3.75 (2.66)	10.61 (7.25)
	N drystorms	Total number of dry thunderstorms within each cell along the period study	3.57 (2.45)	8.46 (6.11)
Meteorological data	N FFMC critical days	Number of days in which the FFMC is above a defined critical FFMC threshold	447.18 (8.99)	416.34 (37.68)
	N DMC critical days	Number of days in which the DMC is above the defined critical DMC threshold	402.58 (38.20)	291.07 (96.29)
	N DC critical days	Number of days in which the DC is above the defined critical DC threshold	290.92 (42.38)	298.69 (60.88)
	N 1-H critical days	Number of days in which the 1-H code is below the defined critical 1 h threshold	417.18 (11.51)	406.12 (48.41)
	N 10-H critical days	Number of days in which the 10-H code is below the defined critical 10 h threshold	417.13 (11.52)	406.25 (48.37)

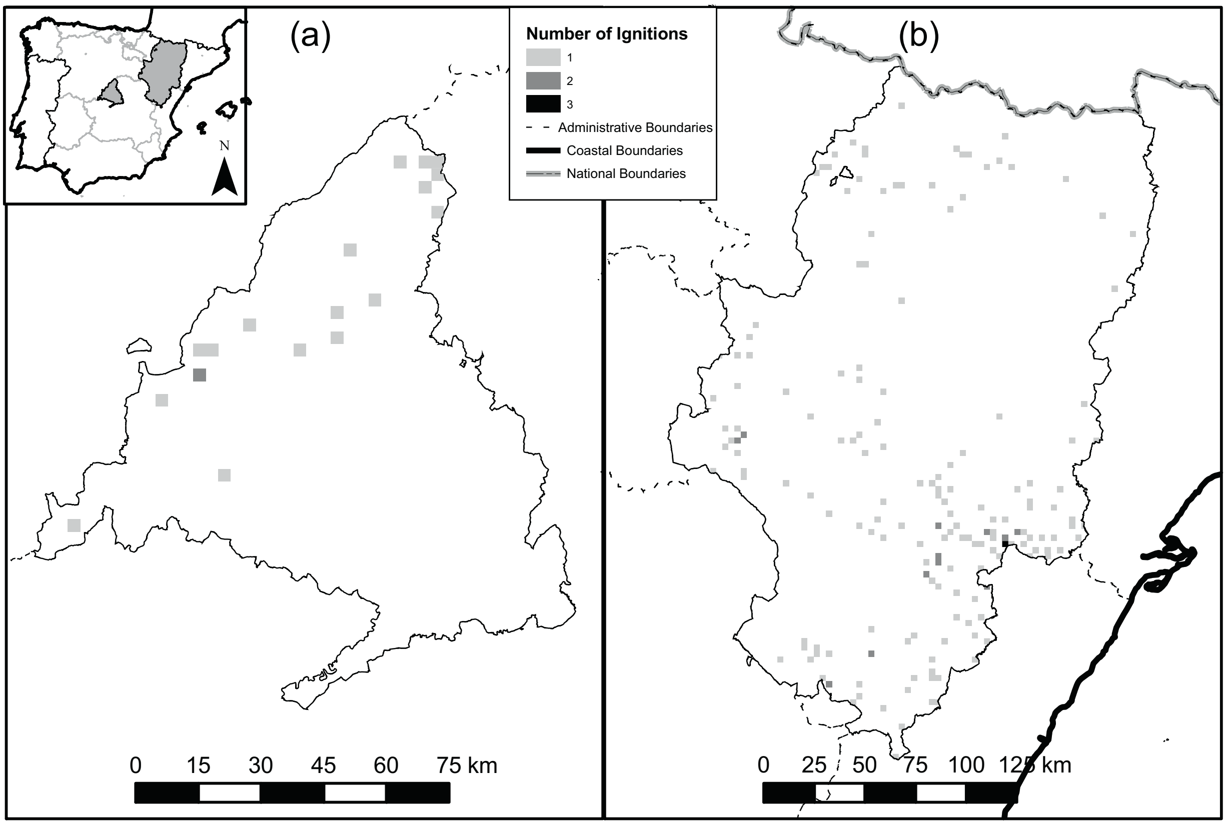

Fig. 3. Location of ignitions within the 3 km ×3 km UTM grid. Such locations were randomly selected from the cells located within a target polygons where a lightning-fire was reported: (a) Madrid and (b) Aragon.

4. Results

Fig. 3 shows the a priori location of ignitions, which were randomly selected from the cells that belonged to a target polygon where a lightning-fire was reported. In Madrid there are few lightning-fires (19) compared to Aragon (183), where the occurrence is especially important around the Iberian Range.

Table 3 shows the rainfall and moisture code critical values based on the histogram analysis of the thunderstorm events. The table shows that most of the lightning-caused fires happened when the daily rainfall associated to a thunderstorm is below 9 mm in Aragon and 23 mm in Madrid. In a similar manner, the 90% of the lightning-caused fires are driven by DMC values above 20 and 17 in Aragon and Madrid, respectively.

The values from Table 3 are the basis to define the thresholds used to create the new time invariant variables defined in Table 2. These variables were computed by counting the number of days along the period study in which each meteorological index was above (or below in case of the rainfall and the NFRDS indices) its respective critical threshold. The most remarkable comment is the great difference between the critical precipitation values of Madrid ($\mathbf{P}_{24h}$ = 22.5 mm) and Aragon ($\mathbf{P}_{24h}$ = 9.3 mm) that defines the variable “N drystorms”.

The resulting logistic models in both regions are shown in Table 4. Both models have in common that the number storms is the most significant variable in the models. However, in Madrid the results show that the probability of occurrence increases with increasing number of dry storms (exp $(\beta) = 1.480$), whereas in Aragon, the probability increases with the number of storms regardless of the precipitation (exp $(\beta) = 1.177$). No additional variable was introduced in the model for Madrid, while in Aragon the probability increases as more days are above the critical value of the DMC (exp $(\beta) = 1.005$), when more surface is oriented Northwest (exp $(\beta) = 1.013$), and with a higher presence of conifer forests (exp $(\beta) = 1.005$). On the other hand, the probability of occurrence in Aragon decreases with altitude ((exp $(\beta) = 0.999$)). The autocorrelation matrix for the coefficients in the model of Aragon is shown in Table 5 (this matrix is obviously not shown for Madrid since only one variable was introduced in the model). Table 5 shows that the correlations between the independent variables are relatively low with exception of the pairs Altitude and Number of Storms, with $r = -0.54$; and Altitude and Number days above the critical DMC ($r = 0.47$).

The Hosmer and Lemeshow test of fit for both logistic models was performed (Loftsgaarden and Andrews, 1992).The resulting χ^2

Table 3
Critical thresholds computed for the studied thunderstorm events. Each value defines the threshold above (below) which a lightning-fire is more likely to occur. The variables shown are the accumulated rainfall in 24 h ($\mathbf{P}_{24h}$), the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), the Drought Code (DC), and the National Fire Danger Rating System 1 h (1-H) and 10 h (10-H) timelag fuel moisture codes.

Region	$\mathbf{P}_{24h}$**(mm)**	FFMC	DMC	DC	1-H	10-H
Madrid	22.5	44.4	16.0	300.9	13.4	16.7
Aragon	9.3	53.1	22.7	207.5	15.4	19.2

Table 4
Logistic coefficients (β) for models in Aragon and Madrid. Also shown the Wald statistic coefficient and its significance.

	Variable	β	Wald	Sig.	exp(β)
Aragon	Constant	−6.237	131.52	0.00	0.002
	N storms	0.163	115.38	0.00	1.177
	N DMC critical days	0.005	12.54	0.00	1.005
	% Conifers	0.005	3.98	0.05	1.005
	% Northwest	0.013	4.64	0.03	1.013
	Altitude	-0.001	11.73	0.01	0.999
Madrid	Constant	−5.547	82.63	0.00	0.004
	N drystorms	0.392	18.82	0.00	1.480

Table 5
Correlation matrix for selected variables in the model of Aragon.

	Altitude	% Northwest	% Conifers	N DMC critical days	N storms
Constant	−0.56	−0.13	0.00	−0.93	−0.21
Altitude		0.06	−0.08	0.47	−0.54
% Northwest			−0.06	0.00	−0.02
% Conifers				−0.05	−0.13
N DMC Critical Days					0.12

values are 6.20 ($p = 0.29$; $d.f. = 5$) and 8.57 ($p = 0.38$; $d.f. = 8$), for Madrid and Aragon, respectively. Both tests showed that there is no significant differences between the observed and the predicted ignitions.

The ROC curves corresponding for the validation years 2005–2007 are displayed in Fig. 4. This analysis represents a validation independent from the study period used for calibration, showing therefore the temporal robustness of the models. The corresponding Area Under the Curve for Madrid was 0.57 (Fig. 4(a)) but not significantly different from 0.5, showing that the algorithm is not able to perform better than a random classifier. On the other hand, the AUC in Aragon is higher (0.71, Fig. 4(b)) and significant.

Finally, Fig. 5 shows the probability map of occurrence for a lightning fire in both regions. The highest probability values are located over mountainous areas. Blank cells are areas with no forest cover and therefore they are not included in the model. The probability values range from 0.0046 to 0.2157 in Madrid, and 0.0001 to 0.3883 in Aragon.

5. Discussion

Both regions have shown common patterns in the occurrence of lightning-caused wildfires since those fires are closely related to mountainous areas (Central System in Madrid and the Iberian Ranges in Aragon). In fact, since the topography plays an important role in the occurrence of storms (Rivas Soriano et al., 2001, 2005; Dissing and Verbyla, 2003) the highest probability of occurrence of a lightning fire should be over mountainous areas (Podur, 2003) as it is shown in Figs. 3 and 5. These mountainous areas are a natural barrier to the warm and humid dominant winds, which are related to a higher convective activity (Rivas Soriano et al., 2001). The variable related to the exposure that were found significant in Aragon shows the influence of these dominant winds. Madrid on the other hand presents a notorious altitude gradient form Northwest to Southeast. Therefore there is barely a variation of exposures in Madrid which drives the aspect to be not significant in the occurrence of lightning ignitions. In addition, these differences of complexity between both regions are also apparent in vegetation cover distribution (Table 1), which explains the different patterns observed related to vegetation cover, particularly for conifer forests.

In any of the regions the absolute number of strikes and the number of positive strikes, were not found significantly related to the occurrence. This can be explained in that the flash rate in a thunderstorm is not related to the ignition of a lightning, since higher flash rates result in higher precipitation (Álvarez Lamata, 2005; Katsanos et al., 2007; Pineda et al., 2007). Rorig and Ferguson (1999,

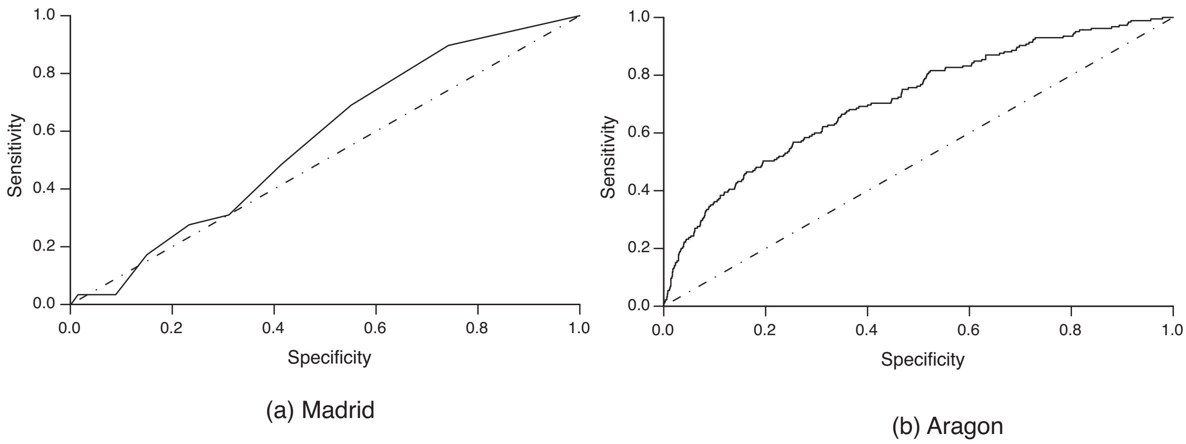

Fig. 4. Receiver Operator Characteristic (ROC) curves for (a) Madrid and (b) Aragon, using the lightning ignitions during 2005–2007 as validation dataset. The resulting Area Under the Curve (AUC) are 0.57 and 0.71, respectively. The dashed line represents the reference line with an AUC = 0.5.

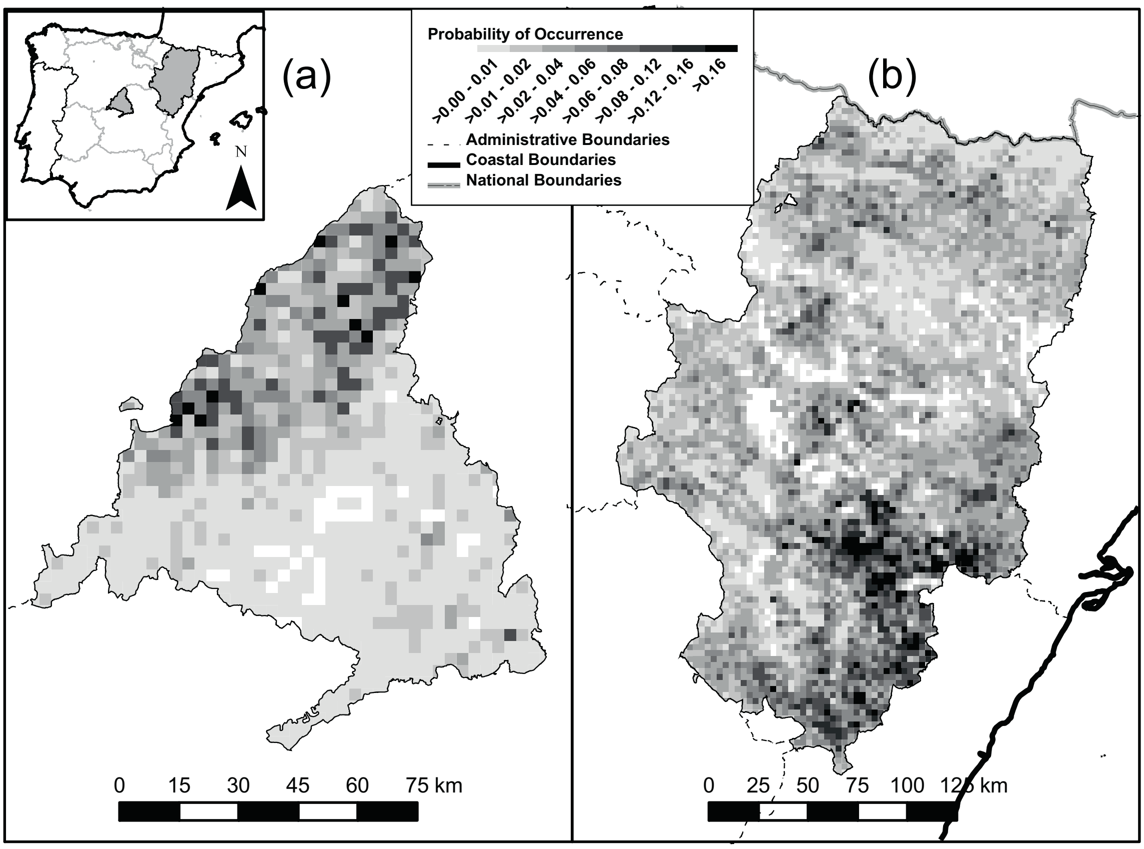

Fig. 5. Modeled probability of occurrence of lightning-caused wildfires in the three year period (2002–2004): (a) Madrid and (b) Aragon. Blank cells are non-natural areas and therefore have not being taken into account in the model.

2002) found similar results for the USA Pacific Northwest region. Unlike previous studies (Latham and Schlieter, 1989; Kourtz and Todd, 1991; Latham and Williams, 2001; Anderson, 2002), which showed that positive lightning have a higher probability of having a long continuum current and hence a higher probability of ignition, it was found that positive strikes were not significant for the ignition in our study. A similar result was found in Finland, where Larjavaara et al. (2005) found no relationship between positive strikes and lightning-caused fires.

Rather than the number of strikes, the precipitation associated with each thunderstorm plays a higher important role in fire ignition. Indeed, rainfall affects the fuel moisture content (Kourtz and Todd, 1991; Rorig and Ferguson, 1999, 2002; Álvarez Lamata, 2005) and this increases the probability of extinction of a smouldering fire. Nevertheless, some differences were found between both regions in terms of the rainfall threshold to have a lightning fire (22.5 mm in Madrid versus 9.3 mm in Aragon, Table 3). This high value in Madrid also contrasts with the results of other studies such as the ones of Álvarez Lamata (2005) or Rorig and Ferguson (1999) with 4 mm and 2.5 mm, respectively. One possible explanation of this issue is due to the few lightning-fires recorded during the period study in Madrid (19 in total).

On the other hand, dead fuel moisture content, expressed in terms of the NFDRS or the CFFWI meteorological indices, resulted a key parameter in the ignition. Particularly, the Duff Moisture Code showed the highest discrimination between thunderstorms that caused ignition from those that did not in Aragon. The latter confirms the observations in Ontario, Canada, made by Podur (2003), who found a similar spatial pattern between lighting strikes on days with DMC above 20 and lightning fires. The critical values of all the meteorological indices were found similar for both study regions. Precisely, the critical values of DMC established for Madrid and Aragon are 16.0 and 22.7, respectively, which is in close agreement to the value of 20 proposed by Podur (2003) in Ontario (Canada). Moreover, Krawchuk et al. (2006) obtained critical values of FFMC and DMC of 87 and 34, respectively, in Alberta (Canada). In this case they proposed the 85th percentile of ignitions instead of the 90th percentile used in our case, being the difference in the selected percentiles the possible explanation of the different values obtained in this study.

Regarding the logistic model, the most influential variable in both regions was the total number of storms through the study period (Table 4), which is in agreement with previous studies (Álvarez Lamata, 2005; Rorig and Ferguson, 1999, 2002; Kourtz and Todd, 1991). It is worth noting that the model in Madrid shows that the selected variable was the total number of dry storms, whereas the selected variable in Aragon is related to number of storms irrespective to the rainfall. However, the inclusion in Aragon of other variables, can compensate the lack of the inclusion of the dryness in storms. In particular, the variable Number of Days below a critical DMC value (N DMC critical days), includes information about rainfall due to the definition of the DMC index (Van Wagner, 1987).

Concerning the rest of variables included in the model for Aragon, their resulting coefficients (Table 4) lead to the following interpretation of the model: Probability of occurrence increases with a larger presence of conifer forest, with lower elevation and in areas exposed to the Northwest. Conifer forests have, in average, a lower albedo compared to other vegetation types, affecting therefore the available energy for latent and heat fluxes and thus they may develop a higher convective activity (Dissing and Verbyla, 2003). Altitude may decrease the probability of occurrence, since although storms are more frequent at higher elevations (Rivas

Soriano et al., 2001; Díaz-Avalos et al., 2001; Wierzchowski et al., 2002; Podur, 2003; Dissing and Verbyla, 2003), those show a larger amount of precipitation as well as lower temperatures, leading to a larger moisture content of dead fuels at higher altitudes. Finally, the dominant winds responsible for storms in Aragon come from the Northwest, and therefore the areas facing this exposure will be more lightning prone. A more detail synoptic analysis of convection and dominant winds such as in García-Ortega et al. (2011) will be required to confirm this hypothesis. The correlation matrix for the coefficients in Aragon, showed in Table 5, leads that the variables in the model are not correlated and therefore it is not expected that the model showed multicollinearity problems.

A further analysis of the spatial autocorrelation between residuals was performed to check the robustness of the models. Moran's Index (Moran, 1950) showed no significant autocorrelation ($p < 0.001$) for Madrid. However, in the case of Aragon, a very slight but significant ($p < 0.001$), positive spatial autocorrelation was found, having the maximum correlation at a radius of 9 km (Moran's I = 0.02). Nevertheless, the autocorrelation was very close to zero and hence, it was concluded that the model was spatially robust for both regions. Regarding the temporal robustness, the ROC Area Under the Curve analysis performed with data from 2005 to 2007 showed that the model in Madrid is not able to discrimate the occurrence in other periods. In Aragon, on the other hand, the model showed certain temporal robustness with an AUC of 0.71.

Finally, the definition of a time-invariant index based on meteorological data would require a longer time series. Indeed, meteorological data are very variable through the years and a robust characterization of these variables would require a longer period than 3 years. In particular, concerning the critical precipitation values for Madrid, we believe that this threshold will decrease if more data were used in the analysis.

6. Conclusion

Throughout this work, a time-invariant model for lightning-caused fire occurrence has been developed for two regions of Spain, Madrid and Aragon. Logistic regression was used to generate a model that predicts the probability of having at least one lighning fire during three years period at 3 km $\times$ 3 km spatial resolution. Some differences were found in the developed models, although the most significant variable for both regions is related to the amount of thunderstorms that occurred.

However, the model has only been developed for a 3-year period, and special care must therefore been taken when extrapolating the results to different years, specially in Madrid, where the independent validation showed a poor performance of the logistic model for years 2005–2007. In a future research it would be therefore required to extend the time period study in order to have more available fire registries and a longer meteorological time series.

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