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Does fire occurrence modify the probability of being burned again? A null hypothesis test from Mediterranean ecosystems in NE Spain

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Abstract

Two main causes have been proposed as drivers of fire regime in Mediterranean-type ecosystems: fuel build-up and weather conditions. If fuel build-up is the main cause, then areas recently burned will not burn again until some years later. Contrarily, if weather is the main cause, then all areas will burn irrespective of their age. We have devised a statistical test aimed to distinguish between these two hypotheses. To use the test is necessary to know the spatial distribution of fires during a period of time as long as possible. Then, a percolation algorithm procedure is applied to mimic the location, extent, and perimeter/area ratio of the real fires, independently of previous fire occurrence. This model is run many times and each run is considered a realization under the null hypothesis that a pixel burns irrespectively of whether it was burnt in the previous years. The actual number of pixels burned twice is then compared to the histogram of the probability density function of pixels burned twice, which is obtained from the simulations. Actual values falling in the right tail of the distribution point to a clumped pattern (fires tend to be more abundant in some locations), while falling in the left tail will indicate a segregated pattern (burning reduces the probability of further fires in the same site). The method was applied to three different areas of Catalonia (NE Spain) by comparing the actual fires from 1975 to 1998 to the pattern obtained from random fire simulations. An aggregated pattern was obtained in two of the studied areas when the origin of the simulated fires was located randomly, indicating that fires were not uniformly distributed in the territory. When the simulations were started at the centroids of the real fires, the null hypothesis of independence from previous fires was not rejected, and the fuel-driven assumption was not supported. In the third area, results were inconclusive because two large fires, occurred in 1994, totally changed the results obtained until then.

Keywords: Fire regime; Fire spatial pattern; Forest; Null hypothesis; Percolation algorithm

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1. Introduction

There is an ongoing debate on the effect of forest fire suppression policies over fire size in areas with Mediterranean climate. One point of view defends that

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the systematic extinction of all reported wildfires allows a build-up of fuel (fuel load and an increased fraction dead materials) that may in the future produce very large fires in periods of adverse weather (Minnich, 1983, 2001; Minnich and Chou, 1997). Moreover, the effect of fire suppression policies on total surface burned and in return periods would be negligible: with no suppression, there would be frequent and small fires, while fire suppression would lead to few larger fires. This view assumes that fire regime is only controlled by fuel, and that ignition probability is uniform throughout the territory. Minnich conclusions were supported from a comparison of wildfires in Southern California (US) and adjacent Baja California (Mexico) based on Landsat imagery. However, these results have been challenged by Keeley et al. (1999). Based on the California Statewide Fire History Database (1910–1998), these authors show that fire size did not increase during that period of time, strongly suggesting that the increased effort in fire suppression in California along the 20th century had no effect in fire size and fire intensity. In short, Minnich view implies that large fires would be fuel-driven, whereas Keeley, among other authors (Keeley et al., 1999; Keeley and Fotheringham, 2001; Moritz, 1997; Moritz et al., 2004) advocate for large fires being mostly wind/weather driven.

In non-Mediterranean ecosystems the role of fuel and climate over the dynamics of vegetation and the subsequent effects of fire suppression on the fire regime are much clearer Thus, for example, the open *Pinus ponderosa* forests of southern Rocky Mountains historically had a fire regime dominated by low-intensity understory fires, and, consequently, fire suppression had an important impact on their dynamics (Allen et al., 2002). On the other hand, many northern and subalpine conifer forests such as those of Yellowstone National Park are naturally characterized by infrequent stand-replacing fires, and is the climate and not fuels the main determinant of the occurrence of large fires (Turner et al., 2003).

In Spain, frequencies of crown fires and total burned area have increased throughout the last decades (Moreno et al., 1998). Several causes have been proposed to explain this increase: (1) increasing fuel build-up as a consequence of agricultural abandonment along the 20th century (Terradas et al., 1998); (2) increasing climatic hazard of fire due to the combination of high temperatures and low air humidity (Piñol et al., 1998); (3) more ignition sources due to extensive human activity across the territory (Terradas et al., 1998). Thus, in this region, fire regime can be driven by fuel, climate, and human activity, providing new insights for the debate.

Previous studies have attempted to characterize fire regime by fitting empirical fire occurrence distributions (for example, time interval between fires, fire probability at time t, extreme fire extant) to theoretical models such as Weibull, Poisson, or extreme event distributions (Johnson and Gutsell, 1994; Mandallaz and Ye, 1997; Moritz, 1997). The ultimate goal of this approach is to correlate fire occurrence to potential drivers, such as climate conditions (Moritz, 1997), fire suppression policies (Johnson et al., 1998), forestry practices (Gauthier et al., 1996) or age of fuel (Moritz et al., 2004). Particularly, an effect of fuel accumulation is assumed to produce an increasing probability of fire with the age since the last fire (fire hazard), which is revealed by the c parameter of the Weibull distribution (Johnson and Gutsell, 1994; Moritz, 2003; Moritz et al., 2004).

In this paper we propose a novel approach to analyze fire occurrence patterns in relation to previous fire events. This is based on randomly simulating fires with features similar to those that really occurred, and on the subsequent comparison of the randomly generated fire maps with the maps of burned areas derived from satellite images. We use a percolation model that does not intend to reproduce fire behaviour, only observed fires with exactly the same origin, area and shape than in the field. The proposed approach intends to give answers to two different questions: (i) do all locations of an area of interest have the same probability of being burned? And (ii) does the occurrence of fire modify the probability of being burned again? These questions are based on the hypothesis that large fires are fuel-driven (so recent fires prevent fuel accumulation). The methodology developed is applied to a historical series of fires occurred in three regions of NE Spain.

2. Material and methods

2.1. Study area

The study region includes an area of around 32,000 km^2 in north east Spain. The region was divided

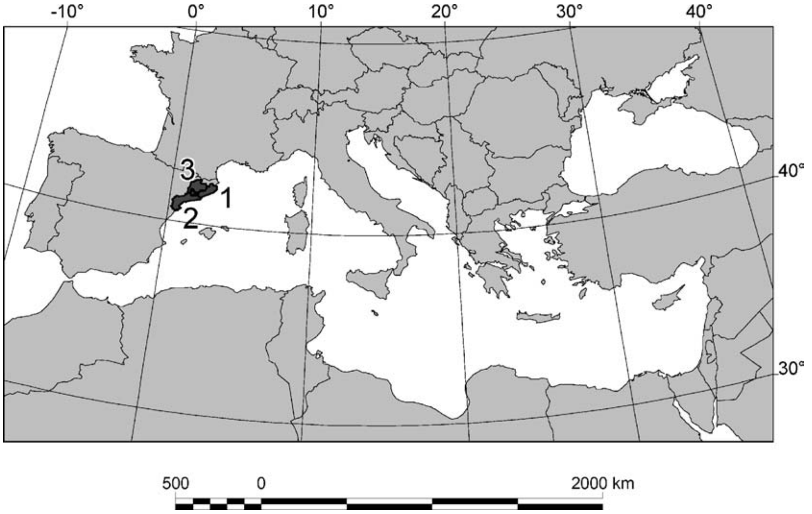

Fig. 1. The three sub-areas (1: North Coast; 2: South Coast; 3: Inland region) of the study region, in dark grey, in the context of the Mediterranean basin.

into three sub-areas (Fig. 1), as there was clear evidence of differences in their fire regimes (Díaz-Delgado et al., 2002). These areas were: (1) North Coast, (2) South Coast, and (3) Inland Region. The proportion of forest and shrubland burnt in the considered period was much lower in the North Coast sub-area than in the other two. In the Inland Region, mean fire area was higher than in the other two sub-areas (Table 1). In part, these differences are consequence of climatic differences among sub-areas: The North Coast Region has more precipitation and lower temperatures than the South Coast; the Inland Region has a more continental climate compared to coastal areas (Table 1). Forests, shrublands and grasslands cover 57% of this region. Agricultural

Table 1
Main characteristics of the three sub-areas

	North Coast	South Coast	Inland Region
Main land uses (%)			
Forest, shrublands and grasslands	62.2	48.6	63.8
Agricultural lands	25.1	44.5	31.7
Urban	9.9	3.6	1.5
Others	2.8	3.3	3.0
Climate			
Annual precipitation (mm)	765	596	727
Mean maximum temperature (°C)	19.3	19.5	17.4
Mean maximum summer temperature (°C)	27.0	28.2	26.3
Wildfires in the dataset			
Number of wildfires	62	203	72
Area burned (km^2)	201.5	964.2	771.5
Total area (km^2)	4509	8435	6339
Proportion of burned forested area (%)	7.7	23.5	19.1

Land use data come from the Land Cover Map of Catalonia (Ibàñez et al., 2002); climatic data come from the Digital Climatic Atlas of Catalonia (Ninyerola et al., 2000).

lands cover most of the remainder, producing considerable fragmentation of natural vegetation. Most of the study area has a Mediterranean climate, with moist, mild winters and hot, dry summers (ICC, 1997), which favor wildfires.

2.2. *Wildfire database*

The period analyzed was 1975–1998, both years included. The database used was built from more than 100 Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) images acquired by Landsat 1 to 5 satellites (with a spatial resolution of 79 m × 59 m and 30 m × 30 m, respectively). Images were geometrically and radiometrically corrected (Pons and Solé-Sugrañes, 1994; Palà and Pons, 1995). Near-infrared and red bands were used to calculate NDVI images (normalized difference vegetation index, Mather, 1999), which can be considered as an estimation of vegetation cover. Areas greater than 0.3 km^2 were considered to have crown burned when the subtractions of consecutive NDVI images were greater than a given threshold obtained from empirical regression models adjusted to 21 fires whose surface was previously known (Salvador et al., 2000); commission and omission errors, evaluated from different sources, are particularly low (Díaz-Delgado, 2000). This procedure allows recognizing areas that have burned more than once along the study period. However, only areas burned twice were considered in the analysis we conduct here, as was very small the territory burned three or more times in the considered period (1.2% of the burned area, Díaz-Delgado et al., 2004).

2.3. *Simulation of fires*

Simulations generating the same number of wildfires as those registered in the database for each year were carried out for all three sub-areas. The objective of these simulations was to randomly reproduce the same number of fires, each one with its observed area and, approximately, with the same area/perimeter ratio. Each fire simulation was performed independently from the previous ones (but burned areas were not allowed to overlap when occurring in the same year; see below for details). Thus, a portion of the total area is expected to have burnt twice along the considered period, under the simulated conditions of independence from previous fires. Then, the resulting frequency distribution of pixels than have burned twice may be compared to the observed in the field. Between 50 and 130 simulated realizations for each sub-area were produced.

We used two criteria to set the location of the ignition point for each simulated fire:

(i) Each pixel considered as able to burn was assigned the same probability of being the ignition point.
(ii) The ignition point of each simulated fire was forced to be in the centroid of its respective actual burned area.

This last criterium mimics more closely the real spatial pattern of ignitions, and assumes that the ignition points may not be independently distributed. The comparison between the results of both criteria allow to discriminate the effect of the spatial pattern of ignition points on the likelihood of a given pixel being burnt.

Obviously, not all surfaces included in the sub-areas analyzed could be considered as equally able to burn. A mask containing all cover types with clearly lower probabilities of burning was applied to discard them from the analysis. These comprise many of the CORINE Land Cover categories (http://reports.eea.eu.int/COR0-landcover/en) including urban areas, extensive agriculture and a mask for deciduous forests derived from a seasonal comparison of pairs of remote sensed images.

Since the spatial structure and evolution of forest fires seems to follow a fractal law (Beer and Enting, 1990) a percolation algorithm was applied to simulate each fire (Bunde and Havlin, 1991). Specifically, for each observed fire, the algorithm assigned a pixel next to the fire front as burned (or otherwise not being burned during the entire fire event) depending on a probability p. For each pixel, a uniform random variable within the interval [0, 1] was generated and, if its value was lower than p, the pixel was considered as burned. Although a p of 0.4 was initially used for each fire, its value was automatically updated in order to allow the growing fire to modify its perimeter towards the value observed in its respective actual fire. Consequently, once the simulated fire reached the same area as the real fire (and its simulation was stopped), the perimeter/area ratio was usually similar to that observed in the actual fire. However, since the whole process was based on randomly generated numbers, this convergence sometimes failed. In these cases, when the logarithms of the observed and simulated perimeter/area ratios differed more than 0.02, the simulation was repeated until the desired ratio was obtained.

In addition, some further considerations were taken into account to ensure the validity of the simulated maps:

(i) Although the selection of the three sub-areas was made considering their internal homogeneity, the necessary setting of the respective specific boundaries would easily lead to strong biases in the results. Thus, to avoid such potential biases, (1) actual fires not included completely within the boundaries of one of the sub-areas of interest were rejected from the study; and (2) simulated fires burning outside the corresponding sub-area were simulated again until they remained inside.
(ii) An area very recently affected by a fire could not have enough fuel to be burned in a short period of time. To avoid such unrealistic situation any two simulated fires with their respective actual fires occurring on the same year were not allowed to overlap their areas.
(iii) When a simulation had to be repeated due to a low degree of convergence on the perimeter/area ratio, the location of the starting point was forced to be the same as the previously selected. This assured that no spatial bias occurred since, depending on the structure of the underlying land cover map, some areas tended to have a higher proportion of failures in convergence.
(iv) Finally, as p was smaller than 1, there was always the possibility of a simulated fire being 'extinguished' before acquiring the area of the actual fire. When this happened, the simulation was restarted from the old perimeter.

2.4. The statistical test

The simulated maps of the previous section gave the same initial probability of burning to all pixels. Thus, they can be considered as realizations under the null hypothesis of equal probability. A single realization includes all the fires occurred in a region during the entire study period (Table 1). The only variable further considered from each realization was the number of pixels burned twice.

Two main departures from the null hypothesis may occur: (a) clumping (fires tend to be more abundant in some locations) or (b) segregation (fires tend to be spatially apart from one another). The occurrence in the actual wildfire dataset of any of both departures from the null hypothesis will lead to differences in the relative frequency of the pixels being burned twice. Hence, while under clumpling the frequency of areas that actually burned twice is expected to be higher than under the null hypothesis, under segregation the contrary will occur.

Such expected changes in the relative frequency of pixels burned twice may be used to develop a statistical test against the null hypothesis of equal probability. Specifically, the relative frequency of pixels burned twice in each of the simulated maps can be used to estimate the probability density function of such relative frequency under the null hypothesis. Provided that a high number of simulations have been carried out, the histogram of the observed relative frequencies will be a good estimate of its density function. Once this estimate is obtained rejection areas in both tails of the function may be set up (Fig. 2).

If the relative frequency observed in the actual fire map clearly fall in the left tail of the function (less ob-

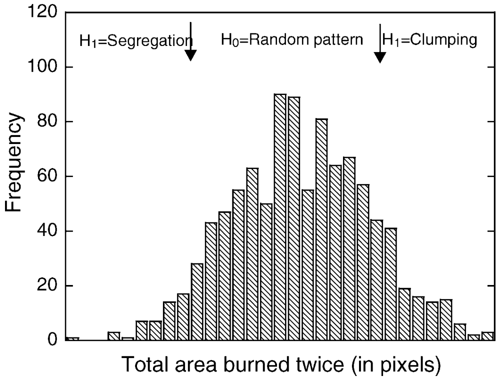

Fig. 2. Histogram of the number of pixels burned twice in a number of random realizations of a given fire record in a region. If the number of pixels that actually burned twice (from satellite imagery data) was higher in relation to the simulations, then a clumped pattern in the actual fire record is concluded (with a given probability). On the contrary, when the number of pixels that actually burned twice in the considered period was low compared to that calculated in the simulations, a segregation pattern has to be accepted. This figure is not the result of a specific set of simulations, but a help to give the reader a conceptual understanding of how the statistical test was done.

served than expected number of pixels burned twice) there will be strong evidence that a segregation pattern has occurred in the spatial distribution of fires. Conversely, if the actual value falls within the right tail (more observed than expected number of pixels burned twice) it will clearly suggest a spatial clumped pattern. Finally, if the observed frequency does not fall in any of the tails it will not be possible to reject the null hypothesis of equal probability (Fig. 2).

Several factors may lead to segregation or clumped spatial patterns. Furthermore, the interpretation of the results will depend on whether the location of the fire starting point in the simulations is random or is fixed in the centroid of the actual fire.

3. Results

Both in the South Coastal (SC) and in the North Coastal (NC) regions, when fires were simulated from a random origin there was a low probability ($p = 0.06$ in SC and $p = 0.08$ in NC) of obtaining a level of clumpling equal or higher than the observed in the actual fires (Fig. 3A and B). These results suggested that fires tended to occur in reality in an aggregated pattern, i.e., more frequently in some places than in other places.

When fires were simulated from the centroid of their corresponding mapped fire (fixed origin) instead of having a random origin (Fig. 3C and D), it was not possible to reject the null hypothesis in any of the two

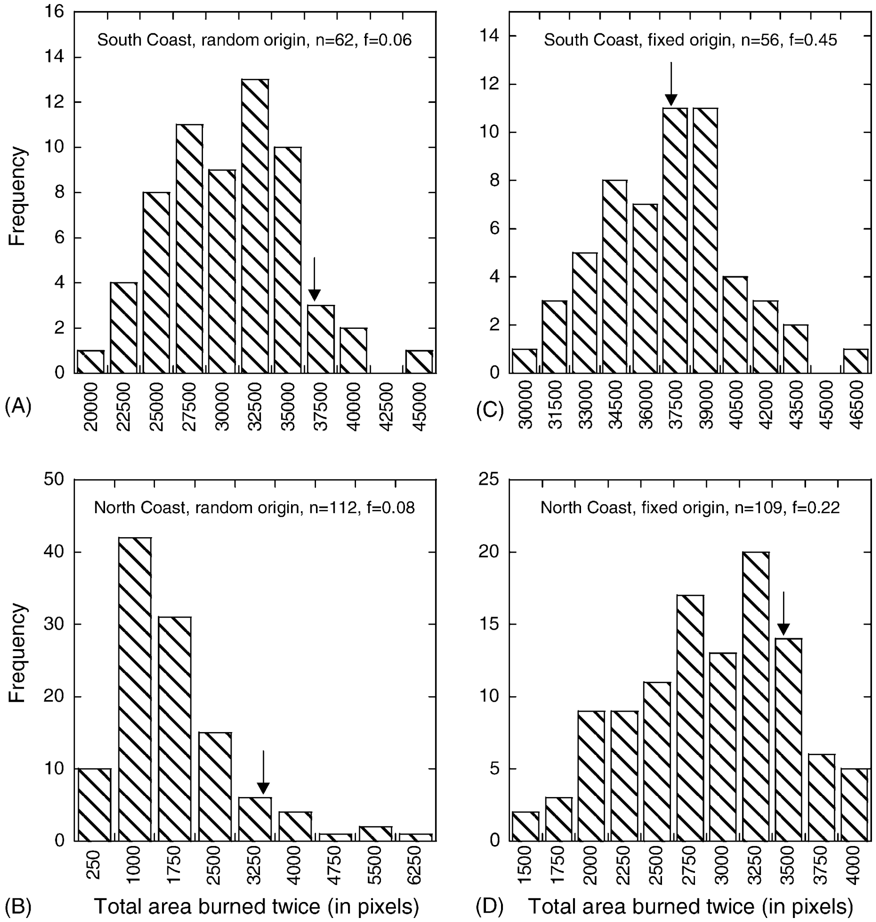

Fig. 3. Actual histograms of the number of pixels burned twice in the South Coast and North Coast, both with random starting points for the simulated fires (left) and with the fixed starting points (right). Each simulation gave a single value of pixels burned twice, and the histogram represents the distribution of the *n* simulations conducted. Arrows indicate the actual number of pixels burned twice during the entire period for which we have satellite imagery. The proportion of simulations to the right of the arrow is indicated as the *f* value.

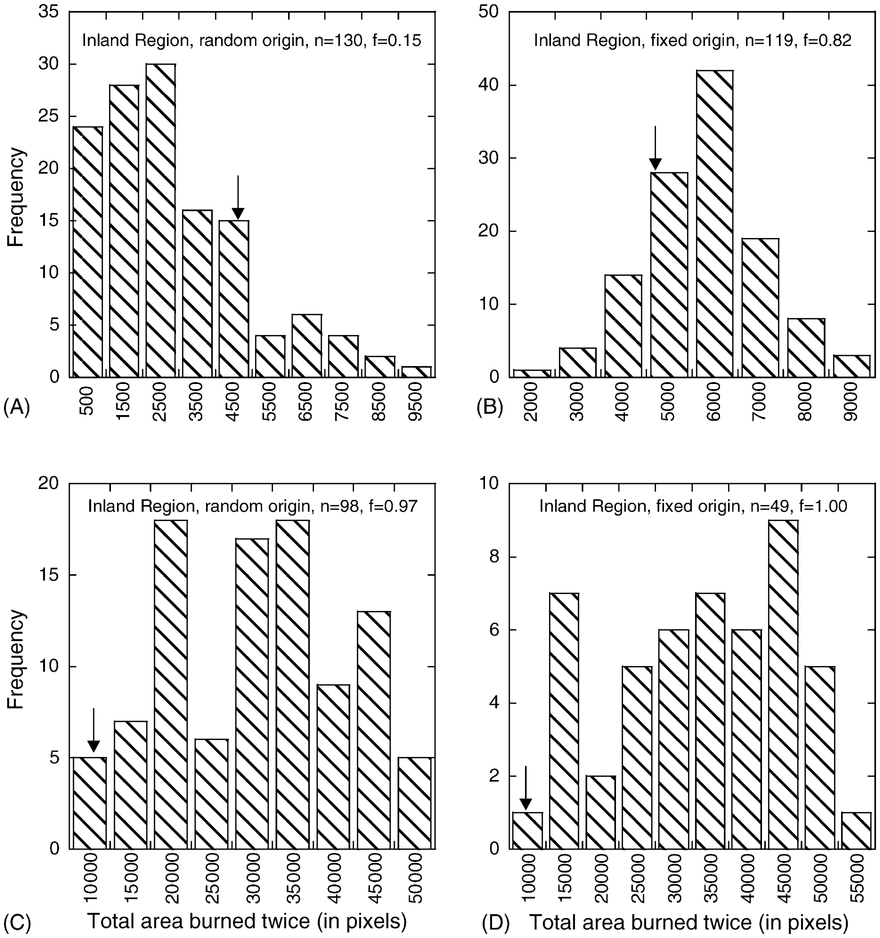

Fig. 4. Actual histograms of the number of pixels burned twice in the Inland Region, both with random starting points for the simulated fires and with the fixed starting points. The diagrams (A) and (B) correspond to the period 1975–1993, whereas the diagrams (C) and (D) to the period 1975–1998. Each simulation gave a single value of pixels burned twice, and the histogram represents the distribution of the *n* simulations conducted. Arrows indicate the actual number of pixels burned twice during the entire period for which we have satellite imagery. The proportion of simulations to the right of the arrow is indicated as the *f* value.

coastal regions ($p = 0.45$ in SC and $p = 0.22$ in NC). These results indicated that the occurrence of a fire in the past did not affect the probability of having a new fire in the future.

The analysis of the Interior Region in the period 1975–1993 (excluding the years 1994 and 1998 with very large fires) gave very similar results to those of the two coastal regions, both with random and fixed origins of the fires: there was a slight clumpling when the origin of fires was set randomly ($p = 0.15$, Fig. 4A), that disappeared when fires were forced to start in their known location ($p = 0.82$, Fig. 4B). On the contrary, when the entire series was analyzed (1975–1998) results showed clearly a repulsion effect (Fig. 4C and D), both with random and fixed fire origins. Considering that a very large proportion of the total burned area was burned in two large fires in 1994 and 1998 (more than 24,000 and 16,000 ha, respectively), the above results simply seemed to indicate that the areas that burned in 1994 did not burn again in 1998, as it indeed occurred.

4. Discussion and conclusions

The wildfires studied showed an aggregated pattern, that is, sites burned twice were more common than expected when fires were simulated from a random origin. Since this pattern disappeared when simulations were started from the 'known' ignition sites, the observed pattern had to be attributed to a non-random probability of ignition across the territory. Thus, the spatial distribution of fires reflects more a non-random distribution of ignitions than the effect of fuel age on the fire spread itself. There are many reasons, which contribute to the fact that some areas are more likely than others to start fires: topography, microclimate, vegetation variability, and human presence. In fact, the two areas in the region with higher fire recurrence (one in the North Coastal area and one in the South Coastal Area) are often submitted to strong north winds (Díaz-Delgado, 2000). This result also challenges the assumption of uniform spatial distribution of fire ignition across the region.

However, when mimicking the actual pattern of fire ignitions, burned areas did not lower or increase the probability of a new fire in the same site, at least within the limits of the period of time considered in this study. This pattern neither supported the hypothesis that low amounts of fuel as a consequence of a recent fire lowered the probability of occurring a new fire (Minnich hypothesis), nor the opposite one, that a shift in vegetation type, for example by fires promoting flammable grasslands (D'Antonio and Vitousek, 1992), increased the probability of having a new fire.

While these results support the importance of fire management focused on areas more likely to become an ignition point, they bring doubts about the effectiveness of prescribed fires as a practice involving large areas. According to our results the rationale under the Minnich hypothesis (Minnich, 1983) appears not to apply to the studied areas of north east Spain, and the alternative point of view of Keeley et al. (1999) seems to hold. Thus, the spatial pattern of fire occurrence would be largely explained by characteristics of the territory. Nevertheless Minnich's main point of large fires occurring mostly in areas that had not burned in many years cannot be refuted by our analysis because the period of time analyzed was too short.

The large fires that occurred in the Interior Region in 1994 and 1998 totally changed the above rules of fire occurrence. Due to the short period of time available after these fires it cannot be known yet if these results indicate or not a real change in the fire regime in that region. That change in the results between before and after the two large fires in the Central Region simply highlights the difficulty of gathering data or even defining what a fire regime is for a particular period of time. This is especially important in the context of the current changes of climate and in land uses, and how they are going to affect the fire number and extension.

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