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Characterizing Alpine pyrogeography from fire statistics

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ABSTRACT

In this paper, we describe current fire characteristics in the Alpine region using a ten-year forest fire record at the third and lowest resolution of the European Classification of Territorial Units for Statistics (NUTS3). To this purpose, we performed hierarchical clustering based on the Bray-Curtis dissimilarity index on five pyrogeographic metrics. This resulted in three main geographically well-distinguished clusters (Southern, Northern, and Maritime Alps) and two small groups of outliers. From a geographic point of view, we found a clear differentiation between the high fire density on the southern slope of the Alps and the substantially lower proportion of burnt areas registered in the north. The most relevant climatic (e.g., frequency and length of drought periods), environmental (e.g., vegetation types, mean elevation and predominant orientation of valleys), and socio-economic (e.g., population density and educational level) drivers for the described clusters of fire characteristics were also identified. The proposed pyrogeographic characterisation may represent an important baseline for detecting future shifts in fire occurrence or anomalous fire seasons.

1. Introduction

Since its domestication by humans, fire on Earth depends on both climatic and ecological factors, as well as the cultural use of fire (Fernandes, 2013; Pyne, 1997). Humans may influence fire activity directly through setting and controlling fires, but also indirectly by modifying the flammability of landscapes through management, and, more recently, anthropogenically induced climate change (Bowman et al., 2011). As a consequence, resulting fire activity reflects not only the natural fire environment (fire proneness based on climate and vegetation) but also the way mankind perceives and relates to the landscape (Coughlan & Petty, 2012). Furthermore, factors affecting fire occurrence may act at different scales resulting in complex spatially-correlated patterns in fire regimes (Boulanger et al., 2013).

The best way to illustrate such multi-scaled spatio-temporal interactions between fire and the environment is to select suitable recurring fire characteristics and dimensions, so that homogeneous pyroregions may be distinguished within defined space-time windows (Bradstock, Gill, & Williams, 2012; Falk & Swetnam, 2003; Krebs, Pezzatti, Mazzoleni, Talbot, & Conedera, 2010; Morgan, Hardy, Swetnam, Rollins, & Long, 2001). Different quantitative and qualitative approaches exist for defining such pyroregions at different temporal and spatial scales (see Moreno & Chuvieco, 2013 for a short review). A large body of literature has been published reporting on global, continental, and regional-level, as well as past, present, and future pyrogeography, including related driving factors (e.g., Archibald, Lehmann, Gomez-Dans, & Bradstock, 2013; Bowman, O'Brien, & Goldammer, 2013; Pausas & Paula, 2012).

The very steep environmental gradient combined with the considerable diversity in legislation and management approaches make the

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Alpine region a particularly challenging case study for determining subareas with homogeneous fire characteristics. Unfortunately, obtaining consistent forest fire data in a politically and administratively fragmented area such as the Alpine region is a very demanding task. As a result, data has been published in the past for specific regions (e.g., Arpaci, Malowerschnig, Sass, & Vacik, 2014; Fréjaville & Curt, 2015; Pedrolli, 1984; Pezzatti, Zumbrunnen, Burgi, Ambrosetti, & Conedera, 2013; Stefanì, 1989; Vacik et al., 2011) or for particular fire characteristics (Conedera, Cesti, Pezzatti, Zumbrunnen, & Spinedi, 2006; Reineking, Weibel, Conedera, & Bugmann, 2010; Wastl et al., 2013), but to date no synthesis exists on present pyrogeography for the whole European Alpine region (see also Valese, Conedera, Held, & Ascoli, 2014).

Within the framework of the two Alpine Space Interreg projects MANFRED (www.manfredproject.eu) and ALPFFIRS (www.alpffirs.eu), it was possible, for the first time, to create a decennial (2000–2009) Alpine forest fire database compiling records and statistics from national and local forest services and fire brigades. Based on these efforts, the aim of this paper is to define the current main homogeneous pryroregions in the Alpine space, and to discuss their possible socio-economic, environmental, and climatic drivers.

2. Study area

The geographical extent of the Alpine region can be identified in different ways based on different purposes. For example, boundaries may be defined based on the Alpine Convention (www.alpconv.org) for developing regional policies, the European Alpine Space Programme (www.alpine-space.eu) which sets the context of European funded projects, or the Greater Alpine Region (Auer et al., 2007) for defining regional climatology. In our study, we consider the Alpine area as defined by the Alpine Convention. In practical terms, we retained all three levels used in the European Nomenclature of Units for Territorial Statistics classification system (NUTS, hereafter referred to as NUTS3) included in or cross-bordering the limits of the Alpine Convention Region (Fig. 1). NUTS refers to the hierarchical system used to divide up the economic territory of the European Union for the collection, development, and harmonization of socio-economic analyses of each region. The three categories include major socio-economic regions at the highest level (NUTS1), basic regions for the application of regional policies (NUTS2) and small regions (< 800,000 inhabitants) for specific diagnoses (NUTS3) (http://ec.europa.eu/eurostat/web/nuts/). The study area so defined includes 82 NUTS3 for a total area of 249,184 km^2.

From a climatic point of view, the Alpine area is part of the transition at the continental scale from “temperate westerly” to “Mediterranean subtropical” climate as defined by Auer et al. (2007) when referring to the Greater Alpine Region. As highlighted by the authors, the climate within the Greater Alpine Region can be used to identify a northern sector, comprising most of Germany, Austria, and northern Switzerland, and a southern sector, including Italy, France, Slovenia, part of Austria (Carinthia), and part of Switzerland (Canton Ticino and minor parts of the Cantons Valais and Grisons) (Fig. 1). In the northern sector, the precipitation series show a distinct maximum during the warm season (Fig. 2, meteorological station of Garmisch-Partenkirchen), whereas in the southern sector, autumn precipitation exceeds that of the summer season (Fig. 2, Embrun, Brescia, and Auronzo). The southern sector is warmer and more affected by dry katabatic fall winds (foehn), especially on the western side (Piemonte, Aosta Valley and Lombardia; Fig. 2, Brescia). In the lake region across the Swiss-Italian border, the special case of the Insubric climate is characterized by sub-tropical-like climatic conditions (Fig. 2, Locarno Monti) whereas the French part of the study area is strongly influenced by the Mediterranean climate (Fig. 2, Embrun). Further distinctions regarding Alpine climatology emerge when considering distance from the sea (continentality) and elevation (altitude gradient). Auer et al. (2007) identify an inner Alpine sector characterized by internal valleys at high elevation which are much drier than on the northern side of the Alps (Fig. 2, Umhausen), even if the seasonal distribution of precipitation is similar.

Finally, a great number of forest and vegetation types are found in the Alps as a consequence of the heterogeneous climatic and topographic patterns, ranging from pseudo-Mediterranean and Mediterranean forests (near seas and lakes, as well as in the foothills) to boreal-like conifer stands at higher elevation. In contrast, in the low to medium range, temperate broadleaved forests dominate (EEA 2007). The spatial distribution of environmental features and especially the continuous change from favorable to adverse fire propagation conditions such as slope orientation (south/north), steepness (cliff *vs.* valley vegetation), abundance of conifers *vs.* broadleaved species, and accessibility (managed *vs.* unmanaged forests) lead to highly variable characteristics in terms of fire ignition and behavior.

3. Material and methods

3.1. Forest fire data

Within the framework of the ALPFFIRS and MANFRED European funded Alpine Space projects, it was possible, for the first time, to collect a high-resolution ten-year dataset of forest fires for the entire Alpine area of France, Italy, Switzerland, Germany, Austria, and Slovenia. All fire records contained information on location (municipality), date of ignition, and total burnt area. Information on ignition sources was not available in all cases, preventing us from using fire cause as a discriminating fire metric. The original dataset consisted of 19,072 forest fires that occurred between 2000 and 2009 in the 82 NUTS3 regions of the study area. The number of fires and burnt area varied greatly among NUTS3 regions ranging from 17 to 2906 events and from 1 to 29,865 ha burnt area, respectively. For statistical reasons, we discarded NUTS3 regions with highly incomplete data series, e.g., with fire data series of fewer than five years or fewer than two events per year on average. This led to the exclusion of 18 NUTS3 regions from further analysis. The final dataset consisted of 17,862 forest fires belonging to 64 NUTS3 regions distributed from France to Slovenia (Fig. 1 and Table 1). At the country level, German forest fire data did not go beyond 2005 and had to be discarded.

We are aware that fire statistics data spanning ten years is rather short for defining fire regimes. Unfortunately, fire records covering most of the study area were available for the period 2000–2009 only. Here, the term fire regime refers to NUTS3 fire characteristics under the current (2000–2009) fire regime.

3.2. Fire regime metrics

Fire metrics were defined in order to take fire density (relative average frequency and burnt area) and phenology (seasonal periodicity) into account. Specifically, we calculated four density-related and three phenology-related metrics (see Table 2).

The two density-related metrics (i.e., number of fires and burnt area per square kilometer of combustible area and year) aim at describing susceptibility to ignition and fire spread (i.e., the number of fires and burnt area per combustible area). In addition, we considered the average size of a fire at the NUTS3 level.

Phenological metrics were derived from previous studies dealing with fire seasonality in specific Alpine regions (Cesti & Cerise, 1992; Pezzatti et al., 2013; Vacik et al., 2011; Zumbrunnen, Bugmann, Conedera, & Burgi, 2009). In particular, we defined two phenological metrics describing the share of fire frequency and burnt area in the non-growing season (from the beginning of December to the end of April, hereafter referred to as winter fires) and during the vegetative period (May to November, hereafter, summer fires). In order to limit the influence of single large fires, we created two additional metrics by log-

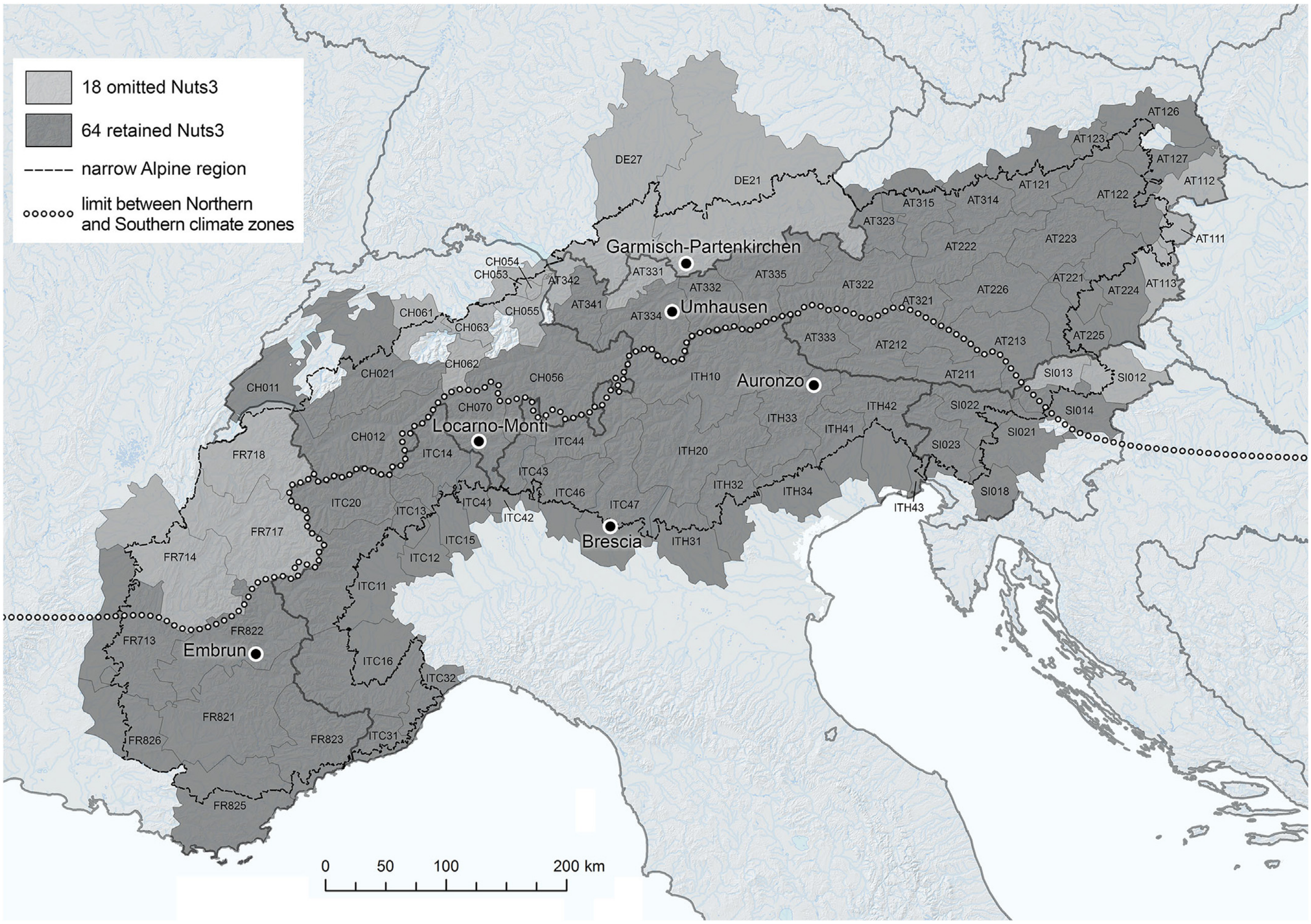

Fig. 1. Geographic distribution of the 64 NUTS3 regions and representative meteorological stations for each Alpine climatic sector (see Fig. 2).

transforming the burnt area (Table 2).

3.3. Climatic, environmental, and socioeconomic parameters

Concerning climate variables, various sources of daily and monthly gridded observational datasets were exploited to calculate the main climate characteristics for each NUTS3 region. In particular, the E-OBS dataset (v10.0) of the European Climate Assessment & Dataset (ECA&D) was used to describe temperature patterns in the form of multi-year monthly means. From the high resolution Alpine Precipitation Grid Dataset (EURO4M-APGD) we calculated several parameters describing rainfall patterns as well as the incidence of dry periods. Wind speed and relative humidity conditions were calculated using two different approaches. First, we extracted mean monthly wind speed and relative humidity data from the gridded climatology datasets released by the Climatic Research Unit of the University of East Anglia (CRU CL v2.0). Secondly, we used daily-modeled data from the ERA-Interim representing the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) to calculate mean monthly wind speeds and the number of consecutive days per month with low relative humidity conditions. Finally, the Global Aridity and Potential Evapotranspiration (PET) Database was used to estimate the monthly average PET.

The topographic parameters mean elevation, mean slope, and dominant aspect were derived from the NASA Shuttle Radar Topographic Mission (SRTM) 90 m digital elevation database (v4.1). Distance and geographic position with respect to the main Alpine drainage divide were calculated based on the catchment and river network system data (ECRINS v1.1) of the European Environment Agency (EEA), whereas the distribution of the direction of the main rivers (in 4 and 8 classes) was based on the CCM river and catchment database (v2.1). Land cover, land use, and vegetation characteristics were obtained from the Corine European database (inventory of land cover in 44 classes, scale of 1:100 000).

We also used the Eurostat database (the EU Statistical Office) to calculate basic socioeconomic parameters describing population size, density, and change over time, the gross domestic product, as well as the relative importance of different economic sectors and different levels of education at the NUTS3 level.

As a general rule, we selected and used only datasets belonging to the same time period as the forest fire database (i.e., 2000–2009) and with a spatial resolution that permitted the reliable calculation of mean values at the NUTS3 level. Table 3 lists the fire regime-related climatic, environmental, and socio-economic variables that were found to be most suitable and were thus retained for the final analysis, whereas Annex 1 report details on all calculated variables.

3.4. Statistical analyses

Different clustering and grouping techniques have been used in other studies to define areas with similar fire regimes (e.g., k-means algorithm by Moreno & Chuvieco, 2013; Random Forests by Boulanger et al., 2013; ArcGis grouping analysis tools by Wu, He, Yang, & Liang, 2015). In the present study, we grouped the NUTS3 according to their fire regimes by performing hierarchical clustering on five pyrogeographic metrics (Table 2) based on the Bray-Curtis dissimilarity (Bray &

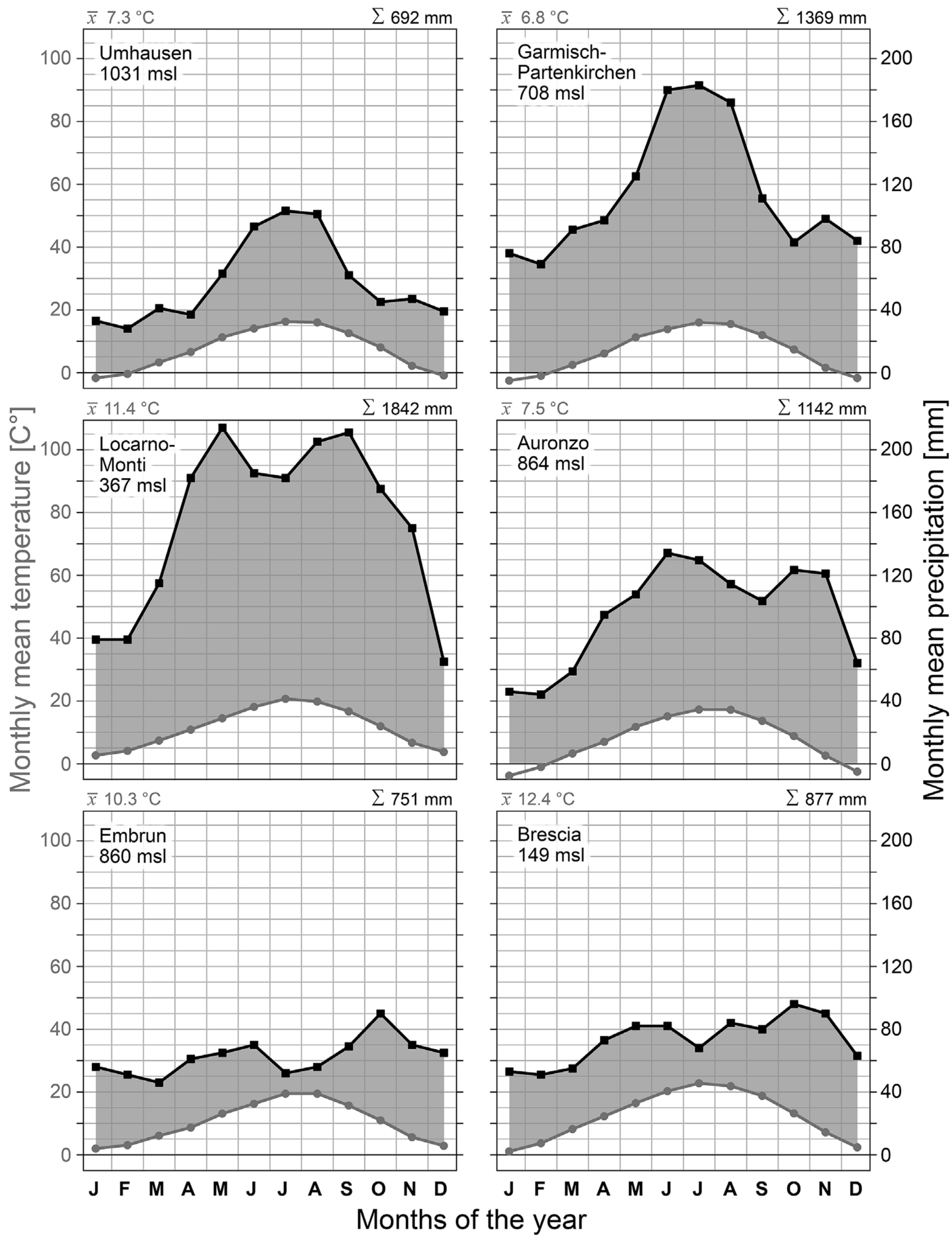

Fig. 2. Climatic diagrams of representative meteorological stations for the Alpine climatic sectors. Grey lines with circles represent monthly average temperatures (units on the left axis); Black lines with squares show precipitation (units on the right axis). Period of reference: 1971–2000.

Table 1
Number of NUTS3 considered and corresponding fires and burnt areas during the study period 2000–2009.

country	nr NUTS3 considered	total area (km2)	combustible area[a] (km2)	forest area[b] (km2)	nr forest fires (n)	burnt area (ha)	yearly ratio of area burnt[c]
Austria	24	63,339	48,905	30,650	955	594	0.132
France	6	33,124	23,312	12,928	6256	45,330	19.445
Italy	24	73,373	47,193	27,202	9419	66,980	14.193
Germany	0	–	–	–	–	–	–
Slovenia	5	10,857	8854	6610	385	3150	3.558
Switzerland	5	24,357	15,441	7283	847	2088	1.355
Total	**64**	**205,050**	**143,705**	**84,672**	**17,862**	**118,141**	-

[a] Combustible area = olive groves (Corinne land cover 17), pastures (18), agriculture land with significant areas of natural vegetation (21), agro-forestry areas (22). Forest area (see below[b]), natural grasslands (26), moors and heathlands (27), sclerophyllous vegetation (28), transitional woodland-shrub (29), sparsely vegetated areas (32), burnt areas (33), peat bogs (36).
[b] Forest area = broad-leaved forest (23), coniferous forest, (24), mixed forest (25).
[c] Yearly area burnt in ha per 10,000 ha of combustible area.

Table 2
Fire metrics used in this study.

	Acronym	Definition (unit)	Formula
fire density	*Fires/Combustible*	Average number of fire events per year divided by combustible area (n x km^{-2}x y^{-1})	$\frac{\sum_{y,1}^{k} FNry / k}{CoAr}$
	Burnt/Combustible	Average burnt area per year divided by combustible area (ha x km^{-2} x y^{-1})	$\frac{\sum_{y,1}^{k} BAry / k}{CoAr}$
	Mean Burnt	Average burnt area per fire event (ha)	$\frac{\sum_{y,1}^{k} BAry}{\sum_{y,1}^{k} FNry}$
	Mean Log Burnt	Average log-transformed burnt area per fire event	$\frac{\sum_{y,1}^{k} \log(BAry+1)}{\sum_{y,1}^{k} FNry}$
fire phenology	*Winter Fires*	Ratio between number of fire events in winter (December to April) and total number of fire events	$\frac{\sum_{y,1}^{k} \sum_{m,Dec}^{Apr} FNrmy}{\sum_{y,1}^{k} FNry}$
	Winter Burnt	Ratio between burnt area in winter (December to April) and total burnt area	$\frac{\sum_{y,1}^{k} \sum_{m,Dec}^{Apr} BArmy}{\sum_{y,1}^{k} BAry}$
	Winter Log Burnt	Ratio between log-transformed burnt area in winter and total log-transformed burnt area	$\frac{\sum_{y,1}^{k} \sum_{m,Dec}^{Apr} \log(BArm+1)y}{\sum_{y,1}^{k} \log(BAry+1)}$

Legend: *FNr* = number of fires; y = year; *BAr* = burnt area; *CoAr* = combustible area; *Apr* = April; *Dec* = December; combustible area: see legend to Table 1.

Curtis, 1957) and by using the average-linkage method. We used the Bray-Curtis dissimilarity coefficient because of its linear response to gradual changes in the data (see Ricotta & Podani, 2017) and the average-linkage method because it represents a good compromise between the methodological extremes of space-dilating and space-contracting approaches. Space-contracting methods may leave some clusters undetected even if they are apparent, whereas space-dilating methods are known to identify clusters even if the data does not show a clear group structure (Gordon, 1999). In contrast, the average-linkage method usually preserves a larger portion of the original dissimilarity structure in the dendrogram when compared to other clustering strategies (Podani & Schmera, 2006). In addition, the burnt areas were log-transformed before the calculation to avoid an exaggerated influence of single or few very large fires within a NUTS3 region.

We then searched for possible differences in the climatic, environmental, and socio-economic characteristics of the obtained fire regime clusters in order to detect the underlying drivers. To that end, we first performed a redundancy analysis (RDA) to assess the influence of selected climatic, environmental, and socio-economic variables on the pyrological characteristics of the different clusters. RDA is an asymmetric canonical ordination technique that measures the proportion of the total variance of one set of response variables explained by a canonical ordination from another set of explanatory variables. RDA can be described as a constrained principal component analysis (PCA) in which the ordination axes of the response variables are also constrained to be a linear combination of the predictor variables, such that the RDA axes represent the percentage of the variance of the response variables explained by the predictors (Legendre & Legendre, 1998). In our case, the predictor variables were the principal axes obtained from the ordination of the climatic, environmental, and socio-economic variables, respectively, while the response variables were all the fire-regime metrics in Table 2. Finally, we tested the significance of differences in the distribution of the environmental, socio-economic, and climatic characteristics among the proposed clusters by means of the non-parametric Wilcoxon signed-rank test. All statistical analyses were performed using R statistical software (version 3.4.0) and the Vegan package.

Table 3
Explanatory climatic, environmental, and socio-economic variables used for RDA analysis.

Category	Parameter	Variable acronym	Description	Unit	Source and periods considered
climatic	temperature	Temp.MarApr	bi-monthly mean (March and April)	°C	Europe Climate Assessment & Dataset (E-OBS v10.0) (1995–2013)
	drought period (DP)	LongDP.mean	longest period during the year	days	Alpine Precipitation Grid Dataset (EURO4M-APGD) (1991–2008)
		DP30.mean	Periods longer than 30 days	n/y	
	wind speed	Wind.JulAug	bi-monthly mean (July and August)	m/sec	European Centre for Medium-Range Weather Forecasts (ERA Interim climate reanalysis) (1990–2010; evaporation 2000–2009)
	relative humidity (Rh)	Rh.JulAug	bi-monthly mean (July and August)	%	
	dry days[a] (DD)	DD.Feb	monthly mean (February)	days	
	evaporation	Evapo.MarApr	bi-monthly mean (March and April)	m	
environmental	Elevation (Alt)	Alt.mean	mean value	m	USGS/NASA SRTM data, Shuttle Radar Topography Mission, SRTM Digital Elevation Database v4.1
	main rivers direction	RivDir4.S	portion of south-oriented rivers	%	Catchment Characterisation and Modelling (CCM v2.1)
	distance to the Alps	DistRid	distance to the Alpine ridge	km	EEA Catchments and Rivers Network System (ECRINS v1.1)
	forest cover	ConifFor	portion of coniferous	%	EEA (European Environment Agency) Corine Land Cover 2006
		ScleroFor	portion of sclerophyllous	%	
socio-economic	population	PopDens	population density	inh./km^2	"Eurostat [demo_r_pjanaggr3] [nama_r_e3gdp] NACE Rev.1.1 [cens_01ractz] ISCED97"(2001–2003)
	economic sectors	EconSect1	portion of people in the primary sector	%	
	education	Education	portion of people with basic educational level (0–2)	%	

[a] Days with less than 50% of daily mean relative air humidity.

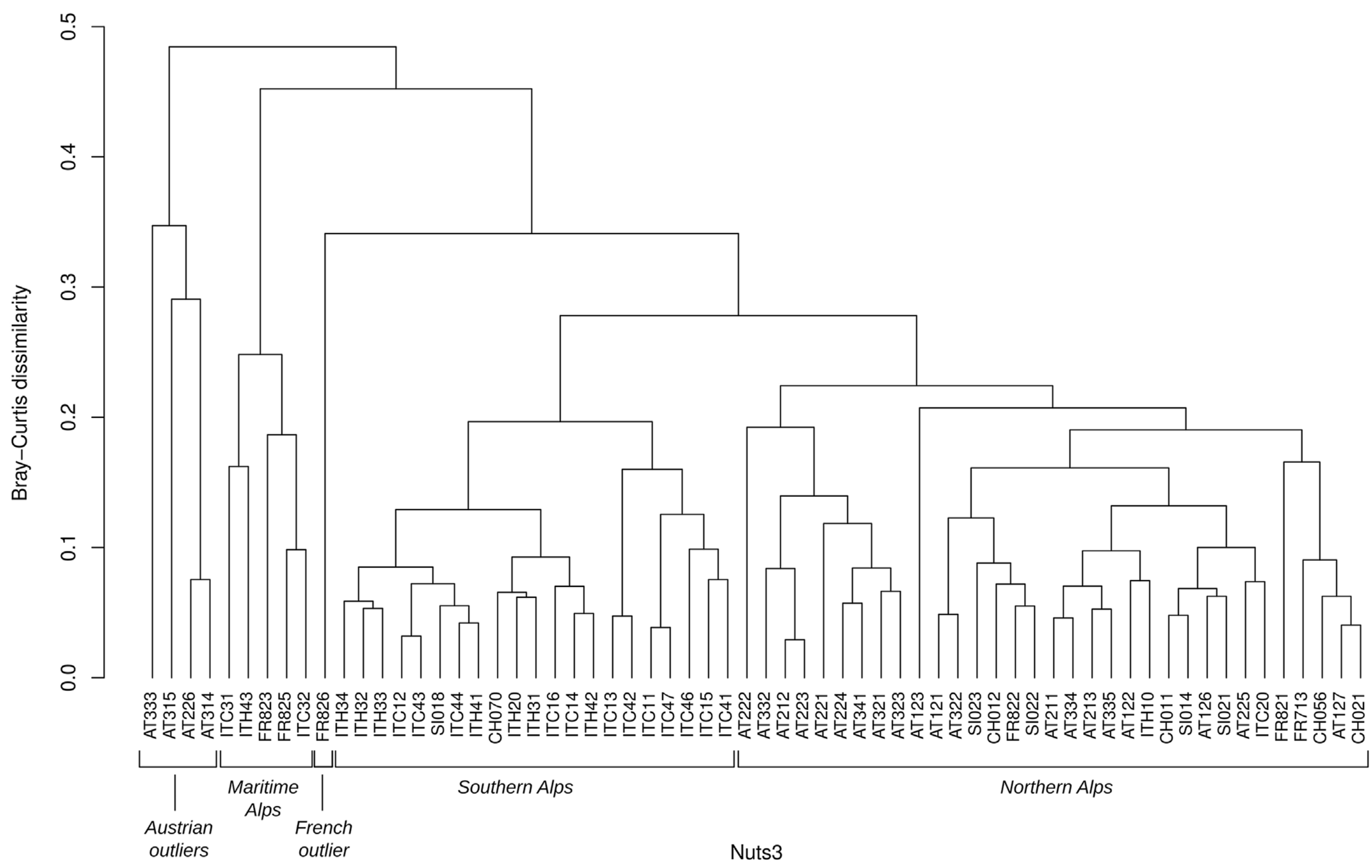

Fig. 3. Results of the cluster analysis.

4. Results

4.1. Dominant fire regimes in the Alps

The cluster analysis identified five different clusters (Fig. 3). The uniqueness of the five clusters was evaluated by means of a permutational multivariate analysis of variance (PERMANOVA; Anderson, 2001) on the Bray-Curtis dissimilarity matrix comparing each pair of NUTS3 regions ($F = 29.05$; $p < 0.0001$; 10,000 randomizations). According to their consistency and geographical position, we labeled the three main clusters as Northern (33 - NUTS3 regions), Southern (21), and Maritime (5) Alps, whereas the two remaining clusters are referred to as the Austrian (4) and French (1) outliers (Fig. 4). The Northern Alps cover the whole northern slope of the Swiss and Austrian Alps (with the exception of the Austrian outliers), the mountainous French departments of Isère (FR714), Savoie (FR717) and Haute-Savoie (FR718), the continental and dry Italian regions of Aosta Valley (ITC20) and South Tyrol (ITH10), and the Central and North-Western Slovenian regions of Savinja (SI014), Central Slovenia (SI021), Upper Carniola (SI022), and Gorizia (SI023). The Austrian outliers include the mountainous region of Western Upper Styria (AT224), the Steyr-Kirchdorf (AT314) and Traunviertel (AT315) regions in Upper Austria, as well as East Tyrol (AT333). The Southern Alps cluster includes all NUTS3 regions on the Italian southern slope of the Alps from Cuneo (ITC16) in Western Piedmont to Udine (ITH42) in Friuli-Venezia Giulia, the southernmost Swiss Canton of Ticino (CH070), and the Littoral–Inner Carniola region in Slovenia (SI018). The Maritime Alps include the coastal Alpes-Maritimes (FR823) and Var (FR825) in the French Côte d'Azur department and the Italian Provinces of Imperia (ITC31) and Savona (ITC32) in Liguria, and Gorizia (ITH43) in Friuli-Venezia Giulia. The department of Vaucluse in Provence represents the single NUTS3 cluster labeled as a French outlier. Assigned fire regime clusters and related main fire metrics for each of the NUTS3 regions considered are reported in Annex 1, whereas Table 4 reports the main fire characteristics for the defined clusters.

Fig. 5 shows the monthly frequencies of fire events and burnt areas for the fire regime clusters. Fire phenology in terms of the number of events clearly differentiates between the Maritime Alps with the French outlier, which have the highest frequency in July–August, and the Southern Alps, which experience the main fire peak in spring, March in particular. The Northern Alps and the Austrian outliers, in contrast, display two distinct fire peaks, the first in spring (March–April), and the second during summer (July–August). Regarding the burnt area, the summer peak in the Maritime Alps and the French outlier is even more pronounced, whereas no spring peak exists in the Northern Alps. Fig. 6 shows the fire density in terms of the number of fires, burnt area per combustible area, and mean burn area. The Maritime Alps is the fire regime cluster with the highest fire frequency (0.071 events/100 km^2 of combustible area) and burnt area (0.531 ha/100 km^2 of combustible area), followed by the Southern Alps (0.018 events/100 km^2 and 0.125 ha/100 km^2, respectively). The Northern Alps and the Austrian outliers, in contrast, have significantly lower fire density metrics.

4.2. Driving factors that differentiate fire regimes

Fig. 7a reports the results of the RDA analysis with the listed climatic fire regime variables as predictors, whereas Fig. 7b shows the results of the RDA when using environmental and socio-economic variables as predictors. The small squares represent single NUTS3 regions, and the shaded areas represent the convex hulls of the fire regime clusters. The length and direction of the arrows show the strength and the sign of correlation between predictor variables (i.e., potential fire drivers) and the first two axes of the RDA. The first two axes obtained from the redundancy analysis of the climatic variables (Fig. 7a) explain

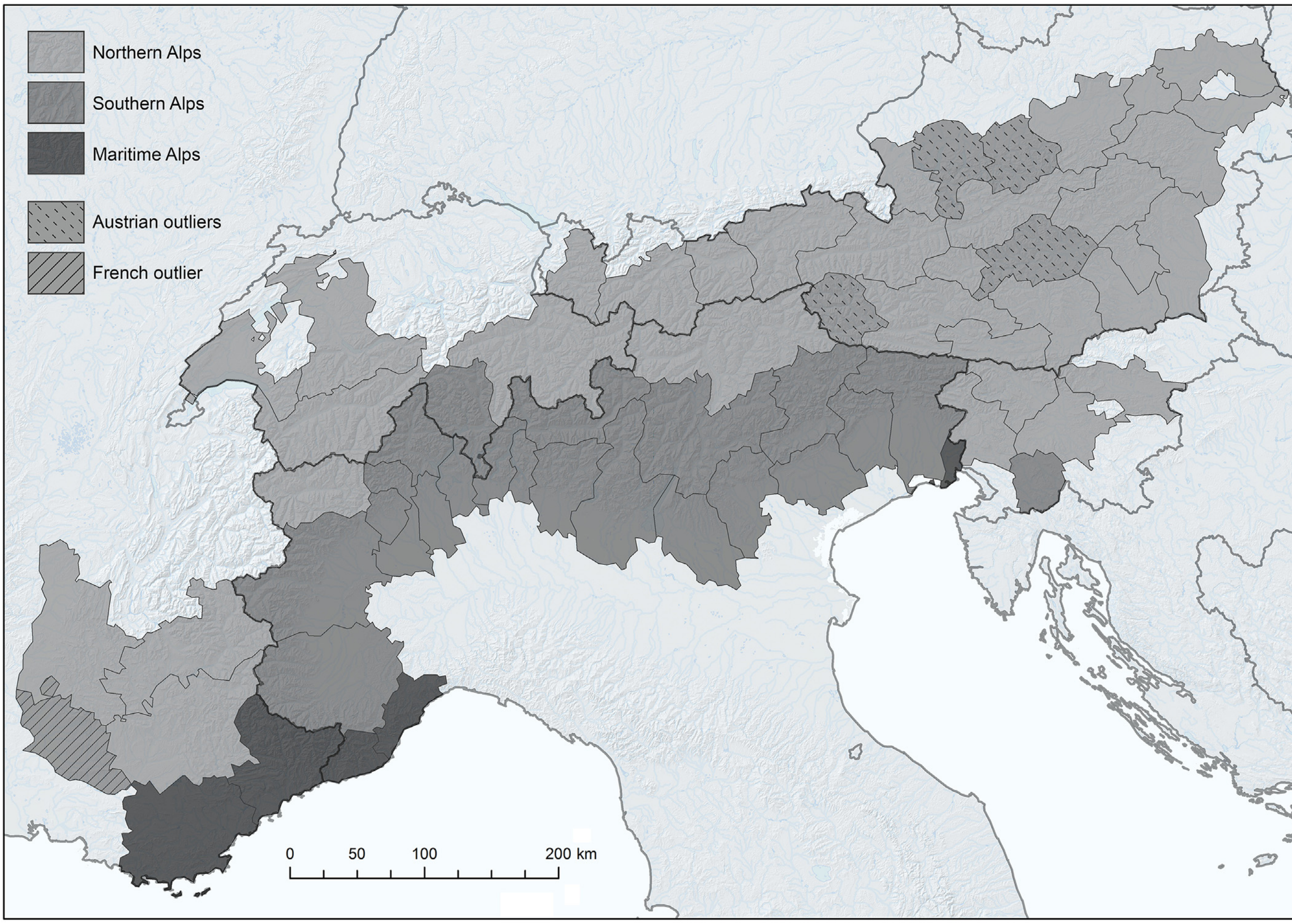

Fig. 4. Geographic distribution of the proposed Alpine fire regime clusters.

Table 4
Fire characteristics of the defined pyroregions.

Pyrologic classes	Nr NUTS3	Total area (km^2)	Combustible area[a] (km^2)	Forest area[a] (km^2)	Nr forest fires (n)	Burnt area (ha)	Yearly nr forest fires (n/y)	Yearly burnt area (ha/y)	Mean event burnt area (ha)	Winter fires (%)	Winter burnt area (%)
Northern Alps	33	114,383	83,710	48,219	2701	11,827	282	1186	4.2	40.6	22.2
Austrian outliers	4	9811	8086	5030	93	132	11	16	1.5	37.6	6.9
Southern Alps	21	63,825	39,868	24,053	7185	49,704	719	4970	6.9	71.9	84.6
Maritime Alps	5	13,458	10,474	6314	7388	55,600	739	5560	7.5	35.5	22.6
French outlier	1	3573	1567	1056	489	871	49	87	1.8	25.2	11.1
Total	**64**	**205,050**	**143,705**	**84,672**	**17,856**	**118,135**	**1799**	**11820**			

[a] Combustible area and Forest area: see legend to Table 1.

39.83% of the total variance of the response variables (RDA1 = 30.86% and RDA2 = 8.97%), whereas the variance explained by the environmental and socio-economic variables (Fig. 7b) accounts for 39.12% (RDA1 = 28.51% and RDA2 = 10.61%). Both RDA plots show a clear separation among the convex hulls of the different fire regimes. The first RDA axis is mainly related to fire density, while the second RDA axis is mainly related to fire phenology. Accordingly, RDA1 shows the main distinction between low-density and high-density fire regimes, while RDA2 shows the transition from winter to summer fire phenology. The main environmental factor related to the fire regime in the Maritime Alps is represented by the presence of sclerophyllous forests, whereas the July and August wind conditions represent the main climatic fire driver. The French outlier displays similar drivers although to a lesser extent. Prolonged drought periods (LongDP.mean), especially in February (DD.Feb), and high evapotranspiration rates in March–April (Evapo.MarApr) are the main climatic fire drivers in the Southern Alps. Here, the marked south orientation of the main valley (RivDir4.S), the high population density (PopDens), and the generally low level of education (Education) appear to play an important role. The Northern Alps and the Austrian outliers in particular are characterized by a relatively high mean altitude (Alt.mean), a high proportion of coniferous forests (ConifFor), a consistent proportion of people that remain active in the primary sector (EconSect1), and relatively high air humidity conditions during summer (Rh.JulAug) (Fig. 7a and b).

The Wilcoxon rank-sum tests permitted the highlighting of significant differences in the distribution of the climatic (Fig. 8) and environmental and socioeconomic variables (Fig. 9) among clusters. For instance, the drought period indicators (LongDP.mean, DP30.mean)

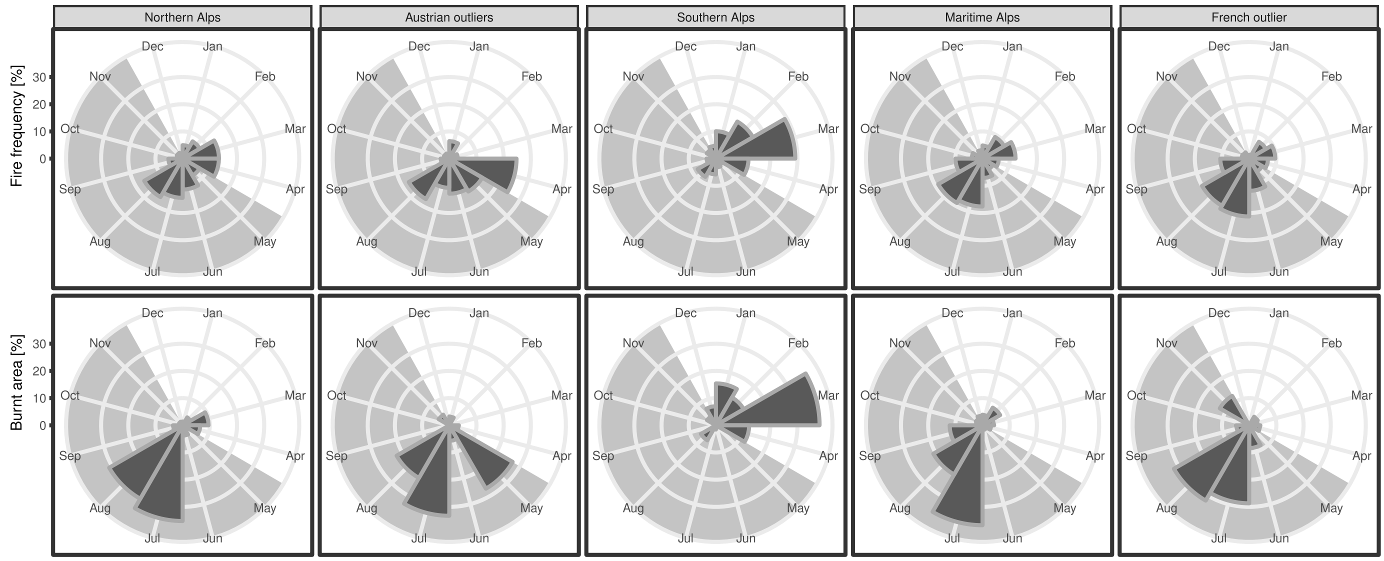

Fig. 5. Monthly frequency of fire events during the study period for the proposed Alpine fire regime clusters.

differentiate between northern (Northern Alps and Austrian Outliers) and southern (Southern and Maritime Alps) clusters, whereas February drought (DD.Feb) levels are significantly different within the southern regimes (Southern Alps vs Maritime Alps). Relative air humidity in July–August differentiates between the Northern Alps and the Austrian Outliers, while spring temperature and evapotranspiration

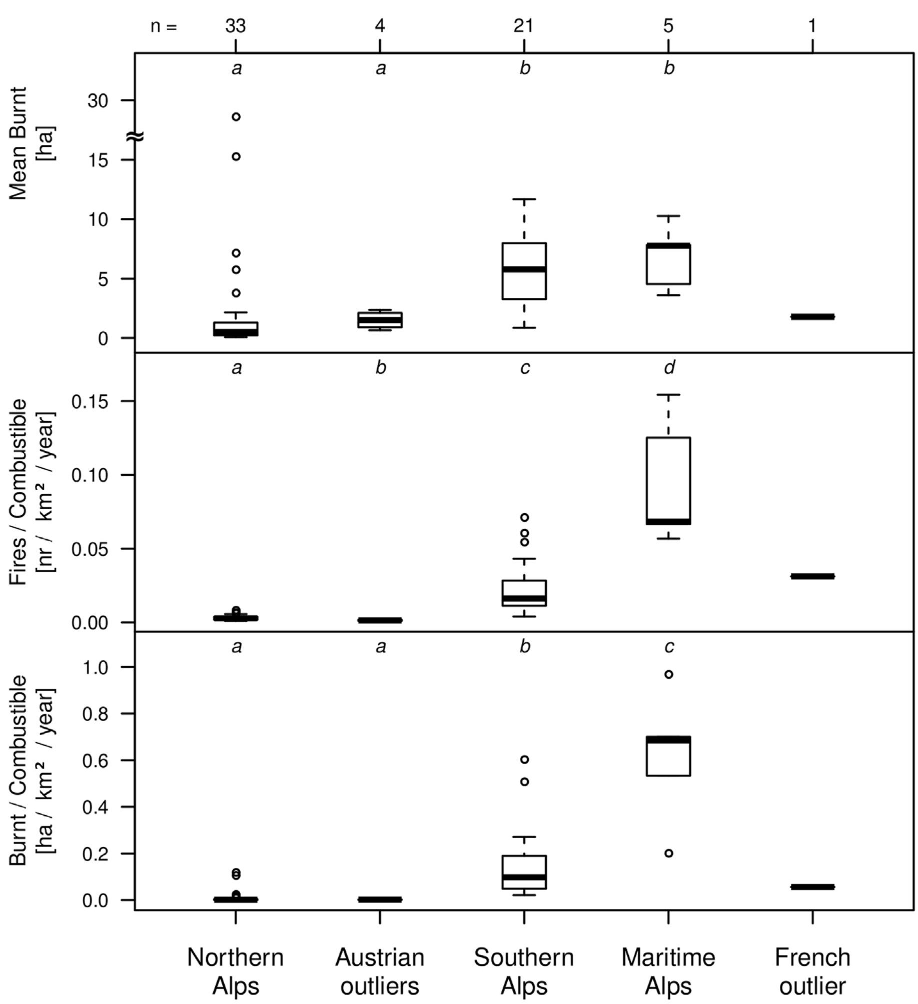

Fig. 6. Box plot of the distribution of fire metrics with respect to the defined Alpine fire regime clusters. Lines in bold represent the median. Boxes extend from the first to the third quartile, whereas whiskers include the smallest and the largest non-outlier points, i.e., points within 1.5 times the extent of the interquartile range. Different letters indicate significantly different distributions ($p < 0.05$, non-parametric Wilcoxon rank-sum test).

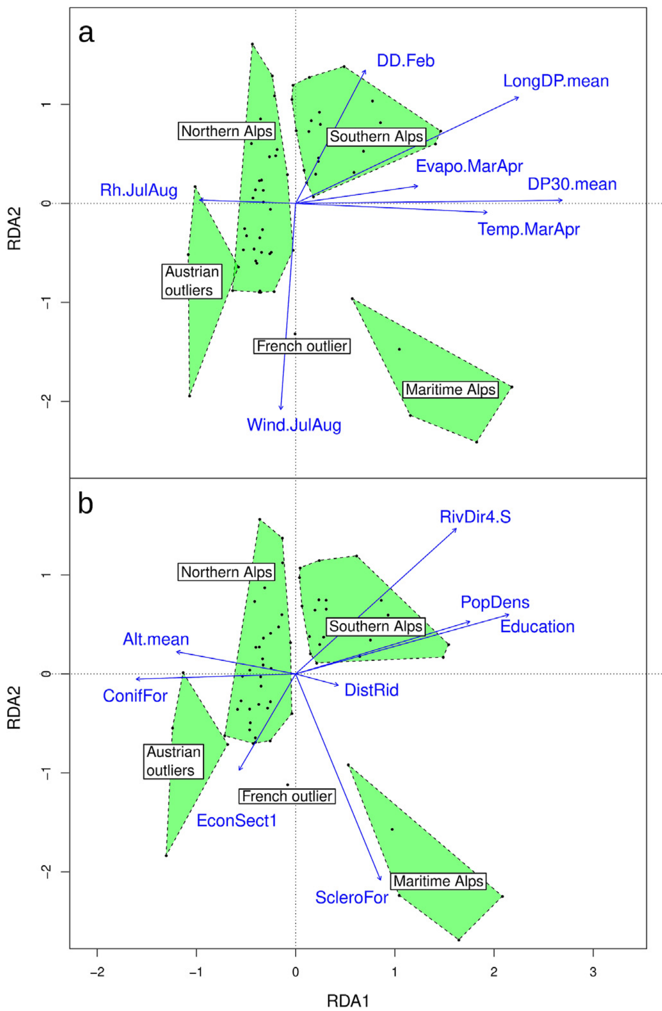

Fig. 7. Results of redundancy analysis for climatic (a) and environmental and socio-economic (b) variables. Squares represent single NUTS3 regions; shaded areas represent the convex hulls of the fire regimes in ordination space (fire regime labels in italics are located at the centre of gravity of convex hulls). Circles represent response variables (i.e., the fire regime metrics used in the cluster analysis in Fig. 3). Grey arrows represent predictor variables (i.e., potential fire drivers considered in this study). The length and direction of the arrows indicate the strength and the sign of correlation between predictor variables and the first two axes of the ordination space (RDA1 and RDA2), respectively.

(Temp.MarApr; Evapo MarApr) are significantly different between northern and southern clusters. Summer wind speed, in contrast, does not distinguish among clusters with the exception of the Southern Alps (Fig. 8). Environmental and socio-economic variables were much less meaningful in terms of discriminating among fire regime clusters. Significant variables include the marked south-north orientation of the main valleys in the Southern Alps, the higher proportion of Coniferous forests in the northern (Northern Alps and Austrian Outliers) clusters, and the differences in population density and level of education (Fig. 9).

5. Discussion

Although the Alpine region is not considered a fire-prone region on a global scale, wildfires in the Alps have been recorded since pre-historic times (e.g., Blarquez, Bremond, & Carcaillet, 2010; Carcaillet et al., 2009; Tinner, Hubschmid, Wehrli, Ammann, & Conedera, 1999). Fire impact on the landscape and vegetation has increased since the Neolithic when humans systematically used fire for woody fuel clearing, although with varying intensities according to local climatic conditions (Tinner, Conedera, Ammann, & Lotter, 2005). In the present study, the Alpine region is still found to be highly heterogeneous in terms of fire regimes as is consistent with its steep climatic and environmental gradient and the long-lasting human impact on the landscape (Conedera, Colombaroli, Tinner, Krebs, & Whitlock, 2017).

From a geographic point of view, a clear difference was found between the high fire density on the southern slope of the Alps and the substantially lower proportion of burnt area registered on the northern slope. This major contrast between the North (low danger) and the South (high danger) was also found by Dupire, Curt, and Bigot (2017) in the French Alps. The Italian regions of the Aosta Valley and South Tyrol are the two exceptions in the Central Alps, likely because of their markedly mountainous character and continental climate. The higher fire conductivity in the southern clusters (Southern and Maritime Alps) is mainly due to the generally low elevation and high population density of the areas combined with environmental and climatic factors that enhance fire ignition and spread. The snow-free upper litter layers that accumulate in the lowland forests dominated by chestnuts, deciduous oaks, and hornbeam, together with prolonged periods without rain associated with episodic north-foehn winds, are the main factors contributing to increased fire conductivity (Mofidi et al., 2015; Reinhard, Rebetez, & Schlaepfer, 2005; Sharples, Mills, McRae, & Weber, 2010) in the southern Alps. Mediterranean vegetation, rich in sclerophyllous and pine tree species, combined with the presence of dry winds (e.g. summer Mistral), in turn render the Maritime Alps particularly prone to rapid spreading fires in summer (Fréjaville & Curt, 2015; Ogrin, 1996). As a general rule, such a Mediterranean influence is much stronger in the western end of the Alpine region.

Interestingly, our analysis did not identify wind speed as one of the major climatic drivers of highly conductive fire conditions in winter for foehn regions. This is not really surprising given that foehn and Mistral are characterized by strong but irregular wind gusts, which renders average wind speed particularly unsuitable as an explanatory variable (Cesti, 1990; Plavcan, Mayr, & Zeileis, 2014; Richner, Duerr, Gutermann, & Bader, 2014). Nonetheless, the degree to which main valley axes deviate with respect to North-South and the average temperature in March and April may represent suitable indirect indicators of dominant foehn conditions. Summer wind speed, in contrast, was found to be relevant for areas with Mediterranean conditions, although without any markedly significant differences among other fire regime clusters with varying wind speed distributions.

The socio-economic variable of population density fits very well in the context of regions with high fire density. The Wildland-Urban Interface (WUI) is usually strongly related to population density (Conedera et al., 2015; Ganteaume & Long-Fournel, 2015) which, in turn, may significantly increase fire starts of voluntary or involuntary anthropogenic origin (e.g., Arndt, Vacik, Koch, Arpaci, & Gossow, 2013; Curt, Frejaville, & Lahaye, 2016; Regione Lombardia, 2009, p. 387; Regione Piemonte, 2011, p. 387). The proportion of the population with a low level of education shows a similar relationship which may also be related to anthropogenic fire ignitions. It is well known that the risk perception of natural and manmade disasters is related to the educational level (Huang et al., 2013; Kellens, Terpstra, & De Maeyer, 2013). It follows that those with low levels of education are less informed and concerned about the effects of forest fires and may be correspondingly less careful when dealing with fire (e.g., burning of wastes resulting from agricultural or forestry activities, campfires, and discarding cigarette butts).

The northern regions of the Northern Alps and Austrian Outliers are characterized by a relatively high mean elevation and a significant presence of coniferous forests that make them particularly prone to summer fires. In contrast, abundant snowfall in winter and persistent snow cover in spring tend to prevent winter/spring fires in such mountain areas. Furthermore, lightning-induced forest fires are frequent in coniferous-rich, steep mountain landscapes (Cesti, Conedera, & Spinedi, 2005; Conedera et al., 2006; Müller et al., 2013; Reineking

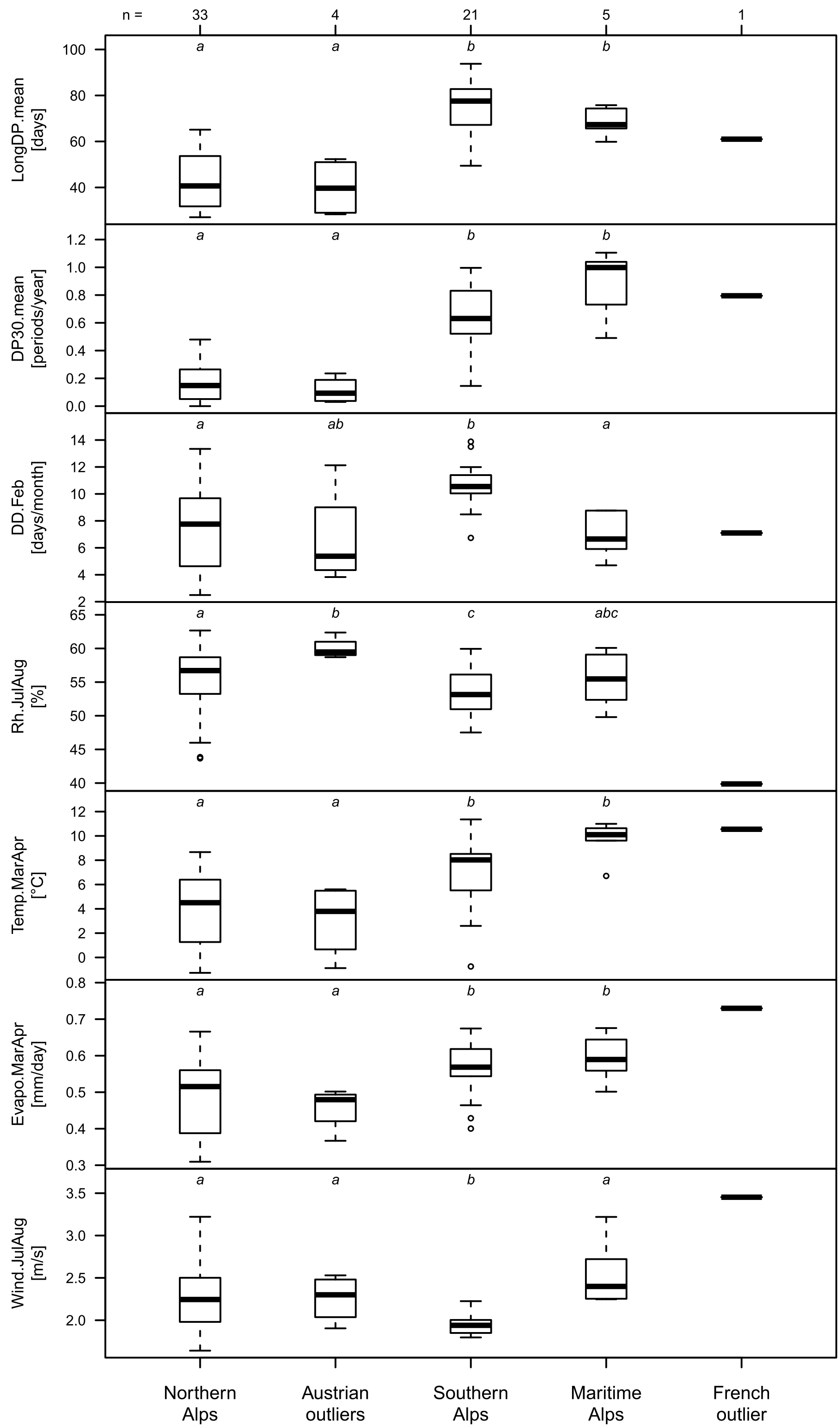

Fig. 8. Box plot of the distribution of the climatic variables retained in the RDA with respect to the defined Alpine fire regime clusters. Lines in bold represent the median. Boxes extend from the first to the third quartile, whereas whiskers include the smallest and the largest non-outlier points, namely, points within 1.5 times the extent of the interquartile range. Different letters indicate significantly different distributions ($p < 0.05$, non-parametric Wilcoxon rank-sum test).

et al., 2010; Vacik et al., 2011). Due to the particular fuel conditions, such fires tend to develop in the upper humus and soil layer, thus remaining confined in terms of burnt area (Conedera et al., 2006; Pezzatti et al., 2013). Although extended dry periods in July and August may occur and enhance fine fuel flammability, overall fire conductivity remains low (Vacik et al., 2011).

When looking in detail at the outliers, it becomes clear how differences with respect to the geographically adjacent cluster (i.e., Northern Alps for the Austrian outliers and Maritime Alps for the French outlier) are due to anomalous fire occurrence in specific years (see Annexes 2 and 3). For the Austrian outliers, this is the case in 2003, when an extraordinarily high level of burnt area was reached in April as

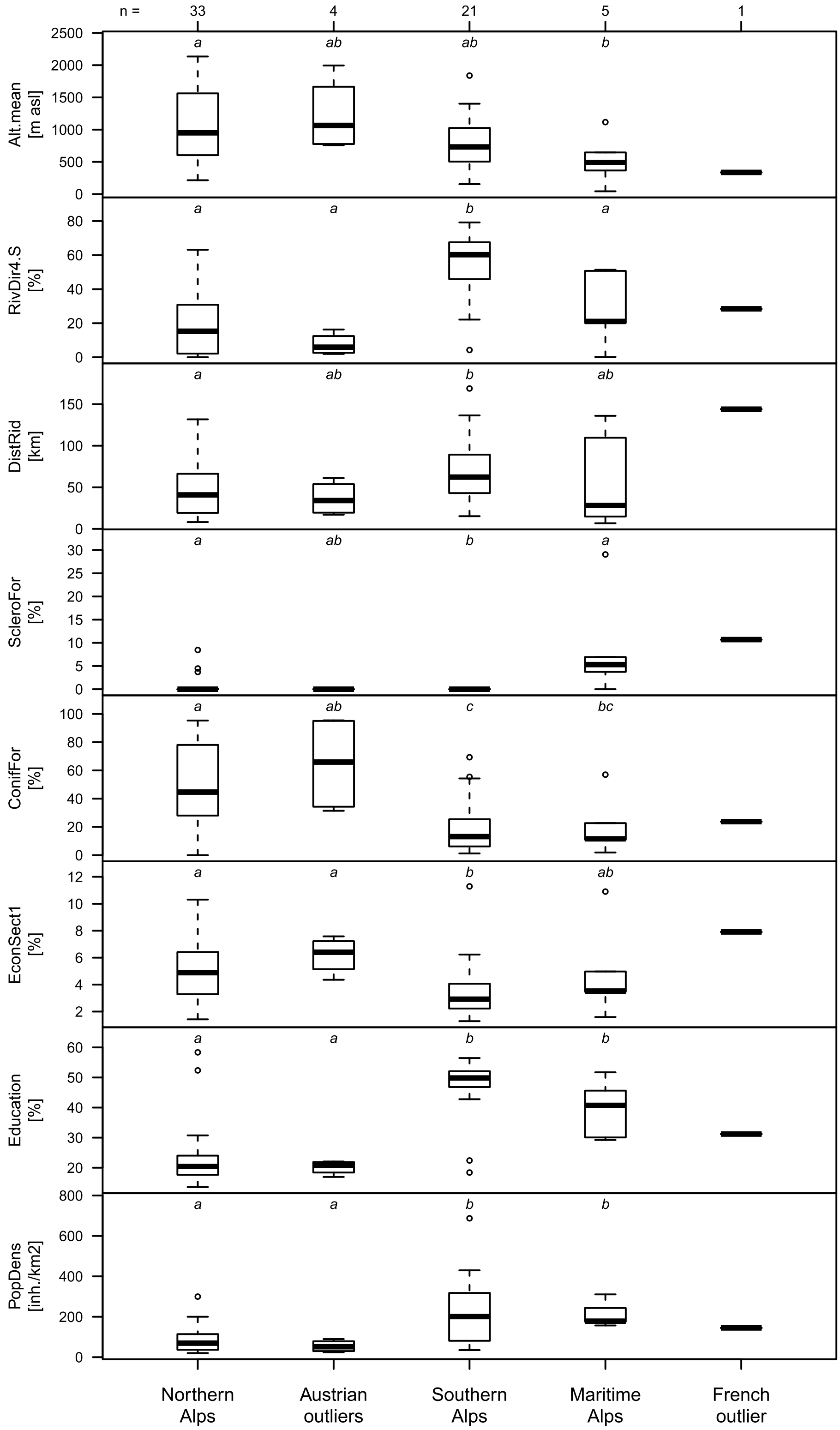

Fig. 9. Box plot of the distribution of the environmental and socio-economic variables retained in the RDA with respect to the defined Alpine fire regimes. Lines in bold represent the median. Boxes extend from the first to the third quartile, whereas whiskers include the smallest and the largest non-outlier points, namely, points within 1.5 times the extent of the interquartile range. Different letters indicate significantly different distributions ($p < 0.05$, non-parametric Wilcoxon rank-sum test).

well as in 2007 and 2009, when an abnormally high number of fire events occurred. The French outlier had an exceptionally high burnt area in August 2000 and in November 2007, which likely caused its exclusion from the Maritime Alps cluster. It is thus reasonable to assume that such anomalous years could be buffered by longer observation periods, resulting in the classification of these outliers into the appropriate adjacent main cluster, namely, the Northern Alps for the Austrian outliers and the Maritime Alps for the French outlier.

According to Valese et al. (2014), the reference period for this study (i.e., 2000–2009) coincides with a period of general reduction in overall fire density in the Alpine environment as a consequence of generally fire-unsuitable climatic conditions and the effectiveness of newly implemented fire management and fire suppression measures. On the other hand, uncommonly large fires episodically took place during the study period, also outside of the usual fire season (Schunk, Wastl, Leuchner, Schuster, & Menzel, 2013). In view of predicted climatic shifts (Schunk et al., 2013; Wastl, Schunk, Leuchner, Pezzatti, & Menzel, 2012) and ongoing land-use changes in mountain areas (Cocca, Sturaro, Gallo, & Ramanzin, 2012; Kulakowski, Bebi, & Rixen, 2011) particular attention should be paid in monitoring the evolution of Alpine fire regimes and of anomalous fire seasons (e.g., Müller et al., 2013, 2015).

6. Conclusions

In the present study, we propose for the first time a systematic fire regime classification of the whole European Alpine area based on fire regime metrics that describe general fire density (relative frequency and burnt area with respect to available combustible area) and fire phenology (fire seasonality).

Despite the short timeframe of the available data (ten years), the resulting classification scheme enabled us to define three main distinct fire regime clusters, including the detection of their main climatic, environmental, and socio-economic drivers. These fire regime clusters may represent an important baseline for detecting future fire regime shifts or anomalous fire seasons. Although forest fires do not currently have a major impact compared to the damage and costs of other natural disturbances (e.g., storms and bark beetles) throughout in the Alpine region, future fire regimes may evolve under the expected impact of climate and socioeconomic changes.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.apgeog.2018.07.011.

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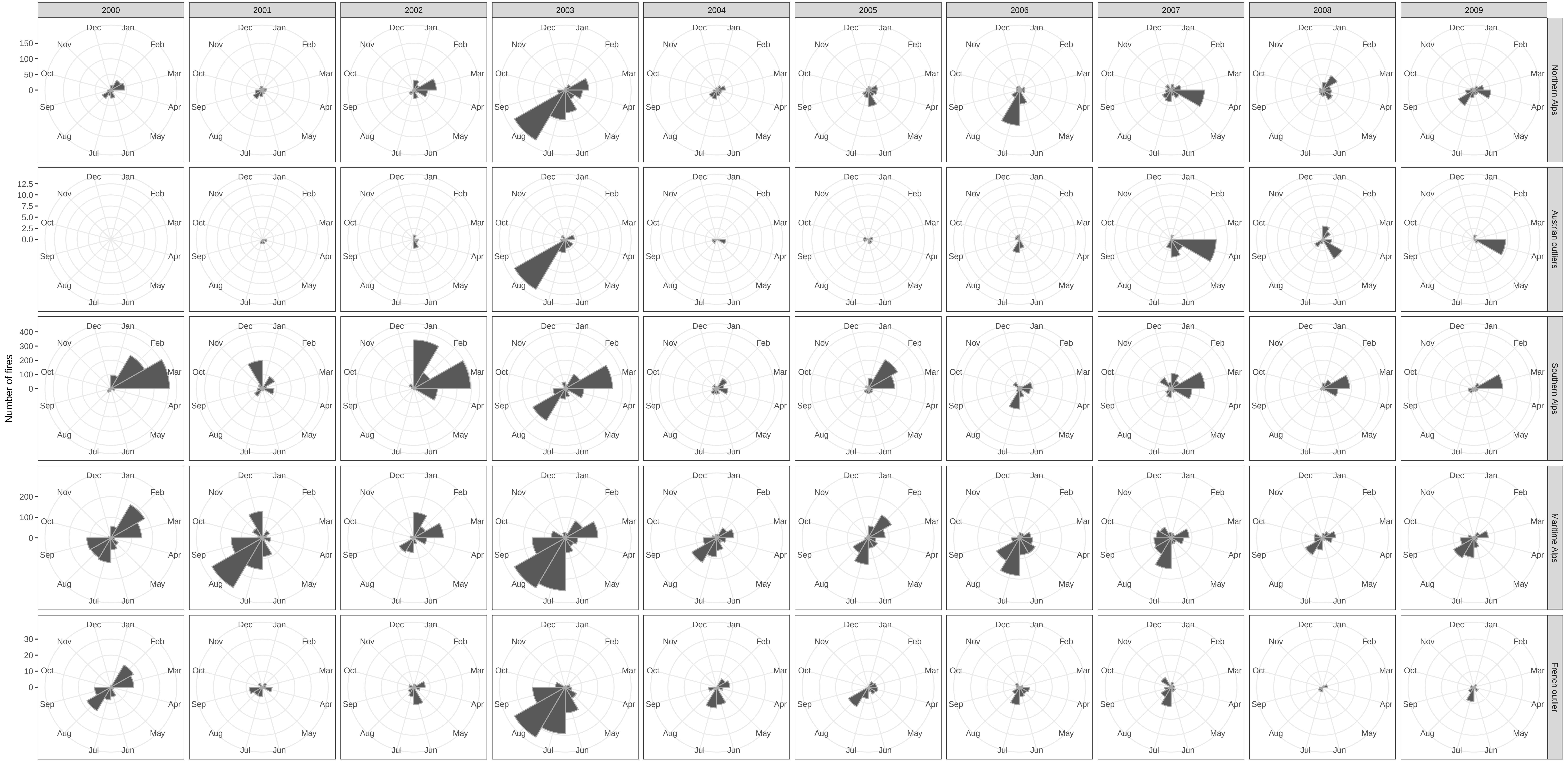
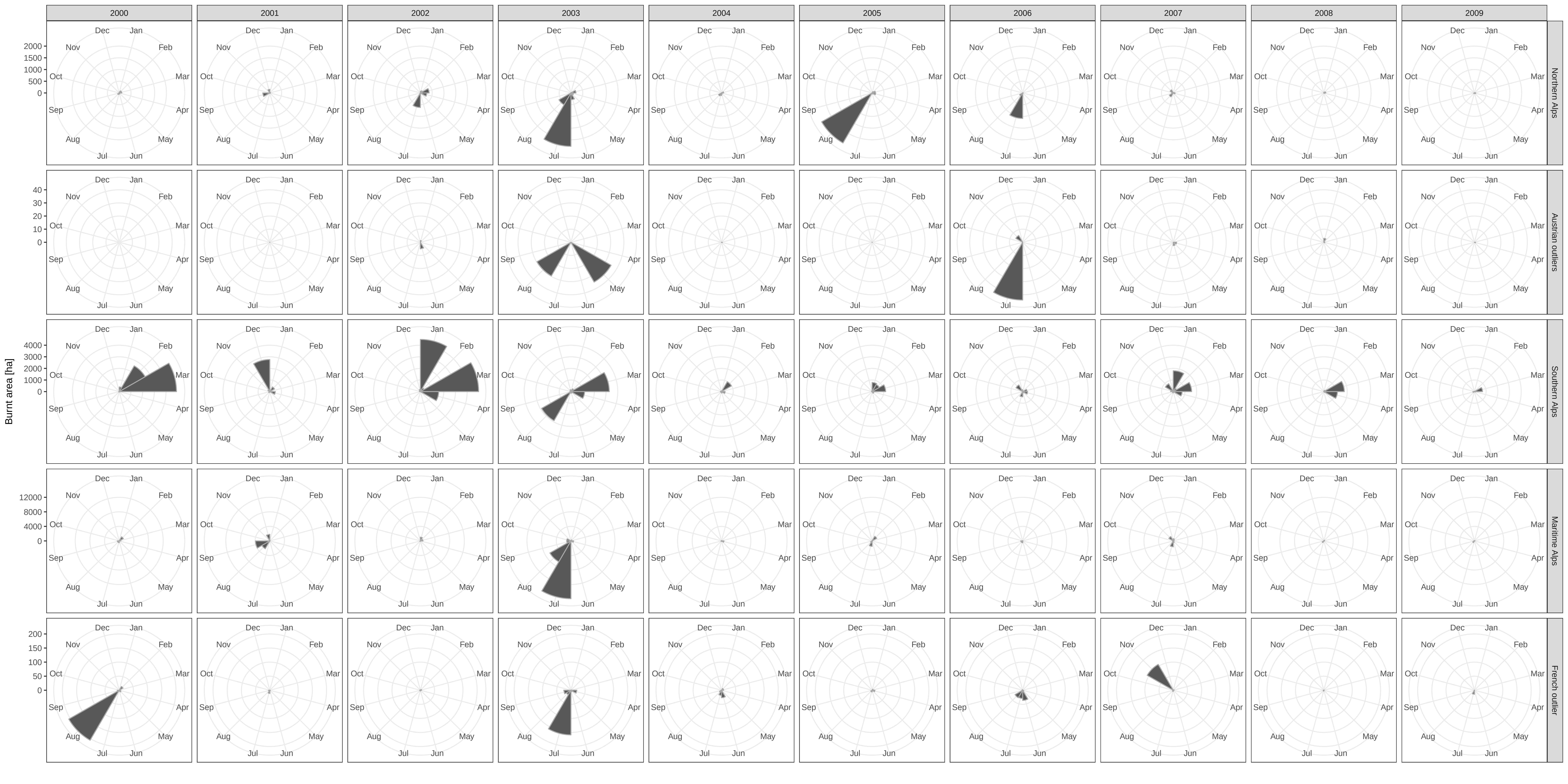
	Country	Nuts3	Cluster	Area *Km²*	Forest area *Km²*	Combustible area *Km²*	Years with fire data	Number of fires	Burnt area *ha*	Winter Fires *%*	Winter Burnt *%*
1	Austria	AT121	Northern Alps	3381.98	1527.86	2094.84	8	30	4.18	40.00	25.36
2	Austria	AT122	Northern Alps	3380.26	2268.98	2714.70	10	155	156.55	37.42	43.13
3	Austria	AT123	Northern Alps	1251.66	444.65	640.09	9	20	4.26	20.00	59.39
4	Austria	AT126	Northern Alps	2748.47	647.55	737.70	8	25	3.24	60.00	54.94
5	Austria	AT127	Northern Alps	1479.44	413.02	508.82	10	34	2.92	29.41	37.67
6	Austria	AT211	Northern Alps	2037.80	1238.30	1472.27	10	82	44.87	34.15	62.67
7	Austria	AT212	Northern Alps	4129.74	2034.25	3603.98	10	60	84.68	43.33	90.07
8	Austria	AT213	Northern Alps	3384.92	2140.10	2803.33	10	63	11.9	46.03	58.15
9	Austria	AT221	Northern Alps	1228.24	660.85	839.32	9	25	31.11	68.00	98.49
10	Austria	AT222	Northern Alps	3310.85	1798.87	3079.63	7	22	1.27	27.27	81.89
11	Austria	AT223	Northern Alps	3240.90	2325.62	3010.32	10	50	24.76	46.00	85.74
12	Austria	AT224	Northern Alps	3422.45	1519.34	1899.75	9	27	5.73	62.96	89.70
13	Austria	AT225	Northern Alps	2247.62	1234.77	1659.65	5	21	1.85	57.14	68.11
14	Austria	AT226	Austrian outliers	3058.84	1777.64	2813.66	8	18	42.81	50.00	11.45
15	Austria	AT314	Austrian outliers	2237.43	1275.72	1776.00	7	18	33.08	33.33	10.73
16	Austria	AT315	Austrian outliers	2525.14	1294.40	1940.04	9	39	45.16	46.15	1.26
17	Austria	AT321	Northern Alps	1036.86	456.86	977.92	7	17	3.94	58.82	80.71
18	Austria	AT322	Northern Alps	4380.71	1905.36	3769.08	9	43	11.96	39.53	30.85
19	Austria	AT323	Northern Alps	1749.68	857.28	1526.72	8	17	4.03	47.06	90.07
20	Austria	AT332	Northern Alps	2099.24	770.48	1694.96	9	43	28.81	30.23	90.04
21	Austria	AT333	Austrian outliers	2016.01	682.65	1555.89	9	18	11.69	11.11	0.68
22	Austria	AT334	Northern Alps	3336.60	854.58	2534.67	8	57	15.58	40.35	56.68
23	Austria	AT335	Northern Alps	3971.50	1846.86	3545.35	10	48	14.72	47.92	52.58
24	Austria	AT341	Northern Alps	1877.57	673.60	1706.62	7	23	5.05	60.87	98.02
25	Switzerland	CH011	Northern Alps	3227.27	1006.82	1463.90	8	44	20.18	52.27	43.66
26	Switzerland	CH012	Northern Alps	5225.53	1198.48	2816.62	10	66	383.18	51.52	16.46
27	Switzerland	CH021	Northern Alps	5936.17	1805.78	3473.42	10	105	22.88	29.52	29.41
28	Switzerland	CH056	Northern Alps	7127.76	1879.51	5431.23	10	153	95.6	27.45	39.28
29	Switzerland	CH070	Southern Alps	2829.61	1391.95	2256.14	10	479	1565.88	54.28	85.15
30	France	FR713	Northern Alps	6552.41	2782.85	4194.88	10	368	788.2974	30.16	26.15
31	France	FR821	Northern Alps	7022.14	2780.25	5479.71	10	389	5969.604	44.22	15.56
32	France	FR822	Northern Alps	5679.15	1684.71	4134.94	10	75	540.994	36.00	27.00
33	France	FR823	Maritime Alps	4290.18	1880.28	3575.16	10	2029	7294.3564	39.23	46.63
34	France	FR825	Maritime Alps	6025.85	2743.95	4360.46	10	2906	29865.3193	27.32	3.88
35	France	FR826	French outlier	3578.83	1055.67	1566.63	10	489	871.3329	25.15	11.10

	Country	Nuts3	Cluster	Area *Km²*	Forest area *Km²*	Combustible area *Km²*	Years with fire data	Number of fires	Burnt area *ha*	Winter Fires *%*	Winter Burnt *%*
36	Italy	ITC11	Southern Alps	6824.61	1961.43	4267.24	10	988	11548.91	68.62	84.55
37	Italy	ITC12	Southern Alps	2053.59	487.09	886.71	10	144	1110.08	77.08	77.39
38	Italy	ITC13	Southern Alps	929.80	374.23	695.66	10	498	3556.89	90.16	95.48
39	Italy	ITC14	Southern Alps	2250.68	1092.21	1908.38	10	249	2885.66	66.27	78.86
40	Italy	ITC15	Southern Alps	1357.32	294.77	481.31	10	294	914.19	79.59	95.33
41	Italy	ITC16	Southern Alps	6889.55	2203.33	4393.26	10	432	3447.13	59.72	53.11
42	Italy	ITC20	Northern Alps	3257.03	736.89	2368.52	10	167	643.52	56.89	72.02
43	Italy	ITC31	Maritime Alps	1168.70	638.31	1065.89	10	1334	10358.87	46.78	54.75
44	Italy	ITC32	Maritime Alps	1533.64	984.67	1340.67	10	915	7155.37	37.49	31.69
45	Italy	ITC41	Southern Alps	1189.60	499.45	621.43	10	269	1370.94	87.36	84.06
46	Italy	ITC42	Southern Alps	1261.37	585.70	871.13	10	479	5280	87.47	95.69
47	Italy	ITC43	Southern Alps	817.42	395.90	600.22	10	134	679.24	73.13	83.49
48	Italy	ITC44	Southern Alps	3190.65	1141.27	2240.67	10	249	1084.46	73.09	78.37
49	Italy	ITC46	Southern Alps	2749.86	1090.35	1752.44	10	340	2348.98	86.76	97.95
50	Italy	ITC47	Southern Alps	4782.14	1574.30	2406.92	10	737	6381.46	74.49	87.53
51	Italy	ITH10	Northern Alps	7426.13	3095.99	5942.40	10	223	157.67	34.98	71.43
52	Italy	ITH20	Southern Alps	6192.14	3382.86	5137.72	10	577	1088.49	59.10	83.51
53	Italy	ITH31	Southern Alps	3086.70	404.33	901.42	10	255	218.5	60.00	75.53
54	Italy	ITH32	Southern Alps	2703.90	974.91	1542.00	10	146	842.45	79.45	95.29
55	Italy	ITH33	Southern Alps	3688.39	2100.37	3113.62	10	124	1403.58	71.77	95.88
56	Italy	ITH34	Southern Alps	2455.33	319.27	516.48	10	65	108.17	75.38	87.74
57	Italy	ITH41	Southern Alps	2273.99	762.96	1107.14	10	168	640.76	69.64	80.74
58	Italy	ITH42	Southern Alps	4847.60	2034.36	2899.43	10	428	2828.23	65.42	72.32
59	Italy	ITH43	Maritime Alps	441.50	66.65	132.21	10	204	926.19	30.88	7.28
60	Slovenia	SI014	Northern Alps	2409.58	1260.50	1793.00	10	55	71.28	50.91	67.40
61	Slovenia	SI018	Southern Alps	1452.87	981.46	1268.94	10	130	399.57	66.92	84.71
62	Slovenia	SI021	Northern Alps	2566.83	1502.15	1927.79	10	67	136.55	62.12	33.07
63	Slovenia	SI022	Northern Alps	2140.46	1362.37	1813.01	10	46	47.56	42.22	21.39
64	Slovenia	SI023	Northern Alps	2327.12	1503.92	2051.08	10	87	2494.86	37.35	9.69



2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Northern Alps
Austrian outliers
Southern Alps
Maritime Alps
French outlier
Number of fires
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0
50
100
150
0.0
2.5
5.0
7.5
10.0
12.5
0
100
200
300
400
0
100
200
0
10
20
30



2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Northern Alps
Austrian outliers
Southern Alps
Maritime Alps
French outlier
Burnt area [ha]
0
500
1000
1500
2000
0
10
20
30
40
0
1000
2000
3000
4000
0
4000
8000
12000
0
50
100
150
200
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec