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Recent fire regime characteristics and potential natural vegetation relationships in Spain

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Abstract. In heavily altered landscapes, where vegetation is not natural and where people are the main source of ignitions, relationships between fire occurrence and climate conditions may be unclear. The objective of this study was to evaluate to what extent territories with similar Potential Natural Vegetation (PNV) in peninsular Spain differ in their forest fire characteristics. From 1974 to 1994, more than 174 000 fires occurred. We used (1) the Spanish data base of forest fires, (2) a PNV map and (3) a land use map. Separate fire characteristics, based either on the number of fires occurred or the area burned, were obtained for each of the ca. 5000 grid-cells (10 km × 10 km) into which peninsular Spain is divided in the UTM projection. Also, meteorological conditions at the time of fire ignition, cause of ignition and present forest cover were referred to the same grid-cells as external factors potentially determinant of fire occurrence. The relationships between fire regime characteristics and PNV units were explored with Principal Components Analysis (PCA). The role of the three sets of external factors in the fire characteristics was evaluated with Redundancy Analysis (RDA). Groups of similar PNV types were clearly segregated, suggesting a gradient of fire characteristics. Higher fire incidence (higher frequencies and spatial incidence of fires, but lower proportions of grid-cells affected by large fires) was associated with Atlantic, warm territories with deciduous forests as PNV. Intermediate fire frequency and rotation period, but with a higher relative incidence of medium and large fires occurred in Mediterranean PNV units, dominated by sclerophyllous oak forests. Low fire frequency and long rotation periods, with strong seasonal and yearly variability occurred for PNV units in the cold uplands (*Fagus, Pinus, Abies, Juniperus*) or in the semi-arid, shrubby PNV units. The cause of ignition best explained the patterns of forest fire characteristics, followed by weather conditions.

Our results indicate that, even in human influenced regions, climate and soil conditions exert control on the resulting forest fire characteristics, as indicated by the high segregation of the PNV types. However, the role of man was crucial in shifting the patterns of fire incidence. This was so that highest fire incidence occurred in regions that, otherwise, would be expected to have a much lower one, thus posing a serious threat for such areas. PNV maps, by providing a phytogeographical framework for characterizing forest fires, could be valuable tools for applying research results to forest fire management policies, taking properly into account the underlying determinant factors.

Keywords: Fire frequency; Fire rotation period; Fire season; Forest cover; Hybrid canonical ordination; Ignition cause; PCA; RDA.

Abbreviations: PCA = Principal Components Analysis; PNV = Potential Natural Vegetation; RDA = Redundancy Analysis.

Introduction

Climate and soil characteristics control primary productivity (Lieth & Whittaker 1975) and the type of vegetation (Woodward 1987) which, in the end, will closely determine availability of fuel. Climate also plays an essential role in fire ignition and propagation, either through its influence on fuel moisture content (Rothermel 1983), on the conditions for fire propagation (McCutchan 1977) or in providing natural (i.e. lightning) ignition sources. Ultimately, all of these factors may determine the fire regime of a given area (Christensen 1987). The relationships between climate and fire are widely acknowledged (Chandler et al. 1983) and, quite commonly, good correlations between fire occurrence and climate variables have been found (Flannigan & Harrington 1988; Vázquez & Moreno 1993; Viegas & Viegas 1994; Davis & Michaelsen 1995). The pattern of relationships between climate variables, such as temperature and precipitation, and fire is so that fire occurrence should be greatest at places where conditions are neither excessively favourable nor unfavourable for vegetation growth. Plentiful water availability and excess moisture would deter fire from igniting or propagating. Dry conditions would prevent vegetation growth, leading to insufficient quantity and continuity of fuel.

In anthropogenic landscapes the relationships between fire characteristics and climate, soil and vegetation properties may be less pronounced. The overriding role of humans in modifying the land may lead to a vegetation cover whose fire-related properties are different from those of the natural vegetation. Similarly, vegetation arrangement in space, including its continuity, may also be different. This is notoriously so in Southern European countries such as Spain, where unaltered vegetation is virtually non-existent. In addition, man can also modify ignition frequencies and locations. Human action is the main source of ignitions in many regions of the world (Vázquez & Moreno 1998). These changes in vegetation, landscapes and ignitions may be conducive to fire regimes that do not necessarily correspond to those expected from the basic characteristics of climate, soil and natural vegetation. A relevant question is then to what extent regional fire occurrence can be related to the phytogeographical divisions of a territory and if such divisions can be used to extrapolate impacts of fire on the ecosystem. Models aiming to predict future incidence of fire occurrence under changing scenarios of climate are usually based on such information (Gardner et al. 1996; He & Mladenoff 1999). At a minimum, empirical studies that can validate these models are needed to achieve a proper understanding of the interactions between the natural and human environments leading to fire occurrence and subsequent fire regime characteristics of a given region.

Fire statistics are usually compiled on the basis of administrative units which, most commonly, have little to do with the vegetation units or any other type of ecological division that better reflects climate and soil characteristics (Moreno et al. 1990, Gavilán & Fernández-González 1997). Evaluating the current role and impacts of fire on the ecosystem, and extrapolating them into the future, requires that information be converted from administrative territorial units to ecologically meaningful entities. One such type of territorial division that may integrate many relevant components of forest fire characteristics at a regional scale can be provided by phytogeographical units based on the Potential Natural Vegetation (PNV). PNV maps are constructed based on the phytosociological classification of the vegetation (Härdtle 1995; Moravec 1998): identification and classification of remnants of natural or near-natural plant communities; detection of their relationships with site factors (macroclimate, topography, soil types and water availability); identification of seral communities and indicator species (whose diagnostic values, in general, decrease with increasing human impact; Härdtle 1995) related to similar habitat conditions of PNV units. Therefore, several determinant factors of fire characteristics (climate, soil, vegetation types and their associated fuel characteristics) are involved in the definition and mapping of PNV units, and could be adequately integrated by them. Even land use could, to some extent, be related to PNV units because some of these factors impose constraints on the viability of some land uses. In fact, areas with similar PNV were highly correlated with the yearly patterns of the satellite derived Normalized Difference Vegetation Index (NDVI, a widely used index for vegetation status) in the Iberian Peninsula (Lobo et al. 1997). NDVI is now being used for fire danger assessment (Burgan et al. 1998). Vegetation maps based on the PNV concept exist for many European countries (Bohn et al. 2000 and references therein).

The objective of this work was to determine whether there were differences in the recent fire regime characteristics among geographic areas of peninsular Spain differing in the type of potential natural vegetation. First, we expected that territories with similar PNV types would show similar fire characteristics. Should natural conditions prevail, this would have been sufficient to have an understanding of differences in forest fire characteristics between the different phytogeographic entities. However, due to the role of humans either in setting fires or in controlling extant landscapes, in a second step we analysed the explanatory power on the fire regime characteristics of the PNV units of three sets of external factors considered as potentially determinants of fire occurrence: (1) the meteorological conditions at the time of fire (which reflect ignition and propagation conditions), (2) the causes of fires and (3) the present forest cover.

Material and Methods

Study area and data sources

The study area was peninsular Spain and the study period 1974-1994 (Fig. 1). Three sources of information were used: the forest fire database, a map of the natural potential vegetation and a map of land uses of Spain.

1. *The Spanish database of forest fires*

Digital reports of fires registered during the study period were provided by the former ICONA (Instituto Nacional para la Conservación de la Naturaleza). They originate from the individual reports filed by Forest Service personnel on each of the nearly 174 000 fires larger than 0.1 ha that occurred during this period which affected more than $4.6 \cdot 10^6$ ha. In these reports each fire was assigned to the 10 km × 10 km grid-cell in which the fire broke out. Hence, this was the available resolution for the analyses and the information from the three data sources was referred to each of the 5006 grid-cells in which peninsular Spain is divided according to the UTM projection. Fire reports include the start date of the fire, the area burned, the cause of fire (Table 1) and meteorological data about the start day of the fire, usually obtained from the nearest available weather station.

Although the database is reasonably exhaustive, not

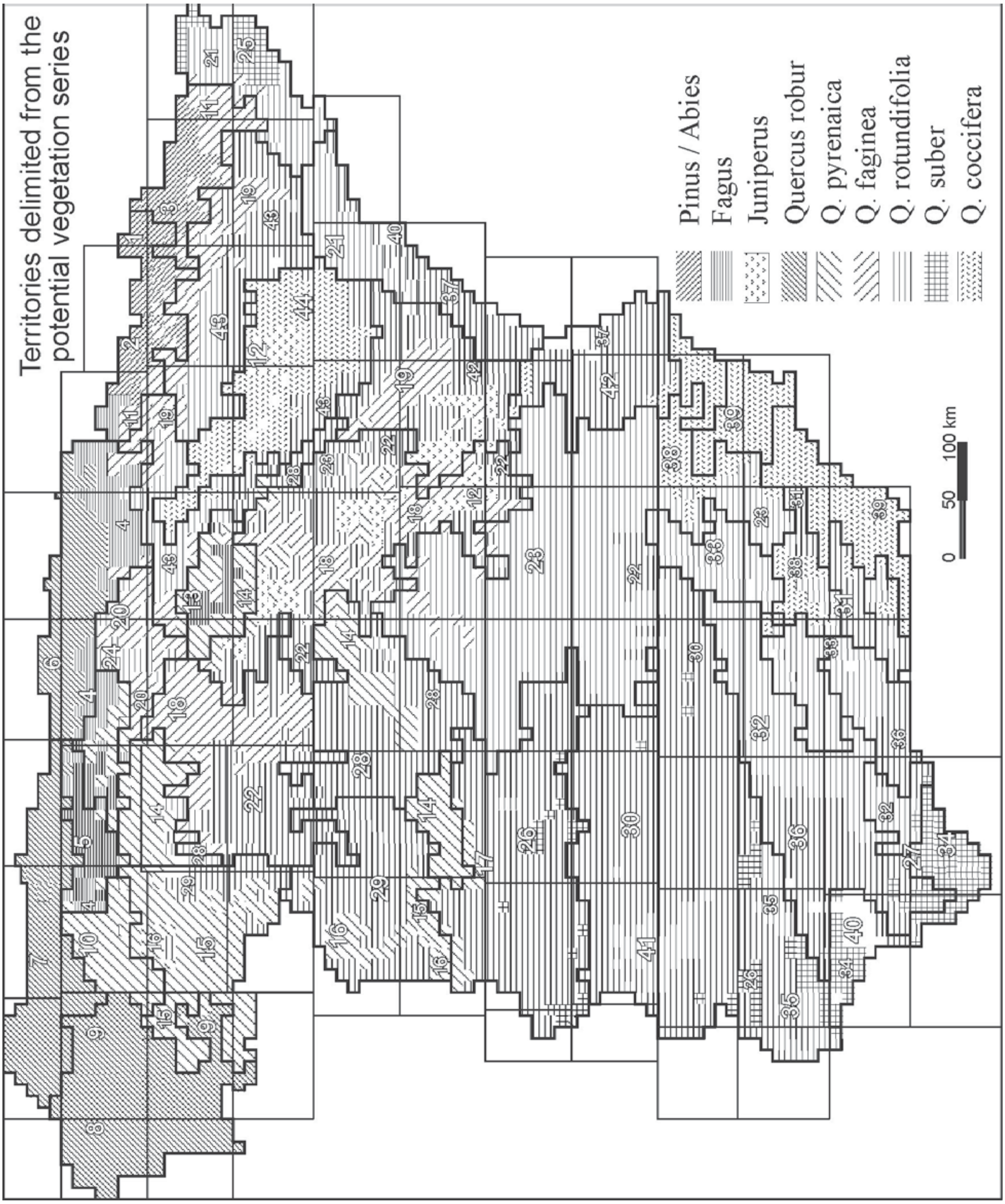

Fig. 1. Distribution in peninsular Spain of the 43 PNV units considered in this study according to the map of Rivas-Martínez (1987a). The legend shows the code, the bioclimatic belt and the dominant tree species (PNV main tree groups) as described in Table 1. Large rectangles correspond to the 1 : 200 000 topographic sheets in UTM projection. The other polygons delimit phytogeographical sectors according to Rivas-Martínez (1987b). A full colour version of Fig. 1 is available at http://www.opuluspress.se/pub/archives/index.htm

all the fires occurred in the country are recorded since information was not available (estimated in an additional 7% of fires) for some provinces during some years (Vázquez 1996; Moreno et al. 1998).

2. *Map of the vegetation series of Spain (1:400 000)*

This map (Rivas-Martínez 1987a), based on the concept of potential natural vegetation, was used to assign each 10 km × 10 km grid-cell to one PNV unit. Assignment was made to the dominant PNV unit that resulted after sampling a regular grid of 25 points laid on each grid-cell of the vegetation map. This sampling procedure reduced the original 110 PNV units of the map to 82. In order to facilitate all subsequent analyses, PNV units with less than 14 grid-cells assigned were merged together with the neighbouring, most similar unit in syntaxonomic or ecological terms. By doing this, the 82 PNV units were reduced to 38. On the other hand, some PNV units had a very large geographic distribution, being present in widely separated areas of the country. Such units were subdivided following additional phytogeographical criteria (Rivas-Martínez 1987b), raising the number of PNV units finally used in the analyses to 43 (Table 2). The criteria used for grouping PNV units were similar to those applied in the preparation of the Map of the Natural Vegetation of Europe (Bohn 1994; Bohn et al. 2000) which, for Spain, is also based on the Rivas-Martínez map. Finally, to interpret the analysis, results will be presented for nine PNV groups with the same dominant tree species (Table 2).

The distribution of PNV units in Peninsular Spain is illustrated in Fig. 1. The north of the country is characterized by moist summers, which favours temperate deciduous forests. *Quercus robur* and other deciduous oaks (*Q. pyrenaica, Q. petraea*) PNV units dominate in the Cantabrian coast and Galicia lowlands (colline and montane belts); *Quercus pubescens* PNVs extend over the lower slopes of the Pyrenees. Beech (*Fagus sylvatica*) PNVs are characteristic of the montane belt of the Cantabrian range and of the Pyrenees. Conifer (*Pinus sylvestris, P. uncinata, Abies alba*) PNV units are present in the high montane and subalpine areas of the Pyrenees.

South of these ranges the climate is Mediterranean and PNV units are mainly dominated by sclerophyllous species, among which *Quercus rotundifolia* is prevalent. *Q. ilex* PNVs occur in the NE of the country, *Q. suber* PNVs are scattered in the warmer and more humid areas of NE, W and SW Spain. Arid and semi-arid areas of the Ebro Basin and SE Spain have *Quercus coccifera* garrigues or thermophilous shrublands dominated by *Pistacia lentiscus* and other shrubby species. Cold and humid areas of the Mediterranean mountains have PNV dominated by deciduous trees such as *Quercus pyrenaica* or *Q. faginea* on siliceous or calcareous soils, respectively. Even though conifers, mainly pine species, represent a high proportion of the present forested area of the Mediterranean areas of Spain, most have been considered in this map as subdominant in other PNV units, forming secondary forests or being extended by afforestation. Pure conifer forests are considered to constitute PNV units mainly in high mountain areas, along with oromediterranean scrub and grasslands. PNV of juniper forests (*Juniperus thurifera)* spread across the inner highlands, along the Iberian Range, under relatively dry and continental climatic conditions.

3. *The map of crops and land uses of Spain (1:10^6)*

This map (Anon. 1989) was drawn based on aerial photography and field work during the mid-1980s, therefore it is a good reference of the extant land use/land cover during the study period. To evaluate the present forest cover in each PNV unit, we determined the proportion of the area covered by the following land-cover types for each 10 km × 10 km grid-cell: conifer forest, broad-leaved forest, mixed (conifer plus broad-leaved) forest, shrublands and grasslands with a tree overstorey. The proportion of forested areas was very variable across the different PNV units (Table 2).

Table 1. Number of fires, area burned and proportion of grid-cells affected by fires of different origins during the study period (1974-1994). The proportion of grid-cells affected is calculated taking as reference the total number of grid-cells with at least one fire.

Cause of fire	Number of fires		Area burned (ha)		% Grid-cells affected
Grassland burning	4284	2.5%	102 121	2.2%	37.9%
Lightning	5663	3.3%	343 421	7.5%	41.7%
Negligence	24 588	14.2%	767 665	16.7%	80.2%
Intentional	73 987	42.6%	1 819 942	39.6%	62.2%
Unknown sources	65 193	37.5%	1 567 841	34.1%	87.3%
Total	173 715	100%	4 600 990	100%	

Table 2. Characterization of the PNV units used for the analyses: code (as in Fig. 1), bioclimatic belt (Rivas-Martínez 1987a), dominant tree (or shrub) species, correspondences with the original codes from the Map of Rivas-Martínez (1987a), PNV main-tree group (as referred in text and Fig. 2), total area occupied by each PNV unit and percentage of forested area within it. PNV units are ordered by phytogeographic regions and bioclimatic belts. When PNV units dominated by different tree species have been merged, either the species of the minor unit is included in brackets or the plus sign is indicated after the main species. PNV units 5, 10, 14, 19, 31 and 33 also include small areas of high mountain bioclimatic belts (alpine and oro-cryoromediterranean).

Code	Bioclimatic belt	Dominant tree species in the PNV unit	Original codes	PNV main-tree group	Total area (1000ha)	Forest area (%)
	Eurosiberian region					
1	Subalpine	*Pinus uncinata*	2a	*Pinus/Abies*	267	54%
2	Subalpine	*Abies alba*	2b, 2c, 2d, 5c	*Pinus/Abies*	204	52%
3	Upper montane	*Pinus sylvestris*	3a, 3b, 3c, 6c	*Pinus/Abies*	390	81%
5	Montane	*Fagus sylvatica (Juniperus nana)*	5h, 2e, 2f	*Fagus*	368	90%
4	Montane	*Fagus sylvatica (Q. robur)*	5a, 5b, 5e, 5g, 9a, 6b, 8b	*Fagus*	478	84%
9	Montane	*Quercus robur*	8d	*Q. robur*	698	62%
10	Montane	*Q. pyrenaica (Betula celtiberica)*	7a, 9b	*Q. pyrenaica*	718	84%
11	Montane	*Quercus pubescens (Q. ilex)*	5d, 7b, 10, 11c	*Q. faginea*	717	77%
6	Colline/montane	*Quercus robur (Q. ilex)*	6a, 11a	*Q. robur*	1039	71%
7	Colline/montane	*Quercus robur*	8a	*Q. robur*	796	65%
8	Colline	*Quercus robur*	8c	*Q. robur*	1111	56%
	Mediterranean region					
12	Supramediterranean	*Juniperus thurifera*	15a, 15b	*Juniperus*	800	67%
13	Supramediterranean	*Fagus sylvatica*	16b	*Fagus*	150	81%
14	Supramediterranean	*Quercus pyrenaica (+)*	13a-c, 18a, 18c	*Q. pyrenaica*	1760	63%
22	Supramediterranean	*Quercus rotundifolia*	22a	*Q. rotundifolia*	3124	34%
24	Supramediterranean	*Quercus rotundifolia*	22c	*Q. rotundifolia*	180	76%
33	Supramediterranean	*Quercus rotundifolia (+)*	14b, 19e, 24f	*Q. rotundifolia*	560	71%
15	Supra/mesomedit.	*Quercus pyrenaica (+)*	13e, 16c, 18b, 23e	*Q. pyrenaica*	1306	74%
16	Supra/mesomedit.	*Quercus pyrenaica*	18e	*Q. pyrenaica*	552	50%
18	Supra/mesomedit.	*Quercus faginea*	19b	*Q. faginea*	1930	30%
19	Supra/mesomedit.	*Quercus faginea (+)*	14a, 19c	*Q. faginea*	1000	64%
20	Supra/mesomedit.	*Quercus faginea*	19d	*Q. faginea*	400	52%
28	Supra/mesomedit.	*Quercus rotundifolia*	24a	*Q. rotundifolia*	1840	37%
29	Supra/mesomedit.	*Quercus rotundifolia*	24b	*Q. rotundifolia*	1296	37%
31	Supra/mesomedit.	*Quercus rotundifolia (+)*	13f, 18g, 24d	*Q. rotundifolia*	340	69%
21	Meso/supramedit.	*Quercus ilex*	21a, 21b	*Q. rotundifolia*	1071	51%
30	Meso/supramedit	*Q. rotundifolia (Q. pyrenaica)*	18f, 24c	*Q. rotundifolia*	6910	56%
17	Mesomediterranean	*Quercus pyrenaica*	18h	*Q. pyrenaica*	208	65%
23	Mesomediterranean	*Quercus rotundifolia*	22b (I)	*Q. rotundifolia*	4570	18%
42	Mesomediterranean	*Quercus rotundifolia*	22b (II)	*Q. rotundifolia*	1162	50%
43	Mesomediterranean	*Quercus rotundifolia*	22b (III)	*Q. rotundifolia*	1883	31%
25	Mesomediterranean	*Quercus suber (Q. canariensis)*	17, 23a	*Q. suber*	218	59%
26	Mesomediterranean	*Quercus suber*	23c	*Q. suber*	414	81%
32	Mesomediterranean	*Quercus rotundifolia (+)*	24e (I), 20a, 20b	*Q. rotundifolia*	2400	20%
41	Mesomediterranean	*Quercus rotundifolia*	24e (II)	*Q. rotundifolia*	391	8%
38	Mesomediterranean	*Quercus coccifera*	29 (I)	*Q. coccifera*	1210	40%
44	Mesomediterranean	*Quercus coccifera*	29 (II)	*Q. coccifera*	1212	22%
27	Meso/thermomedit.	*Quercus suber*	23d	*Q. suber*	140	83%
37	Thermo/mesomedit.	*Q. rotundifolia (P. lentiscus)*	27c, 30a	*Q. rotundifolia*	580	18%
34	Thermomediterranean	*Quercus suber (Olea sylvestris)*	26, 28	*Q. suber*	746	54%
35	Thermomediterranean	*Quercus rotundifolia*	27a	*Q. rotundifolia*	354	69%
36	Thermomediterranean	*Quercus rotundifolia*	27b	*Q. rotundifolia*	1452	12%
39	Thermomediterranean	*Pistacia lentiscus (+)*	31a, 31b, 32a, 32b	*Q. coccifera*	1032	32%

Fire regime characteristics: sets I-II

The characteristics of the forest fires registered in the grid-cells assigned to each of the 43 PNV units during the study period were summarized in two sets of six variables each (Table 3).

Set I was based on information dealing with the number of fires occurred:

I-1 fire frequency;
I-2 yearly variability;
I-3 seasonal variability;
I-4 spatial incidence;
I-5 relative importance of medium and large fires;
I-6 relative importance of large fires.

Set II was based on information dealing with the area burned in each PNV unit:

II-1 fire rotation period;
II-2 yearly variability;
II-3 seasonality;
II-4 spatial incidence;
II-5 relative importance of the area burned by medium and large fires;
II-6 relative importance of the area burned by large fires.

Fire regime factors: sets A-C

The external factors considered as potentially determinants of fire characteristics were organized into three different sets:

A: meteorological conditions at the time of fire;
B: causes of ignition;
C: present forest cover.

Variables in the first two sets were computed in a different way, on the basis of the number of fires (A_I, B_I) or of the total burned area (A_{II}, B_{II}), depending on the set of fire characteristics (I or II) involved in the subsequent analysis. A description of these variables is given in Table 4.

Based on the information available for the day each fire broke out, four meteorological variables were computed on all fires occurring in each PNV unit: A1: maximum air temperature, A2: relative humidity, A3: wind speed and A4: number of days elapsed since the last rain. We calculated separately simple arithmetic means (A_I) as well as the mean for each meteorological variable weighted by the area burned by each fire (A_{II}), because large differences in fire sizes mean that conditions when a fire breaks out may differ greatly from the conditions in which an area continues to burn.

The causes of fire ignition entered in the fire reports were pooled into five different types: B1: pasture burning (including forestry burning practices), B2: lightning, B3: negligence or accident, B4: intentional and B5: unknown. The corresponding variables were computed as proportions to the total number of fires (B_I) or to the total area burned (B_{II}) registered in each PNV unit. Finally, based on the information obtained from the map of land uses, the following variables were computed for each PNV unit: C1: proportion of PNV unit covered by forest, and the proportions of its area covered by C2: non-wooded, C3: broad-leaved forest and C4: conifer forest.

Multivariate analyses

The structure of the relationships between the fire regime characteristics and the PNV units was explored by means of Principal Components Analysis (PCA) which was performed separately for the two data matrices

Table 3. Description of the variables included in each of the two data sets of fire regime characteristics. The last column contains the variable labels used in Figs. 2 and 3.

Data set I: variables related to the number of fires			
I-1	Fire frequency	Number of fires registered in 10 000 ha of forest territory per year	FIRE FREQUENCY
I-2	Yearly variability in the number of fires	Yearly coefficient of variation of the number of fires	YEARLY VARIABILITY
I-3	Seasonal variability in the fires	Yearly coefficient of variation of the mean starting Julian day of fire	SEASONAL VARIABILITY
I-4	Spatial incidence of fires	Proportion of grid-cells with ≥ 50 ha burned	SPATIAL INCIDENCE
I-5	Relative importance of medium and large fires	Proportion of fires ≥ 50 ha to total number of fires	MEDIUM FIRES %
I-6	Relative importance of large fires	Proportion of fires ≥ 500 ha to total number of fires	LARGE FIRES %
Data set II: variables related to the area burned			
II-1	Fire rotation period	Number of years necessary to burn an area equivalent to the total forested area within the PNV unit	ROTATION PERIOD
II-2	Yearly variability in the area burned	Yearly coefficient of variation in the area burned	YEARLY VARIABILITY
II-3	Seasonality in the area burned	Mean fire starting Julian day weighted by the area burned by each fire	SEASONALITY
II-4	Spatial incidence of the area burned	Proportion of grid-units with ≥ 500 ha burned	SPATIAL INCIDENCE
II-5	Relative importance of medium and large fires	Proportion of area burned by fires ≥ 50 ha to total burned area	MEDIUM FIRES %
II-6	Relative importance of large fires	Proportion of area burned by fires ≥ 500 ha to total burned area	LARGE FIRES %

Table 4. Description of the variables included in the three data sets of external factors used for RDA. The data sets A and B were calculated in two alternative ways (indicated by the subscript), to be analysed in combination with data sets I or II.

Data sets A_{I}-A_{II}: Meteorological conditions				
Temperature	$A_{I}1$	Mean of the maximum temperature reported for each fire	$A_{II}1$	Mean, weighted by the area burned, of the maximum temperature reported for each fire
Relative humidity	$A_{I}2$	Mean of the air relative humidity reported for each fire	$A_{II}2$	Mean, weighted by the area burned, of the relative humidity reported for each fire
Wind velocity	$A_{I}3$	Mean of the wind velocity reported for each fire	$A_{II}3$	Mean, weighted by the area burned, of the wind velocity reported for each fire
Last rain	$A_{I}4$	Mean of the number of days since the last rain reported for each fire	$A_{II}4$	Mean, weighted by the area burned, of the number of days since the last rain reported for each fire
Data sets B_{I}-B_{II}: Causes of ignition				
Grassland burning	$B_{I}1$	Proportion of pasture burning fires to the total number of fires	$B_{II}1$	Proportion of the area burned by pasture burning fires to the total area burned
Lightning	$B_{I}2$	Proportion of lightning fires to the total number of fires	$B_{II}2$	Proportion of the area burned by lightning fires to the total area burned
Negligence	$B_{I}3$	Proportion of negligence fires to the total number of fires	$B_{II}3$	Proportion of the area burned by negligence fires to the total area burned
Intentional	$B_{I}4$	Proportion of intentional fires to the total number of fires	$B_{II}4$	Proportion of the area burned by intentional fires to the total area burned
Unknown	$B_{I}5$	Proportion of fires of unknown origin to the total number of fires	$B_{II}5$	Proportion of the area burned by fires of unknown origin to the total area burned
Data set C: Present forest cover				
Total forest area	C1	Proportion of the forest surface to the total area of each PNV territory	C1	Idem
Non-wooded area %	C2	Proportion of non-wooded surface to the total forest area of each PNV territory	C2	Idem
Broad-leaved forest %	C3	Proportion of broad-leaved forest surface to the total forest area of each PNV territory	C3	Idem
Conifer forest %	C4	Proportion of the conifer forest surface to the total forest area of each PNV territory	C4	Idem

(6 variables × 43 PNV units) corresponding to sets I and II. The relationships extracted by PCA were evaluated by means of distance biplots (ter Braak 1994).

The role of the external factors (sets A to C) in the ordination of the two fire characteristic data sets was evaluated using Redundancy Analysis (RDA) (Rao 1964; ter Braak 1986, 1994), a canonical ordination technique based on the linear context of PCA. In this analysis, the ordination axes, *response variables* are forced to be a linear function of the *predictor variables*, in our case the external factors data sets. The relationships between main variables and predictor variables are expressed through RDA correlation biplots, whose interpretation is similar to that of PCA distance biplots (ter Braak 1994). To evaluate the residual variation after fitting the external factors, we performed hybrid ordinations (Daudin 1980; ter Braak 1988) in which only the first two axes were constrained while the rest were free. The free axes represent the main directions of the remaining variation when the information attributable to the 'predictor variables' has been extracted from the main matrix. The comparison of the eigenvalues between the first constrained (canonical) axis and the first free axis provides an evaluation of the correspondence between the fire regime variables and the matrices of external factors (ter Braak & Prentice 1988). Validity of the canonical ordinations was assessed using Monte Carlo permutation tests for the first canonical axis (n = 100). In total, six hybrid RDAs were performed, three for set I (using as constraining variables the sets A_I, B_I and C) and the other three for set II (constrained by sets A_{II}, B_{II} and C, respectively). In this way the significance and the relative contribution of each set of external factors to the explanation of the fire regime data sets were evaluated, as well as the relationships among fire characteristics of the PNV units and external factors in the space constrained by the latter.

The variables describing fire regime characteristics (sets I and II) and meteorological conditions (set A) were subjected to the logarithmic transformation $y = \ln(x+1)$ and standardized. Variables of sets B and C, calculated originally as proportions, were subjected to logarithmic transformation prior to analysis. Ordinations were carried out with CANOCO 3.1. Spatial analysis and mapping were performed with the raster based Geographic Information System IDRISI (Eastman 1992).

Results

Fire regime characteristics and PNV units

The ordination of the data sets I and II by means of PCA provided high proportions of explained variance for the first two axes (58% for set I and 76% for set II; Fig. 2). In the ordination of set I (variables related to the number of fires, represented as vectors in the small diagram of Fig. 2, set I), the percentage of explained variance was 30% for the first axis and 28% for the second. PCA of set II (variables related to area burned, small diagram in Fig. 2, set II) accounted for a larger proportion of explained variance (41% in the first axis and 35% in the second).

The distance biplot obtained from set I (number of fires) showed a clear separation among territories belonging to different PNV main-tree groups (Fig. 2, set I).

Quercus robur PNV units were clearly segregated from the others, and were related to high frequencies and spatial incidence of fires. *Q. pyrenaica* PNV units were also related to these variables and presented a certain overlapping with part of the *Q. rotundifolia* units which, in some territories, had high fire frequencies. *Q. rotundifolia* units were characterized by a high proportion of medium to large fires. *Q. suber* territories were mainly located within the *Q. rotundifolia* ones. *Q. faginea* territories presented a wide distribution between *Fagus* and *Q. rotundifolia*. *Fagus* and *Q. coccifera* units were characterized by a high yearly and seasonal variability in fire incidence and, to some extent, were similar to the *Pinus*/*Abies* territories. *Pinus/Abies, Q. coccifera* and *Juniperus* territories presented the lowest fire frequency and spatial incidence of fires.

PCA biplot of set II (area burned) shows also a clear separation among PNV units (Fig. 2B). *Q. robur* and *Q. pyrenaica* territories were characterized by a high spatial incidence, and most commonly with short fire rotation periods. *Q. rotundifolia* territories were characterized by the relative proportion of area burned by medium or large fires. Some of these territories had long fire rotation periods (overlapping with *Q. coccifera* and *Q. faginea*) and others shorter fire rotation periods, similar to the *Q. robur* territories. The *Q. suber* territories behaved similarly although usually had shorter fire rotation periods. *Fagus, Pinus*/*Abies* and *Juniperus* PNV units were characterized by long fire rotation periods and greater variability in the area annually burned.

Fire regime characteristics and external factors

The variance explained by the first two canonical axes of RDA was higher when the data sets of causes of ignition (B_I-B_{II}) were used as *predictor variables* (Table 5), especially for set I (number of fires). The two data sets of meteorological variables (A_I-A_{II}) produced similar values of explained variance in the canonical axes. The present forest cover provided the lower variance values of the six canonical ordinations performed. The ratio between the first canonical and the first free axis showed large values for the six ordinations and the Monte Carlo permutation test was statistically significant in all cases (Table 5). Following is a brief description of the six correlation biplots based on the canonical ordinations (Fig. 3).

Meteorological variables (sets A_I-A_{II})

In the canonical ordination of set I (number of fires) and set A_I, the main positive correlations were obtained between the proportion of large fires and high temperatures and a large number of days since the last rain (Fig. 3A). High relative humidity values were mainly correlated with a high fire frequency and a large spatial incidence of fires. For the variables of set II (area burned) the highest correlations were obtained for the spatial incidence of the area burned (proportion of grid-cells with more than 500 ha burned) and high values of relative humidity (Fig. 3B). The rest of the forest fire characteristics were negatively related to relative humidity. Other variables such as the relative importance of medium or large fires, or the seasonal variability in the area burned were positively related to temperature and the number of days since the last rain.

Cause of ignition variables (sets B_I-B_{II})

High fire frequencies and a large spatial incidence of fires were closely related to a large proportion of intentional fires. A high seasonal variability in fire occurrence was correlated with a larger proportion of pasture burning fires, while the relative importance of large fires was correlated with a large proportion of fires of unknown origin (Fig. 3C). Intentional fires were negatively correlated with the proportion of area burned by large fires and positively with a high spatial incidence of fires (Fig. 3D). The proportions of area burned by fires started by negligence or lightning exhibited a reverse pattern, and were positively related with most of the other fire regime variables.

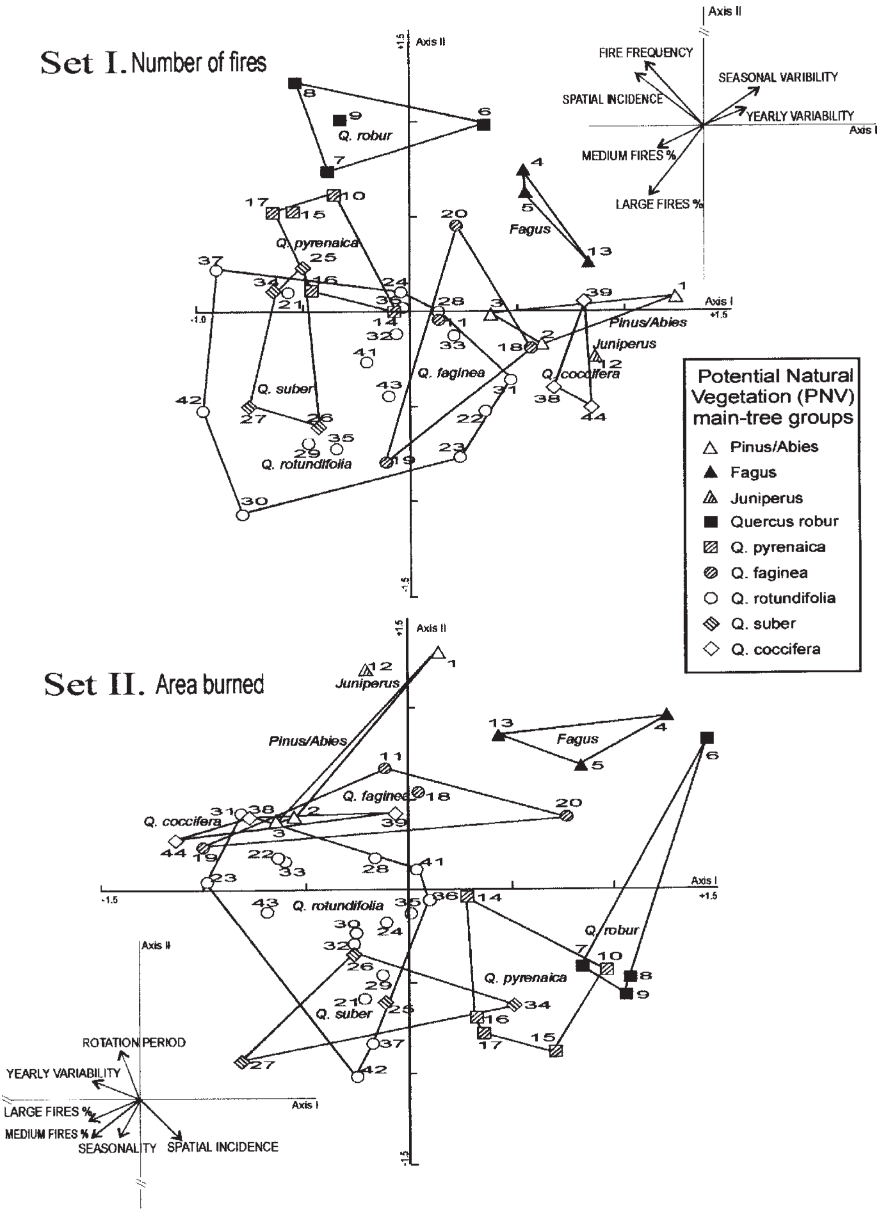

Fig. 2. Distance biplots based on PCA applied to the data sets I (variables related to number of fires) and II (variables related to area burned). The symbols for PNV units correspond to the PNV main-tree groups indicated in Table 1. Fire regime variables (Table 3) are represented as vectors in the small diagrams.

Table 5. Results of the six RDA performed: eigenvalues for the canonical axes (I-II), amount of explained variance (Total), eigenvalues for the free axes (III-IV), ratios between the eigenvalues of the first canonical and the first free axis (Rat. I/III) and significance (*p*-value) of the Monte Carlo permutation test for the first canonical axis (*p*MC).

Fire characteristics	**External factors**	**Canonical axes**			**Free axes**		**Validation**	
data sets	**data sets**	I	II	Total	III	IV	Rat. I/III	*p*MC
Number of fires (I)	Meteorological conditions (A_I)	0.17	0.09	26%	0.26	0.22	66%	< 0.05
"	Cause of ignition (B_I)	0.22	0.17	38%	0.24	0.22	90%	< 0.05
"	Present forest cover (C)	0.16	0.11	27%	0.30	0.20	54%	< 0.05
Area burned (II)	Meteorological conditions (A_{II})	0.20	0.08	28%	0.28	0.23	71%	< 0.05
"	Cause of ignition (B_{II})	0.21	0.10	31%	0.26	0.21	80%	< 0.05
"	Present forest cover (C)	0.17	0.04	21%	0.33	0.25	52%	< 0.05

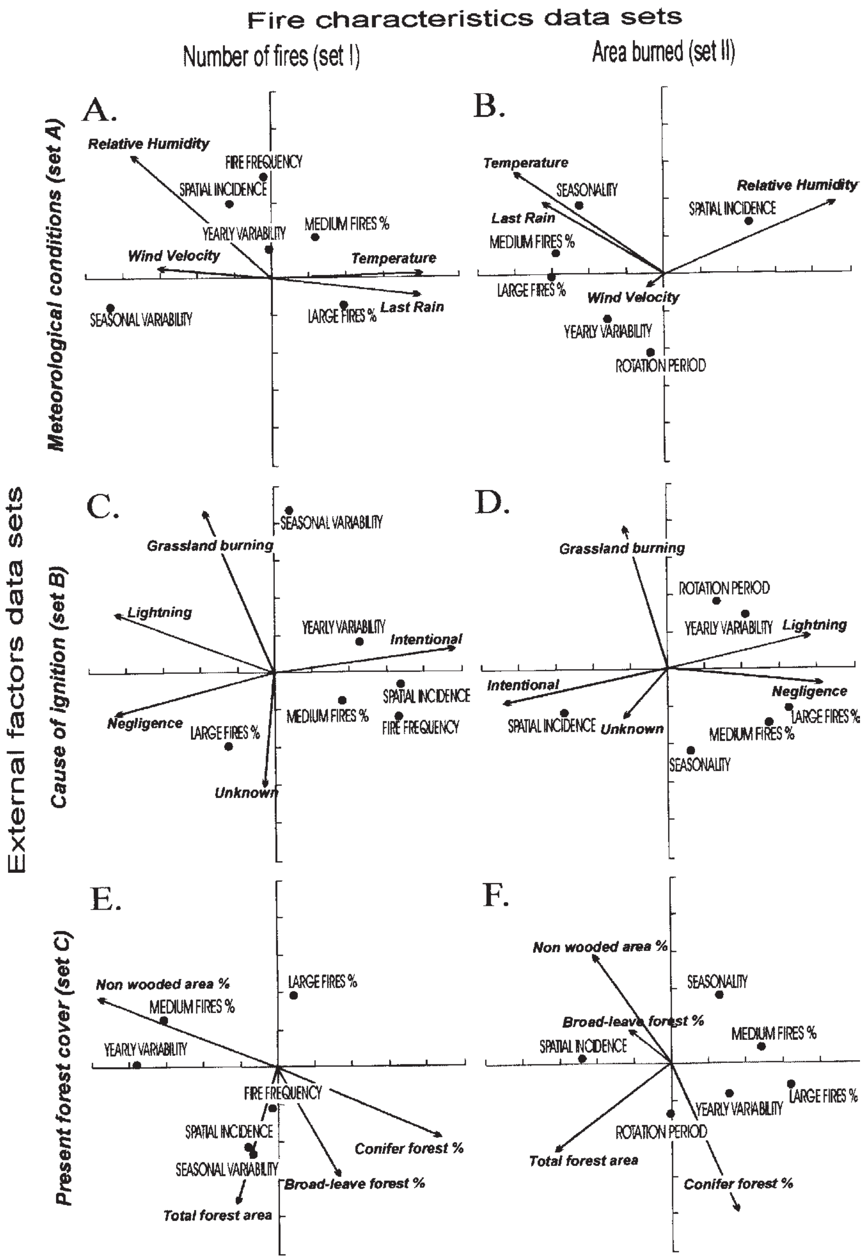

Fig. 3. Correlation biplots derived from RDA performed with the two fire characteristics data sets and the three data sets of external factors (displayed as vectors with labels in italics). **A.** Number of fires *vs.* Meteorological conditions; **B.** Area burned *vs.* Meteorological conditions; **C.** Number of fires *vs.* Cause of ignition; **D.** Area burned *vs.* Cause of ignition; **E.** Number of fires *vs.* Present forest cover; **F.** Area burned *vs.* Present forest cover. Labels and descriptions of the fire regime variables are shown in Table 3 and those of the external factors in Table 4.

Present forest cover (set C)

The relative importance of medium or large fires and the yearly variability in the number of fires was correlated with a high proportion of non-wooded forest cover (Fig. 3E). Fire frequency was not correlated with any of the external variables of this set. The relative proportion of large fires was negatively correlated with the proportion of total forest area. Fire rotation period exhibited low correlation with the proportions of total forest area or conifer forest cover (Fig. 3F). The proportion of total forest area showed moderate positive correlation with the spatial incidence of fires and of area burned, and negative with other fire variables. Some, such as the relative importance of area burned by large fires were, to some extent, related to a large proportion of conifer forests.

Discussion

Fire regime characteristics and PNV

The underlying hypothesis of our work was that territories with similar PNV should have similar fire characteristics based on the assumption that the process of identifying and mapping PNV units could adequately integrate several determinant factors of fire occurrence. Nevertheless, the persistence of natural vegetation in Spain is very variable. In some of them, due to agricultural uses, the forest cover represents a low proportion of the total area. Large areas of conifer forests characterize the territories of many PNV units considered to belong to broad-leaved forests, indicating the importance of human induced landscape changes or even in some cases, the controversial role of certain conifers in PNV definition (Blanco et al. 1997). These elements introduce important discrepancies between potential and present vegetation that have to be taken into consideration when making predictions about fire incidence in relation to climate and other conditions. An additional warning concerns the prevalence of human induced fires in Spain and the changing trends of country-wide dimensions recorded in the recent history of forest fires (Moreno et al. 1998).

The results obtained from the ordination analyses carried out with either of the sets of variables related to number of fires (I) or to area burned (II) have provided a clear and coherent segregation of the major PNV groups. The climatic conditions of the territories in which deciduous forests constitute the PNV units are among those conducive to lower fire danger. Nevertheless, the warmer and oceanic, highly productive territories of the *Q. robur* units showed a fire regime characterized by extremely high values of fire frequency and spatial incidence of fires. On the contrary, beech forest units of the same phytogeographical region, but located in colder and more humid mountain areas, presented a regime defined by infrequent and small fires, with high inter-annual and seasonal variability. Mediterranean deciduous PNV units (*Q. pyrenaica*, *Q. faginea*) which are mainly restricted to mountain areas with moderate summer drought, showed forest fires characteristics intermediate between the other deciduous forests and the sclerophyllous PNV units. The internal configuration of the group in the ordination space shows a gradient of decreasing fire frequency and spatial incidence and increasing fire rotation period, from the western and northwestern *Q. pyrenaica* units (climatically and geographically closer to *Q. robur* units) to the eastern Iberian *Q. faginea* units.

Typical Mediterranean PNV units belonging to sclerophyllous forests had variable characteristics, which is not surprising given their large geographic range. Yet they presented a clear trend towards higher incidence of fires of medium-large extent, together with a reduction of inter-annual and seasonal variability. The internal configuration of these major groups positioned the warmer and more productive PNV units at the extreme of this trend. The higher fire danger conditions of these territories, and the higher flammability of Mediterranean vegetation seems to be reflected in a more regular and seasonally concentrated fire regime, in which fire propagation is also favoured.

Despite their large ecological and geographical divergences, *Pinus*/*Abies*, *Juniperus* and *Q. coccifera* PNV major groups shared similar forest fire characteristics, defined by low fire frequencies and a great variability in the number of fires, area burned annually and time of burning. In the first group, the cold climatic conditions of the high mountain areas limit primary productivity, hence being unfavourable for fire occurrence. In the arid and warmer territories of *Q. coccifera* units the scarcity of rainfall is the limiting factor for productivity, hence for fuel accumulation. Finally, the territory of *Juniperus thurifera* forests combines cold winters and moderate rainfall throughout the year. All these units characterized by lower primary productivity were placed close together in the ordinations and close to the beech PNV units.

These results suggest a double gradient of fire regime characteristics of peninsular Spain, in which the higher fire incidence (higher fire frequencies, larger proportions of grid-cells affected by fire and lower proportions affected by large fires) is related to territories of higher productivity, which coincided with deciduous PNV types, while fire propagation (higher proportion of medium and large fires) is enhanced under warm and sufficiently humid Mediterranean climatic conditions. Both trends can reduce the fire rotation periods to similar values (Fig. 2B). Therefore, it appears that fire occurrence was not related to more favourable conditions for fire, as could be inferred from climatically related fire danger conditions, but rather to better conditions for plant growth. In general, primary productivity calculated on the basis of climatic models (Lieth & Whittaker 1975) is higher in the Eurosiberian region than in the Mediterranean region and, in general, decreases with elevation, except where a parallel water gradient occurs (Moreno unpubl.). This means that there is a control in the forest fire characteristics, even in humanized regions, associated with climatic conditions and hence the type of potential vegetation. The overlap between territories belonging to different PNV groups suggests that other factors have also played a role in recent fire regimes.

Fire regime characteristics and external factors

The RDA analyses constrained by meteorological variables (sets A_I-A_{II}) also points to the PCA results. The meteorological conditions promoting fire propagation were not associated with territories of higher fire frequency or greater spatial incidence of fires. The relative importance of medium or large fires was associated with more extreme meteorological conditions (low relative humidity, higher temperatures and longer period since last rain). Wind velocity was only important when other conditions were unfavourable for burning.

The external factors related to the cause of ignition (sets B_I-B_{II}) were best in explaining the variability in fire characteristics among PNV units. Higher fire frequencies, or shorter fire rotation periods, and a high spatial incidence of fires were related with territories with a large proportion of intentional fires. The relative importance of large fires was not strongly related with the different causes of ignition when it was expressed on the basis of the number of fires, but it did when it was expressed on the basis of the area burned. This implied that a high proportion of area burned by large fires was clearly related with areas in which the relative importance of lightning fires was higher. Lightning-caused fires were a small percentage (3.3%) of all fires but affected 7.5% of the total area burned. In addition, it should be noted that eight of the 21 very large fires (>10 000 ha) recorded during the study period were caused by lightning (Vázquez & Moreno 1998). Lightning and grassland burning seemed to be the main sources of ignition associated with PNV units which rarely burned.

Relationships between the present forest cover and fire characteristics were weaker and more complex, suggesting that they could operate at scales finer than those of PNV units. The proportion of broad-leaved forest cover is moderate in almost all PNV units and was the variable least related to the patterns of fire characteristics. Territories with high conifer forest cover are located mainly in the eastern Mediterranean areas of the country, in part of the *Q. robur* units and also in other low fire danger units; they were not strongly related with high fire frequency and were poorly related with higher rotation periods and the proportion of area burned by large fires. Non-wooded forest areas are mainly concentrated in Mediterranean PNV units, including semi-arid territories and were strongly related to the proportion of medium to large fires. The proportion of total forest cover was correlated with the spatial incidence of fires and seasonal variability. This proportion is larger in the northern PNV units and in mountain areas. Taking into account the patterns of variability of forested areas among PNV units, these results are consistent with the increasing spatial incidence of fires in Spain (Moreno et al. 1998). Forest fires have affected different tree species unequally. Among the fires that have affected wooded areas, only 14% have burned *Quercus* and other broad-leaved species, while conifer species were burned in 68% and *Eucalyptus* in 18% (Moreno et al. 1998). Moreover, forest fires that have affected only non-wooded areas represented 45% of the total number of fires during the study period.

In conclusion, significant relationships have been detected between fire regime characteristics and PNV units, but these did not coincide with what would be expected based on climate. The Spanish example indicates that when a region is under strong human pressure, assumptions about fire must acknowledge the role of man. Our results indicate that more productive areas burned more frequently and extensively, despite the fact that climatic conditions would not generally be as favourable for fire occurrence. The possible limitation for fire occurrence might be compensated by intentional fires. This caused these areas to be at the extreme in fire frequency and rotation, exposing them to an unusual fire regime. The long term impacts of such fires are unknown, but most probably represent a serious threat for maintaining the integrity of these ecosystems.

This study also documents the need to set specific fire management policies for different PNV territories. In Atlantic territories characterized by low fire danger but high fire occurrence the problems are conflicts among alternative land uses. In the Mediterranean areas the main focus should be on silvicultural practices to reduce fire hazard. In both cases, current afforestation policies resulting from the EU Common Agricultural Policy will not help to alleviate the increasing trends in fire incidence (Moreno et al. 1998) in the absence of accompanying measures adapted to the territorial peculiarities.

The group of PNV units characterized by low frequency and low spatial incidence of fires and long rotation periods were strongly associated with natural (lightning) or traditional land use (grassland burning) causes of ignition. Some of these units include conifer forests dominated by trees unable to regenerate adequately after severe crown fires, such as *Juniperus thurifera* (Blanco et al. 1997) and *Pinus sylvestris* (Herranz et al. 1996; Escudero et al. 1999). Similar behaviour is found in *Pinus nigra* ssp. *salzmannii* (Trabaud & Campant 1991), which forms pine forests mainly within the territory of some *Quercus faginea* PNV units and in *Abies pinsapo* (Arista et al. 1997), an endemic fir species not differentiated in our analyses due to its restricted distribution in southern Spain. As some of these forests are considered to be retreating their role in PNV is controversial. The fact that their main distribution appears to be linked to territories maintaining this particular fire regime is very important. Even though changes in fire regime have been evoked in the interpretation of past vegetation changes (Pons & Quézel 1985), their influence is not usually taken into account in PNV analysis but could have implications for the conservation of these forests.

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