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What causes large fires in Southern France

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ABSTRACT

In Southern France, where most wildfires occur, the fire size has never exceeded 6744 ha since 1991, whereas mega-fires have burned huge areas in other Mediterranean countries such as Spain and Portugal. It was interesting to find out what main factors drove the ignition of the largest fires that had occurred in this region of France.

The study was carried out using the forest fires database Prométhée that records all fires occurring in the 15 départements of Southern France since 1973. However, the records preceding 1997 are not reliable, only the 1997–2010 period was investigated.

Less than 1% of the fires ($N = 260$) recorded during this period were equal or larger than 100 ha whereas 78% of the fires were smaller than 1 ha. However these large fires accounted for 78% of the burned area and 66% of these fires occurred during the summer (July–August). The number of large fires and the burned area per year and per département were calculated and the proportions of fires causes were determined.

In each département, the impact of different explanatory variables (land-cover, topographic, climatic or socio-economic) on the number of large fires and on the size of the burned area was investigated using multivariate and regression analyses.

Results showed that high shrubland and pasture covers, high population and minor road densities as well as dryness in fall to spring were positively linked to the number of large fires whereas high forest cover, ruggedness, wetness in fall to spring were negatively linked to this parameter. High wildland vegetation cover, especially shrubland, wetness in fall–winter, dryness in summer during a long period, high unemployment rate and tourism pressure were positively linked to the burned area whereas wetness in summer, high farmland and pasture covers and high population density were negatively linked to this parameter. However, only shrubland cover and ruggedness were significant descriptors of both fire occurrence and burned area.

The départements the most affected by such fires were those situated in the eastern part of the region, on the Mediterranean coast and the main fire cause was arson.

1. Introduction

A 'large fire' has been considered to be one that has the potential to become very large (Viegas, 1998) or to attain a 'large' area, the size varying according to different works (Knapp, 1998; Shvidenko and Nilsson, 2000; Stocks et al., 2002). In the Mediterranean basin, large forest fires are becoming more and more frequent and are responsible for most of the overall area burned over the last 20 years as a consequence of global change (Piñol et al., 1998; Pausas, 2004). An understanding of the factors that govern the incidence and spread of large fires is therefore needed to support effective planning of fire mitigation and suppression, along with planning for ecological and urban interface management (Amiro et al., 2004). The incidence and size of fires are influenced by a range of factors, such as ignition sources, fuels, terrain, suppression forces and weather. In particular, weather is considered to have a significant influence on the incidence of large fires (Davis and Michaelsen, 1995; Gill and Moore, 1998; Moritz, 2003; Keeley, 2004; Peters et al., 2004). Contrary to other Mediterranean regions in the world, like South Africa (Polakow and Dunne, 1999; Kraaij, 2010), US California (Moritz et al., 2009) or SW Australia (O'Donnell et al., 2010), very few studies on large fires are available for Southern Europe (none in France) and they are usually focused on fire frequency studies (Vázquez and Moreno, 2001; Díaz-Delgado et al., 2004a; Oliveira et al., 2012).

The Southern region is the area the most affected by wildfires in France. It accounted for 55% of the total number of fires that had occurred in the country in 2010 according to the national forest fire database. However, since 1991, the maximum burned area, by a single fire event, has never exceeded 6744 ha; though larger fires

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(which can be called mega-fires) burned up to 11,580 ha in 1990 in this region (EU, 2011). In contrast, mega-fires burned huge areas in other Mediterranean countries such as Spain and Portugal (EU, 2011), especially in 2004 (up to 25,899 ha in Portugal and up to 2500 ha in Spain, each time, by a single fire event) and 2005 (up to 17,388 ha in Portugal and more than 12,000 ha in Spain), and the number of large fires (>100 ha or >500 ha depending on the works) represented less than 1% of the total number of fires (Moreno et al., 1998; Díaz-Delgado et al., 2004b; Pereira et al., 2005; De Zea Bermudez et al., 2009). Despite being few, most resulting damage was concentrated in those few, large fires. Thus it is very important to investigate the major events and their pattern in the region to improve our understanding of the driving forces behind them and to mitigate the adverse impacts of such wildfires. The aim of this study was to identify the main driving factors and causes of the large fires that had occurred in Southern France between 1997 and 2010, building upon previous work such as those of Catry et al. (2008, 2009) and Moreira et al. (2010). Identifying these factors will improve our ability to target resource protection efforts and manage fire risk at the landscape scale.

2. Material and methods

2.1. Study area

The study area was located in the southern part of France, which is composed of 15 administrative districts called "départements" of a total surface area of 7,951,500 ha (Fig. 1). This area presents different natures of bedrock including acidic soils in the most easterly part and limestone-derived soils located more to the West. The main fuel types on limestone soils are *Pinus halepensis* forests (Quézel, 2000) and mixed pine-oak forests, often the pre-forest vegetation type before oak forests (Quézel and Barbéro, 1992). With acidic soils, *Quercus suber* woodlands occupy the majority of the forested area, sometimes mixed with *Pinus pinaster* and with *Q. pubescens* in mature stands. More than 100,000 ha of the French Mediterranean region are occupied by shrubland either called "garrigue" on limestone-derived soils or "maquis" on acidic soils, which corresponds to the predominant successional stage after woodland degradation (Barbéro et al., 1998). Wildfires occur frequently in the whole area and overall, the study area is a mosaic of all the previously mentioned types of vegetation.

Our study area included a high elevation range, especially to the North (up to 4101 m). Mean annual precipitation ranged from 700 to 1000 l m^{-2} $year^{-1}$ and mean maximum temperature ranged from 18 to 23 °C from the North to the South of the study area.

2.2. Data description

2.2.1. Dependent variables

We compiled the regional forest fires database Prométhée (www.promethee.com) that records all the forest fires that had occurred in the 15 départements of the study area since 1973. However, the records before 1997 being not reliable, only the 1997–2010 period was investigated. We restricted our analyses to fires ⩾100 ha defined in our paper as "large fires". Among data available in the database, we used date of occurrence, place (département), burned area and fire causes for the analyses. The number of large fires and the burned area were taken into account as dependent variables in the statistical analyses.

2.2.2. Explanatory variables

The importance of land cover types that could burn (in percentage) were derived from the Corine land-cover database 2006. Five types were retained: forest, pasture, shrubland, wildland vegetation (taking into account the first three types of land-cover) and farmland (agricultural area).

The density of transportation networks (railways, main roads and minor roads) that could lead fires was calculated by the Joint Research Centre (Ispra, Italy) from the Tele Atlas database.

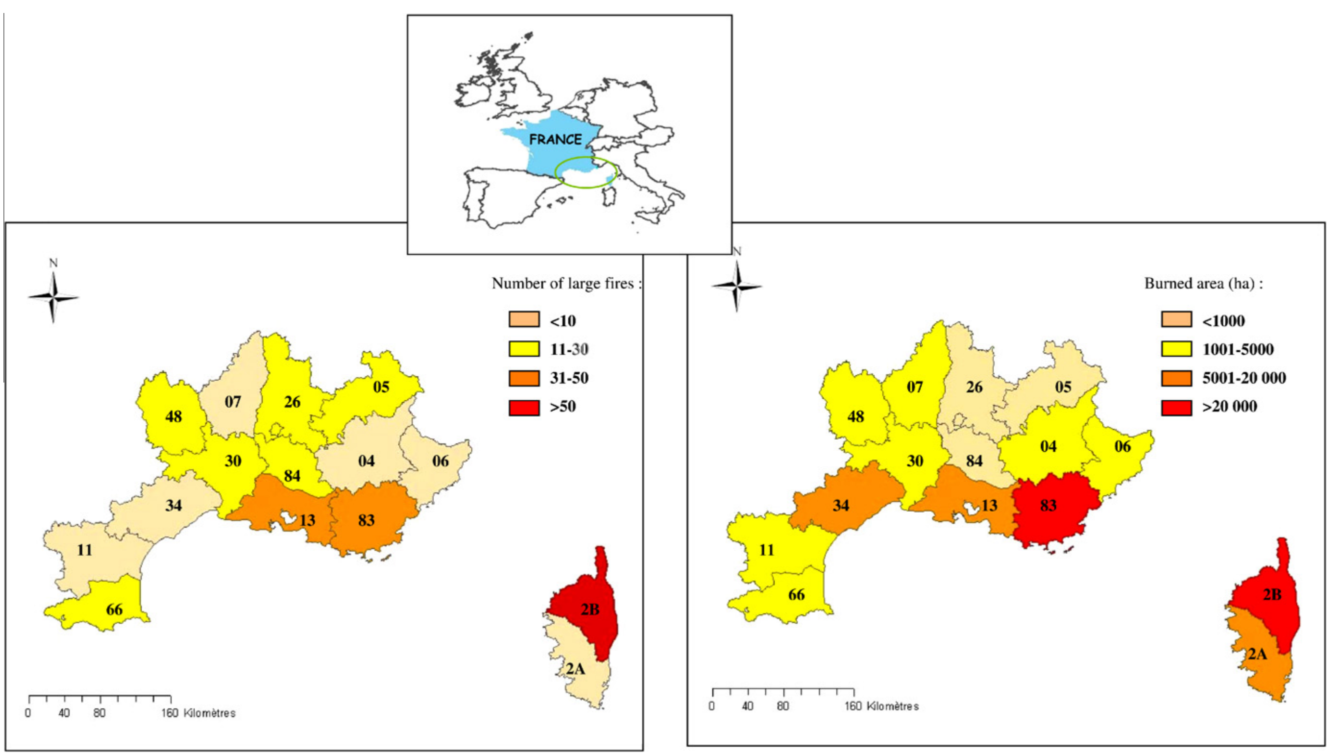

Fig. 1. Study area with number of large fires and burned area in each département during the 1997–2010 period (04: Alpes de Haute-Provence; 05: Hautes-Alpes, 06: Alpes-Maritimes, 07: Ardèche, 11: Aude, 13: Bouches du Rhône, 26: Drôme, 30: Gard, 34: Hérault, 48: Lozère, 66: Pyrénées Orientales, 83: Pyrénées Orientales, 83: Var, 2A: Corse du Sud, 2B: Haute Corse). *Source*: BD Carto® IGN 2003; Corine land-cover 2006; Regional forest fire database Prométhée (www.promethee.com).

The topographic variable was built from the global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds. This variable was the Topographic Ruggedness Index (TRI) developed by Riley et al. (1999) to express the amount of elevation difference between adjacent cells in a digital elevation grid. This index was recorded into four classes: the 0–10 m range represented a flat terrain surface, the 10–50 m range represented a slightly rugged surface, the 50–100 m represented an intermediately rugged surface and the values exceeding 100 m represented a high rugged surface. Only the latter class was taken into account in the analyses.

The climatic variables were built from the daily mean temperature and the daily precipitation amount per month from 1971 to 2000. They were derived from the European Climate Assessment and Dataset. Two climate variables were taken into account (i) the number of dry month calculated from the Gaussen index (Gaussen and Bagnouls, 1952) and a dry severity index per month calculated from the De Martonne method (De Martonne, 1926) for spring, summer and fall–winter; high index values meaning wetness. Other weather and fuel variables such as wind or fine fuel moisture content are also very important drivers of large fires, however, datasets regarding such variables were not available at the scale of the study area.

Three socio-economic variables were derived from Eurostat databases: (i) mean population density, (ii) mean unemployment rate and (iii) mean non-resident nights (tourism) for the period 1999–2008.

2.2.3. Statistical analyses

First, using Statgraphics Centurion XV software, comparisons of medians, using the non-parametric Wilcoxon–Mann–Whitney test, were performed on the dataset for each year to check if the number of large fires and the burned area varied significantly according to the year so that we could evaluate the independent influence of this factor. Then, two-way ANOVAs were performed to assess the impact of the year and of the fire cause on the occurrence of large fires and on their burned area. A significant relationship between the variables was assumed when the *p*-value was $\leqslant 0.05$. When the distribution of data did not follow the expected parametric pattern, data was log-transformed.

Co-inertia analysis (Dolédec and Chessel, 1994), fitted when a large number of variables compared with a small number of data, was performed on the dependent variables (number of large fires and burned area) and on the explanatory variables (climate, land-cover, network density, topographic, socio-economic) to examine associations between these two types of variables. The complete matrix of data was transferred to the statistical package under R 2.5.1 (R Development Core Team, 2005) then analyzed using the ADE-4 package (Thioulouse et al., 1997). The first step of the co-inertia analysis (Ter Braak and Schaffers, 2004) was to conduct a correspondence analysis on the dependent variables, then a principal component analysis on the explanatory variables. A factorial plane was thus created and enabled a new ordination of each data set. The statistical significance of each effect or combination of effects has been tested using the Monte-Carlo permutation test with 1000 permutations using the 'coin' package on R.

Partial Least Squares (PLSs) regression analysis was used to examine the influence of explanatory variables on the number of large fires and their burned area. The dependent variables were normalized using a logarithmic transformation prior to calculations and data was centered and scaled to unit variance to give all variables of the same relative importance. The significance of components for the models was determined by uncertainty tests carried out within a full cross-validation. PLS was carried out using Statgraphics Centurion XV software. Then, using *R* statistical packages, a bootstrap procedure (bootsize = 1000) was performed on the set of variables that presented the highest regression coefficients to rebuild the model, followed by a backwards elimination process was performed until all predictor variables in the model were significant with *P* values < 0.05..

3. Results

3.1. Fire occurrence

Between 1997 and 2010, 260 large fires ($\geqslant$100 ha) occurred in the study area that represented only 0.82% of the total number of fires recorded during this period (Table 1) whereas 72% of the fires

Table 1
Proportions of large fires and burned area in the study area during the 1997–2010 period.

Id	Département	Large fires (%)	Area burned by large fires (%)
4	Alpes de Haute-Provence	1.52	62.58
5	Hautes-Alpes	0.83	42.17
6	Alpes-Maritimes	0.59	38.96
7	Ardèche	0.51	50.02
11	Aude	0.99	62.09
13	Bouches du Rhône	1.13	93.68
26	Drôme	0.21	10.59
30	Gard	0.70	35.78
34	Hérault	0.74	82.50
48	Lozère	0.81	71.29
66	Pyrénées Orientales	0.88	63.45
83	Var	0.77	90.98
84	Vaucluse	0.57	42.41
2A	Corse du sud	0.45	105.49
2B	Corse du nord	1.18	79.51
	Total study area	0.82	77.58

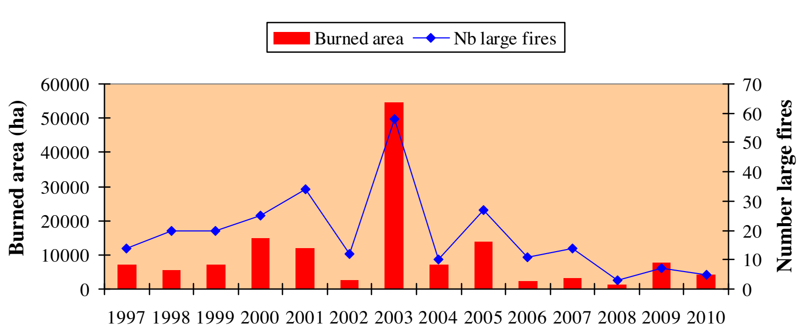

Fig. 2. Mean number and mean area burned by large fires between 1997 and 2010 in Southern France. *Source*: Regional forest fire database Prométhée (www.promethee.com).

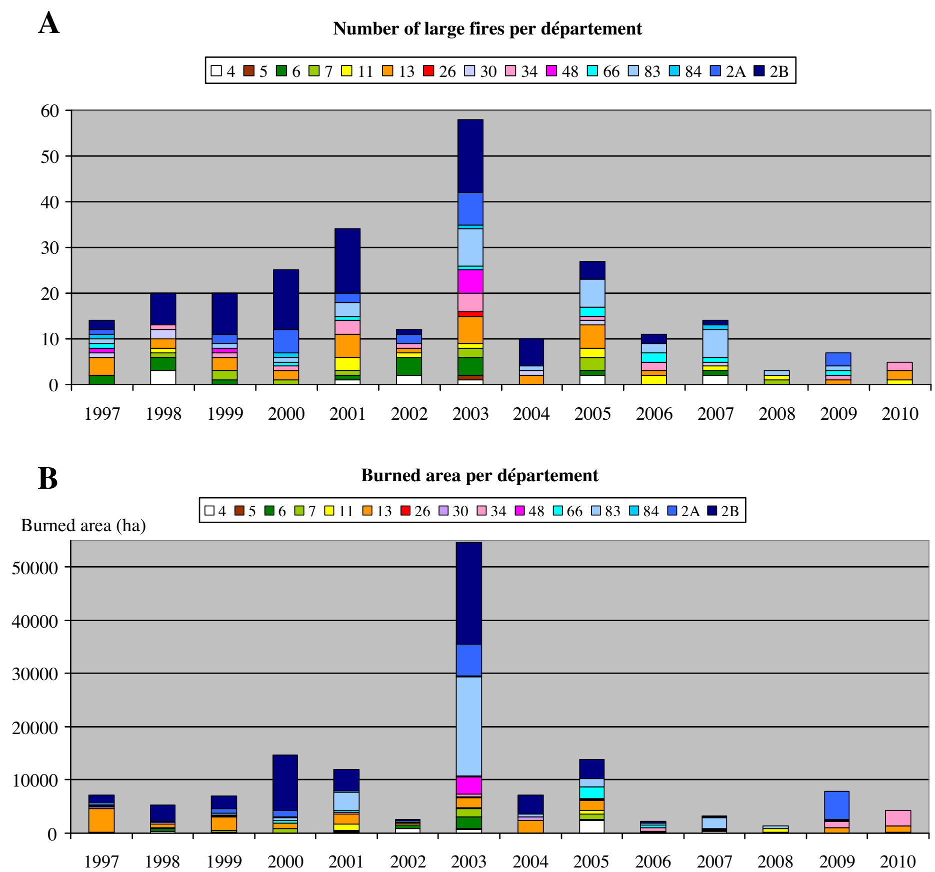

Fig. 3. Mean number of large fires (A) and mean burned area (B) per département and per year between 1997and 2010 (04: Alpes de Haute-Provence; 05: Hautes-Alpes, 06: Alpes-Maritimes, 07: Ardèche, 11: Aude, 13: Bouches du Rhône, 26: Drôme, 30: Gard, 34: Hérault, 48: Lozère, 66: Pyrénées Orientales, 83: Pyrénées Orientales, 83: Var, 2A: Corse du Sud, 2B: Haute Corse). *Source*: Regional forest fire database Prométhée (www.promethee.com).

were smaller than 1 ha. However these large fires accounted for 78% of the burned area (143,140 ha; Table 1) and 66% of these fires occurred during the summer (July–August). The highest number of these fires occurred during summer 2003 ($N = 58$) and burned 54,682 ha. The year 2003 corresponded to the largest area burned by this type of fire compared to other years (54,682 ha *vs* <15,000 ha/year the other years) (Fig. 2). Results of the comparisons of medians showed that the year 2003 had a significant impact on the occurrence of large fires and on the burned area (KW = 37.31, $p = 0.0004$ and KW = 32.43, $p = 0.002$, respectively). This result was confirmed by the two-way ANOVA performed on the number of large fires taking into account the factors "year" and "fire cause" ($F = 2.61$, $p = 0.007$; $F = 3.14$, $p = 0.002$).

The highest proportions of large fires and of burned area occurred in four départements (Haute Corse, Corse du Sud, Bouches du Rhône and Var) of the study area (Fig. 3A and B), with more than 20 large fires and burned area >14,000 ha. These départements are located on the eastern part of the Mediterranean coast where the tourism pressure is high in summer (South-Eastern départements). On the contrary, only one large fire occurred in both départements Hautes-Alpes (in July 2003) and Drôme (in June 2003) (Fig. 3A); which are located in the northern part of the study area (Fig. 1).

3.2. Fire causes

The proportion of large fire causes in the study, according to the size of the fire, is presented in Fig. 4. Arson was the most frequent cause (42% on average, Fig. 4A), especially pyromania (in most départements) and conflict/interest due to hunters, shepherds

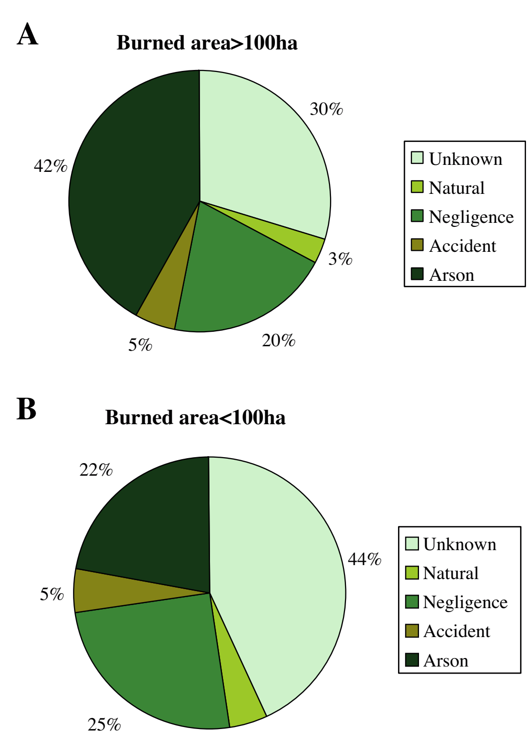

Fig. 4. Proportion of fire causes for large fire (A) and smaller fires (B) in Southern France. *Source*: Regional forest fire database Prométhée (www.promethee.com).

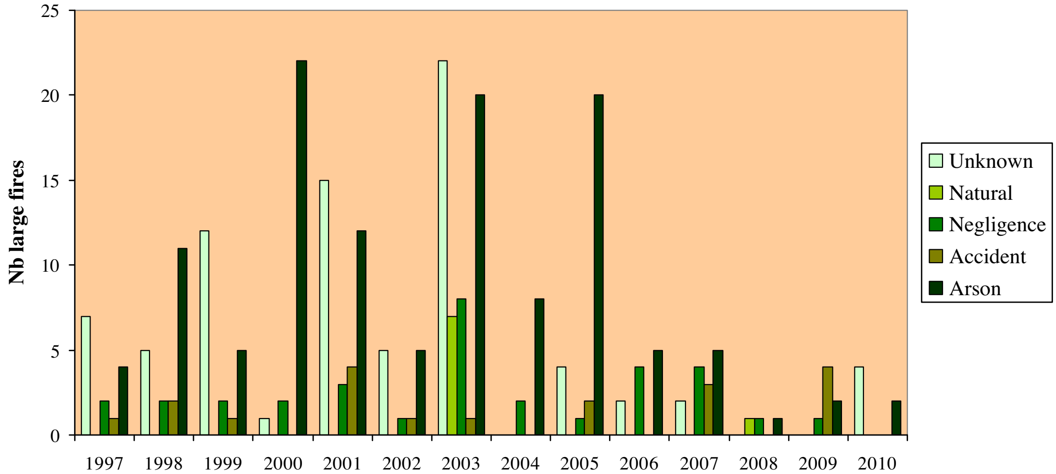

Fig. 5. Variation of the number of large fires according to the causes between 1997 and 2010 in Southern France. *Source*: Regional forest fire database Prométhée (http://www.promethee.com).

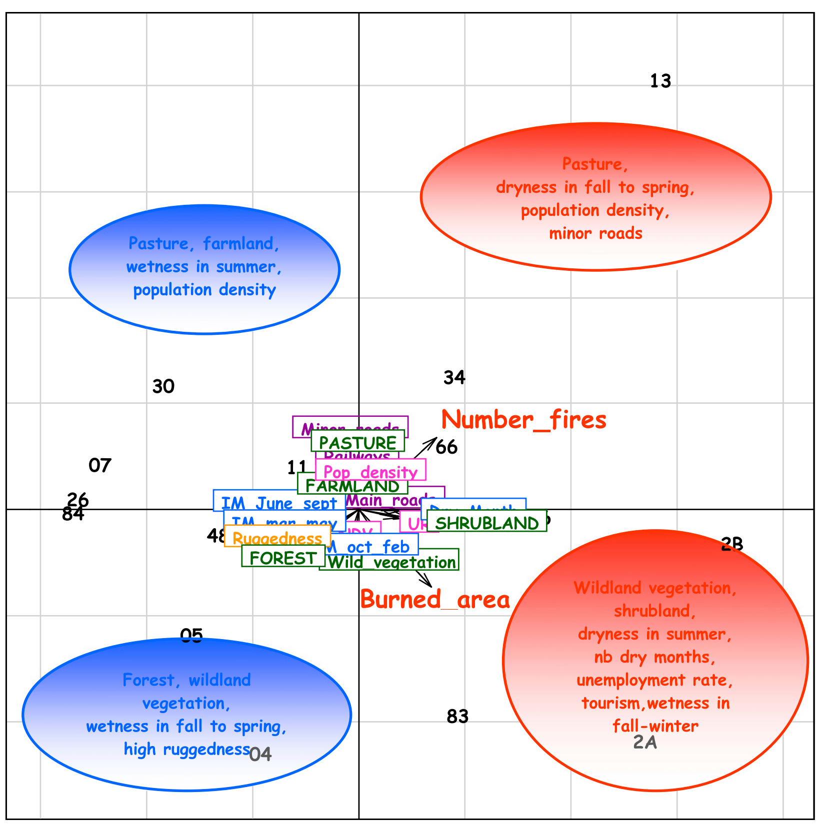

Fig. 6. Co-inertia analysis showing the impact of climate, land-cover topographic and socio-economic variables on the number of fires and on the size of burned area in Southern France). Positions of départements, dependent and explanatory variables on the F1 × F2 co-inertia plane. (IM: De Martonne Index, UR: unemployment rate, NRV: tourism, Pop: population, 04: Alpes de Haute-Provence; 05: Hautes-Alpes, 06: Alpes-Maritimes, 07: Ardèche, 11: Aude, 13: Bouches du Rhône, 26: Drôme, 30: Gard, 34: Hérault, 48: Lozère, 66: Pyrénées Orientales, 83: Pyrénées Orientales, 83: Var, 2A: Corse du Sud, 2B: Haute Corse).

and real estate). In contrast, negligence was the most frequent cause for fires smaller than 100 ha (Fig. 4B). Knowledge of fire causes varied within the study area (poor in the départements Alpes-Maritimes, Drôme and Haute Corse) and accounted for 30% of the occurrences. Negligence was the main cause of large fires only in two départements (Hautes-Alpes and Lozère), averaging 20% for the study area whereas accidental and natural causes were not frequent (respectively 5% and 3% on average).

The variation of the number of large fires according to the cause, between 1997 and 2010, is presented in Fig. 5. Arson remained the main large fire cause during almost the whole period. The number of large fires due to unknown cause tended to decrease during this

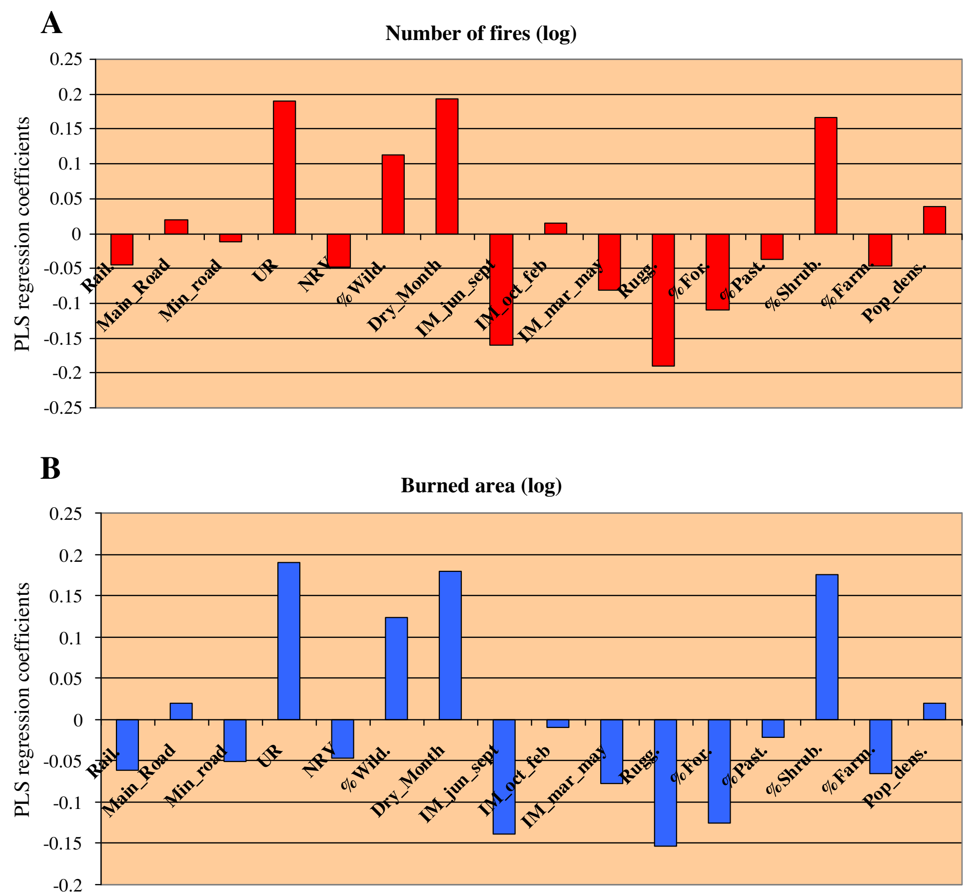

Fig. 7. Significant predictor variables resulting from a Partial Least Squares (PLSs) regression analysis carried out with the number of large fires (A) and the burned area (B). Abreviations of variables: Rail.: Railway density * 1000; Main_Road: Main road density * 1000; Min_Road: Minor road density * 1000; UR: Unemployment rate; NRV: Tourism; %Wild.: % Wildland vegetation; %For.: % Forest; %Past.: % Pasture; %Shrub.: % Shrubland; %Farm.: % Farmland; IM: De Martonne Index; Rugg.: Ruggedness; Pop_dens.: Population density.

period while the number of large fires due to negligence and accident remained quite constant. Large fires due to natural cause remained infrequent between 1997 and 2008, with a small peak in 2003 (seven lightning-caused fires).

The two-way ANOVA performed on the number of large fires and on their burned area, taking into account the factors "year" and "fire cause" showed that there was a significant variation of the number of large fires and of the burned area according to the cause ($F = 10.28$, $p < 0.0001$; $F = 3.99$, $p = 0.007$). The number of large fires due to arson ($N = 8.71$) was significantly the highest and occurrence of large fires due to unknown causes ($N = 5.64$) was significantly higher than that of large fires due to negligence ($N = 2.36$), accident ($N = 1.36$) and lightning ($N = 0.57$). Even though they occurred infrequently, large fires caused by lightning burned large areas up to 1346 ha in four départements (Alpes-Maritimes, Ardèche, Var and Corse du Sud). The burned area was significantly larger when the fire cause was arson (4908.3 ha).

3.3. Determination of the main driving factors

In each département, the impact of the different explanatory variables on the number of large fires and on the size of burned area was investigated using multivariate analysis (co-inertia analysis). Results showed that high pasture and shrubland covers, high population, minor road and railway densities as well as dryness in fall to spring (low Dry Severity Index according to the de Martonne method, IM, in October–February and March–May) and high unemployment rate, which characterized especially the département Bouches du Rhône (located on the South of the study area), were positively linked to the occurrence of large fires. In contrast, high wildland vegetation cover, especially forest cover, wetness in fall to spring (high IM, in October–February and March–May) and high ruggedness, which characterized the mountainous départements Alpes de Haute-Provence and Hautes-Alpes (located to the North-East of the study area), were negatively linked to this parameter. High wildland vegetation cover, especially shrubland, wetness in fall–winter (high IM in October–February) as well as dryness in summer (low IM in June–September), high number of dry months, high unemployment rate and tourism pressure, which characterized the départements Var, Haute-Corse and Corse du Sud (located in the South of the study area), were positively linked to the size of the burned area whereas high farmland and pasture covers, high population density and wetness in summer (high IM in June–September), which characterized especially the département Drôme (located on the North of the study area), were negatively linked to this parameter (Fig. 6).

After Partial Least Squares regressions, including the dataset of explanatory variables according to the number of large fires (2 components, $p < 0.001$, $R^2 = 59.85\%$) and the size of the burned area (2 components, $p < 0.001$, $R^2 = 60.79\%$), both dependent variables

Table 2
Regression coefficients of the significant explanatory variables (PLS model with two components with bootstrap procedure).

	0.1%	1%	5%	95%	99%	99.9%	BootSize	*P*-value
Dependent variable: Number of fires								
Ruggedness	−0.8587	−0.7755	−0.6747	−0.2089	−0.1064	−0.0037	1000	***
Shrubland cover	0.3318	0.4089	0.5348	0.8711	0.9736	1.0584	1000	***
Dependent variable: Burned area								
Ruggedness	−0.8016	−0.6726	−0.5844	−0.1314	−0.0217	−0.0962	1000	**
Shrubland cover	0.009	0.2747	0.4321	0.8572	0.9479	1.0332	1000	***

were positively correlated with unemployment rate, number of dry months and wildland vegetation and shrubland covers. These variables were also negatively correlated with IM June–September, ruggedness and forest cover (Fig. 7). After the bootstrap procedure, only the explanatory variables ruggedness and shrubland cover remained significant predictors of the occurrence of large fires and of the size of the burned area (Table 2).

4. Discussion

4.1. Fire occurrence and fire causes

During the 1997–2010 period, large fires mainly occurred in the eastern part of Southern France, especially in the départements located on the Mediterranean coast. The year 2003 was very severe in terms of drought and accounted for the largest burned area and the highest fire occurrence. This same year, there was also an exceptional fire season in Portugal (Trigo et al., 2006; Pereira et al., 2005).

In the study area, the occurrence of large fires represented less than 1% of the total number of fires but the area burned by these fires represented more than 70% of the total burned area for the period investigated. This trend has already been highlighted in other Mediterranean countries and elsewhere in the world (Strauss et al., 1989; Knapp, 1998; Moreno et al., 1998; Niklasson and Granström, 2000; Stocks et al., 2002; Díaz-Delgado et al., 2004b; Pereira et al., 2005; De Zea Bermudez et al., 2009).

At spatial level, the relationship between occurrence and burned area varied between départements during the period investigated. For instance, départements can be very affected by large fires regarding both occurrence and size of the burned area like in Haute-Corse ($N = 75$ and 48,000 ha burned), or can be affected more regarding occurrence than burned area (Bouches du Rhône) or more regarding burned area than occurrence (Var). The large burned area occurred in départements where the proportion of wildland vegetation (often shrubland and pasture) was high and smaller areas affected by large fires in the Bouches du Rhône, compared to the département Var, could be explained by the structure of the wildland area which forms narrow strips oriented perpendicular to the dominant wind (Mistral).

Although the current land-cover and population density change trends are increasing the likelihood of fire ignitions resulting in large fires, the analysis of the database Prométhée did not suggest an increasing trend in the number of fires $\geqslant$100 ha in the study area but in contrast, showed a decrease since 2004 (except a peak in 2005) and especially after 2007. The same trend was observed by De Zea Bermudez et al. (2009) in Portugal and a cyclic behavior of extreme fire sizes was suggested by several authors such as Moreira et al. (2010). The absence of a long severe drought period since that of 2003 could possibly explain this trend.

Regarding the causes of large fires during the period investigated, the proportion of unknown causes was high till 2003 then decreased a lot since then, with the improvement of the knowledge of fire causes thanks to efficient investigations. Arson was the main known cause in the study area, especially in 2000, 2003 and 2005 during which fire weather conditions were the most severe. Mees (1991) also found that, during such conditions, fires set by arsonists tended to burn large areas in Southern California, and the number of fires set appeared to be larger. This could explain the difference of main cause we found between large fires (arson) and smaller fires (negligence). Large fires caused by lightning were rare in Southern France contrary to what happened in the South-Western USA that had experienced wildland fires of relatively unprecedented size and severity especially in 2000 and 2002 (USDA Forest Service, 2004; Stephens, 2005; Dickson et al., 2006).

4.2. Main driving factors

Increased fuel accumulation and connectivity as well as more frequent extreme weather events were thought to have promoted an increased in large fires in the Western Mediterranean basin over the last decades (Díaz-Delgado et al., 2004b). The synergistic effect of fuel and weather also explained the occurrence of large and catastrophic wildfires in other countries such as Greece (Koutsias et al., 2012). In our work, regression analyses showed that the main driving factors of the occurrence of large fires were the same as those of the size of burned area (shrubland cover and ruggedness). According to our analyses, high forest cover was a land-cover variable negatively linked to the occurrence of these fires contrary to several works carried out in Southern Europe which revealed that ignitions resulting in large burned areas were more likely to occur in shrubland and forest areas (Catry et al., 2008; Bajocco and Ricotta, 2008; Pezzatti et al., 2009; Moreira et al., 2010; De Angelis et al., 2012). According to Dickson et al. (2006), wildland vegetation was not an important predictor for the probability of occurrence and Nunes et al. (2005) showed that small fires exhibited stronger land-cover preferences than large fires. In our study, the shrubland cover was positively correlated to both the number of large fires and the burned area, and the high proportion of large fires set by shepherds or hunters could explain why the land-cover type was targeted.

From a bioclimatic point of view, shrubland and pasture are adapted to dry climate conditions and our results showed that ignitions resulting in large burned areas were more likely to occur during a drought period, especially in summer, like that of 2003. This is consistent with several works carried out in Northern America (Allen, 2002; Baker, 2003; Schoennagel et al., 2004), in Australia (Cunningham, 1984; Gill, 1984) and in other countries of Southern Europe (Viegas et al., 1992; Pereira et al., 2005; Hoinka et al., 2009; Dimitrakopoulos et al., 2011). Moreover, extreme fire weather is usually expected to prevail over the effect of fuel on fire spread (Fernandes and Botelho, 2003; Moritz, 2003; Keeley and Zedler, 2009). In Southern France, wetness in fall–winter and dryness in summer during a long period (high number of dry months) were the climatic factors that were positively linked to the size of burned area. Indeed, research has shown that timing and the amount of precipitation each year, especially in months before the fire season, can have a strong influence on subsequent fire activity (Davis and Michaelsen, 1995; Westerling et al., 2003), usually attributed to the accumulation and drying patterns of herbaceous fine fuels that could propagate fires. Wind also appeared to be an important factor, especially for the burned area in the South-West USA and in Southern California (Cohen and Miller, 1978; Schoennagel et al., 2004; Keeley, 2004). Unfortunately, this factor could not be taken into account in our analysis but strong dry winds (Mistral and Tramontane) frequently blow in the départements which are the most affected by large fires.

Results of PLS regressions showed that ruggedness was one of the most significant variables negatively affecting either fire occurrence and burned area. In our study, this variable was only positively linked to mountainous départements mainly located in the North of the study area where the occurrence and size of large fires were low (Alpes de Haute-Provence, Hautes-Alpes, Lozère), mainly because of the wetter climatic conditions. In contrast, several works showed that the probability of occurrence of large fires was greatest in areas of high topographic roughness which could facilitate fire occurrence and behavior and limit the access for fire fighting (Guyette and Dey, 2000; Dickson et al., 2006).

In our work, network variables and population density were positively linked to the occurrence of fire; however none of these variables were significant predictors of the number of fires or burned area. Human-caused ignitions frequently occur along transportation corridors (Keeley et al., 2004; Stephens, 2005), so it was surprising that our network variables were not significantly explaining at least the occurrence of large fires. However, as notified by Syphard et al. (2007), detecting the influence of such variables on fire ignition may be difficult at the level of the study area since they are narrow, linear features. Other works revealed that large fires were inversely related to population density, and were more likely to occur farther away from roads (Dickson et al., 2006; Catry et al., 2008; Moreira et al., 2010; De Angelis et al., 2012). These different results could be explained by the cause of these fires. Indeed, in the works of Dickson et al. (2006) and of Cardille et al. (2001), the large fires were caused by lightning and occurred in areas with low road density, far away from populated areas while in our study, the main cause was human (arson) and fires often set along minor roads. Most works did not detail the type of transportation network as we did in the current study but they showed that human-caused fires were more likely to occur in areas of high road density improving access to remote forested locations (Swetnam, 1990; Cardille et al., 2001; DellaSala and Frost, 2001), and near those roads (Chou et al., 1993).

Our statistical analyses showed that the socio-economic variables, especially unemployment rate, but also tourism, were positively linked mainly to the size of area burned by large fires (although these variables were not significant predictors of occurrence or burned area according to the PLS regressions). Indeed, the most affected départements were located in the East of the region (Corsica, Var and Bouches du Rhône), on the Mediterranean coast, where the tourism pressure was the highest, especially in summer. These results were consistent with the main motives of arson found on our study area (pyromania and conflict/interest due to real estate for instance). The unemployment rate has been clearly proven to be related to the occurrence of fires, regardless of their size, in several Mediterranean countries (Ferreira de Almeida and Vilacae-Moura, 1992; Chuvieco et al., 1999; Sebastián-López et al., 2008).

4.3. Management and research implications

Management could help to diminish future increases in fire risk due to climate change (Christensen et al., 2007) or socioeconomic change (Syphard et al., 2008) and forest fuel reduction could be important in managing the threat of fire for communities and resources (Covington, 2000). Our results suggested that treatments intended to reduce fire threat around communities should first target areas along minor roads bordering shrubland and pasture areas, thus providing a fuel break in areas where fires are more likely to ignite and to spread. Often, fuel loadings were the only characteristics taken into account when planning management actions to reduce fire threat. However, fires require not only fuel, but ignition sources and conditions that promote fire spread. While fuel reduction is important in managing fire risk, treatments designed for this purpose may do little to reduce fire threat if they are not strategically placed in or around areas where large fire events are most likely to occur. Our results showed that arson was the main cause of large fires (⩾100 ha) in Southern France contrary to smaller fires mainly due to negligence. As arsonists are thought to be primarily active during periods of severe fire danger, current prevention measures should tend to be designed to prevent arson and to meet the arsonist during these times. Targeting the arsonist at almost all levels of fire danger may help identify and discourage some of these individuals (Mees, 1991). Furthermore, the whole study area must be concerned by these measures because the area with the highest fire risk will probably shift toward the North with the global change (Piñol et al., 1998; Brown et al., 2004; Millar et al., 2007).

5. Conclusions

During the 1997–2010 period, large fires (⩾100 ha) affected 78% of the total burned area and represented nearly 1% of the total number of fires that had occurred in Southern France. These fires mainly occurred during periods of drought in populated areas that were characterized by high pasture and shrubland covers as well as high density of minor roads. The size of burned area mainly depended on wildland vegetation, especially shrubland covers, long dryness in summer, wetness between fall and spring as well as the unemployment rate and tourism pressure. However, shrubland cover and ruggedness were the only significant predictors of occurrence and burned area, the latter predictor being negatively correlated to the dependent variables. The most affected départements were located in the East of the region, on the Mediterranean coast (a lot of tourism in summer) and the main fire cause was arson (especially pyromania and conflict/interest due to hunters, shepherds and real estate). However, with the global change, the départements located in the North of the region will be more and more affected by large fires. Therefore, more management of fire risk and of fire prevention planning will be needed in this part of the study area.

Predicting the incidence of large fires and managing their impact will be especially important if global warming and other social drivers of change increase the likelihood of large fires. Human activity will continue to affect the nature of global fire regimes, including the incidence of large fires, as the climate changes. Weather, fuels and topography are the greatest influences on the fire environment and Mediterranean biomes have one of the most complex mixtures of these three factors. Although fuel reduction may help in some locations and circumstances, the severity of large fires in the region poses serious challenges. The expansion of the WUI in the study area exacerbates an already difficult situation. The French Mediterranean area presents one of the most flammable and fire-adapted ecosystems but also one of the largest and fastest growing populations in France. In this region, further research into the fire environment and its unavoidable connection with human activities is of utmost importance, as already highlighted by Blodgett et al. (2010).

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