

## Seasonal changes in the human alteration of fire regimes beyond the climate forcing

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## LETTER

# Seasonal changes in the human alteration of fire regimes beyond the climate forcing

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## Abstract

Human activities have altered fire regimes for millennia by suppressing or enhancing natural fire activity. However, whether these anthropogenic pressures on fire activity have exceeded and will surpass climate forcing still remains uncertain. We tested if, how and the extent to which seasonal fire activity in southern France has recently (1976–2009) deviated from climate-expected trends. The latter were simulated using an ensemble of detrended fire–climate models. We found both seasonal and regional contrasts in climatic effects through a mixture of drought-driven and fuel-limited fire regimes. Dry contemporary conditions chiefly drove fire frequency and burned area, although higher fire activity was related to wetter conditions in the last three years. Surprisingly, the relative importance of preceding wet conditions was higher in winter than in summer, illustrating the strong potential dependency of regional fire–climate relationships on the human use and control of fires. In the Mediterranean mountains, warm winters and springs favour extensive fires in the following dry summer. These results highlight that increasing dryness with climate change could have antagonistic effects on fire regime by leading to larger fires in summer (moisture-limited), but lower fire activity in winter (fuel-limited fire regime). Furthermore, fire trends have significantly diverged from climatic expectations, with a strong negative alteration in fire activity in the Mediterranean lowlands and the summer burned area in the mountains. In contrast, alteration of winter fire frequency in the Mediterranean and Temperate mountains has shifted from positive to negative (or null) trends during the mid-1990s, a period when fire suppression policy underwent major revisions. Our findings demonstrate that changes in land-use and fire suppression policy have probably exceeded the strength of climate change effects on changing fire regime in southern Europe, making regional predictions of future fires highly challenging.

## Introduction

For millennia, human activities have altered fire regimes, which are defined as the frequency, seasonality, intensity and size of wildfires (Gill 1975). Addressing this human dimension of fire is critical when attempting to predict how changing fire regimes will impact the Earth's systems (Bowman *et al* 2009, 2011, Archibald *et al* 2013). However, whether human-induced changes in fire activity were significant or negligible as compared to climate forcing is still widely debated. Indeed, at broad scales, climate is

generally recognized as the main fire driver (Krawchuk *et al* 2009, Daniau *et al* 2012), by determining the variability in the resource to burn (fuel biomass) and the occurrence, intensity and duration of dry conditions (fuel moisture) (Meyn *et al* 2007, Lehmann *et al* 2014). Beyond climate forcing, temporal shifts in global biomass burning over recent centuries have been related to increasing anthropogenic pressures on ecosystems (Marlon *et al* 2008). At local scales, the predominant effects of human factors have been highlighted by asynchronous shifts in fire regime (Carcaillet *et al* 2009, Fulé *et al* 2012). Therefore, it

appears that regional changes in human practices such as land-use, fire ignitions (intentional or accidental) or suppression may override the effects of climate on fire. Addressing how anthropogenic factors drove fire regime changes in the past is thus critical if we are to anticipate the extent to which future fire activity will deviate from expectations based on climatic factors (Liebmann *et al* 2016, Taylor *et al* 2016). It is particularly important at regional scales to separate potential contrasts in fire drivers among biogeographical and socioeconomic contexts (Boulanger *et al* 2012, Trigo *et al* 2016, Bedia *et al* 2014b). From these perspectives, we aimed to test the recent changes in the human effect on seasonal fire activity in the pyroclimates of southern France, i.e. among regions which differ in climate, fire regime and their recent temporal trends (Fréjaville and Curt 2015).

Fire–climate relationships can be summarized by considering two antagonistic effects. The rarity of wet conditions limit fire activity in dry ecosystems due to a lack of fuel availability (fuel-limited fire regime), whereas in moist ecosystems the rarity of dry conditions keep fuel from being sufficiently dry (drought-driven fire regime) to sustain fire spread (Krawchuk and Moritz 2011, Pausas and Ribeiro 2013). This antagonistic effect also operates on a multiannual scale through the alternation of wet and dry conditions favouring fires (Meyn *et al* 2007, Pausas 2004, Zumbunnen *et al* 2009), by increasing the amount of fine fuel in litter, grass and shrub layers during wet periods, which burn more intensely in subsequent dry periods (Fréjaville *et al* 2016). Therefore, drier conditions under a warmer climate may have antagonist effects on fire depending on whether fuel-limited or drought-driven fire regimes dominate (Boer *et al* 2016), as for instance in Mediterranean ecosystems where both are present (Batllori *et al* 2013).

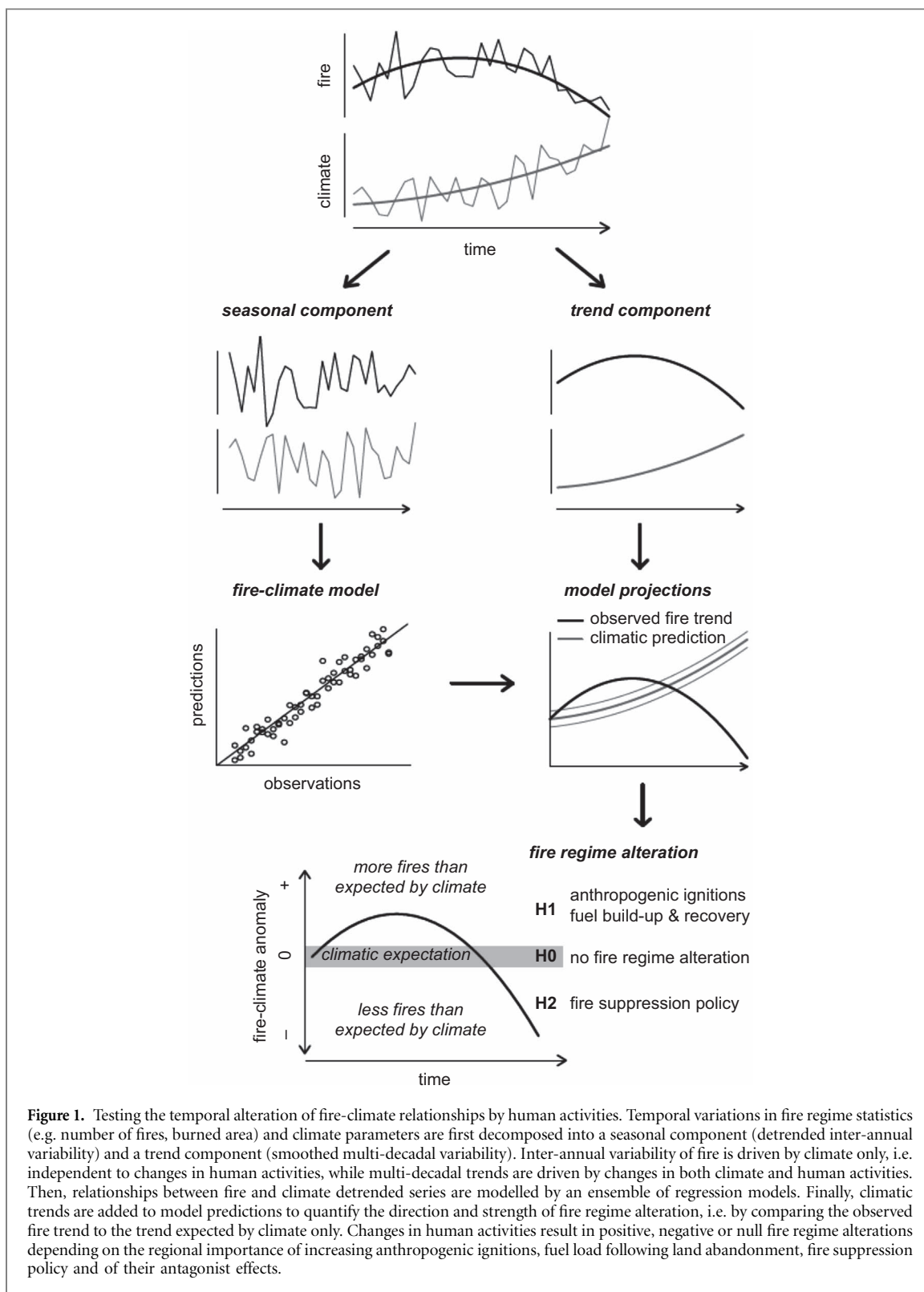
In the Mediterranean Basin, human activities directly modify the fire regime by setting or suppressing fires and by changing patterns of vegetation in the landscape (Moreira *et al* 2011). Moreover, the fuel build-up following agricultural land abandonment as a result of the rural exodus has created an increasing fire hazard in Mediterranean Europe (Moreira *et al* 2011, Pausas and Fernández-Muñoz 2012). On the other hand, changes in fire suppression policy over the last few decades have probably induced sharp decreases in fires (Pezzatti *et al* 2013, Moreno *et al* 2014). Hence the functional relationships linking fire to climate have been partially modified by human activities (Higuera *et al* 2015), decreasing or increasing the fire activity independently of climate change. Elsewhere, analysing changes in fire–climate relationships has commonly been addressed by comparing (multi-)decadal periods (Higuera *et al* 2015, Keeley and Slyphard 2015, Ruffault and Mouillot 2015). However, we lack an analytical framework to identify the functional mechanisms

linking climate to fire variability properly, i.e. by first removing the potential effects induced by human activities, to ensure that causal relationships are not biased from common (or opposite) trends in the data (Lobell *et al* 2011). For instance, in Euro-Mediterranean ecosystems, the interannual variation in fire activity is reported to be strongly and positively related to extreme fire weather (Fréjaville and Curt 2015, Urbietta *et al* 2015). However, building statistical models based on trending data with, on one hand, a decreasing fire trend (probably induced by fire suppression), and on the other hand, increasing extreme fire weather (with global warming) might incorrectly indicate a decreasing effect of a warmer climate on fire in these ecosystems.

We developed an analytical framework for modelling the functional relationships between fire and climate and testing seasonal human alteration of regional fire regimes (figure 1). Our method is based on separating fire and climate temporal variation into trend (multi-decadal) and seasonal (interannual variability) components, and on the assumption that effects of changes in human activities predominantly operate at the former level (Turco *et al* 2014, Urbietta *et al* 2015). We hypothesize that human activities have recently altered fire regimes beyond the effect of climate forcing in Euro-Mediterranean ecosystems, either: i) by promoting fires (positive alteration) through increasing anthropogenic ignitions along with more extensive wildland–urban interface and tourism pressure (Ganteaume and Jappiot 2013), and increasing landscape flammability associated with fuel recovery dynamics following land-use changes (Moreira *et al* 2011); or ii) by suppressing fires (negative alteration) with increasing efficiency over time, especially since the recent major changes in fire policy (mid 90s; Moreno *et al* 2014). In southern France, we expected that the nature and strength of fire regime alteration would vary both seasonally and along a fire-proneness gradient, i.e. by stronger negative alteration in summer and in Mediterranean fire-prone ecosystems than in winter and in Temperate mountains.

## Material and methods

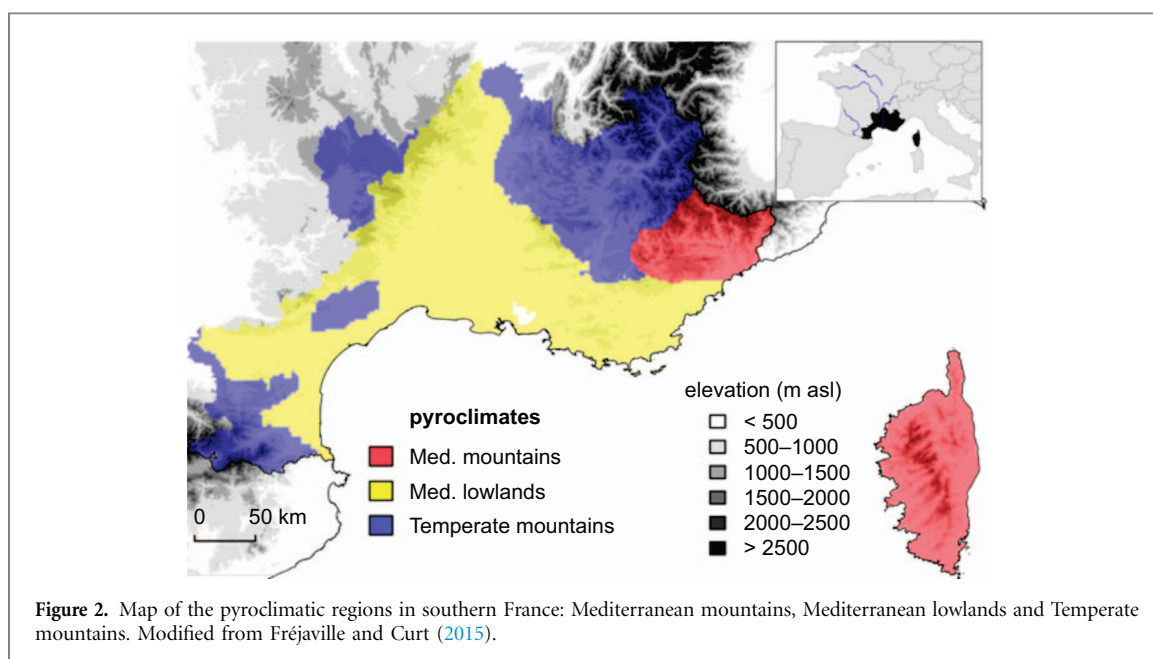
Analyses of fire–climate relationships (1976–2009) were based on disentangling the effects of contemporary and previous weather conditions (wet or dry) on fire, separately for each of the three pyroclimates of southern France (table 1, figure 2). We focused on these regional contexts, because the potential of human activities to alter fire in recent decades is thought to vary greatly with spatial or socioeconomic context (Pausas and Keeley 2009). The Mediterranean mountains (MM) are characterized by a high seasonality in precipitation and fires (dry summers and wet winters) with the highest burned area fraction, fire season length and the strongest increase in fire



**Figure 1.** Testing the temporal alteration of fire-climate relationships by human activities. Temporal variations in fire regime statistics (e.g. number of fires, burned area) and climate parameters are first decomposed into a seasonal component (detrended inter-annual variability) and a trend component (smoothed multi-decadal variability). Inter-annual variability of fire is driven by climate only, i.e. independent to changes in human activities, while multi-decadal trends are driven by changes in both climate and human activities. Then, relationships between fire and climate detrended series are modelled by an ensemble of regression models. Finally, climatic trends are added to model predictions to quantify the direction and strength of fire regime alteration, i.e. by comparing the observed fire trend to the trend expected by climate only. Changes in human activities result in positive, negative or null fire regime alterations depending on the regional importance of increasing anthropogenic ignitions, fuel load following land abandonment, fire suppression policy and of their antagonist effects.

**Table 1.** Descriptive statistics (yearly mean values) of southern French pyroclimatic regions over 1976–2009. Fire statistics were computed from fires larger than one hectare.

variable	unit	Mediterranean mountains MM	Mediterranean lowlands ML	Temperate mountains TM
Annual burned fraction	%yr <sup>-1</sup>	0.69	0.29	0.07
Winter-to-annual burned area ratio	no unit	0.21	0.24	0.40
Temperature of the warmest month	°C	20.3	22.3	17.9
Precipitation of the driest month	mm	9.1	10.2	16.3
95th percentile FWI	no unit	25.0	37.5	22.4



danger over the last four decades. In contrast, the wettest/coldest climates, the shortest fire seasons and the lowest fire activities are found in the Temperate mountains (TM). The Mediterranean lowlands (ML) have the driest and warmest climates with strong and dry winds (the Mistral and Tramontane) that favour fire spread in summer. This region has experienced the strongest decrease in fires over the last four decades (Fréjaville and Curt 2015). Human presence and activities decrease from the Mediterranean coast to the rural hinterland, with anthropogenic ignitions accounting for 90% of the number of fires and 96% of the total burned area (Curt *et al* 2016).

### Data

Regional fire regimes were analysed based on two standard metrics, the fire density (FD, number of fires  $\# \text{ yr}^{-1} \text{ km}^{-2}$ ) and burned area fraction (BA,  $\% \text{ yr}^{-1}$ ) within each pyroclimatic region (table 1, figure 2). FD and BA were computed annually for the period 1976–2009 from the Prométhée national database ([www.promethee.com/](http://www.promethee.com/)), for two fire seasons, winter–spring (December to May, hereafter ‘winter’) and summer–autumn (June to November, hereafter ‘summer’) to distinguish the two seasonal peaks of fire activity in southern France (Fréjaville and Curt 2015). Only fires larger than one hectare were considered and FD and BA were log-transformed before analyses to satisfy normality assumptions.

Climate data were obtained from Fréjaville and Curt (2015) and include annual extreme (75th and 95th percentiles) or annual and seasonal mean temperature and cumulative precipitation. Data also included mean temperature and cumulative precipitation for the hottest/coldest and driest/wettest month. We also used the indices of the Canadian Fire Weather Index System (van Wagner 1987) to incorporate the lagged effects of daily variation in precipitation,

temperature, relative humidity and wind. Increasing values of these indices describe an increasing weather suitability for fire, from the dryness of superficial (ffmc, the fine fuel moisture code) and deep litter layers (dmc, the duff moisture code) to drought (dc, the drought code) and the overall fire danger given by the composite fire weather index (fwi). Correlation with fire activity has been previously reported for most of these climatic parameters (Carvalho *et al* 2008, Dimitrakopoulos *et al* 2011, De Angelis *et al* 2015). All climatic parameters were averaged over the yearly fire season (contemporary) and lagged periods (past seasons up to 3 years), to account for differential effects of dry or wet weather conditions over time.

### Models

#### Fire–climate models

In cases where the fire trend is partially shaped by anthropogenic factors (other than climate change), correlating fire and climate trends may yield correlations that are not causal. Our modelling approach is based on the assumption that changes in the human alterations of fire regimes occur on a decadal time scale, not inter-annual, with slowly changing preferences, technologies and demographics (Guyette *et al* 2002). Hence, our model estimates for climatic effects rely on inter-annual fire–climate relationships. For each pyroclimatic region, fire season and fire variable, we applied the following procedure. First, fire ( $Y_t$ ) and climate ( $X_t$ ) time series (1976–2009) were detrended by Loess regression models (degree of smoothing = 0.75; degree of polynomials = 2) to decompose the data into a trend component ( $T_b$ , multi-decadal trend), a seasonal component ( $S_b$ , interannual variability) and a remainder component (residuals) (Cleveland *et al* 1990):

$$Y_t = TY_t + SY_t + \varepsilon; X_t = TX_t + SX_t + \varepsilon \quad (1)$$

where the trend component ( $T_t$ ) is dependent on the predicted trend ( $T_t^*$ ) and the intercept value for the



first year of the studied period ( $T_{t=1}$ , here 1976),  $T_t = T_t^* + T_{t=1}$ . According to this notation,  $TY_{t=1}$  is the pyroclimate-specific fixed effect for the studied fire variable and season (i.e. the fire trend intercept for 1976). Then, modelling of the seasonal component of fire was performed using multi-linear regression (MLR) models, calibrated on  $n$  detrended climatic predictors:

$$SY_t = \sum_i^n (a_i SX_{i,t}) + b + \varepsilon \quad (2)$$

Climatic predictors ( $X_1, \dots, X_n$ ) were selected in two steps. First, we ranked all available climatic variables from their cross-correlation with the studied fire variable, season and pyroclimate, using Spearman's correlation coefficients computed on the seasonal components (St, detrended series). Multi-collinearity was removed by selecting the best predictor among collinear variables ( $r > 0.7$ ). Selected predictors were then used to build an initial balanced pool of two sets of predictors, one expressing contemporary ( $n_{t0} = 7$ ) and the other lagged ( $n_{lag} = 7$ ) effects of climate on fire. Second, the best model among an ensemble of models with a final set of  $n = 6-8$  predictors was selected using stepwise regressions with the Akaike's Information Criterion (R package MuMIn). By carrying out this selection procedure, we were able to test the contribution of each climatic predictor in explaining the seasonal component of fires, i.e. the temporal variation in fire activity after removing the potential influence of changes in human activities. In order to estimate a confidence interval of the seasonal component of fires for each pyroclimatic region, fire season and fire variable, an ensemble of  $N$  MLR models ( $N = 50$ ) was built following this procedure, by randomly removing five years over the study period (1976–2009). The confidence interval is defined by the 10th and the 90th percentiles of the ensemble of the  $N$  MLR models, i.e. the ensemble of regression parameters calibrated on different sets of years and climatic predictors.

#### Partitioning climatic effects

To quantify the relative effects of 'contemporary' versus 'previous' and 'dry' versus 'wet' conditions on fire, the explained variance of  $SY_t$  was partitioned at each iteration (for each MLR model) into the unique contribution of each of these four climatic sets of drivers. The distinction between the 'contemporary' and 'previous' sets was based on the time period during which parameters were computed, i.e. during the fire season or over preceding seasons and years, respectively. Then, the sets of climatic predictors describing increasing effects of 'dry' versus 'wet' conditions were assembled relative to the predictors' t-value in the MLR model. Specifically, temperature and drought variables were pooled in the 'dry' (or 'wet') set of drivers if their t-values were positive (or negative), indicating an increasing effect of dry (or

wet) conditions on year-to-year fire activity; the opposite was applied for precipitation variables. Partitioning the variance was then performed with the R package *vegan*, following Peres-Neto *et al* (2006). The relative contribution of each climatic fraction was computed on the basis of the ratio of the variance exclusively explained by one fraction (unique contribution, adjusted R-squared) to the sum of the unique contributions. In this way, we were able to determine the combinations of preceding, contemporary, dry or wet climatic conditions that best explained the fire seasonal component (year-to-year variation).

#### Testing fire alteration

Following a trend attribution method (e.g. Lobell *et al* 2011, Turco *et al* 2014), we applied the trend component to the predicted seasonal component to simulate the fire variation as a function of both climatic and anthropogenic effects ( $F*t$ ):

$$F*t = TY_{t=1} + TY*t + \sum_i^n (a_i SX_{i,t}) + b \quad (3)$$

And the fire variation as a function of climate only ( $C*t$ ):

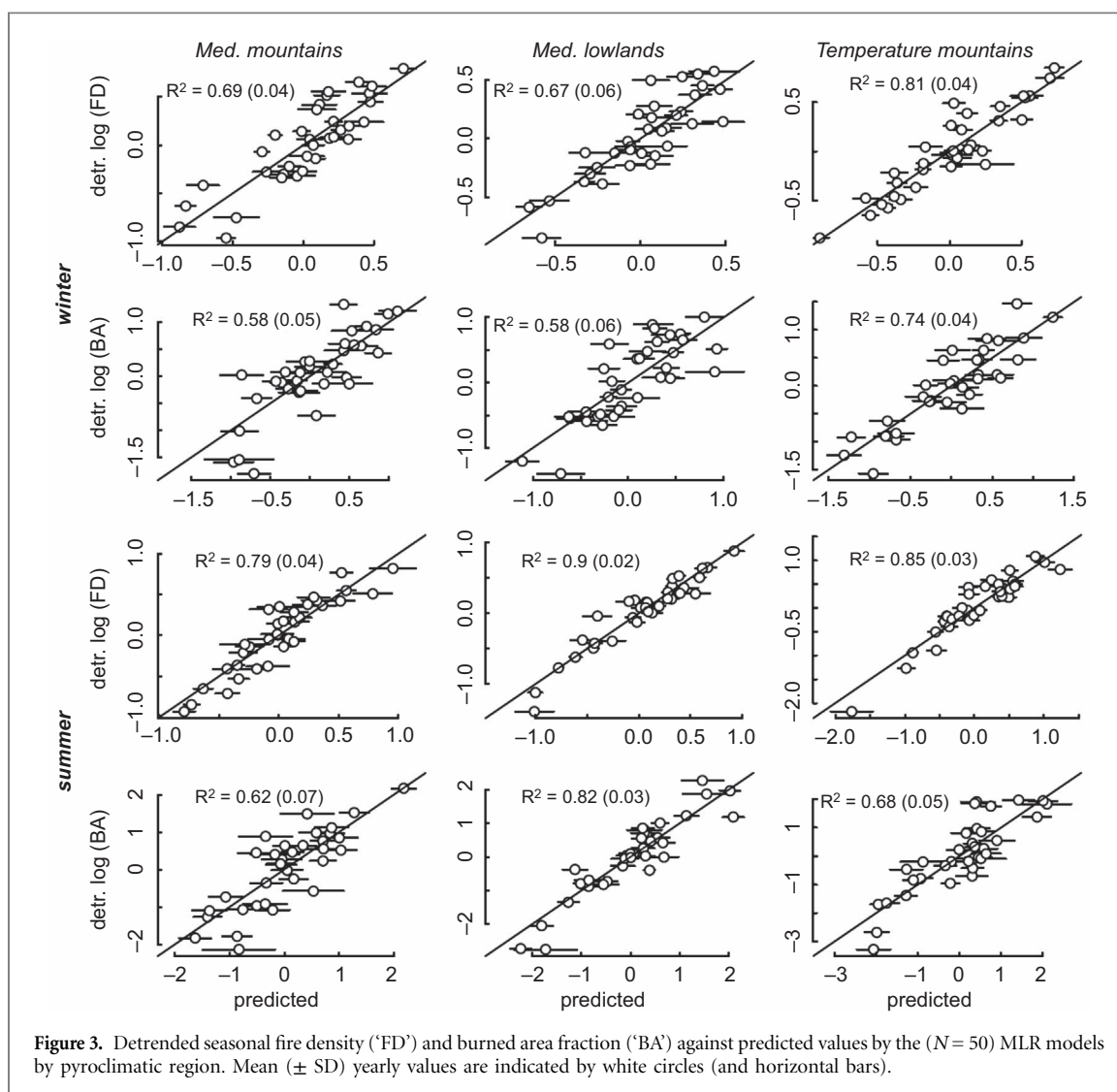
$$C*t = TY_{t=1} + \sum_i^n (a_i (SX_{i,t} + TX*i, t)) + b \quad (4)$$

This type of model assumes that fire–climate relationships are functionally the same for the seasonal and trend components, i.e. fires respond similarly to year-to-year climate fluctuations and to longer-term trends in climate (Turco *et al* 2014). Yearly values of fire alteration ( $A_t$ , %) were finally computed as the difference between  $F*t$  and  $C*t$ , which expresses the deviation at year  $t$  of the fire trend compared to the trend expected on the basis of climate:

$$A_t = 100(F*t - C*t)/F*t \quad (5)$$

The null hypothesis of no fire regime alteration ( $H_0$ ) is given by  $F*t = C*t$ . At a given year  $t$ , the significance of fire alteration (deviation from  $H_0$ ) was tested by the Student's t-test, whereby the  $A_t$  distribution of sample size  $N$  ( $N = 50$ ), mean  $\mu$  and variance  $S$  was compared to a zero-centred normal distribution of equal sample size  $N$  and variance  $S$ . Deviation from  $H_0$  is assumed to be exclusively induced by changes in human activities (i.e., independent of climate change), such as increases or decreases in anthropogenic ignitions, increasing efficiency of suppression strategies as well as human-mediated changes in land cover and species composition. For instance,  $A_t$  is independent of the climate-dependent inter-annual variation in fuel productivity, because the latter was accounted for in  $C*t$  by the inclusion of the 'previous' climatic set of drivers in MLR models.

To address uncertainties related to our approach, and in particular to ensure that  $H_0$  ( $A_t = 0$ ) is conserved when removing the potential influence of

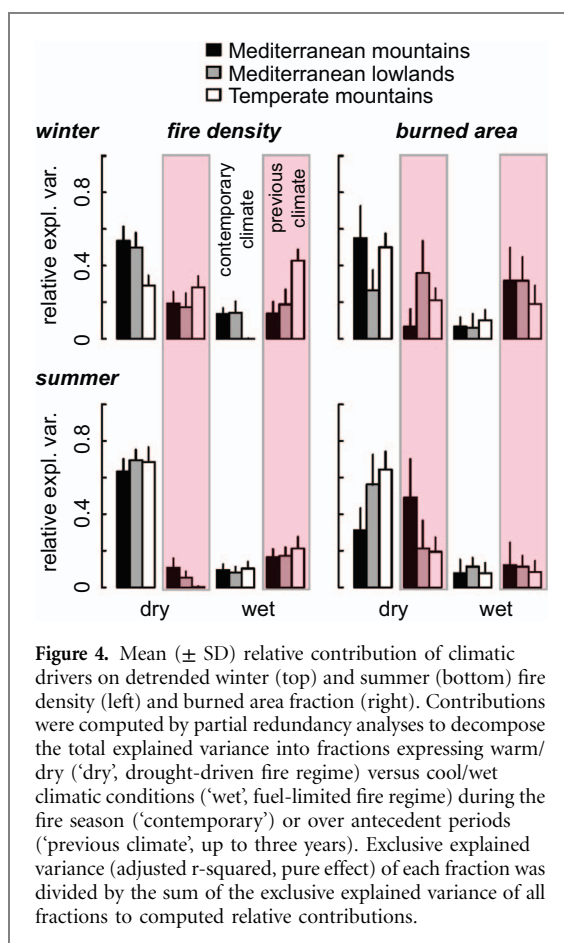


changing human activities on a decadal time scale, we applied MLR (climate-only) models to randomized time series of fire and climate. Specifically, for each region, fire season and fire metric, we tested whether the observed fire trend deviates from trends expected on the basis of climate only, when time series are random. This procedure consists of removing the anthropogenic component of the fire trend and adding it to the year-to-year variability. Time series were randomized on an annual basis, but each permuted fire year was still related to actual previous climatic conditions (up to the three preceding years) to retain their influence on fires. Results of these sensitivity analyses show convergent trends between fire observations and predictions (conservation of  $H_0$ ) when removing the long-term influence of human activities (figure S2).

## Results

Fire–climate models indicate a strong dependency of the year-to-year seasonal variation of both fire density (FD) and burned area (BA) on climate fluctuation

(figure 3). Variance explained by the MLR models was slightly lower for BA than FD, indicating a lower climatic explanation of the cumulative size of fires compared to the occurrence of fires reaching at least 1 ha. Variance partitioning of the fire seasonal component indicated that a mixture of drought-driven and fuel-limited fire regimes operated in southern France (figure 4). In winter, the number and size of fires increased with drier contemporary conditions, but also with the antecedent climate. Precisely, FD and BA increased with wetter antecedent conditions (up to three years) in the Mediterranean mountains or with wetter and warmer previous summer-autumns in the Mediterranean lowlands and Temperate mountains (figure 4, table S1 available at [stacks.iop.org/ERL/12/035006/mmedia](http://stacks.iop.org/ERL/12/035006/mmedia)). In summer, wet years also increased FD and BA in the following dry summer, while in the Mediterranean mountains warm previous winter-springs chiefly increased the extent of fires (relative explained variance, mean  $\pm$  SD,  $49 \pm 21\%$ ). Surprisingly, the relative contribution of preceding wet conditions was higher for winter fires (from  $14 \pm 7\%$  to  $43 \pm 6\%$ ) than for summer fires (from  $8 \pm 6\%$  to  $21 \pm 6\%$ ). In general, selection rates for climatic predictors in



**Figure 4.** Mean ( $\pm$  SD) relative contribution of climatic drivers on detrended winter (top) and summer (bottom) fire density (left) and burned area fraction (right). Contributions were computed by partial redundancy analyses to decompose the total explained variance into fractions expressing warm/dry ('dry', drought-driven fire regime) versus cool/wet climatic conditions ('wet', fuel-limited fire regime) during the fire season ('contemporary') or over antecedent periods ('previous climate', up to three years). Exclusive explained variance (adjusted r-squared, pure effect) of each fraction was divided by the sum of the exclusive explained variance of all fractions to computed relative contributions.

MLR models (table S1) indicated that the drought code and, to a lesser extent, the fine fuel moisture code, better described the effects of contemporary dry conditions on fire than did precipitation, temperature or the fire weather index.

Accounting for these differential climatic effects during the fire season and previous years, observed fire trends weakly to strongly diverged from climatic expectations (figure 5). In addition, these divergences showed contrasting patterns between seasons and regions. Winter and summer fire activity have both decreased in all regions (figure S1). Climate-only models predict increasing fire trends in the Mediterranean mountains and to a lesser extent in the Mediterranean lowlands. In the Mediterranean mountains, climatic predictions of winter fires shifted from increasing to decreasing trends at the end of the 90s. In the Temperate mountains, there was a greater expectation of no change according to the climate-only models.

Divergences between fire and climate trends, or fire regime alterations, occurred in all seasons and pyroclimates with specific patterns (table 2, figure 6). In the Mediterranean lowlands, winter and summer fires have been increasingly smaller and less frequent than expected on the basis of climate ( $-31$  to  $-48\%$  at the end of the study period), like in the Mediterranean mountains for summer fires ( $-77$  and  $-84\%$  at the end of the study period, respectively). In contrast, the alteration in winter fires was positive in the

Mediterranean and Temperate mountains (mean values:  $+28\%$  and  $+16\%$ , respectively) in the 70s and 80s, before dropping to being zero or weakly negative since the mid-late 90s. In the Temperate mountains, however, summer fire alteration has been less negative (tends towards a positive change) since the early 90s.

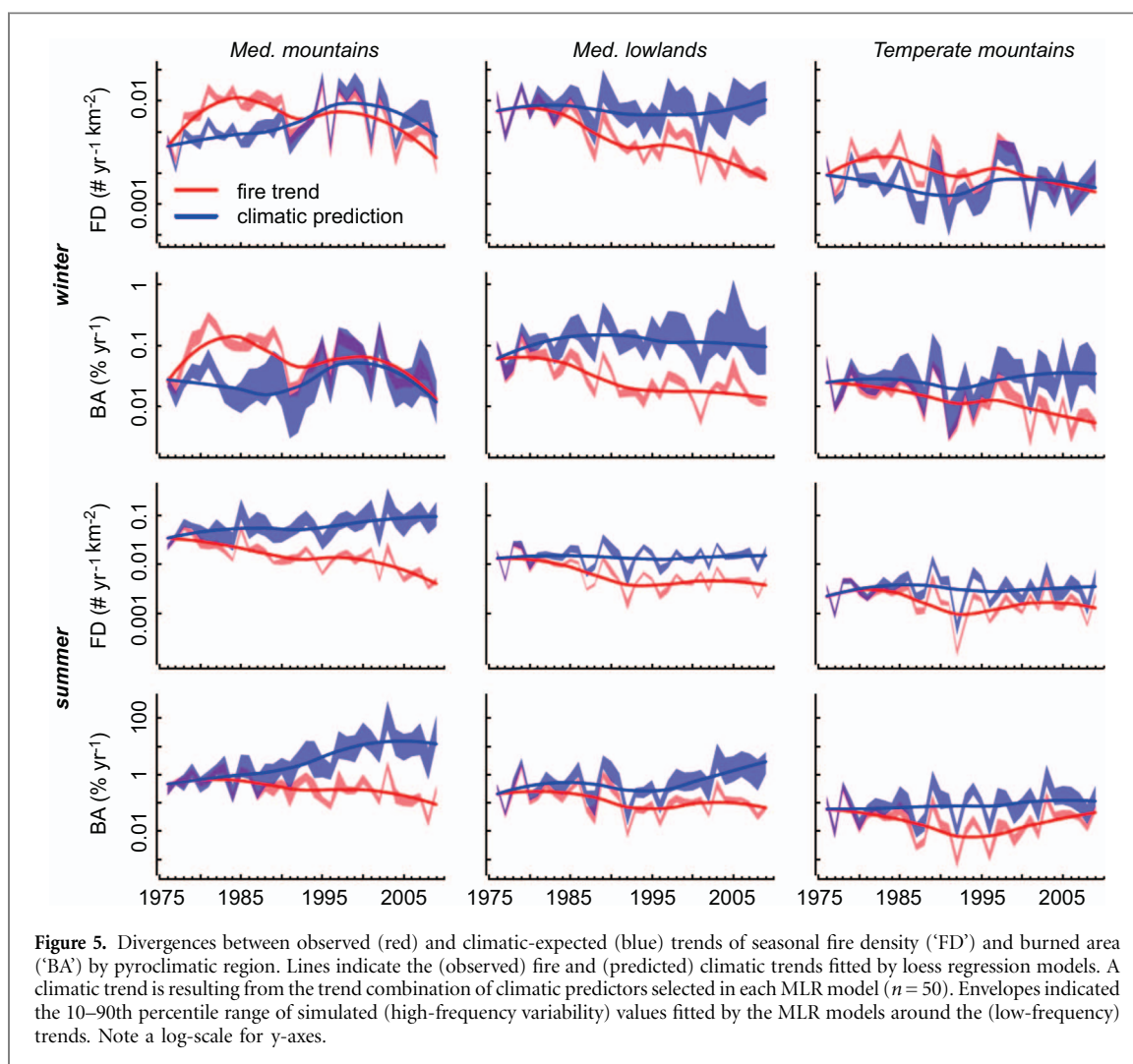
## Discussion

Fire-climate relationships during the past four decades vary substantially between regions and seasons in southern France, as do the direction and strength of fire regime alteration, corresponding to the results of Fréjaville and Curt (2015). Our findings revealed that in Euro-Mediterranean ecosystems, the climatic influence on fires was not restricted to the occurrence and duration of drought during a particular year, but that a mixture of drought-driven and fuel-limited fire regimes operated, emphasizing the lagged effects of warm or moist periods on fire (Keeley 2004, Pausas 2004, Meyn *et al* 2007, Zumbrunnen *et al* 2009, O'Donnell *et al* Pausas 2011). Furthermore, our modelling approach allowed us to quantify the climate-independent alteration of fire regimes, specifically the part induced by human activity. As expected, we found both positive and negative changes, supporting our hypotheses of contrasting short-term impacts of changes in land-use and fire suppression policy on fire regime, respectively. Because the direction and strength of fire regime changes were also different between regions and seasons, our findings highlight that predicting regional changes in fire activity in response to climate change is highly challenging, at least in areas where fire regimes are strongly shaped by human activities, such as in Euro-Mediterranean areas and beyond (Taylor *et al* 2016, Bird *et al* 2012, 2016).

### Heterogeneity in climatic effects on fire

Our results show that year-to-year variation in fire activity was induced by regional and season-specific combinations of preceding *versus* contemporary, and dry *versus* wet conditions. This finding indicates that relatively homogeneous spatial changes in climate can induce divergent responses by fires among regions and seasons. For instance, warmer/drier conditions with climate change should increase fire activity in southern Europe (Pereira *et al* 2005, Gudmundsson *et al* 2014, Sousa *et al* 2015), but to a greater extent in the Mediterranean mountains during summer due to an increasing effect of warm previous winter-springs, and to a lesser extent in winter due to a decreasing effect of dry previous summer-autumns. Indeed, we did not find strong increasing trends in the expectation of fires based on climatic data, in contrast to a suggested increase in fire activity in southern Europe in response to more extreme fire weather (Bedia *et al* 2014a, Venäläinen *et al* 2014, Sousa *et al* 2015).



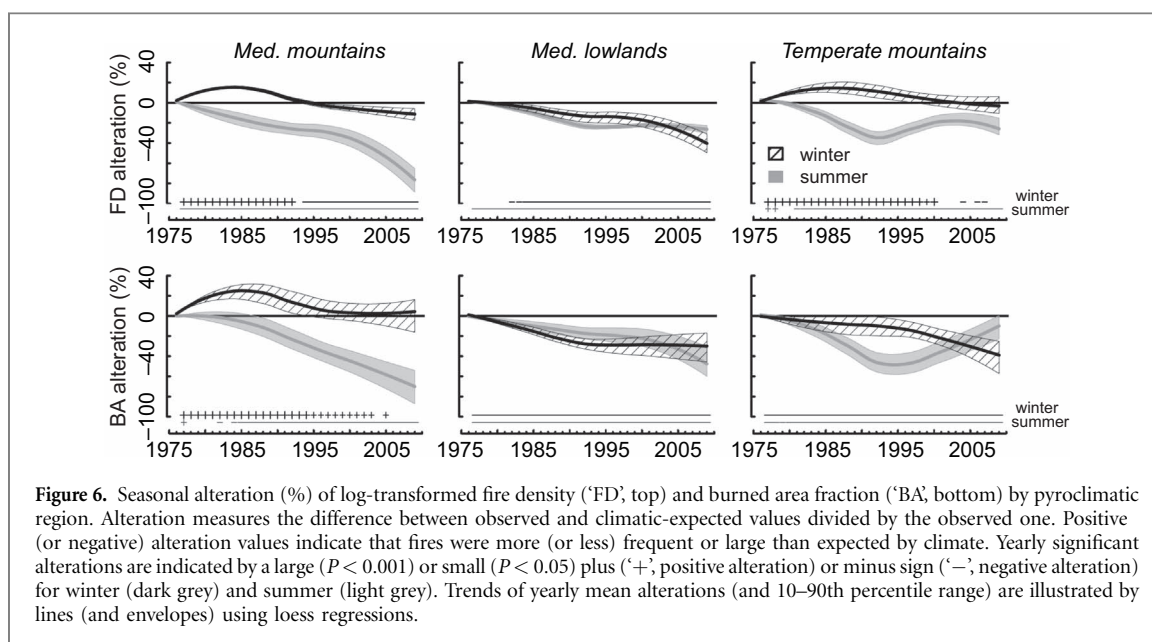


**Table 2.** Mean fire temporal alteration (% and range) simulated by the 50 MLR models over 1976–2009. Positive (or negative) alteration values indicate that fires were more (or less) frequent or large than expected by climate. Significance of yearly mean alteration values is reported in figure 6.

		Mediterranean mountains MM	Mediterranean lowlands ML	Temperate mountains TM
winter	fire density	+2 (−14,+17)	−14 (−41, 0)	+7 (−3,+16)
	burned area	−29 (−77, 0)	−17 (−31, 0)	−18 (−76,+1)
summer	fire density	+12 (0,+28)	−21 (−34, 0)	−15 (−38, 0)
	burned area	−27 (−84, 0)	−18 (−48, 0)	−25 (−78, 0)

These findings illustrate that fuel abundance is an important constraint on Euro-Mediterranean (and other) fire regimes, even when drought is the main driver. Surprisingly, we found that the sensitivity of fires to wet prior conditions was higher in winter than in summer, and especially in the Mediterranean mountains. These results may be explained by seasonal differences in ignitions, burning vegetation (fuel type) and human behaviour. Indeed, in mid-elevation mountains most winter fires are ignited by people for pastoral purposes, agriculture and forestry (land clearing) and there is a low probability of these becoming large fires (Curt *et al* 2016). Under these moderate weather conditions, the spread and intensity of fires could be more sensitive to vegetation

flammability (i.e., the amount of fine fuel in grass and shrub layers), which increases with the alternation of wet and dry periods, as demonstrated in the Temperate mountains (Fréjaville *et al* 2016). While the existence of a fuel-limited fire regime is rather counter-intuitive for relatively moist ecosystems, fuel constraints (e.g. abundance of surface fine fuels) on fire spread and intensity have already been demonstrated in other temperate ecosystems (Parks *et al* 2014, Prior *et al* 2016). In contrast, summer BA is mostly driven by intentional anthropogenic fires, which preferentially induced large fires, in particular in the Mediterranean mountains (Curt *et al* 2016). Under these extreme weather conditions during which fire suppression activity is greatest, the importance of fuel dryness may



**Figure 6.** Seasonal alteration (%) of log-transformed fire density ('FD', top) and burned area fraction ('BA', bottom) by pyroclimatic region. Alteration measures the difference between observed and climatic-expected values divided by the observed one. Positive (or negative) alteration values indicate that fires were more (or less) frequent or large than expected by climate. Yearly significant alterations are indicated by a large ( $P < 0.001$ ) or small ( $P < 0.05$ ) plus ('+', positive alteration) or minus sign ('-', negative alteration) for winter (dark grey) and summer (light grey). Trends of yearly mean alterations (and 10–90th percentile range) are illustrated by lines (and envelopes) using loess regressions.

exceed the importance of fuel load in promoting fires that are not completely contained by fire crews. In addition, these contrasting effects of previous climate conditions between seasons could be explained by differences in burning vegetation. Indeed, grass/shrub fires (promoted by anthropogenic burning for agropastoral purposes in winter) respond to preceding wet conditions whereas forest fires (promoted by severe weather conditions in summer) respond to preceding dry conditions (Littell *et al* 2009, Barbero *et al* 2014). These findings emphasize the potential of human activities to shape current fire–climate relationships by altering the functional links with climatic conditions (Higuera *et al* 2015, Parks *et al* 2015) in addition to long-term trends (Marlon *et al* 2008, Liebmann *et al* 2016, Taylor *et al* 2016).

### Fire regime alteration

Departures of fire trends from the climatic simulations indicated that the human effects on fire regimes have been strong and rapid over the past four decades. This emphasizes the potential of human activities to reshape the fire regime rapidly and severely, in particular during the most recent decades (Guyette *et al* 2002, Pausas and Keeley 2009). It also implies that Euro-Mediterranean fire regimes are mainly human driven and that this dominant anthropogenic control of fires is not restricted to regions shaped by intensive agriculture and deforestation (Archibald *et al* 2013). In addition, we found contrasting alteration patterns between regions and seasons, adding to the evidence that the human potential to alter fire varies along a fire-proneness gradient, from more fires where fire activity is low and fuel biomass high to fewer fires in fire-prone ecosystems (McWethy *et al* 2013). Indeed, in the Mediterranean lowlands, which are densely populated and highly susceptible to extreme fire weather due to strong winds (Ruffault *et al* 2017), both winter and summer fire activity were strongly

suppressed, suggesting a gradual increase in the efficiency of fire suppression policy (Turco *et al* 2014), rather than abrupt changes as previously suggested (Pezzatti *et al* 2013, Pausas and Keeley 2014, Ruffault and Mouillot 2015). In mountains, where summer suppression of fires was also the rule and especially in the fire-prone Mediterranean mountains, winter fire activity has been higher than expected based on climate data only until the mid-1990s, when shifts from positive to zero or negative alteration occurred. These findings suggest that anthropogenic burning (accidental or not) and/or fuel build-up following the abandonment of rural areas probably increased winter fire activity by providing an increasing number of ignitions and/or an increasing amount of fine surface fuels (grass and shrubs), respectively. However, the major changes in fire policy that occurred in the mid-1990s in France and neighbouring areas (Brotons *et al* 2013, Moreno *et al* 2014, Ruffault and Mouillot 2015) probably reversed the direction of the change to the Euro-Mediterranean fire regime as a result of robust suppression of fires (Turco *et al* 2013, Salis *et al* 2014). The decreasing suppression of summer fires in the Temperate mountains in recent years may indicate a recent increase in human activity within these ecosystems, which had previously been abandoned for a long period.

The complex nature of both the climatic and human influence on fires underlines the fact that predicting future fire regime changes is very challenging, at least in Euro-Mediterranean areas. The non-linear trends in fire regime alteration over short spatial and temporal scales largely limit the reliability of climatic predictions of fire regime changes and illustrate that our understanding of fire–climate–vegetation relationships in human-shaped ecosystems is still limited (Leys and Carcaillet 2016). Explicitly accounting for vegetation and socio-economic drivers (Curt *et al* 2016, Parisien *et al* 2016) should help

our understanding of how the climatic controls of fires vary with vegetation type and human behaviour, and assist in disentangling the human drivers of the regional changes to the fire regime among anthropogenic ignitions, suppression and land-use changes. In our study, we assumed that climate-induced changes in vegetation (other than short-term variation in fuel load) over the three last decades had negligible impacts on the fire trends. At broader scales, changes in vegetation with global climate change should be accounted for in predicting past or future fire regimes (Liu and Wimberly 2016). Otherwise, our results indicate that the choice of climatic predictors is critical in modelling climate change impacts on fire. For instance, we found that the fine fuel moisture code and especially the drought code were generally better predictors than the Canadian fire weather index. Because temporal trends in the drought code did not vary as strongly as the fire weather index (Fréjaville and Curt 2015), modelling fire trends based on the latter could lead to possible regional overestimation of increasing fire activity with increasing drought (Carvalho *et al* 2008, Bedia *et al* 2015, Urbietta *et al* 2015), even more so if the lagged climatic influence is not appropriately accounted for, i.e. from the previous season to the (at least) three prior years.

## Conclusions

Based on the distinction between the year-to-year and the decadal variation in fires, we developed statistical climate models for the three pyroclimates of southern France in order to extract the human component of the temporal trend in regional fire regimes—i.e. the influence of slowly changing patterns in anthropogenic ignitions, fire suppression policy and land-use (vegetation types) with demography, preferences and technologies. The climatic drivers of fires differed between seasons and regions, with important effects of preceding wet conditions on the frequency and size of fires. In the Mediterranean mountains, however, summer BA increased with positive temperature anomalies for the previous spring and the three previous winters. The past four decades have marked a transition from sometimes positive to always negative changes to the fire activity in southern France, with a predominant influence of fire suppression in recent years. We believe that this analytical framework is well suited to test changes in the human effect on fire regimes across a range of ecosystems and time periods, notably to test when, how and the extent to which fire regimes have been reshaped during the Anthropocene (Guyette *et al* 2002, McWethy *et al* 2013, Valse *et al* 2014). For instance, while fire suppression has probably driven recent decreases in fire in southern Europe (Moreno *et al* 2014, Turco *et al* 2016), another hierarchy of anthropogenic drivers may have been responsible for increasing fire trends in the western United States (Dennison *et al* 2014), including the

introduction of flammable invasive species (Balch *et al* 2013). In addition, our findings highlight that predicting changes in fire regime associated with climate changes requires accounting for lagged climatic effects as well as rapid changes in socio-economic drivers, such as anthropogenic ignitions, land-use change and fire suppression.

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