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Explaining the spatio-seasonal variation of fires by their causes: the case of southeastern France

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Highlights:

- The spatial and seasonal variation of fire metrics could be due to the spatial and seasonal variation of fire causes.
- Undetermined arson and negligence during agricultural work which had a strong impact on both fire metrics were the most deleterious causes in the study area.
- Some causes showed a strong seasonal pattern due to the seasonality of the practices.
- In the whole study area, knowledge of fire causes was poor and the high contribution of unknown causes to the total burned area underlined the necessity to improve this knowledge.

1 Introduction

In France, the South-East is the region the most affected by wildfires (on average 65% of the total occurrence in France during the past decades according to EC 2016, and up to 80% in 2003 according to EC 2004). Large fires (size ≥ 100ha) which were mostly deliberate summer fires represented less than 1% of the total occurrence, but were responsible for more than 70% of the total burned area (Ganteaume and Jappiot 2013). However, according to these authors, the entire area was not affected in the same way, as its southeasternmost part concentrated the highest occurrence and the largest area burned by large fires. In SE France, according to the climate change, a shift in fire occurrence and fire size may occur, especially in the northern part of the region which currently presents less severe climate conditions; thus, is less impacted by fires.

During the last decades, in most Mediterranean regions, the increase in wildland-urban interfaces (WUI) has led to an increase in the number of ignitions, which were mostly human-caused (Keeley and Fotheringham 2001; Prestemon *et al.* 2002; Badia-Perpinyá and Pallares-Barbera 2006; Romero-Calcerrada *et al.* 2008; Syphard *et al.* 2008). This trend has also been identified in SE France (Lampin-Maillet *et al.* 2010) and WUIs have been highlighted to be a significant explanatory factor of fire density at the local scale in this area (Ganteaume and Long-Fournel 2015). This part of France is also highly populated and characterized by a high tourist pressure, especially in summer, making this region a highly sensitive area.

With the increasing fire issue, fire policy and management mainly focus on fire suppression, but also on fire prevention. Accordingly, since the past decades, investigations on fire causes have been more and more developed (with varying levels of efficiency according to the region or country) to further improve prevention. Most previous works focused on the identification of the main driving factors of fire occurrence, density, or spread in the Mediterranean basin (i.e. Catry *et al.* 2009; Koutsias *et al.* 2012; Diaz-Delgado *et al.* 2004; Penman *et al.* 2013, 2014; Ganteaume and Jappiot 2013; Ganteaume and Long-Fournel 2015). Some works linked causes and spatial and/or temporal analysis of ignitions (Genton *et al.* 2006), or hotspot of ignitions (Bar-Massada *et al.* 2012; Gonzalez-Olabarria *et al.* 2012) according to their environment (Stephens 2005; Penman *et al.* 2013, Syphard and Keeley 2015). However, most works did not differentiate the fire causes responsible for larger burned area and for higher occurrence (which may not be the same), nor investigate in depth the spatial and seasonal variation of these fire metrics according to the causes, as did the current work. Besides, the novelty in this work was to present the effects of interactions between regions, seasons and fire causes on the number of fires and their burned area. Moreover, working on the detailed nature of fire causes (and not just on the main classes, i.e. natural, negligence, and arson), especially those related to deliberate fires, was an added-value to this contribution.

Given the gaps previously identified, our main objectives were to determine and to better understand (i) how the fire metrics varied within SE France, in identifying different regions that showed the same trends of environmental and socio-economic characteristics, (ii) a possible spatial and seasonal variation of the main fire causes that could correspond to the variation of the fire metrics, and (iii) which causes were more deleterious (in terms of burned area) but, also, in some cases, which ones could be easily mitigated. Achieving these goals will help to more accurately target fire prevention in the SE part of France.

2 Material and methods

2.1 Study area

The study area was located in the southeastern part of France which is composed of 15 administrative districts, called “départements”, that represent a total surface area of 7,951,500 ha (Fig 1). Some of them are frequently subjected to wildfires. The cover of the different flammable fuel types varies within the study area (15 to 70% of forests and shrublands, for instance), mainly according to the nature of the bedrock (acidic soils located in the most easterly part as well as in the mountains, and limestone-derived soils located more to the West) and to the altitude. Mostly, in the study area, the fire regime, especially the fire recurrence, helped form a mosaic of different types of flammable vegetation.

The study area covers a large gradient of elevation from sea level to the subalpine ecosystems of the French Southern Alps (ca. 2500 m asl, up to 4101m). 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. The southern part of the study area, along the Mediterranean Sea, has a typical Mediterranean climate, characterized by hot and dry summers, often windy, which favors fire activity. The peri-Mediterranean area has a supra-Mediterranean climate, characterized by hot summer temperatures but cold winters, whereas the mountain climate of the French Alps is typically cold in winter and cool in summer.

2.2 Data description

2.2.1 Descriptive factors

Five types of descriptive factors of each “département” were taken into account to highlight different regions composed of “départements” that presented same trends in socio-environmental characteristics:

(i) Land cover: The proportions of land cover types (in percentage) in each “département” were derived from the Corine land cover database 2006. Four types were compiled from the classes that could be involved in wildfires: forests (For), grasslands (Grass), shrublands (Shrub), and agricultural lands (Agri).

(ii) The densities of networks - roads and railways - were calculated by the Joint Research Centre (Ispra, Italy), from the Tele Atlas database. Regarding road density, only minor roads (R2_D) were taken into account in the analyses because most fires occurred along this type of road (Ganteaume and Long-Fournel 2015).

(iii) The climate variables, derived from the European Climate Assessment and Dataset, were built from the daily mean temperature and the daily precipitation amount per month since 1971. Two climate variables were taken into account: the number of dry months (Dry_Mth) calculated from the Gaussen index (Gaussen and Bagnouls 1952), and a dry severity index (DSI) calculated from the De Martonne method (De Martonne 1926) for spring, summer, and fall-winter; high index values indicated wetness.

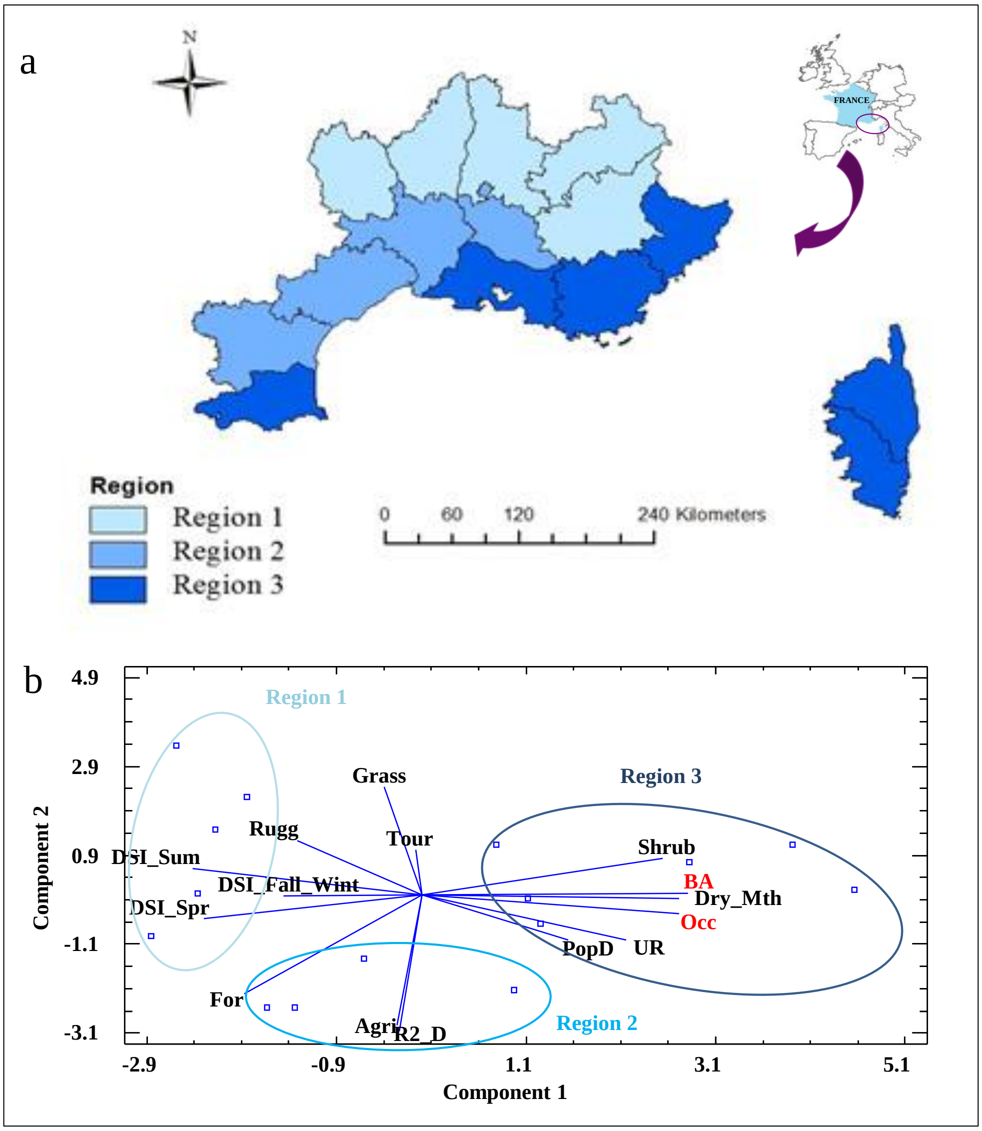


Figure 1: Map of the study area (southeastern France) showing the three regions (i.e. clusters) highlighted by Hierarchical Cluster Analyis (a) and their characteristics identified by Principal Component Analysis (b).

DSI: dry severity index, Sum: summer, Spr: spring, Wint: winter, Grass: grassland, For: forest, Agri: agicultural land, Shrub: shrubland, Rugg: ruggedness, Tour: tourist pressure, R2_D: density of secondary roads, Dry_Mth: number of dry month, PopD: population density, BA: burned area, Occ: fire occurrence. BD Carto®.

(iv) The topographic variable was built from the global digital elevation model with a horizontal grid spacing of 30 arc seconds. This variable was the Topographic Ruggedness Index (Rugg) developed by Riley *et al.* (1999) to express the amount of elevation difference between adjacent cells of a digital elevation grid. In this work, only the index that corresponded to the most rugged terrain was used to characterize mountainous areas.

(v) Three socio-economic variables were derived from Eurostat databases: the mean population density (PopD, number of inhabitant per km^2), the mean unemployment rate (UR, %) and the mean number of overnight hotel stays used as a proxy for tourist pressure (Tour).

2.2.2 Fire metrics

In the current work, fire data come from the regional fire database Prométhée (www. promethee.com) that has recorded all wildfires that have occurred in the 15 "départements" of SE France, since 1973. Among the data available during the period 1973-2015, we compiled, for each ignition, the date (to determine at what season the ignition occurred) and place (to determine in which "département" the ignition occurred), the burned area, as well as the level of certainty (known and unknown) and the nature (when it was known) of the fire cause. In this database, fire ignitions are located on the basis of a 2km*2km grid reference (used by the firefighting services for approximating the location of the fire event); this georeferencing system was used for the GIS analyses.

The total number of fires (defined as the fire occurrence) and the total burned area recorded in each "département" during the 1973-2015 period were taken into account as dependent variables in the statistical analyses. Fires were also analyzed according to three size classes (small: S1 < 1 ha, moderate: 1 ha ≤S2 <100 ha, and large S3 ≥ 100 ha).

2.2.3 Fire causes

The database Prométhée identifies five main classes of causes (one-digit codes) which are defined in Camia *et al.* (2013): (i) natural (any wildfire caused by natural origin, with no human involvement in any way; in the study area, only lightning ignitions belong to this class), (ii) accidental (wildfires unintentionally and indirectly caused by humans, without use of fire, connected neither to will nor to negligence, rather to fate; this included fires due to structures, such as power lines, railways, vehicles, or garbage dumps), (iii) deliberate (wildfire intentionally caused by humans with the use of fire for different motives, such as conflict, interest, or pyromania), (iv) negligence during professional works (wildfire unintentionally caused by humans using fire or glowing objects during professional activities, not connected to fate), and (v) negligence during leisure activities (wildfire unintentionally caused by humans using fire or glowing object during recreation, not connected to fate). Each class was divided into different sub-classes of two-digit, and three-digit codes (except for the natural cause) for the most detailed causes. In this current work, these two sub-classes were merged because of the low number of fires due to the causes identified with three-digit codes (Table 1).

2.3 Statistical and spatial analyses

The identification of homogeneous regions from the 15 "départements" of SE France was performed using Hierarchical Cluster Analysis (Ward method, based on squared Euclidian distance; R 2.15-0, package ADE-4 1.5-1, R Development Core Team 2005), using the different descriptive factors (socio-environmental characteristics) of each "département". This analysis was used to group the “départements” into clusters (hereafter called regions), in such a way that two “départements” from the same region were more similar than two “départements” from different regions, regarding these socio-environmental characteristics. To highlight what were the main characteristics of each region identified, Principal Component Analysis was performed taking into account the socio-environmental factors as well as the total fire occurrence and burned area of each “département” (Statgraphics Centurion XV, StatPoint Technologies).

Representing wildfire incidents as points on a map made it difficult to distinguish “clusters” of ignitions, because the points overlapped. To address this limitation, we used the Kernel density method to highlight, for each main cause, the hotpots of ignitions (and of large fire ignitions) throughout the study area. This method is a non-parametric statistical technique that was aimed at producing a smooth density surface; thus, accounting for the uncertainty regarding the accuracy of the original ignition location. In assigning a buffer area around each spatial fire ignition, a normal distribution of density surfaces (based on the number of ignitions per point) was created over each point. When multiple buffers overlapped, the kernel density values were combined to derive the ignition density surface. This provided a much clearer illustration of where the ignitions were the most frequent (hotspot) and allowed the use of a straightforward and quantitative value (number of ignitions per square kilometer). For this analysis, we used the Spatial Analyst Extension of ArcGIS 10.2 whose kernel function was based on Silverman’s quartic kernel function (Silverman 1986). However, spatial analyst provides a search radius algorithm based on the distance between ignitions giving a too smoothed result. In order to obtain sharper density changes, we empirically chose a shorter search radius (6000 m-radius, including 28 possible locations) according to the initial grid of the Prométhée database. A 50m-resolution was chosen for the output raster. The spatial analysis was based on the total number of fires with known causes during the 1973-2015 period.

Using Statgraphics Centurion XV software, multi-factor ANOVAs were performed to assess the impact of region, cause, and season on the fire metrics. In addition to the tests of overall significance, the Least Significance Difference (LSD) test was used to check for significant differences between the different means. A significant relationship between the variables was assumed when the p-value was ≤ 0.05. When the distribution of data did not follow the expected parametric pattern, data were log-transformed. When the three parameters (region, season, cause) interacted, regression trees were used to refine the results obtained and to give probabilities of fire occurrence and predicted mean burned area (analyses run only on fires ≥ 1 ha, using R 2.15-0, package rpart, R Development Core Team, 2005).

3 Results

Hierarchical cluster analysis allowed the 15 “départements” to be grouped into three homogeneous regions (clusters) according to the socio-environmental factors. Principal Component Analysis performed on these explanatory factors revealed the main characteristics of each region (Fig. 1). Region 1 was mainly characterized by climatic (wettest climate conditions) and topographic trends (highest elevation), as this region is comprised of the “départements” located in the northern part of the study area, most of them being mainly mountainous. Trends in land cover (high proportion of forest and agricultural lands) and in network density (high density of secondary roads) best characterized region 2, which is more central in the study area, whereas socio-economic (high unemployment rate and population density), climatic (driest climate conditions), and land cover (high proportion of shrubland) trends better characterized region 3, this densely populated region being located mainly in the southeastern part of the study area (except for the "département" Pyrénées-orientales which is located at the western part of the study area). If the total number of fires and burned area of each "département" were added to the analysis, the composition of the three regions would not change.

3.1 Characterizing the spatial and seasonal variation of fire metrics

In total, during the 1973-2015 period, 106,904 fires occurred and burned 884,492 ha in the study area, mostly in summer.

Regarding the spatial variation of fire metrics, region 3 was the area the most impacted by wildfires, in terms of occurrence and burned area (68% of the total occurrence and 73% of the total burned area) in contrast to regions 1 and 2 (13% and 19% of the total occurrence and 10% and 16% of the total burned area) (Table 2). Fires of small (S1 < 1 ha) and moderate (1 ha ≤ S2< 100 ha) sizes were the most frequent in regions 1 and 2 (between 47 and 51%) whereas, in region 3, most fires were small (S1=69%). The proportion of large fires (S3 ≥ 100 ha) was the lowest regardless of the region (less than 1.2% of the fires), but these fires greatly affected region 3 in terms of burned area (78% of the total burned area in region 3 *vs* 48% and 56% in regions 1 and 2, respectively).

Regarding the seasonal variation of fire metrics, in region 1, fires mainly occurred in summer and winter whereas they were concentrated mostly during the summer season in region 3 (57% of occurrence and 83% of burned area). Regions 2 and 3 presented higher proportion of autumn fires than region 1 (9% *vs* 6%) but the proportion of area burned in fall was higher in region 1 (9% *vs* 7 and 5%). Region 1 also presented the highest occurrence (20%) and burned area (18%) due to spring fires (Table 2). In each region, fire occurrence and

Table 1: List of the fire causes and motives recorded in the study area, their occurrence and burned area (in %), as well as their mean burned area (in ha) according to the regional fire database Prométhée (in bold: main cause > 5%).

Code	Fire cause/motive	Occurrence	Burned area	Mean burned area
Natural				
1	**Lightning**	**8.3**	**6.53**	**5.33**
Accidental				
2	Undetermined accidents	1.62	1.06	0.86
21	**Power lines**	3.09	**5.92**	**4.82**
22	Railways	0.96	0.54	0.44
23	Vehicles	2.29	1.6	1.30
24	**Garbage dumps (legal-illegal)**	3.74	**8.88**	**7.24**
Deliberate (intentional)				
3	**Undetermined arson**	**16.7**	**28.2**	**22.98**
31	Deliberate-conflict (real estate, hunting)	2.12	1.76	1.43
32	**Deliberate-interest** (real estate, hunting, **shepherds**)	3.15	**6.98**	**5.69**

33	**Pyromania**	**5.51**	**6.28**	**5.12**
Negligence in professional works				
4	Undetermined professional works	1.41	0.83	0.67
41	**Forestry works**	**11**	**5.97**	**4.87**
42	**Agricultural works**	**14.7**	**9.17**	**7.48**
43	Industrial works	0.9	0.27	0.22
44	Rekindle	2.35	1.98	1.61
Negligence in recreation				
5	Undetermined leisure activities	2.79	0.93	0.76
51	**Private works**	**9.37**	2.51	2.05
52	Recreation activities (**children's games**, fireworks, BBQ/bonfire)	**5.56**	3.66	2.99
53	**Glowing items** (**cigarettes**, distress rocket, hot ashes**)**	4.48	**6.97**	**5.68**

burned area were significantly affected by season (Chi^2=1955.18, p<0.0001; Chi^2=71894.96, p<0.0001, respectively).

Table 2: Characteristics of the study area and of regions in terms of fire metrics (size 1 < 1 ha; 1≤ size 2 <100 ha, size 3 ≥ 100 ha).

Known/unknown fire means fire whose cause is known/unknown.

Study area and Fire metrics	Region 1	Region 2	Region 3	Study area
Surface area (ha)	2 996 126	2 204 647	2 833 867	8 034 640
Total number of fires	13 629	20 390	73 078	107 097
% occurrence in SE France	12.7	19	68.2	
% fall occurrence	5.8	9.4	9.3	8.9
% winter occurrence	31.8	20.3	17	19.5
% spring occurrence	19.9	16.7	16.8	17.2
% summer occurrence	42.4	53.6	56.9	54.4
Total burned area (ha)	92 006	141 966.8	650 518.8	884 491.5
% burned area	10.4	16.0	75.5	
% fall burned area	9.0	6.7	4.6	5.4
% winter burned area	27.1	9.2	6.6	9.1
% spring burned area	17.8	10.0	5.7	7.7
% summer burned area	46.1	74.1	83.1	77.8
% fires size 1	47.4	50.7	68.8	62.6
% fires size 2	51.5	48.1	30.0	36.2
% fires size 3	1.15	1.16	1.22	1.20
% known fires	53.6	45.8	33.8	33.7
% unknown fires	46.4	52.2	66.2	66.3
% area burned by known fires	55.7	52.1	38.1	28.1
% area burned by unknown fires	44.3	47.9	61.9	71.9

3.2. Spatio-seasonal variation of fire metrics according to fire causes

In SE France, during the 1973-2015 period, knowledge of fire causes was poor; only 33.7% of the total number of fires had a known cause that corresponded to 35,960 fires and 243,523 ha burned but this knowledge varied spatially in the study area. Indeed, the nature of the fire causes was better known in region 1, in which 54% of the fires had known causes than in regions 2 (46%) and 3 (34%) (Table 2).

For the study area and regarding both fire metrics, the main fire causes taken into account in the analyses are presented in table 1. It is worth noting that the deliberate fires due to interest (cause 32) mainly involved shepherds (hunting activities and real estate were the other motives of these deliberate fires) and the unintentional fires due to glowing items (cause 53) were mainly due to cigarette butts. Lightning (cause 1), negligence during forestry and private works (causes 41 and 51, respectively) were the most frequent causes of small fires (S1), while negligence during agricultural works (cause 42) was the most frequent cause of fires of intermediate size (S2). Undetermined arson caused most large fires (S3, 0.24% of the total number of fires), even if this fire size was the least represented in the study area. Globally, undetermined arson (18%), forestry and agricultural works (12% and 16%, respectively) accounted for the highest occurrence and undetermined arson (29%) resulted in the largest burned areas.

At the level of the study area, hotspots of fire ignitions due to five of the main causes were highlighted by kernel density and large fire ignitions were pinpointed on the maps thus obtained (Fig. 2). Hotspots of ignitions due to undetermined arson (Fig. 2a) which was the cause the most densely aggregated were mainly located in the southern part of the study area (corresponding to region 3 in which these fires were the most frequent: 19%; fig. 3c). Clusters of large fires (up to two large fires) were situated in the southeastern area. Hotspots of ignitions due to professional (forestry and agriculture; fig. 2b, c) and private works (Fig. 2d) were mainly located in the northwestern and southeastern part of the study area; large agricultural fires being more aggregated in the western area.

On the whole, the different fire metrics varied spatially. For instance, fires due to professional activities were the most frequent in region 1 (cause 41: 16% and cause 42: 23%; fig. 3a) and in region 2 (agricultural fires: 18%; fig. 3b). Most burned area was due to undetermined arson and agricultural works in regions 1 (17% and 21%, respectively; fig. 3a) and 2 (26% and 14%, respectively; fig. 3b) as well as to undetermined arson, mainly in region 3 (32%, fig. 3c). It is worth noting that, regarding the mean burned area, the largest fires were due to undetermined arson (18 ha) in region 1, to railways in region 2 (11 ha), and to garbage dumps in region 3 (14 ha). Hotspots of natural ignitions, less densely aggregated than those due to the previous causes (up to 0.97 fires per km^2 instead of up to 2.1 fires per km^2), were spread throughout the study area (Fig. 2e). However, the occurrence and area burned by these fires were higher in region 1 (Fig. 3a) because the proportions were calculated on the total number of fires of each region. Lightning ignitions spatially varied from 6% and 7% of occurrence in regions 2 and 3 to 13% of occurrence in region 1, and from 4% of burned area in region 2 to 10% of burned area in region 1. Their mean size was larger in region 3 than in the other regions (7 ha *vs* 4 and 1 ha in regions 1 and 2, respectively).

Regarding the seasonal variation of fires, our results highlighted the fact that most causes presented a seasonal trend that could, however, differ between the causes (Fig. 4). Fires due to power lines entailed the largest total burned area in fall (due to their larger size at this season), despite their low occurrence (Fig. 4a). On the whole, most causes mainly occurred and had more severe effect in summer. Some, such as undetermined arson, presented high fire metrics most of the year (except in winter), with maximum values in summer: 24% of occurrence and 34% of total area burned by these deliberate fires at this season (Fig. 4b), but the largest mean burned area in summer being due to garbage dumps (22 ha). Private works presented a higher occurrence in spring and winter (Fig. 4c, d) but their mean burned area was small resulting in a smaller total burned area, regardless of the season. Accordingly, fires due forestry and agricultural works were small but very frequent nearly year-round (except in summer), resulting in a large total burned area (mostly in winter, fig. 4d). Other fires, such as natural fires, were frequent during one particular season (i.e. in summer for natural fires; fig. 4b) but presented a larger total burned area during a different season (i.e. in spring for natural fires; fig. 4c). Moreover, some causes were less frequent but presented larger fires at a particular season resulting in a large total burned area (garbage dumps and glowing items in summer and spring respectively, and power lines in fall). Finally, others, such as pyromania and recreational activities, were neither frequent nor large regardless of the season (Fig. 4).

On the whole, regardless of region and season, fires due to railways, vehicles, deliberate-conflict, negligence during industrial works, rekindle, as well as unidentified accidents and negligence were the least frequent and severe (<5%; table 1).

3.3. Effects of interactions between factors on fire metrics

Region, season, and fire cause were the three factors that significantly affected both fire occurrence and burned area. Region was the most important factor for fire occurrence, and season most impacted burned area (Multi-factor ANOVA; table 3). In terms of fire occurrence, the trends highlighted in figure 5 showed that this variable significantly decreased from region 3 to region 1, and from undetermined arson (as well as agricultural and forestry works) to the other fire causes. On the whole, this metric was, maximum in summer and minimum in fall (in between, decreasing from spring to winter). In terms of fire severity (Fig. 6), the total burned area was significantly the largest in region 3 and the largest areas were

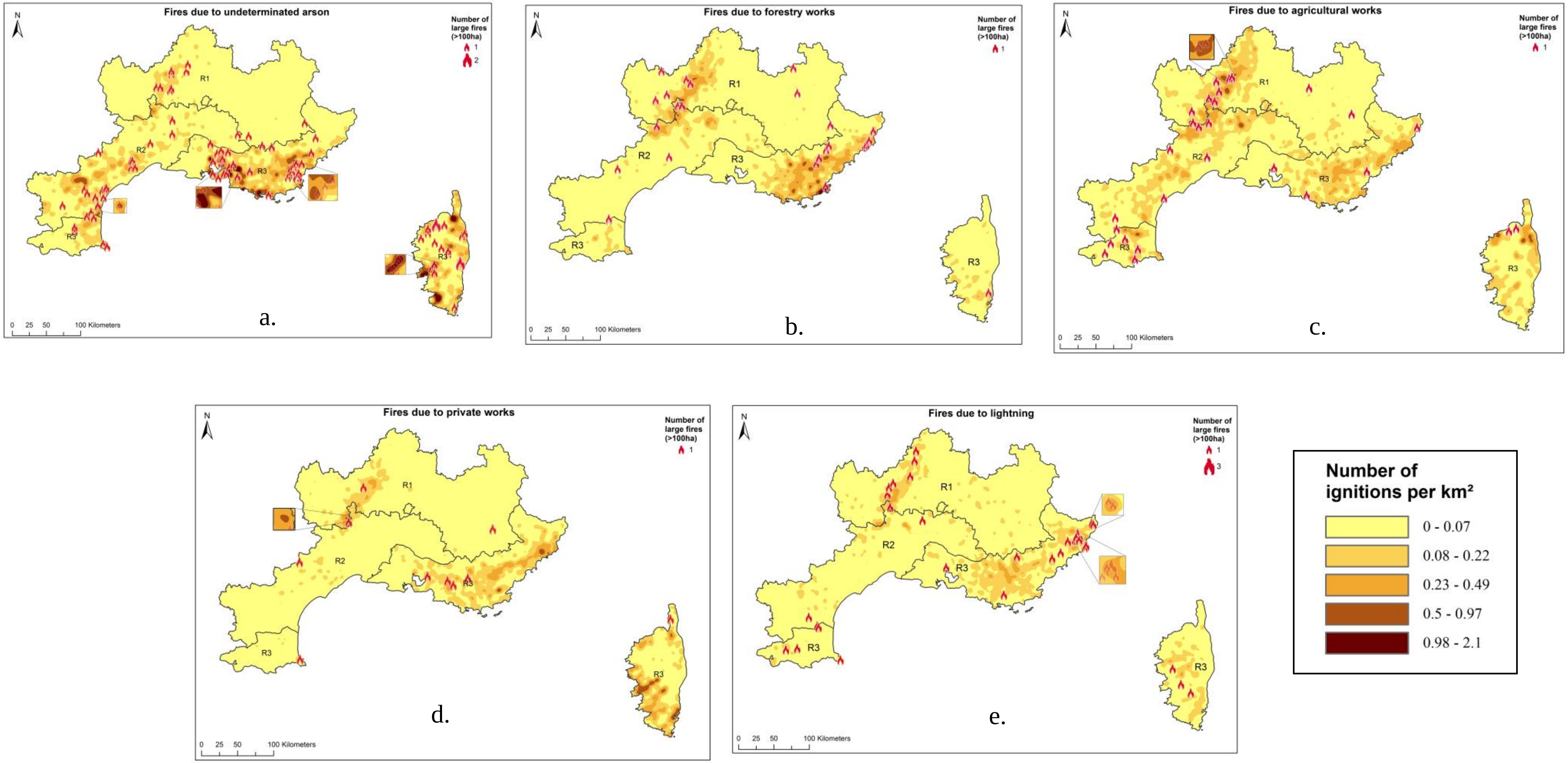
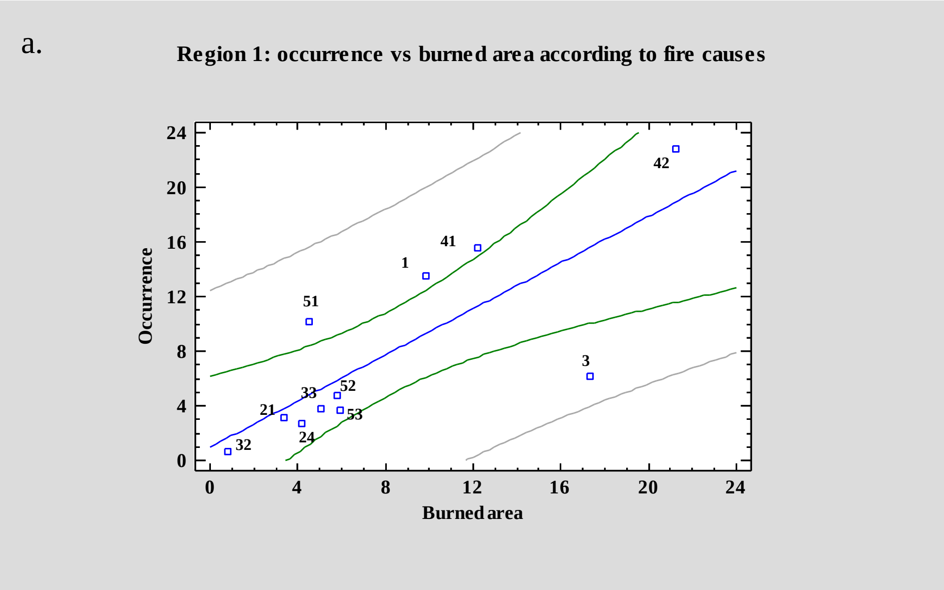
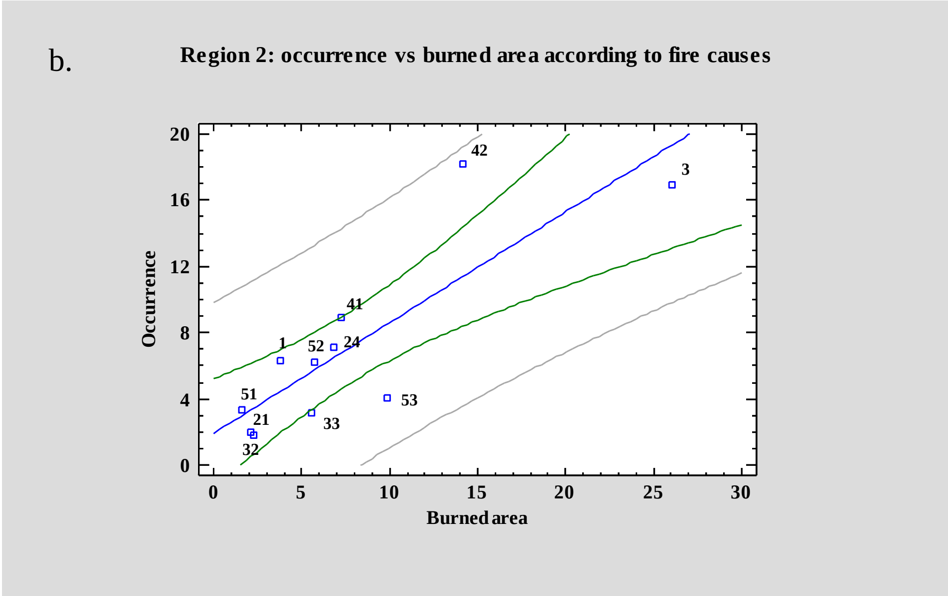


Figure 2: Hotspots of total fire ignitions and locations of large fire ignitions of five of the main fire causes in SE France (BD Carto®): a. undetermined arson, b. forestry works, c. agricultural works, d. private works, and e. lightning.





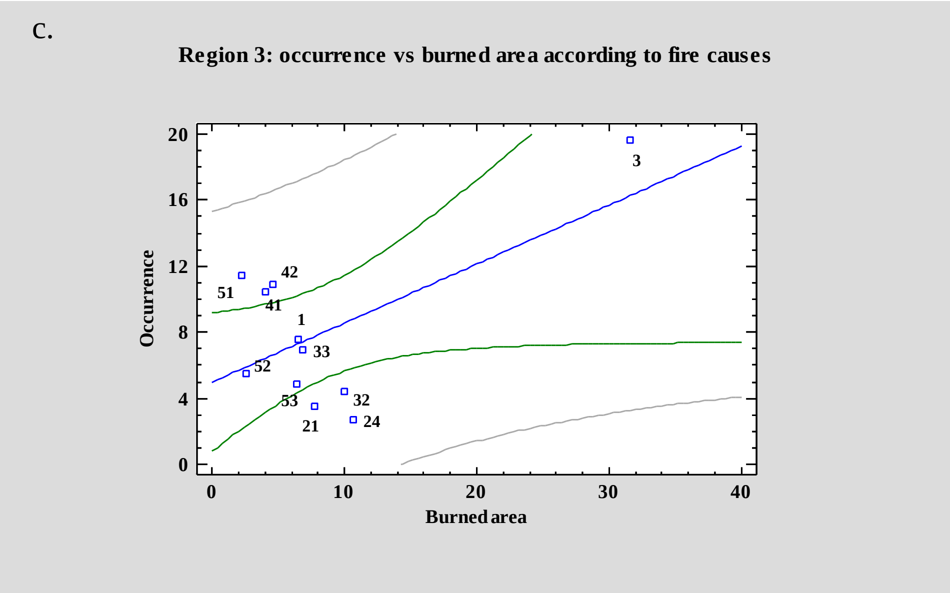


Figure 3: Spatial occurrence and total burned area (in percentage) according to the main fire causes: a. region 1, b. region 2, c. region 3 (For the codes of each cause see table 1. Causes 2, 22, 23, 31, 4, 43, 44, and 5 were not shown because of their too low impact in terms of both fire metrics).

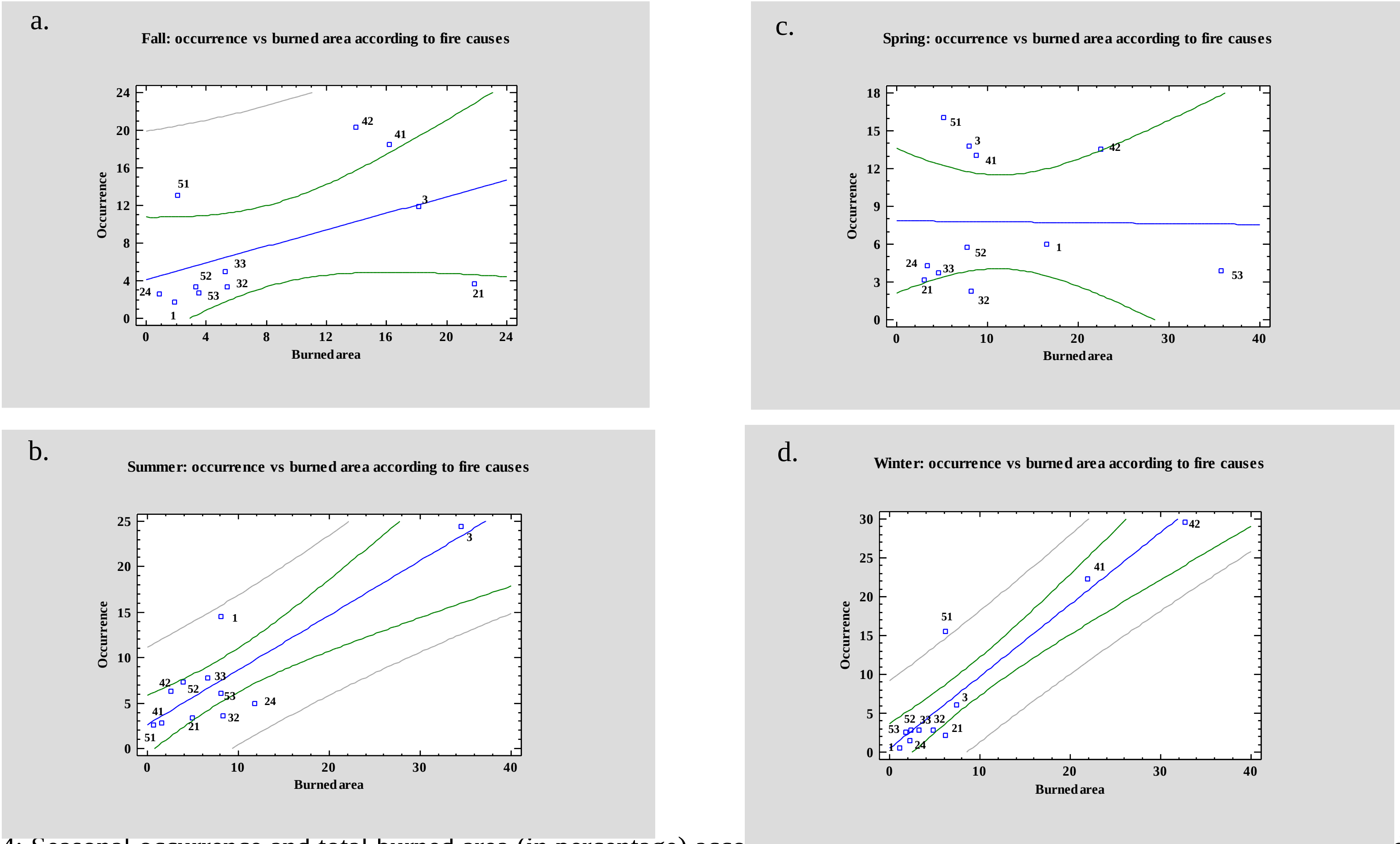


Figure 4: Seasonal occurrence and total burned area (in percentage) according to the main fire causes: a. fall, b. winter, c. spring, d. summer (For the codes of each cause see table 1. Causes 2, 22, 23, 31, 4, 43, 44, and 5 were not shown because of their too low impact in terms of both fire metrics).

burned in summer, mostly because of fires due to undetermined arson. Moreover, fires were globally more severe in winter and in spring (mostly due to forestry and agriculture) than in fall.

However, the interactions between factors taken two by two had a significant impact on the fire metrics and the strongest interaction occurred between season and cause (Table 3). Indeed, both occurrence and total area burned by fires due to deliberate-interest, forestry, agricultural and private works were higher and larger in winter than in summer (Fig. 5a and 6a) contrary to the general trend. Moreover, as shown by the interaction cause-region, agricultural works did not follow the general spatial trend (described above), especially regarding the burned area which was not the largest in summer (Fig. 6c). The interaction highlighted between region and season showed that occurrence and burned area in region 1 were higher and larger in winter than in spring (Fig. 5a and 6a).

Table 3: Multi-factor ANOVA performed on fire occurrence and total burned area (log-transformed) according to cause, region, and season (F: Fisher test, Ddl: degrees of freedom).

Occurrence				**Burned area**		
	Ddl	*F*	*Probability*	*Ddl*	*F*	*Probability*
Cause	15	6.44	p<0.0001	15	11.21	p<0.0001
Region	2	288.69	p<0.0001	2	43.59	p<0.0001
Season	3	163.97	p<0.0001	3	48.98	p<0.0001
Interactions						
Cause/Region	30	9.43	p<0.0001	30	3.81	p<0.0001
Cause/Season	45	15.13	p<0.0001	45	3.88	p<0.0001
Region/season	6	8.05	p<0.0001	6	2.77	p=0.0192

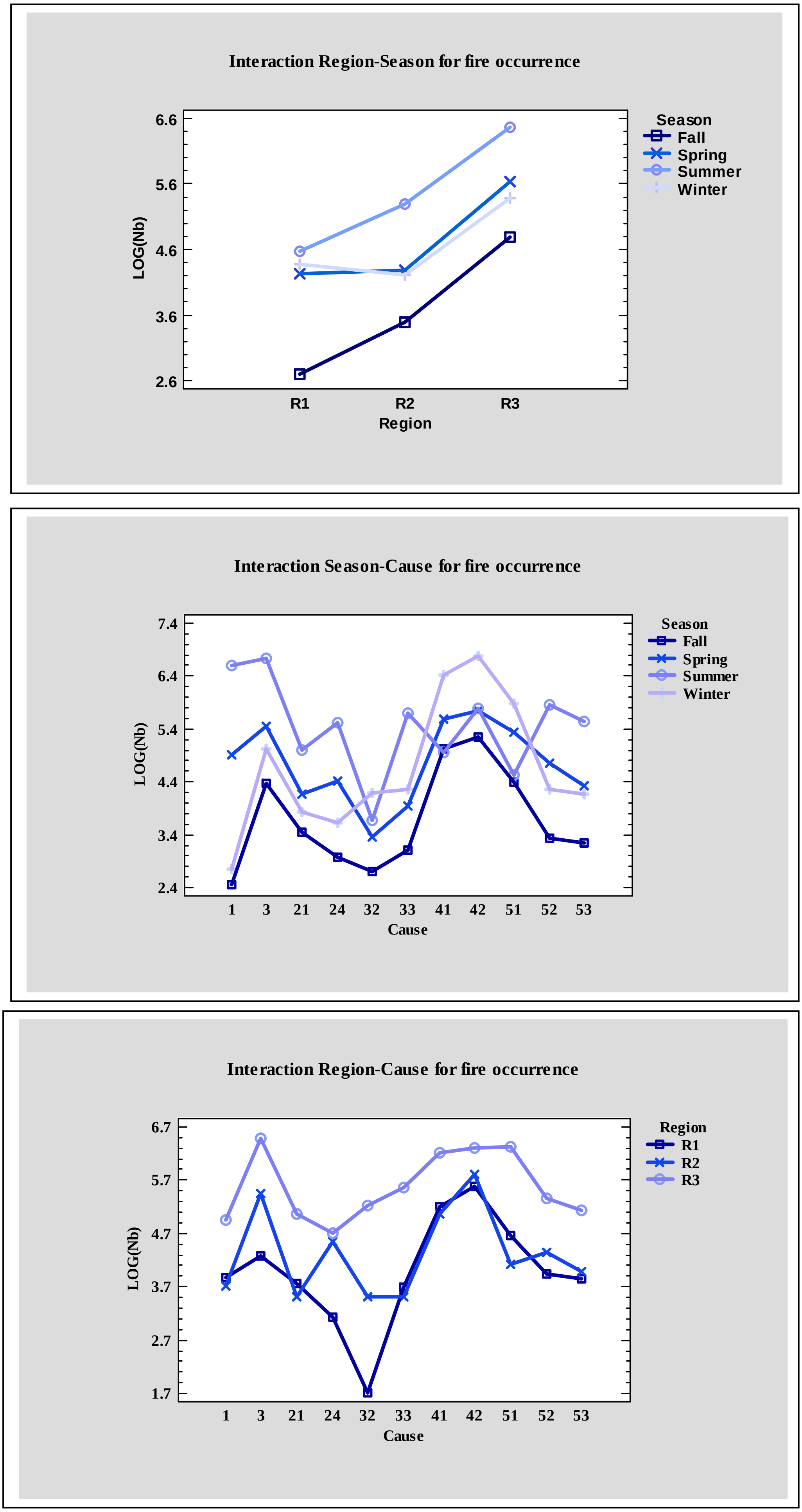


Figure 5: Interactions between fire cause, region, and season regarding fire occurrence.

Multi-factor ANOVA, Nb: number of fires, F: Fall, Sp: Spring, Su: Summer, W: Winter, R1: Region 1, R2: Region 2, R3: Region 3 (For the codes of each cause see Table 1. Causes 2, 22, 23, 31, 4, 43, 44 and 5 were not taken into account in the analyses because of their too low impact in terms of fire occurrence).

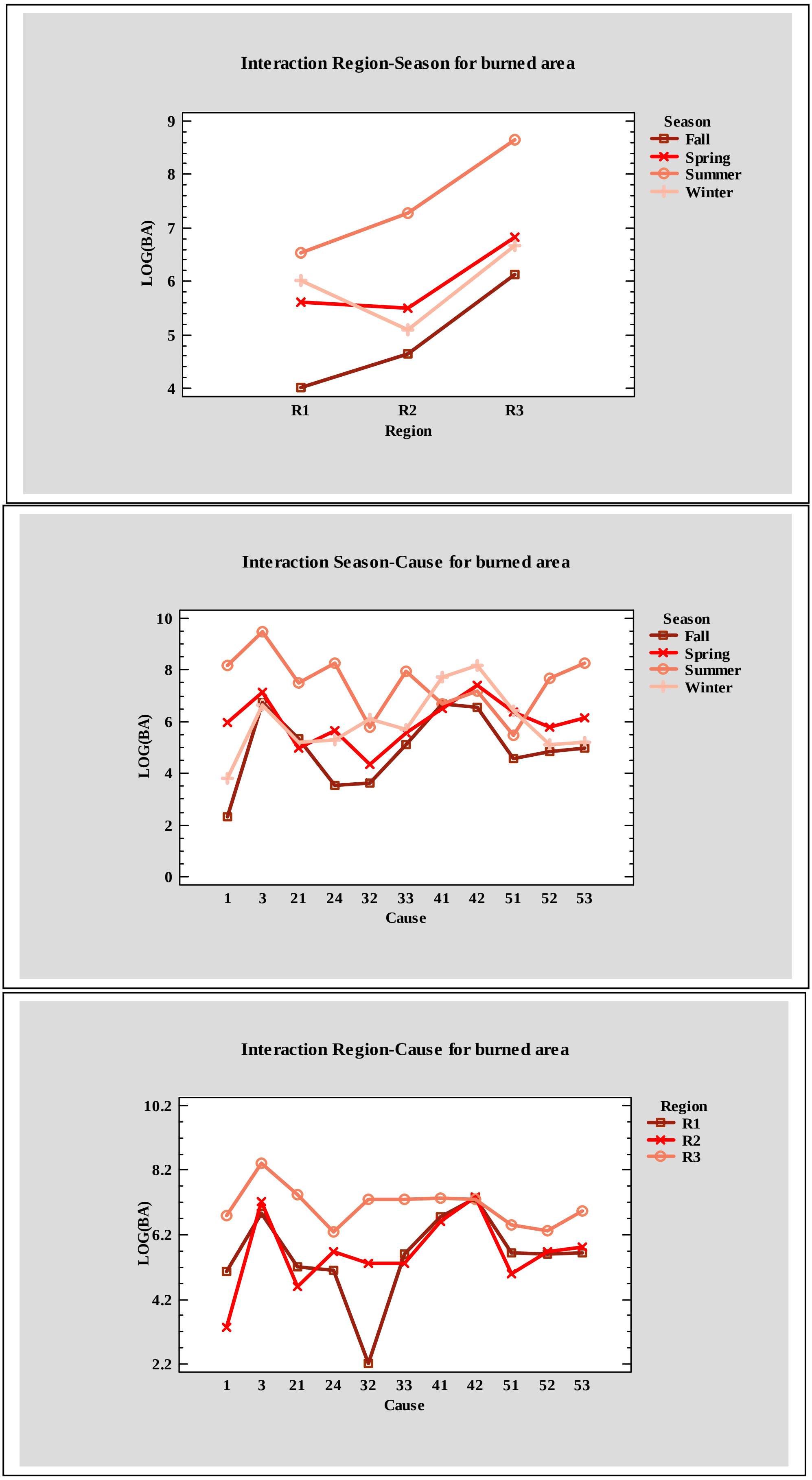


Figure 6: Interactions between fire cause, region, and season regarding burned area.

Multi-factor ANOVA, BA: Burned area, F: Fall, Sp: Spring, Su: Summer, W: Winter, R1: Region 1, R2: Region 2, R3: Region 3 (For the codes of each cause see table 1. Causes 2, 22, 23, 31, 4, 43, 44 and 5 were not taken into account in the analyses because of their too low impact in terms of burned area).

The regression tree analyses[1] performed on fire occurrence and mean burned area simultaneously took into account the three factors cause, region and season (Table 4). Regarding fire occurrence, these analyses showed that, for most causes, the number of fires decreased from summer to the other seasons and was higher in region 3, which was consistent with the previous results. However, because of the interactions between factors, some causes did not follow this general trend: fires due to lightning and to recreational activities were more frequent in summer in region 1, as were fires due to power lines in fall in region 3 (an example of output data produced by the regression tree analysis run on cause 21 is given in fig. 7a), to forestry and agricultural works in winter in regions 1 and 2, and to private works in spring in region 3. Except for power lines and deliberate-interest, season better predicted the fire occurrence (contrary to the results of ANOVAs) and showed different patterns according to the cause. Some causes opposed summer to the other seasons regardless of the region: lightning, garbage dumps, undetermined arson, and pyromania presented a higher occurrence at this season contrary to forestry and agricultural works (lower occurrence in summer). Others opposed spring and summer to winter and fall: fires due to private works were more frequent in fall-winter contrary to fires due to recreational activities that were more frequent summer. In contrast, region was the best predictor of fire occurrence due to power lines and to deliberate-interest, opposing region 3 to regions 1 and 2, as shown for power lines in figure 7a. The number of splits required to obtain the highest occurrence varied according to the cause, ranging from two splits for causes 1, 32, 33, 21, and 24 to five splits for cause 51. In these analyses, the accuracy was always higher than 0.90 (Table 4).

Regarding mean burned area, regression tree analyses predicted, for each cause, the mean area burned according to the two other factors. Results showed that season was the best predictor of mean burned area regardless of fire causes. This fire metric decreased from

[1] Analyses run only on fires $\geq$ 1ha.

summer to the other seasons (an example of output data produced by the regression tree analysis run on cause 3 is given in figure 7b), except for power lines and recreational activities which caused larger fires in fall in regions 3 and 2 respectively, as well as for pyromania (larger fires in spring) in region 3 and for agricultural works (larger fires in spring) in region 1 (Table 4). The largest fires predicted by the regression trees occurred in region 3 (as shown, for instance, for fires due to undetermined arson in figure 7b), except for agricultural works and recreational activities (larger fires in regions 1 and 2, respectively) (Table 4). The number of splits required to obtain the largest predicted mean burned area varied according to the cause, ranging from three splits (causes 1, 3, 32, 24, 41, 51, and 53) to six splits (cause 42). In these analyses, the accuracy was always higher than 0.98 (Table 4).

Except for power lines, undetermined arson, deliberate-interest, and glowing items, the most impacted region and season, in terms of fire occurrence, differed from those that presented the largest mean burned area. For instance, fires due to garbage dumps mostly occurred in summer in region 2 but they were the most severe at the same season in region 3 (Table 4).

4 Discussion

4.1 Spatial and seasonal variation of fire metrics and causes

The spatial analysis (Kernel density) allowed us to highlight hotspots of ignitions due to five of the main fire causes in the study area. If natural fires were not heavily aggregated, the locations of highly aggregated ignitions due to the other causes, especially undetermined arson, were precisely pinpointed mainly in the southern part of the area. Gonzalez-Olabarria *et al.* (2012), using the same method, also showed that, in Catalonia (Spain), fire ignitions

Table 4: Probability of fire occurrence (in %) and mean burned area (in ha) predicted by regression trees according to cause, region, and season. Regional total and mean burned area are also given for each cause.

Analyses were run on the dataset of fires ≥ 1ha. In bold: highest values for each cause; in italic: highest value per region; accuracy: relative error; n: number of fires≥ 1ha, BA: burned area, Mean BA=total BA/occurrence. For the codes of cause see table 1. Causes 2, 22, 23, 31, 4, 43, 44 and 5 were not taken into account in the analyses because of their too low impact in terms of both fire metrics.

	Season/Causes	1	21	24	3	32	33	41	42	51	52	53
	(n)	650	438	607	1740	526	634	1676	2723	727	551	553
Fire occurrence												
Region 1	Fall	2.7	6.0	1.1	7.1	0.0	2.7	24.0	30.0	8.8	4.9	4.4
	Winter	0.3	1.4	0.6	3.2	1.2	2.1	**26.0**	39.0	11.0	2.2	2.6
	Spring	6.2	4.1	1.8	7.7	0.5	2.1	20.0	31.0	7.3	3.3	4.2
	Summer	**24.0**	4.4	7.8	11.0	0.1	6.8	5.1	13.0	1.6	**8.1**	4.9
Region 2	Fall	0.0	3.2	5.4	11.0	3.5	1.1	16.0	38.0	2.4	1.9	3.2
	Winter	0.0	0.6	1.8	7.0	3.5	1.9	23.0	**42.0**	5.0	1.2	1.6
	Spring	3.2	3.8	9.6	9.9	3.1	1.9	15.0	25.0	4.8	6.7	3.2

	Summer	6.7	2.6	**14.0**	21.0	2.0	5.1	3.5	9.9	1.4	7.0	6.3
Region 3	Fall	2.7	**6.3**	2.2	12.0	7.1	7.6	19.0	19.0	8.0	3.2	2.3
	Winter	1.0	4.7	1.7	7.9	6.8	3.6	22.0	30.0	10.0	3.5	3.3
	Spring	3.6	4.5	3.7	14.0	5.2	5.8	14.0	14.0	**13.0**	4.9	5.4
	Summer	7.9	4.4	4.5	**27.0**	**8.3**	**10.0**	2.5	7.7	1.7	5.1	**6.8**
Accuracy		0.928	0.993	0.959	0.942	0.979	0.981	0.931	0.905	0.967	0.99	0.992
Mean burned area												
Region 1	Fall	1.3	6.2	6.0	46.0	0.0	27.0	9.9	9.0	6.2	5.2	4.6
	Winter	6.4	3.2	34.0	13.0	18.0	17.0	8.5	8.3	5.9	6.2	4.8
	Spring	24.0	8.8	11.0	7.6	2.3	3.8	6.5	**13.0**	12.0	13.0	19.0
	Summer	18.0	26.0	19.0	59.0	4.0	22.0	10.0	7.9	6.5	26.0	40.0
	Total	3911.7	1333.8	1684.6	6991.9	316.7	2013.6	4851.4	*8471.9*	1717.4	2321.6	2391.4
	Mean	15.04	14.19	18.93	*35.13*	15.08	18.82	8.31	9.21	7.04	17.72	20.98
Region 2	Fall	0.0	2.5	4.7	11.0	7.6	11.0	13.0	9.6	3.8	**58.0**	19.0
	Winter	2.0	6.2	3.5	5.9	6.7	5.2	5.1	4.9	5.7	2.9	5.6
	Spring	3.0	3.2	5.6	27.0	6.4	13.0	3.6	10.0	6.0	4.8	6.3

	Summer	13.0	18.0	11.0	27.0	16.0	27.0	1.4	6.6	7.6	17.0	38.0
	Total	1667.3	931.3	3040.4	*11732.5*	1000.0	2507.0	3231.2	6283.6	694.4	2529.4	4454.7
	Mean	10.76	11.09	9.19	22.39	9.62	21.07	7.01	6.76	5.99	14.54	*29.12*
Region 3	Fall	19.0	**94.0**	2.1	28.0	18.0	15.0	13.0	3.9	3.4	5.0	22.0
	Winter	22.0	28.0	13.0	11.0	9.8	7.0	7.5	7.6	3.3	9.5	5.5
	Spring	15.0	3.5	14.0	23.0	7.9	**36.0**	7.0	8.3	15.0	13.0	30.0
	Summer	**45.0**	59.0	**141.0**	**62.0**	**64.0**	30.0	**19.0**	11.0	**17.0**	21.0	**46.0**
	Total	10091.7	12037.2	16782.8	*49396.6*	15571.3	10577.8	6003.2	6977.3	3290.6	3867.1	9956.0
	Mean	37.38	46.30	*89.75*	48.62	38.83	25.93	9.51	7.99	8.97	15.72	34.81
Accuracy		0.99	0.99	0.987	0.989	0.99	0.99	0.99	0.989	0.99	0.99	0.99

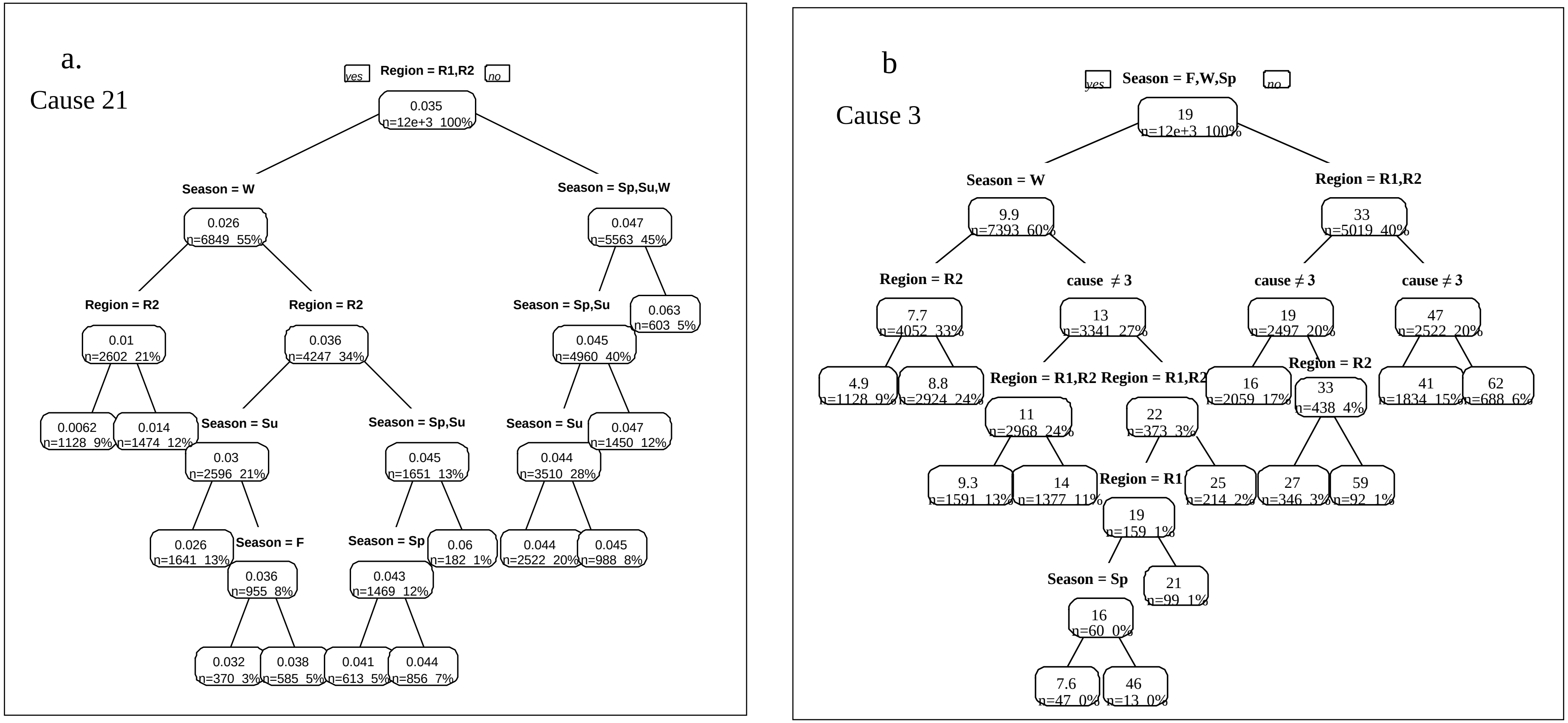


Figure 7: Two examples of regression trees giving the probability of occurrence of fires due to power lines (cause 21) (a) and the predicted mean burned area (in ha) due to undetermined arson (cause 3) (b) according to region and season: region best predicted the probability of occurrence of fires due to cause 21 and season best predicted the mean area burned by fires due to cause 3. Analyses were run on the dataset of fires ≥ 1ha.

tended to be spatially aggregated depending on their causality, especially the deliberate ones. Thus, mapping these hotspots would help to efficiently allocate means in terms of fire prevention or suppression.

The spatial variation of fire metrics has already been noted in previous works at a regional scale (Badia-Perpinyá and Pallares-Barbera 2006; Conedera *et al.* 2006) or at a more global scale (Syphard *et al.* 2009). Likewise, our results, obtained on the entire dataset, showed a spatial variation of both fire occurrence and total burned area which increased from regions 1 and 2 to region 3; region being the most significant factor of fire occurrence (contrary to the results of regression tree analyses run on the dataset of moderate and large fires). Our results also highlighted a seasonal variation of fire metrics which were higher in summer (and in spring to a lesser extent). Season mostly impacted total burned area (as well as the mean burned area in the regression tree analyses), likely because the climate conditions were driest and hottest in summer, especially in region 3. Accordingly, previous works already showed that fire weather, for instance the timing and the amount of precipitation each year especially in months before the fire season (usually attributed to the accumulation and drying patterns of herbaceous fine fuels), strongly influenced burned area (Davis and Michaelsen, 1995; Westerling *et al.* , 2003; Bradstock *et al.* 2009; Cary *et al.* 2009; Penman *et al.* 2011; Price and Bradstock 2011; Bradstock *et al.* 2012). However, the interaction between region and season highlighted in the analyses indicated that this trend could change (higher metrics in winter than spring in region 1). Eventually, this spatio-seasonal variation of fire metrics was found to be directly related to the fire causes. Indeed, some causes presented a strong spatio-seasonal pattern that can be due to climate conditions (i.e. stronger impact of fires due to power lines in fall in region 3) or to the seasonality of the practices, such as for forestry works. In this case, fuel treatments by prescribed burning, for instance, mainly occur between fall and spring, when the climate conditions are less severe. In Algeria, Meddour-

Sahar *et al.* (2013) also highlighted a spatial variation of fires due to their cause, the highest occurrence varying between deliberate-conflict, pyromania, and garbage dumps depending on the region.

Undetermined arson presented a seasonal pattern (less pronounced in region 3) with more frequent and severe fires in summer throughout the study area, agreeing with previous works carried out in other Mediterranean countries (Moreno *et al.* 2011; Vilar del Hoyo *et al.* 2009). In the current work, intentional ignitions with identified motives (conflict, interest, pyromania) mostly occurred in region 3 which was characterized, among others, by a high population density which can be a driving factor of the occurrence of such fires. In this region, better knowledge of these motives could be due to a better investigation of fire causes or to their regional specificity. For instance, deliberate fires due to interest in pastoral activities (deliberate-interest) which is a regular practice in the "département" Haute-Corse (located in the Corsica island in region 3) had more severe effects in summer, when shepherds seek to get free new grasslands by burning shrublands before the autumn rains. Meddour-Sahar *et al.* (2013) underlined a similar problem in Algeria where deliberate fires due to pastoral activities were one of the main fire causes in the country (in terms of occurrence) and could be defined as a cultural trait of the local population. In region 3, pyromania was the most frequent motive of deliberate fires, especially in summer and presented larger burned areas in spring; however, this cause had a much lesser impact than undetermined arson. It is worth noting that, according to the French classification of fire causes, pyromania takes into account a large range of motives (from mental illness to drawing attention, vandalism, crime concealment, etc.) which do not fall into the classes "deliberate-interest" and "deliberate-conflict". In several other countries, pyromania has often been misappropriated and used as a synonym of undetermined arson, resulting in an "artificial" increase in the occurrence of this cause (Ganteaume *et al.* 2012).

Agricultural work was another main cause of occurrence and total burned area (except in summer), especially in regions 1 and 2. This cause encompassed ignitions due to agricultural machines, legal pastoral fires, as well as burning residues and standing vegetation before sowing (the latter being the most frequent). Lovreglio *et al.* (2010) and Martìnez *et al.* (2009) showed that countries, such as Italy, Algeria and Spain, linked by a similar context of a very traditional rural society, were highly impacted by agricultural fires (in terms of occurrence). Furthermore, in Sardinia (Italy), agricultural and forestry activities caused most fire ignitions (Lovreglio *et al.* 2014). However, these latter studies did not specify the season of maximum occurrence.

Regarding the spatial variation of fire causes, Syphard and Keeley (2015) found that the impact of fires due to equipment spatially varied in California, this cause entailing high fire effects in this region (however, only in terms of burned area), but in their work, the type of equipment responsible for these fires was not pinpointed. In the French classification of causes, these fires are part of the fires due to negligence during professional (causes 41 to 44) and private works (cause 51) but, within these categories, the proportion of fires due to equipment (i.e. machines or engines used during works) was low according to the Prométhée database. Frequently occurring along the roads, accidental fires set in garbage dumps and unintentional fires due to glowing items which were mostly cigarettes carelessly tossed by people, were more frequent in region 2 (mainly characterized by a high density of secondary roads), especially in spring and summer (only for garbage dumps). These fires were responsible for more than 10% of the total area burned, in summer mostly, in regions 2 and 3, despite the mandatory brush-clearing along networks that should prevent the occurrence and minimize the spread of such fires. Under normal weather conditions, cigarette butts do not usually start large fires unless drought and fuel conditions exist (Markalas 1985; Satoh *et al.* 2003; Dainer 2003), thus making of roads and trails critical ignition points in severe climate conditions (Cardille *et al.* 2001; Romero-Calcerrada *et al.* 2008). Awareness-raising campaigns regarding this cause must be reinforced in targeting especially tourists in summer. Likewise, the same recommendations could be made for garbage dumps which was one of the main causes in summer in regions 2 (regarding the occurrence) and 3 (regarding the burned area). These two latter causes were also identified as problematic in Algeria and garbage dumps, especially illegal ones, were among the most frequent causes of fires, as a direct consequence of extreme population density, which made garbage collecting difficult (Meddour-Sahar *et al.* 2013).

Even if the hotspots of natural fires (in terms of fire density) were spread throughout the study area (mostly in its SE part which also concentrated most fires regardless of the cause), at the regional level, region 1 was the most affected both in terms of occurrence and burned area (> 10% in summer mostly), as wet climate conditions can favor fires due to lightning strikes, especially at high elevation (Renkin and Despain 1992; Nash and Johnson 1996). It is worth noting that, on the whole, these fires remained small in size (mean burned area < 8 ha), but were larger on average in winter, in region 3 (10 ha).

As noted in previous works (Ganteaume and Jappiot 2013; Meddour-Sahar *et al.* 2013; Syphard and Keeley 2015), the high proportion of unknown causes (66% on average in SE France) can be a hindrance to a better understanding of the spatial variation of fire causes, as well as to the development of any efficient fire policy aiming to reduce the occurrence of the most deleterious fires. During the last few decades, investigations on fire causes have been improved by the creation of official investigation teams, including forest rangers, police officers, and fire fighters. These teams follow a procedure similar to that of a criminal investigation to determine as precisely as possible the ignition point as well as the nature of its cause. Unfortunately, this procedure is still not yet widely used in SE France. Our results showed that knowledge of fire causes spatially varied, being better in region 1, perhaps because of the lower fire occurrence in this region. However, this poor knowledge can be explained in two main ways: (i) the investigations were either inconclusive or did not occur at all (Martín 2004 ; Castedo Dorado *et al.* 2007; Penman *et al.* 2013), and/or (ii) the database was not correctly filled out or was incomplete, as already found by Langhart *et al.* (1998) in Switzerland. Unknown causes contributed to a high extent of area burned (70 % on average in the study area), especially in region 3 (73% of the burned area). However, in this latter region, a significant proportion of the fires with unknown cause was strongly suspected of being deliberate (Ganteaume *et al.* 2012).

4.2 Focus on deleterious causes

Agricultural works were one of the two main causes responsible for the highest fire effects in the study area. Fires due to this cause presented larger total area burned from fall to spring, when most agricultural burnings occurred (especially in winter) despite their small size (less than 9 ha on average regardless of region and season). Knowledge of these fires being better (very small proportion of undetermined professional works, e.g. cause 4) than that of the deliberate fires, for instance, they can be better targeted during fire prevention initiatives.

Undetermined arson, the other main deleterious cause, presented the opposite seasonal pattern. Regardless of the region, this cause presented the highest fire effects, mostly in summer (>30% of the total burned area) but also had a strong impact in fall in regions 1 and 3, as well as in spring in regions 2 and 3, mostly because the large size of such fires at these seasons. Region 3 was the most impacted by these deliberate fires likely because of long dry summer conditions (conducive to high fire propagation) that characterized this region and because, most of the year, this cause was the major source of ignitions. This important result highlighted the need to extend preventive measures against such fires, before and after the fire season (summer in the study area). Usually, severe climate conditions (hot, dry and windy), entailing an extreme fire hazard, were preferentially targeted by arsonists in order to affect as large burned areas as possible (Ganteaume and Jappiot 2013; Syphard and Keeley 2015); this idea was, however, refuted by Mees (1991). The high proportion of these arson fires with unidentified motives prevents understanding the behavioural patterns driving arson ignitions because of its complexity, and mainly highlights a lack in the investigation of fire causes (Mees 1991; Prestemon and Butry 2008; Syphard *et al.* 2008; Penman *et al.* 2013).

Moreover, as already highlighted by Syphard and Keeley (2015), some causes could have disproportionally high fire effects, even if they were not the most frequent ones, and the prevention of these causes must be targeted as a priority in each region. Our results also showed that the same cause did not always impact both fire metrics in the same way. Some of the least frequent causes can entail high fire effects (large total burned area), as it was typically the case for fires due to glowing items (such as cigarette butts) in region 2 or to garbage dumps and recreational activities in summer in region 3. Thereby, these causes also have to be carefully targeted by fire prevention measures. Accordingly, regardless of region and season, for some causes, those driving high fire effects were not necessarily those entailing fires with high mean burned area, such as forestry and agricultural works (small fires but burning large areas, because of their high occurrence). Special attention should be also paid to causes such as garbage dumps and power lines (especially in summer) that drove globally small fire effects, but whose fires could be large, and thus could have high fire effect on a smaller scale. As found in California (USA) and Australia (Cruz *et al.* 2012; Keeley *et al.* 2012; Syphard and Keeley 2015), accidental fire causes due to power lines had a greater impact in terms of burned area in region 3, especially in fall, when bad climate conditions (autumn storms) can provoke ruptures of power lines. In this case, the fire effects due to these installations could be mitigated using underground power lines in high risk wind corridors, as proposed by Keeley *et al.* (2009) in California.

5 Conclusions and management implications

The current work showed that spatial and seasonal patterns of fire metrics (region 3 being the most affected part of the study area, especially in summer) often were the result of the nature of fire causes (mainly undetermined arson in summer in region 3 and agricultural works, especially in winter in regions 1 and 2).

In the study area, unknown causes contributed to a high extent of burned area, especially in region 3. This result highlighted the fact that, for better fire prevention, it is necessary to improve our knowledge of fire causes, mostly by increasing the investigations (in number and quality) and in accurately documenting the fire databases. As pointed out by Chas-Amil (2007), it is drastically important to better target the fire causes, especially the deliberate ones (and their different motives), in the implementation of fire prevention measures as proposed by Gonzalez-Olabarria *et al.* (2012). To improve intentional fire prevention, actions including educational campaigns and law enforcement measures that target sensitive areas could be developed, especially during the peak season of each region. In summer in region 3, the impact of fires set by shepherds highlighted the need for supporting these pastoral activities in a better management of the pastures (in increasing the implementation of prescribed burnings, for instance). Some authors as Mees (1991) refuted the idea that most arson fires occur under severe weather conditions. The author also validated the need to maintain arson prevention programs (enhanced patrols and detection) during such weather conditions. Our results also showed that prevention measures must be extended before and after the fire season.

Regarding the fires due to negligence, ignitions set by professional and private works depended, on the one hand, on the characteristics of the location of these works (regions) and, on the other hand, on the seasonal practices related to these activities (such as brush-clearing and prescribed burning in forestry works, or burning to clean gardens in private works). The prevention of these fires should require a better awareness of people (professionals or not) in order to modify their behaviour for safer practices （improvements in the management of these activities and in the training of professionals for prescribed burning activities, for instance).

In the future, according to global change, the climate conditions will likely become warmer and dryer in the northern part of the study area, i.e. region 1, becoming more like those of regions 2 and 3. This change, combined with the land cover/land use change, will increase the fire risk in this region, which is currently the lowest in SE France. In a further work, the study of the temporal variation of fires as well as of the driving factors of their causes will attempt to better understand the role of global change on the fire metrics and causes. This improvement in knowledge of fire causes will allow a better prediction of these changes on the local scale, in adapting fire prevention in the most sensitive areas where the population is currently less aware of the fire risk.

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