

# Spatiotemporal patterns of changes in fire regime and climate: defining the pyroclimates of south-eastern France (Mediterranean Basin)

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**Abstract** The impacts of climate change on fires are expected to be highly variable spatially and temporally. In heavily anthropized landscapes, the great number of factors affecting fire regimes further limits our ability to predict future fire activity caused by climate. To address this, we develop a new framework for analysing regional changes in fire regimes from specific spatiotemporal patterns of fires and climate, so-called pyroclimates. We aim to test the trends of fire activity and climate (1973–2009) across the Mediterranean and mountain ecosystems of south-eastern France, and to define the spatial distribution of pyroclimates. Stepwise-PCA and cluster analyses reveal that three pyroclimates capture the spatiotemporal patterns associated with fire regime and climatic conditions. Trend tests indicate a high significant increase in spring temperature and fire weather severity for most of the study area. In contrast, a general decreasing pattern of fire activity is observed since the early 1990s, specifically during summer in historically burned regions. However, winter and spring fires are becoming more frequent and extensive in less fire-prone mountains. Cross-correlation analyses indicate that inter-annual variations in extreme fire weather and fire activity were highly correlated. However, the intensity of relationships is pyroclimate-dependent. Our findings reveal that fire-climate relationships changed rapidly over space and time, presumably according to regional changes in land-use and fire policy. Assessing pyroclimates offers new perspectives for fire management and policy by delineating homogeneous zones with respect to fire, climate and their recent trends, and by revealing geographic contrasts in the underlying fire drivers.

## 1 Introduction

It is widely thought that a warmer climate will increase fire activity at regional (Westerling et al 2006) to global scales (Scholze et al 2006). However, recent modelling studies have demonstrated a high spatial heterogeneity in future fire activity induced by climate changes (e.g.

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Moritz et al 2012). Thus, identifying the regional determinants of changes in fire regime (e.g. the frequency, size, intensity and seasonality of fires) remains a challenging task.

Climate is probably the main driver of fires because, at broad scales, it controls fire weather (Flannigan et al 2000), lightning-induced ignition (Price and Rind 1994) and the amount and distribution of flammable biomass (Bond and Keeley 2005; Pausas and Paula 2012). In contrast, anthropogenic pressure on ecosystems can be seen as an altering driver. For instance the human imprint on vegetation patterns and dynamics may impair the interplay between climate and plant community composition and, as such, the properties of vegetation fuels. Otherwise, the density and timing of ignitions are largely dependent of human practices and population density, especially in Euro-Mediterranean regions (Ganteaume et al 2013), which thus strongly reshape fire regimes (Bowman et al 2011; Archibald et al 2012). In addition, the fire-climate relationship at a regional scale should be offset by temporal changes in land use and fire management policies (Mouillot and Field 2005; Marlon et al 2008). Therefore, it appears that no description or projection of the climate effects on wildfires makes sense without reference to particular climatic, ecological and human contexts. Consequently, in heavily anthropized landscapes like the European Mediterranean regions, determining the part climate effects play on fire regimes requires to design analyses within appropriate geographic units and time periods to encompass the dominant ‘switches’ (*sensu* Bradstock 2010) of the local fire regime.

A growing interest has focused on considering fire regime to be a geographic feature, because this multidimensional and complex process is fed by spatially dependent environmental gradients (Murphy et al 2011). Founded on this perspective, we developed an analytical framework for analysing regional changes in fire regimes based on spatiotemporal patterns of fires and climate, i.e. pyroclimates. We defined a ‘pyroclimate’ as a geographic entity that presents homogeneous attributes with respect to fire regime, climatic conditions and the temporal trends of both. In relation to the pyroclimatic hypothesis (Biondi et al 2011) – underpinned by an a priori causal relationship between climatic temporal variability and fire occurrence – we hypothesize that two areas belonging to one pyroclimate should be characterized by a specific expression and hierarchy of fire environmental drivers including climate, vegetation and human activity. In contrast, pyroclimates with different fire regimes but similar climatic conditions (or vice versa) should implicitly reveal differences in the type and strength of human-driven alterations of their fire regime.

We aimed to assess the diversity of pyroclimates in south-eastern France. This area offers a good case study by providing wide gradients of climate, vegetation and anthropogenic pressures within a rather small area, and because recent variations in fire activity have not yet been studied. We tested how the main components of fire regime, climate and fire danger have changed regionally over the past four decades and we described how pyroclimates draw the outlines of their spatiotemporal patterns.

## 2 Methods

### 2.1 Pyroclimatic space

The pyroclimatic space of south-eastern France has been quantified for the period 1973–2009 at a 2 × 2 km resolution from the national fire database (Prométhée 2011) and downscaled

climate data from the near-surface daily atmospheric parameters of the Safran reanalysis system (8×8 km resolution) (Vidal et al 2010). We defined it on the basis of four components: i) fire regime, ii) climate (bioclimatic and fire danger indices) and iii-iv) recent temporal trends of both.

The Prométhée database includes date of ignition, size and location (2×2 km resolution) of wildfires which occurred since 1973 in the 15 departments of south-eastern France, anthropogenic (accidental, arson, agricultural burning, etc.) or not (naturally ignited). To assess the fire regime, we quantified several components from 2×2 km aggregates of i) fire season length (number of days between the ignition of the first and the last fire of the year), ii) yearly and seasonal fire occurrence (fire density) and iii) yearly and seasonal cumulated size of fires (burned area) which ignited in a given pixel. In the less fire-prone areas, fire events are too scarce to occur each year within a given pixel. Consequently we applied a smoothing procedure to prevent too high spatial heterogeneity in fire regime attributes (Boulanger et al 2012). The latter were first computed by accounting for fire records within moving windows of 5 km radius. Fire attributes were then smoothed by an inverse distance weighting function using a larger moving window (30 km). In this way we focused on the deterministic part of the regional fire regime by reducing the stochasticity inherent in the fire process and in local-scale factors such as urbanization or micro-topography.

Bioclimatic indices include annual statistics of daily mean temperatures and daily precipitation. Fire danger was assessed using the components of the Canadian Fire Weather Index System, which rate the initiation, spread and control of forest fires (Wotton 2009). Calculations of the Fire Weather Index (FWI) and of its drought components (Fine fuel Moisture Code FFMC, Duff Moisture Code DMC and the Drought Code DC) were carried out from daily mid-day parameters of temperature, relative humidity, wind speed and daily rainfall (Van Wagner 1987), using the equations given by Van Wagner and Pickett (1985). It has recently been noted that using conditions at noon (12 h GMT) instead of daily means achieves more reliable estimates of mean and extreme conditions of fire danger (Herrera et al 2013). Long-term mean values of both bioclimatic and fire danger indices (hereafter referred to as ‘climate indices’) – from monthly, seasonal and yearly averages to annual extreme values (70th and 95th percentiles) – were computed at an 8×8 km resolution over the period 1960–2009 (the ‘reference period’).

Climate indices were then interpolated to 1×1 km resolution with the help of regional statistical modelling using lapse rates (Schumacher and Bugmann 2006; Zimmermann and Kienast 2009; Wang et al 2012). Specifically, regionalized linear regressions were employed to model, *per* homogeneous climatic zone (‘symposium’, Vidal et al 2010), the relationships between long-term mean values of climate indices (‘reference’ period) and elevation (Safran data, 8 km resolution). Regression intercepts and lapse rates were spatially interpolated between ‘symposiums’ using an inverse distance weighting function with a buffer of 30 km. We constrained the interpolation from well fitted vertical gradients of climatic indices, i.e. for a determination coefficient threshold of 0.7. We used a 0.5×0.5 km Digital Elevation Model (DEM) supplied by the National Geographic Institute to construct fine-scale climatic maps from spatially interpolated regression intercepts and lapse rates. Finally using an ‘anomaly approach’ (Zimmermann et al 2013), we applied the anomalies – computed at 8 km resolution between the ‘reference’ period and shorter ones (monthly to annual scale) – to the fine-scale maps, after interpolating anomalies by inverse distance weighting. Downscaled values were then aggregated to the 2 km-resolution fire grid.

Temporal trends were quantified by the correlation coefficient of a modified Mann-Kendall trend test (Hamed and Ramachandra Rao 1998). With respect to the annual distribution of fire occurrence (Online Resource Fig. S1), fire spatiotemporal patterns were separately mapped for the two peaks of the fire season: winter-spring (December to May) and summer-autumn (June to November). Among all the variables used to partition south-eastern France into pyroclimatic regions, the most discriminating ones are presented in Table 1, i.e. those that presented significant differences ( $p < 0.05$ ) amongst pyroclimates. To limit

**Table 1** Distribution of the three pyroclimates along seasonal and annual gradients of fire regime, climate and their temporal trends over the period 1973–2009. Variables presented here are those which best discriminated pyroclimates in the partition analyses or which showed the strongest temporal trends. For each of these gradients, average positions of pyroclimates were analysed by testing deviation from the overall mean (bootstrap resampling procedure, see section 2): blue (lower than average,  $p < 0.01$ ), light blue (lower than average,  $p < 0.05$ ), orange (higher than average,  $p < 0.05$ ), red (higher than average,  $p < 0.01$ ), no colour ( $p > 0.05$ ). Pyroclimate mean values for fire and climate parameters are indicated. Trend values are the correlation coefficients ( $\tau$ ) of the modified Mann-Kendall trend test, with significant trends in bold ( $p < 0.05$ )

dataset	variable	Unit	PYROCLIMATES		
			PCr-1	PCr-2	PCr-3
FIRE REGIME	fire density	$y^{-1} \cdot km^{-2}$	0.073	0.035	0.008
	fire size †	$ha \cdot y^{-1} \cdot km^{-2}$	<b>0.67</b>	0.30	0.07
	fire season length	Days	<b>87</b>	67	14
	winter fire size †	annual ratio	0.19	0.10	<b>0.30</b>
	spring fire size †		0.05	0.11	0.18
	summer fire size †		0.69	0.73	0.45
FIRE TRENDS	$\tau$ winter fire density	no unit	<b>0.27</b>	<b>-0.26</b>	0.16
	$\tau$ spring fire density		<b>0.36</b>	-0.21	-0.01
	$\tau$ summer fire density		<b>-0.20</b>	<b>-0.35</b>	<b>0.06</b>
	$\tau$ autumn fire density		<b>0.19</b>	<b>-0.29</b>	-0.08
	$\tau$ winter fire size †		-0.18	<b>-0.41</b>	<b>-0.15</b>
	$\tau$ spring fire size †		-0.14	<b>-0.27</b>	-0.23
	$\tau$ summer fire size †		<b>-0.33</b>	<b>-0.23</b>	<b>-0.16</b>
	$\tau$ autumn fire size †		<b>-0.13</b>	<b>-0.33</b>	-0.14
CLIMATE	driest month precipitation	Mm	9.1	10.2	<b>16.3</b>
	hotter month temperature	°C	20.3	<b>22.3</b>	17.9
	winter precipitation	annual ratio	<b>0.25</b>	0.23	0.22
	spring precipitation		0.22	0.23	<b>0.26</b>
	summer precipitation		<b>0.16</b>	0.20	<b>0.22</b>
	autumn precipitation		<b>0.37</b>	0.34	0.30
	95 percentile FFMC	no unit	89.0	<b>91.2</b>	90.1
	95 percentile DMC		91.8	109.6	61.9
	95 percentile DC		547.5	578.0	388.0
	95 percentile FWI		25.0	<b>37.5</b>	22.4
CLIMATE TRENDS	$\tau$ spring temperature	no unit	<b>0.63</b>	<b>0.66</b>	<b>0.62</b>
	$\tau$ summer temperature		<b>0.26</b>	<b>0.22</b>	0.14
	$\tau$ winter precipitation		<b>-0.29</b>	<b>-0.24</b>	<b>-0.16</b>
	$\tau$ 95 percentile FFMC		<b>0.73</b>	<b>0.61</b>	<b>0.57</b>
	$\tau$ 95 percentile DMC		<b>0.48</b>	<b>0.30</b>	0.20
	$\tau$ 95 percentile DC		<b>0.33</b>	0.20	0.20
	$\tau$ 95 percentile FWI		<b>0.71</b>	<b>0.29</b>	<b>0.40</b>
	$\tau$ spring FWI		<b>0.57</b>	<b>0.24</b>	<b>0.40</b>
	$\tau$ summer FWI	<b>0.56</b>	<b>0.28</b>	<b>0.30</b>	

† Fire size here means the cumulated size of fires that started within a given area of one square kilometre

autocorrelation between seasonal and annual values of a given variable we normalized seasonal variables into annual ratio:

$$Y'_{si} = Y_{si}/Y_{yi}. \quad (1)$$

Where the value of the variable  $Y$  for the season  $s$  at the cell  $i$  was normalized by its annual value  $Y_{yi}$ .

## 2.2 Pyroclimatic regions

Partitioning the pyroclimate space of south-eastern France into areas with regional affinities was achieved by ordination and cluster analyses without the explicit use of spatial constraints (i.e. spatial coordinates). Specifically, we first independently synthesized each of the four dimensions of the pyroclimate space (fire, climate and their temporal trends) from Principal Component Analysis (PCA) using a backward selection procedure. Backward selection was applied to remove the variables that contributed least when the three first orthogonal components of the PCA did not account for 80 % of the variation for a given dimension. In this way, the variability of fire regime, climate and their temporal trends was described by only 10 ‘super-variables’ (two or three principal components *per* dimension) which explain most of the pyroclimatic variability. Secondly, we performed hierarchical agglomerative clustering (HAC) on the ‘super-variables’ based on a Euclidean distance matrix and the Ward criterion (Ward 1963). An independent k-means clustering with Monte Carlo simulations (Makarenkov and Legendre 2001) was first carried out in order to obtain statistically optimal numbers of groups. Specifically we applied the Calinski-Harabasz criterion (Caliński and Harabasz 1974) using the ‘cascadeKM’ function of the R package ‘vegan’ (Oksanen et al 2013). Because using this decision tool resulted in dual spatial partitioning from supra-regional trends and inside variability of pyroclimates, only the broader classification is detailed here for simplicity; indeed, it captures most of the information.

Discrimination of pyroclimates based on fire and climate gradients was analysed using a bootstrap resampling procedure. Specifically, for each variable we ran 1000 random samplings of observations *per* pyroclimatic region (70 % of pixels) and we tested the deviation between their arithmetic mean and the mean value for the study area. The significance of alternatives to the null hypothesis (i.e. upper or lower mean value of the  $i^{th}$  pyroclimate compared to that expected by chance on the  $k^{th}$  variable) was computed using the number of times a positive or negative deviation (respectively) was observed.

Relationships between inter-annual variation in fire parameters and extreme fire weather (FWI 95th percentile) were assessed *per* pyroclimate from cross-correlation analyses (Venables and Ripley 2002). Cross correlations were computed on detrended time series using LOESS fitting (Cleveland et al 1990), i.e. after removing potential effects of climatic-independent fire drivers (Turco et al 2014). All analyses and calculations were performed in the R environment (R Core Team 2013), with the help of the ‘fume’ package for FWI calculations and trend tests (Santander Meteorology Group 2012).

## 3 Results

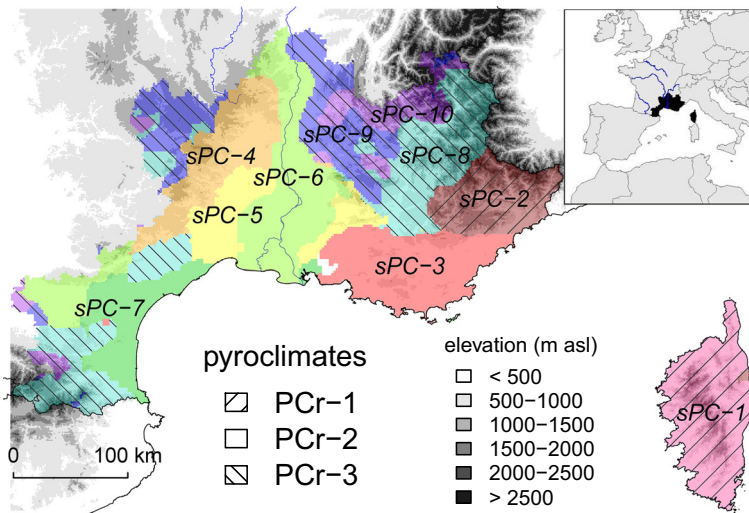
### 3.1 Pyroclimates

Partitioning analyses indicated that spatiotemporal patterns of fire regime, fire weather and climate divided south-eastern France into three main pyroclimatic regions with 10 sub-regions

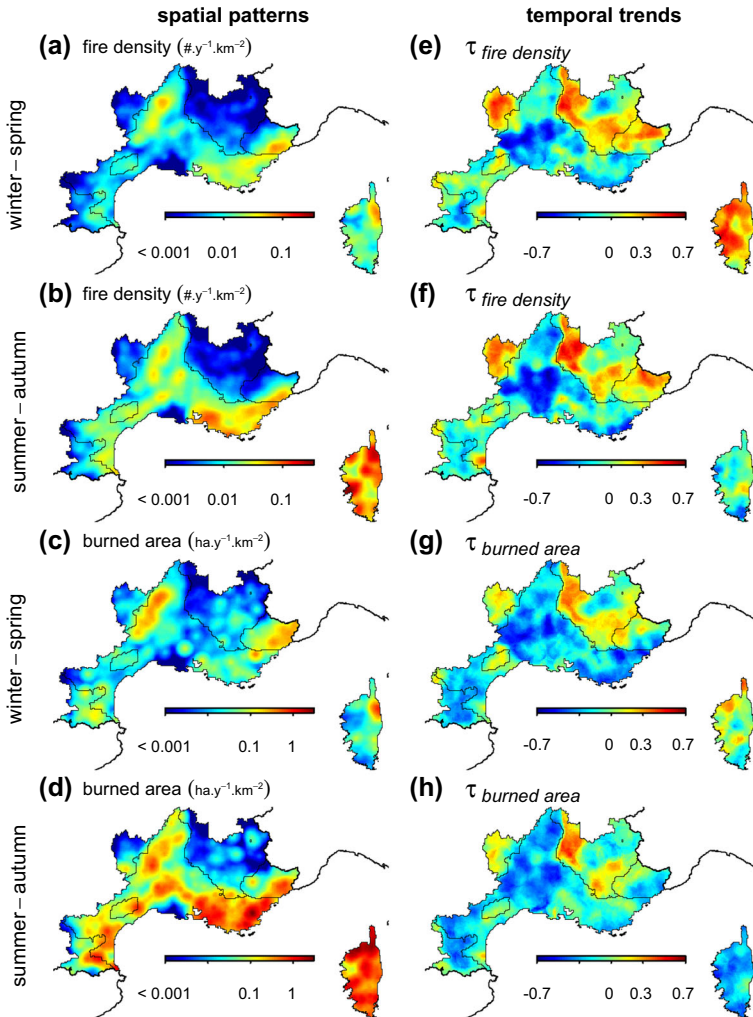
(Fig. 1). These regions have contrasting combinations of climate and fires, from high fire-prone maritime mountains (PCr-1: Corsica sPC-1 and maritime Alps sPC-2) to moderate fire-prone Mediterranean plains and foothills (PCr-2: Provence sPC-3, Ardèche plateau sPC-4, Rhône valley sPC-5-6 and western Mediterranean coast sPC-7) and low fire-prone temperate mountains (PCr-3: eastern Pyrenees, Cévennes and southern Alps, sPC-8 to 10). Analyses of pyroclimate distribution along the most discriminating spatiotemporal gradients of climate and fire are reported hereafter and in Table 1.

Mean seasonal patterns of fire density and burned area for the period 1973–2009 exhibit large spatial gradients in fire activity (Fig. 2a-d). Fire activity is stronger in the most thermophilic ecosystems, i.e. around the Mediterranean coast, with the exception of wetlands (Rhône delta, central coast) and largely urbanised and cultivated areas (plains of the western coast). We also found high fire-prone areas in north-western elevated inland areas (Ardèche plateau, sPC-4, Fig. 1). In winter-spring, burned areas were the most extensive in elevated areas (Eastern Pyrenees, Ardèche plateau and Maritime Alps from west to east, Fig. 2c) in contrast to the situation in summer-autumn (Fig. 2d). These general trends are partly corroborated by spatial patterns of fire danger and fuel dryness indices from the Canadian Fire Weather Index System (Fig. 3a-d). Indeed, high annual extreme values are found close to the sea for FWI and are associated with indices that estimate the moisture of moderate and deep organic layers (DMC and DC respectively) (Fig. 3b-c). Contrastingly, low levels of moisture for fine dead and cured surface fuels (FFMC) occurred further inland (Fig. 3a).

Consequently, burned areas and fire season length were higher in PCr-1 ( $p < 0.05$ ) whereas PCr-3 has the lowest averages of both fire density, size and season length ( $p < 0.05$ ), and PCr-2 an intermediate fire activity (Table 1). The least fire-prone pyroclimate PCr-3 is also the moistest and the coldest ( $p < 0.05$ ) with the lowest fire danger and the greatest, in terms of annual proportion, spring and summer rainfall ( $p < 0.05$ ) (Table 1). In contrast, the most fire-prone pyroclimate PCr-1 has the lowest annual ratio of spring and summer rainfall ( $p < 0.05$ , Table 1).



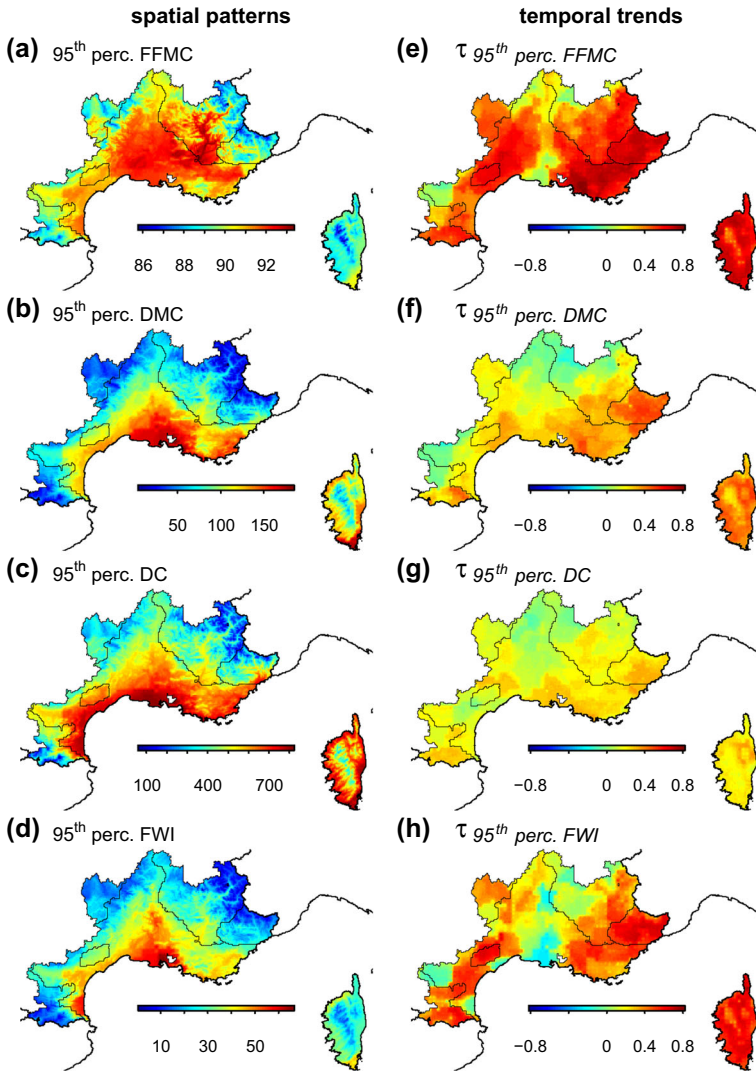
**Fig. 1** Pyroclimates of south-eastern France. Pyroclimatic regions (PCr) were subdivided into 10 sub-pyroclimates (sPC). Sub-pyroclimates were represented by different colours. See section 2 for details of pyroclimate partitioning, and Table 1 for pyroclimate attributes



**Fig. 2** Spatiotemporal trends (1973–2009) across pyroclimates for seasonal fire density (*top*) and burned area (*bottom*). The fire metrics distribution was smoothed by an inverse distance weighting function over a 30 km moving window (log-scale, **a–d**). Here, burned area represents the cumulative size of fires which ignited in a given square kilometre per year. Temporal trends (**e–h**) are mapped by computing, for each pixel, the correlation coefficient ( $\tau$ ) of the Mann-Kendall modified trend test

### 3.2 Spatiotemporal heterogeneity

Mann-Kendall trend tests indicated strong spatial heterogeneities in the temporal dynamic of these features (Figs. 2e–h and 3e–h). Surprisingly, fire activity has not changed in recent decades or has strongly decreased in the most fire-prone regions and increased within the less fire-prone mountains (Fig. 2e–h). In particular, PCR-2 has experienced the greatest decrease in fire density and burned area ( $p < 0.05$ ) with significant trends in almost all seasons ( $p < 0.05$  except for density of spring fires, Table 1). In contrast, PCR-1 has experienced the highest increase in fire density with significant trends in winter and spring (Table 1, Fig. 2e) while fire

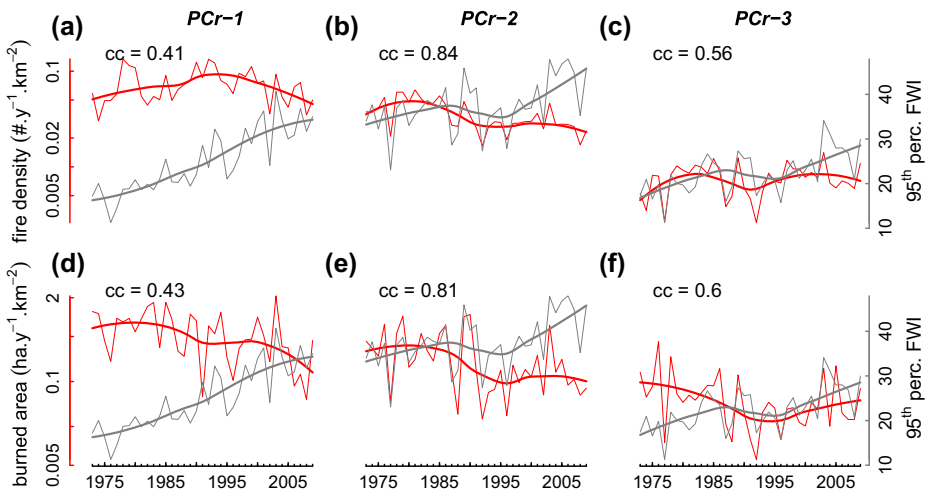


**Fig. 3** Spatiotemporal trends (1973–2009) across pyroclimates for annual extreme conditions in dryness and fire danger (Canadian Fire Weather Index System). Annual extreme values (95th percentile) over the period 1973–2009 of drought indices (a–c) and fire weather index (d) were averaged *per pixel*. Their temporal trends (e–h) were mapped by computing, *per pixel*, the correlation coefficient ( $\tau$ ) of the Mann-Kendall modified trend test. FFMC fine fuel moisture code, DMC duff moisture code, DC drought code, FWI fire weather index

density and burned area have both decreased in summer (Table 1, Fig. 2f, h). On average, fire activity has not changed in recent decades in the less fire-prone pyroclimate PCr-3 ( $p > 0.05$ , Table 1) despite the fact that some areas have experienced a significant increase in fire density (Fig. 2e, f), especially in winter, spring and summer in the sub-region sPC-9 (Fig. 1; tau=0.41, 0.20 and 0.32 respectively,  $p < 0.05$ ).

On the other hand, fire danger has greatly increased during the past four decades within all pyroclimates (Table 1, Fig. 3h, Fig. 4) and especially where the 1973–2009 average values





**Fig. 4** Averaged temporal trends (1973–2009) in annual fire activity (log-transformed fire density and burned area, in red) and fire weather index (95th percentile, in gray) within the three pyroclimatic regions (PCr-1 to PCr-3). Cross correlations (cc) were computed for detrended time series using LOESS fitting (thick curves)

range from low to moderate levels (Fig. 3d). We note that increasing trends in underlying dryness conditions were more likely for the fast-reacting FFMC and DMC (Fig. 3e, f) than for DC (Fig. 3g). In summary, PCr-1 has experienced the greatest increase in fire danger ( $p < 0.05$ ), although both the spring temperature, 95th percentile of FFMC and FWI, and spring and summer FWI have also significantly increased within the other two pyroclimates (Table 1).

### 3.3 Fire versus climate change

Trajectories over the 1973–2009 period for mean annual fire density and burned area versus the FWI 95th percentile suggest two interesting points (Fig. 4). First, cross-correlation analyses on detrended time series indicated moderate to strong relationships between inter-annual variability of fire activity and the 95th percentile of FWI. Second, temporal trends in fire activity and climatic fire danger have recently diverged in the most fire-prone pyroclimates. In PCr-1, annual fire density has followed the trend of climatic fire danger before fire density begins to fall since the early 1990's (Fig. 4a) and since the early 1980's for burned area (Fig. 4d). These trends were also found in PCr-2 with a shift between FWI and fire trends since the early 2000s (Fig. 4b, e). Despite the fact that burned area trends were not significant within low fire-prone mountains (PCr-3, Table 1), annual burned area has increased during the two last decades in the same way as annual extreme FWI (Fig. 4f).

## 4 Discussion

### 4.1 Spatiotemporal scales and pyroclimatic classification

The pyrogeography concept implies that fire activity can be predicted from climatic spatial gradients at global (Krawchuk et al 2009; Moritz et al 2012) to supra-regional scales (i.e. the Mediterranean biome, Batllori et al 2013). These studies are based on satellite-derived fire

statistics that focus their analyses on short temporal windows (e.g. one decade) and thus do not account for temporal variability of fire and climate. In contrast, our study analysed the spatiotemporal trends of several components of fire regime and climate at high spatial resolution over the four past decades. We found a high variability in these features across the rather small area of SE France. Our findings also emphasized that fire-climate relationships change over space and time.

Our pyroclimatic classification revealed contrasting geographic units that correspond to biogeographic units. The most fire prone areas correspond to two Mediterranean pyroclimates with high summer fire activity and dry summers: the maritime mountains with a productive climate (PCr-1) and the thermophilic hills and plains (PCr-2). A third pyroclimate (PCr-3) comprises temperate mountains which are less fire-prone and where fires occurred both in winter and summer (Table 1, Online Resource Fig. S1). Fire regime zonation has recently been emphasized because it has strong implications for fire protection agencies, sustainable forest management and conservation planning (Boulanger et al 2012). The authors of that study suggested that taking into account the temporal variability in fire activity (as we did) should provide a better representation of fire zones by refining homogeneity in both time and space. Therefore, our classification offers a new perspective on fire management and policy by delineating homogeneous zones in terms of fire danger, seasonal fire activity and recent temporal trends of both. This provides a first step towards an optimization of fire management in SE France through adaptive regional strategies for fire prevention, fuel management and fire-fighting. Moreover, as fire and climate are rapidly changing in south-eastern France (Fig. 2-4), our current pyroclimatic classification is well suited for detecting changes in the future by providing a reference map of recent fire-climate features.

#### 4.2 Fire and climate changes

We found that extreme conditions in fire weather (fire danger indices) have greatly increased in south-eastern France over the past four decades as has already been reported in the Mediterranean Basin (Piñol et al 1998; Moriondo et al 2006; Bedia et al 2013). Strong variations in fast-reaction moisture indices (FFMC, DMC) and weak variations in long-reaction DC suggest that there have been more frequent or intense droughts but of moderate duration. As suggested by calibration studies in the Mediterranean Basin, these changes in drought indices could be translated into a decreasing trend in the moisture associated with litter and cured herbaceous fuels (Aguado et al 2007) with, however, no clear potential changes in live woody fuel moisture (Pellizzaro et al 2007). Nonetheless, this implies that the flammability of ecosystems in south-eastern France has probably increased in these recent decades. This may have been associated with an increase in fire intensity, a fire regime component that we have not taken into account.

The increase in fire activity has been correlated to a rise in spring temperatures in the south-western United States (Westerling et al 2006) and to increases in annual or summer temperatures in other Mediterranean areas (Piñol et al 1998; Pausas 2004). In the heavily anthropized landscapes of south-eastern France, changes in fire regime appear more heterogeneous despite a highly significant warming, in particular in spring. Indeed, we found that fire density and burned area have increased in some regions and decreased in others, with season-specific trends. Significant increases in fire density and burned area correspond to either less fire-prone seasons (winter, spring and autumn in PCr-1) or less fire-prone areas (increase in burned area within PCr-3). In contrast, regions with historically high fire activity (PCr-1, PCr-2) have experienced a significant decrease in fire activity in summer although fire danger has

increased during all seasons. These results mirror recent findings in north-eastern Spain (Catalonia) where summer fire activity has also decreased (Turco et al 2014), but they seem to differ somewhat from those reported in other Mediterranean areas (Pausas 2004; Pausas and Fernández-Muñoz 2012). This may stem from human-driven changes in fire regimes through enhanced fire suppression strategies (Mouillot and Field 2005; Brotons et al 2013) or land use changes (Mouillot et al 2003).

#### 4.3 Fire-climate tipping points

Cross-correlation analyses indicated clear relationships between inter-annual variation in fire activity and the Canadian FWI (95th percentile). The predictive ability of FWI has already been demonstrated in south-eastern France for the last decade (Bedia et al 2013) as well as in other Mediterranean areas (Carvalho et al 2008; Dimitrakopoulos et al 2011; Venäläinen et al 2014). In the light of climate projections (Bedia et al 2013), fire activity is likely to increase in the future in south-eastern France. Nevertheless, we have found that fire activity trends have diverged from fire danger trajectories and there is evidence of tipping points for some regions. Specifically, asynchronous sudden drops in fire density and burned area have occurred in the most-fire prone pyroclimates (PCr-1 and PCr-2) within the period 1980–2000. On the other hand, the less fire prone pyroclimate (PCr-3) did not show evidence of fire-climate disruption over the period 1973–2009. Recent fire regime shifts have also been reported in the Western Mediterranean Basin where, in contrast, the annual burned area has increased since the early 1970s (Pausas and Fernández-Muñoz 2012). All these results seem to illustrate that fire drivers differ among pyroclimates and that their strength changes with time. For instance, we found that winter-spring burned areas were most extensive in several mountainous areas despite low fire danger. This fire-climate ‘anomaly’ could be related to the regional persistence of burning practices for agro-pastoral purposes (Métailié 2006). At the same time, the increase in fire density and burned area in less fire-prone mountains may have been the result, rather paradoxically, of an increase in fuel load following land abandonment (Chauchard et al 2007). In contrast, the recent reduction in summer fires over historically burned regions could have been the result of recent increased efficiency in fire suppression policies (Mouillot and Field 2005). Otherwise the observed tipping points in fire-climate relationships may be simply related to recent shifts in the way climate drives fires, as for instance through fuel limitation processes induced by drier conditions (Batllori et al 2013). These findings emphasize the fact that predictions about future fires based on climatic fire danger should be made with caution within the human-shaped landscapes of Euro-Mediterranean areas.

## 5 Conclusions

We have demonstrated that south-eastern France has experienced in recent decades a high regional variability with respect to changes in climate, fires and underlying environmental drivers. The original pyroclimatic classification that we have developed in this study offers new regional perspectives on fire management and policy because areas with similar climate and fire regime and similar evolution would benefit from specific management. In addition, our work provides a suitable framework to test how anthropogenic factors have recently altered fire-climate relationships. Thus, future studies are needed to test how different

environmental drivers lead to fire regime shifts, allowing us to enhance our ability to predict how fire activity will evolve in response to global changes.

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