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Future expansion, seasonal lengthening and intensification of fire activity under climate change in southeastern France

François Pimont[A,*] (iD), Julien Ruffault[A] (iD), Thomas Opitz[B], Hélène Fargeon[A], Renaud Barbero[C], Jorge Castel-Clavera[A] (iD), Nicolas Martin-StPaul[A], Eric Rigolot[A] and Jean-Luc Dupuy[A]

For full list of author affiliations and declarations see end of paper

*Correspondence to:
François Pimont
URFM, INRAE, Domaine Saint Paul, Site Agroparc, 84000 Avignon, France
Email: francois.pimont@inrae.fr

ABSTRACT

Background. An increase in fire weather is expected in a warming climate, but its translation to fire activity (fire numbers and sizes) remains largely unknown. Additionally, disentangling the extent to which geographic and seasonal extensions as well as intensification contribute to future fire activity remain largely unknown. **Aims.** We aimed to assess the impact of future climate change on fire activity in southeastern France and estimate changes in spatial and seasonal distributions. **Methods.** We projected future fire activities using a Bayesian modelling framework combined with ensemble climate simulations. Changes in numbers of escaped fires (>1 ha), large fires (>100 ha) and burned area were studied for different emission scenarios or degrees of global warming. **Key results.** Fire activity could increase by up to +180% for +4°C of global warming, with large expansions of fire-prone regions and long seasonal lengthenings. Overall, changes will be dominated by intensification within the historical fire niche, representing two-thirds of additional future fire activity, half of this occurring during the high fire season. **Conclusions.** This study confirms that major changes in fire niches would be expected in Euro-Mediterranean regions. **Implications.** Long-term strategic policies for adapting prevention and suppression resources and ecosystems are needed to account for such changes.

Keywords: climate change, expansion, extension, fire niche, fire risk severity, fire season length, *Firelihood*, Mediterranean, projections, risk assessement, seasonal, spatial.

Introduction

The impacts of climate change on wildfires have already been observed over the last decades with an increase in burned areas across parts of the globe (Jones *et al.* 2022). This trend is expected to further increase over the current century (Amatulli *et al.* 2013; Williams and Abatzoglou 2016; Dupuy *et al.* 2020), as will the potential for large fires (Barbero *et al.* 2015; Ruffault *et al.* 2020), even if certain other bioclimatic and human factors may mediate or override the effects of fire weather (Jones *et al.* 2022). Quantifying future fire activity (i.e. number and sizes of fires) at regional scales is critical to set out strategic policies, to determine long-term requirements for human and equipment resources and to anticipate future ecological impacts of fire (Taylor 2020). However, quantifying those changes remains challenging at a regional scale because of the complex interactions between climate, meteorology, vegetation, humans and fires (Jones *et al.* 2022).

With the future predicted increase in fire weather, the fire niche (Balch *et al.* 2017) – the location and period of year with significant fire activity – is expected to expand, with a spatial expansion of fire-prone areas and a lengthening of the current fire season (i.e. more days with fire-prone conditions) (Flannigan *et al.* 2013). Moreover, an intensification (i.e. increased fire activity) is expected within the historical niche (Dong *et al.* 2022; Senande-Rivera *et al.* 2022). Thus, future changes in fire activity could reflect both an intensification inside the historically fire-prone region and outside these areas by expansion. Similarly, future changes could arise from an intensification during the

historical fire season and outside this period. To date, disentangling the extent to which intensification inside the niche, seasonal lengthening and spatial expansion contribute to future fire activities has rarely been addressed.

Southeastern France shows a gradient between lowland areas exhibiting already strong fire activity and more mountainous areas where activity is more limited. Such a limitation is not due to lower fuel availability, but to human ignitions and climate conditions (Fréjaville and Curt 2015; Dupire *et al.* 2019). However, drought conditions are expected to worsen throughout the Euro-Mediterranean basin (Drobinski *et al.* 2020; Cos *et al.* 2022) through the mediterranean amplification (Brogli *et al.* 2019). This may affect fire activity, as the relationships between fire weather and burnt areas are exceptionally strong in Euro-Mediterranean areas (Jones *et al.* 2022). As a consequence, mountainous regions may turn from fire-free to fire-prone locations (Resco de Dios *et al.* 2021). Southeastern France has already seen an increase in heat waves mostly attributed to anthropogenic climate change, resulting in drastic increase in the frequency and magnitude of extreme fire weather conditions (Barbero *et al.* 2020). This region is also expected to be the most impacted by changes in fire weather in France, with a high degree of confidence (Fargeon *et al.* 2020).

However, translating fire weather increases into realised fire activity is, for several reasons, not straightforward. First, the relationship between fire weather and fire activity is not linear, because the response of numbers of fires and their size are not proportional to fire weather indices, exhibiting both convex increase and saturation depending on the range of fire weather values (e.g. Pimont *et al.* 2021). As a result, an increase in fire weather is not expected to turn into a proportional increase in burned area or numbers of fires, which limits the conclusions drawn from fire weather index projections. Second, fire suppression, land use or land management strongly shapes fire activities (Andela *et al.* 2017; Jones *et al.* 2022), especially in this region (Ruffault and Mouillot 2015; Evin *et al.* 2018), causing large spatial and temporal variations in atmosphere–fire relationships (Fréjaville and Curt 2015; Ruffault and Mouillot 2017; Turco *et al.* 2018; Pimont *et al.* 2021; Castel-Clavera *et al.* 2022). Finally, a large part of fire activity in this region occurs during day-scale meteorological events (Ruffault *et al.* 2017), challenging projections based on monthly or seasonal fire weather (Williams and Abatzoglou 2016).

Here, we projected fire activity in southeastern France with the Bayesian probabilistic *Firelihood* model (Pimont *et al.* 2021), which is described in the Methods section. In brief, *Firelihood* uses the widespread Fire Weather Index (FWI, Van Wagner 1987) to rate daily fire danger and accounts for fire stochasticity and the spatial variations in fire weather relationships observed at regional scales. We studied changes in the fire niche by analysing the spatial expansion, seasonal lengthening and intensification of

future fire activities under two emission scenarios (Representative Concentration Pathways, RCP 4.5 and 8.5) of the EURO-CORDEX initiative (Kotlarski *et al.* 2014) for mid and long terms, as well as global warming levels from +1.5 to 4°C.

Methods

The workflow of the study is presented in Fig. 1. The first step consisted in projecting the FWI obtained from 13 climate models for two representative emission concentration pathways (RCP 4.5 and 8.5). In the second step, *Firelihood* was used to simulate fire activity metrics for the 26 projected FWI simulations. Then, projected fire activity metrics were analysed to estimate the future spatial and seasonal distributions of fire activity.

Projections of the Fire Weather Index

FWI values were estimated from weather data simulated by 13 climate models of the EURO-CORDEX initiative for both RCPs (Kotlarski *et al.* 2014), leading to 26 FWI simulations (Supplementary Table S1). Simulations resulted from dynamical downscaling through coupling of Global Climate Models (GCMs) with Regional Climate Models (RCMs). FWI was computed using the 'cffdrs' R package (Wang *et al.* 2017). Following Bedia *et al.* (2014), FWI calculation was based on daily cumulated precipitation, mean wind speed and temperature, and minimum relative humidity calculated using specific humidity and maximum temperature of the day (Fargeon *et al.* 2020). We considered two scenarios: RCP 4.5 and 8.5, developed for IPCC (Intergovernmental Panel on Climate Change) Assessment Reports. Climate simulations were downscaled and bias-corrected at 8-km resolution with a multivariate bias-correction method based on quantile mapping (MBC_n from the R package MBC, Cannon 2018) and using the 1971–2005 SAFRAN reanalysis data set (Vidal *et al.* 2010) as reference.

Projections of fire activity metrics

Firelihood (Pimont *et al.* 2021) is a probabilistic Bayesian framework designed for stochastic modelling of fire activity (number and size) in southeastern France during the warm season (June–October, days of year 149–308). The occurrence of escaped fires (i.e. number of fires larger than 1 ha) is modelled through a space–time Poisson process simulating the number of fires occurring in each 8-km pixel and day of year. For each fire, its burnt area (fire size in ha) is assigned by sampling from the estimated distribution of fire sizes in each pixel and day. This distribution is modelled with a combination of exceedance thresholds, as well as piecewise Pareto and Generalised Pareto distributions based on fire size intervals of 1–10, 10–100, 100–1000
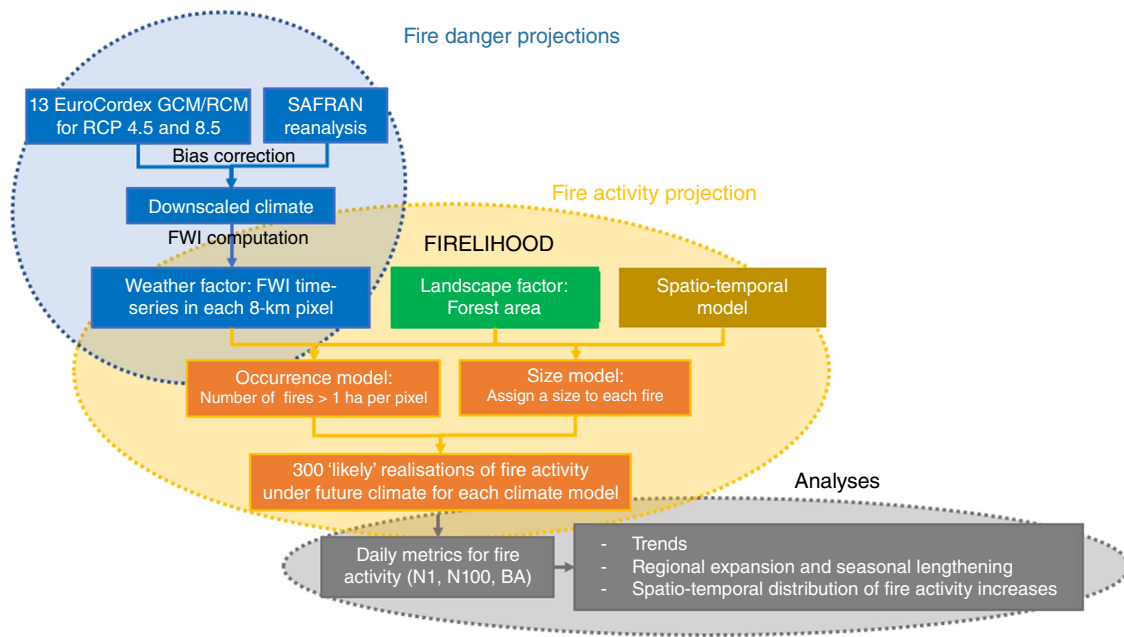
Fig. 1. Workflow of the study. In orange, the *Firelihood* probabilistic model of fire activity; in blue, the FWI projections derived from climate models; in grey, the spatiotemporal analyses of fire activity.

and larger than 1000 ha. Explanatory variables are the FWI, which summarises the influence of fire weather on daily fire danger, and the forest area as a landscape factor representing exposure to fuel availability. *Firelihood* also includes sophisticated spatio-temporal effects to account for patterns that remain unexplained by explanatory variables. They include a random spatial effect with Matérn covariance, and seasonal and yearly random effects to appropriately capture residual spatiotemporal variability of the occurrence patterns (Pimont *et al.* 2021). More recent work revealed that the size distribution also exhibited spatial dependencies (Koh *et al.* 2023). In order to improve the spatial accuracy of fire projection, the original version of the model (Pimont *et al.* 2021) was slightly improved with the introduction of a spatial effect operating at NUTS3 levels (Nomenclature of Units for Territorial Statistics, which corresponds to aggregations of municipalities or provinces) in exceedance threshold and piecewise Pareto models (Supplementary Table S3), allowing improved spatial distributions of fire sizes. The model was estimated over 1995–2014 and evaluated over 2014–2018 (Pimont *et al.* 2021). It implements a fixed effect 'post 2003' in the occurrence model component, which can be viewed as a simplified annual effect to account for abrupt changes in the atmosphere–fire relationship near 2003 (Pimont *et al.* 2021). This estimated 'post-2003' effect was applied to our 2001–2100 projections, so that these projections could be considered as representative of the atmosphere–fire relationship of 2004–2018. More recent studies have shown that atmosphere–fire relationships have been stable over these recent periods (Castel-Clavera *et al.* 2022; Koh *et al.* 2023),

which strengthens the modelling assumption of a fixed 'post 2003' annual effect, initially done in Pimont *et al.* (2021). This modelling strategy hence allows us to project a meaningful extrapolation of the current situation.

For each of the 26 FWI simulations, *Firelihood* was used repeatedly by sampling from the posterior distribution of the Bayesian model to provide 300 replications of fire activities, which represented both the distributional uncertainty associated with stochastic processes at play (Poisson, Bernoulli, Pareto and Generalised Pareto), and the statistical uncertainty from the estimation of model parameters. These fire activities were used to compute five different fire metrics in each pixel and day: the expected numbers of fires larger than 1, 10, 100 and 1000 ha (N1ha, N10ha, N100ha and N1000ha respectively) and burnt areas (BAs), which were aggregated over time and space for each climate model. Multi-model means were therefore computed, as well as the model standard deviation, which represents the uncertainty associated with climate models (Fargeon *et al.* 2020).

Emission scenarios, time horizons and global warming levels

For RCP 4.5 and 8.5, we considered mid- (2041–2060) and long-term (2080–2099) horizons by averaging projected fire activities for these periods. For comparison, we also defined a 20-year reference corresponding to the recent 'historical' period, labelled '2001–2020', constructed from mean *Firelihood* projections for RCP 4.5 and 8.5 during these years. This historical estimation should be considered

as a theoretical reference, which differs from observations for two main reasons. First, simulations were based on the atmosphere–fire relationships of the stable 2004–2020 period, but underestimate observations for the 2001–2003 period, which includes the catastrophic 2003 year (Supplementary Table S4). Secondly, climate simulations lead to lower fire weather than observed, which is explained by the fact that only half of the observed increase in FWI at this period (approximately +20%) was reproduced by climate models (Barbero et al. 2020). As a result, fire activities simulated by Firelihood were lower when derived from climate models than from SAFRAN reanalysis.

We considered four global warming scenarios (+1.5, +2, +3 and +4°C) by averaging fire activities over 20-year periods centred on the dates at which corresponding global warming levels were reached for each GCM under the RCP 8.5. For the +4°C scenario, only 8 of the 13 climate models were used, as this level was either unknown or not reached at simulation end dates (Supplementary Table S2).

Spatial expansion and seasonal lengthening of the future fire niche

The spatial and seasonal extents of the fire niche for the different time horizons and global warming levels were determined from objective levels obtained from spatial and seasonal clustering applied to three important fire metrics (N1, N100ha and BA). Spatial and seasonal changes in levels were then used to estimate the expansion and the lengthening of future fire niches.

Fire metrics were first aggregated per pixel and day of year to estimate spatial and seasonal fire activities, respectively. Then, they were classified according to five levels corresponding to low, moderate, high, very high and extreme fire activities using 'k-means' clustering. We applied two different clusters for spatial and seasonal metrics and estimated these clusters from fire metrics of the three time horizons under RCP 8.5 (historical reference, mid and long terms). A 'Butterworth' filter was applied to seasonal metrics with 7-day smoothing to increase the robustness of seasonal patterns (Mann 2004, 2008).

We defined the fire-prone and highly fire-prone regions as the locations with spatial levels of fire activity 'at least moderate' and 'at least high' during the reference period, respectively. We then considered the spatial expansion of the fire niche, based on future pixel shifts towards higher levels.

Similarly, we defined the fire season and the high fire season as the periods with seasonal levels of fire activity 'at least moderate' and 'at least high' during the reference period, respectively. We then considered the seasonal lengthening of the fire niche, based on the number of days shifting towards higher levels.

Relative contributions of intensification, expansion and lengthening to future increases in fire activity

We studied how additional fire activity induced by climate change was distributed with respect to the historical spatio-temporal fire niche, in order to disentangle whether increases in fire activity mostly occurred owing to intensification inside the fire niche or from extension of the fire niche. For spatial patterns, we aggregated the anomalies (computed with respect to the 2001–2020 reference) of fire metrics (N1ha, N100ha, BA) in pixels located respectively inside and outside the historical fire-prone and highly fire-prone regions. Similarly, anomalies in those fire metrics were aggregated within and beyond the historical fire and high fire seasons.

Results

Projected trends in fire activity for the whole region

Projected trends for N1ha, N100ha and BA are represented in Fig. 2. Overall, projected global warming induced large increases of the three metrics compared with the reference period (2001–2020). Similar increases were observed until 2050 under both RCPs, RCP 8.5 being slightly higher than RCP 4.5. The trends , however, contrasted greatly in the second half of the century, with an acceleration under RCP 8.5, but a stabilisation under RCP 4.5. According to these projections, ~15 000 ha burned, 20 large fires and 350 escaped fires per year would be expected for the end of the century under RCP 8.5. The mean emergence dates of +2 and +4°C were respectively ~2040 and 2080 (under RCP 8.5).

Climate model uncertainties (vertical lines) increased with time and magnitude of fire activities. They were also larger for fixed horizons than for global warming levels, because the forced convergence of global predictions reduced the climate model uncertainty, but at the cost of uncertainty in timing (horizontal lines). Finally, simulated fire activity during the reference period (2001–2020) was slightly below the observations (2004–2019, in black), as explained in the Methods section.

Fig. 3 shows the relative increase in different fire metrics (N1ha, N10ha, N100ha, N1000ha and BA) under RCP 8.5 (RCP 4.5 in Supplementary Fig. S1). Near the end of the century, the increase factor ranged between 2.1 and 3.4 for N1ha and N100ha, respectively. N1000ha and BA increased by 3–3.1, which was slightly less than N100ha, the fire activity metric exhibiting the largest increases. In agreement with Fig. 2, these factors were slightly higher than those reached for +2 and +4°C of global warming (Supplementary Table S4). The increase factor would
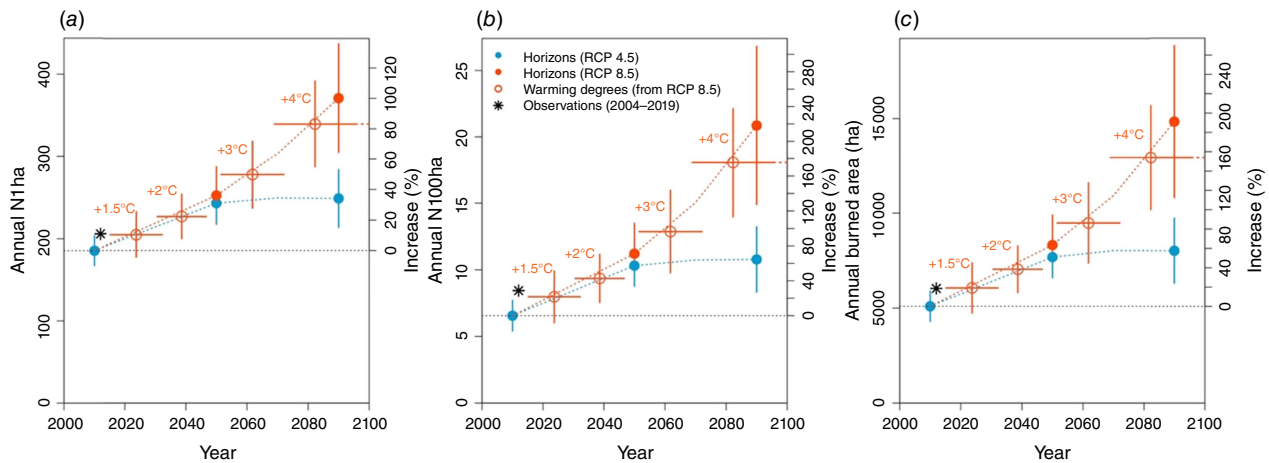
Fig. 2. Trends in fire activities for different emission scenarios and levels of global warming for: (*a*) N1ha; (*b*) N100ha; and (*c*) burned areas. The extents of vertical lines correspond to the uncertainty from the climate models regarding the metrics (N1ha, N100ha, BA). The extent of horizontal lines corresponds to the uncertainty in the temporal timing at which each level of warming will be reached under RCP 8.5. NB: for +4°C, the timing and the standard deviation were underestimated as two climate models did not reach +4°C until 2100.
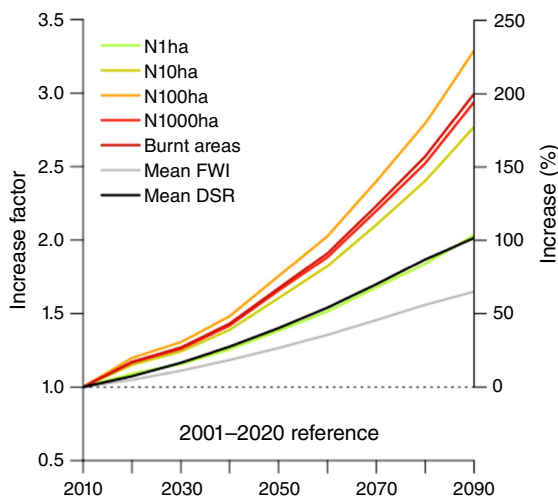
Fig. 3. Trends in fire activity metrics projected under RCP 8.5 (same figure for RCP 4.5 is provided in Supplementary Fig. S1).

reach a plateau at ~1.5 in 2050 under RCP 4.5 for all metrics except N1ha (1.34). For reference, these trends were compared with mean FWI and Daily Severity Rating (DSR, often used to estimate the difficulty to control fires, Flannigan *et al.* 2013). The increase was faster for all fire activity metrics than for FWI and DSR, except for 1 ha fires (see also Supplementary Table S4).

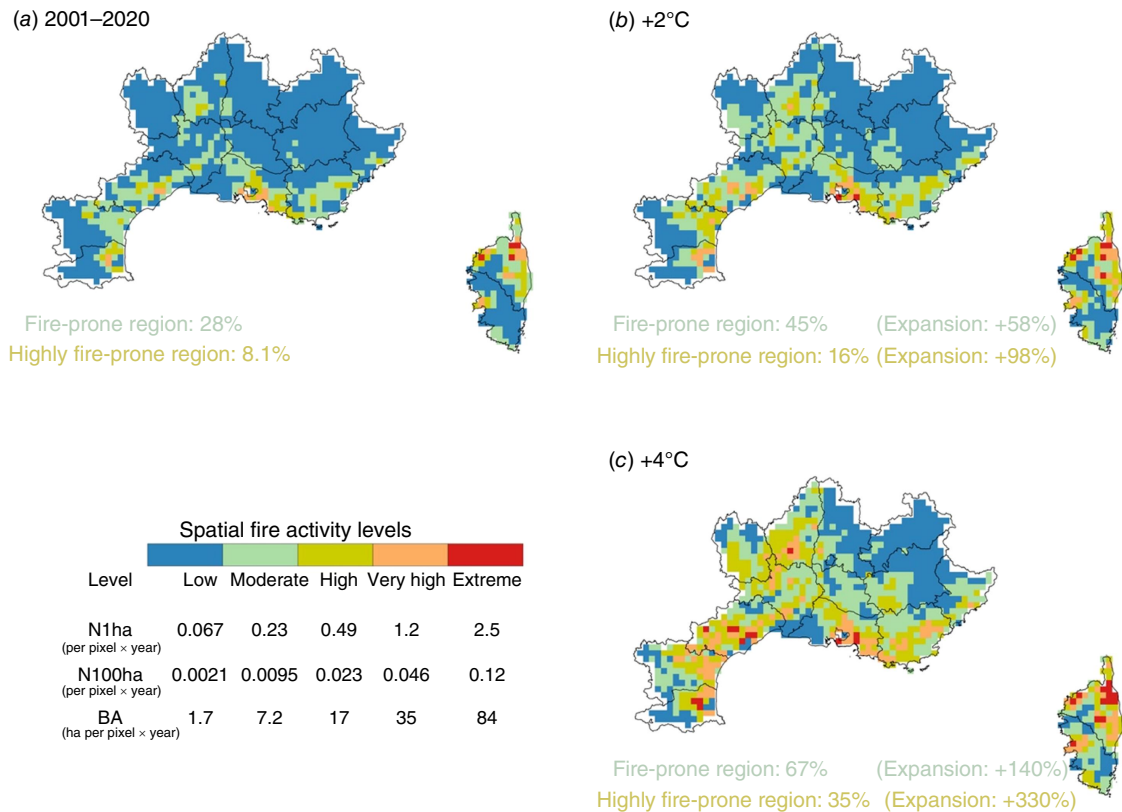## Spatial expansion of the fire-prone and highly fire-prone regions

Reference and future (+2 and +4°C) fire activities were mapped by spatial levels of fire activity in Fig. 4

(other horizons and global warming levels are available in Supplementary Fig. S1). During the reference period, areas with moderate or higher fire activities (i.e. fire-prone region) covered 28% of southeastern France. We note here that the fire metrics for the 'low' spatial level of fire activity were of the order of 3–4.6 times lower than for the moderate levels, highlighting the huge contrast between the fire-prone region and the rest of the territory. Areas with levels at least 'high' covered 8% of the territory (highly fire-prone region). Spatial coverages of other levels are shown in Fig. 5a. Fire activity metrics typically increased by a factor of 2 when switching levels.

With +2 and +4°C, the spatial extent of the fire-prone and highly fire-prone regions strongly increased, these regions covering approximately two-thirds and one-third of the territory with +4°C, with a marked expansion in the western part of the region. A potential expansion in Corsica and Alpine parts was apparently more limited, probably because of mountainous barriers. These shifts in fire activity levels were associated with an increased in occurrence of highest fire activity levels, namely up to 5.5–6.5 times for very high and extreme levels, and up to 3.8 times for the high level (Fig. 5a).

Lengthening of the fire and high fire seasons

The reference and future (+2 and +4°C) seasonal extents of the fire niche are shown in Fig. 6. The historical lengths of the fire and high-fire seasons were 78 and 38 days, respectively. The length of the high fire season would increase by between 20 and 53 days (from 17 June to 16 September in the worst scenario), with a slightly more pronounced lengthening at the beginning than at

(*a*) 2001–2020

(*b*) +2°C

Fire-prone region: 28%
Highly fire-prone region: 8.1%

Fire-prone region: 45%   (Expansion: +58%)
Highly fire-prone region: 16% (Expansion: +98%)

Spatial fire activity levels

Level	Low	Moderate	High	Very high	Extreme
N1ha (per pixel × year)	0.067	0.23	0.49	1.2	2.5
N100ha (per pixel × year)	0.0021	0.0095	0.023	0.046	0.12
BA (ha per pixel × year)	1.7	7.2	17	35	84

(*c*) +4°C

Fire-prone region: 67%   (Expansion: +140%)
Highly fire-prone region: 35% (Expansion: +330%)

Fig. 4. Spatial distribution of fire activity levels for (*a*) the 'historical' reference period; (*b*) +2 and (*c*) +4°C degrees of global warming. Fire-prone and highly fire-prone regions respectively correspond to percentage cover in pixels with spatial fire activity levels at least moderate and at least high. Expansion percentages were computed for +2 and +4°C. Fire activity metrics per pixel and per year corresponding to each level are indicated below the colour bar.

(*a*)

(*b*)
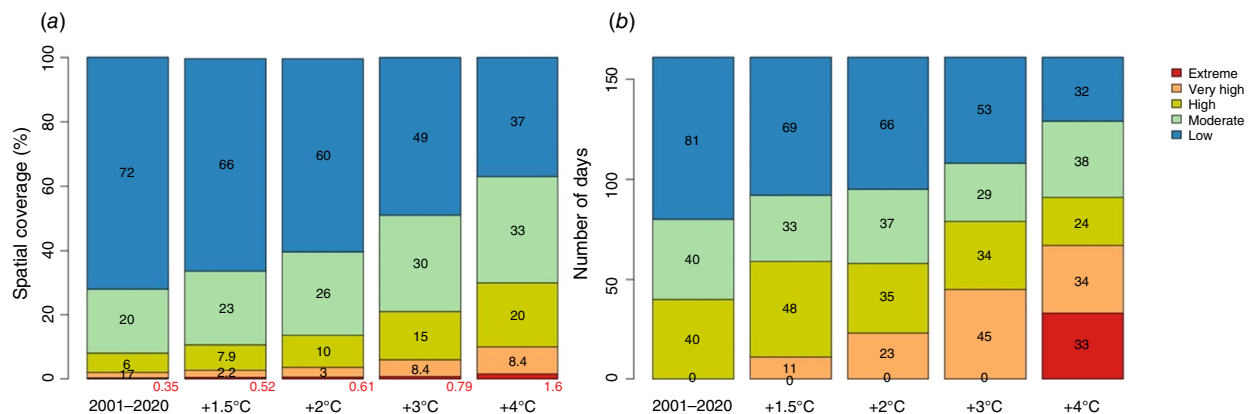
Fig. 5. Changes in distribution of (*a*) spatial, and (*b*) seasonal fire activity levels for the degrees of global warming.

the end of the season. Very high and extreme levels would emerge at +2 and +4°C, respectively. Extreme days would occur during 33 days with +4°C (Fig. 5*b*), which is close to the historical high fire season length (38 days), highlighting the major intensification of activity in the core of the season, switching from 'high' to 'extreme' levels.

Relative contributions of intensification, expansion and seasonal lengthening in changes in spatiotemporal distributions of fire activity induced by climate change

Spatial expansion and seasonal lengthening revealed a strong extension of the fire niche, which does not necessarily
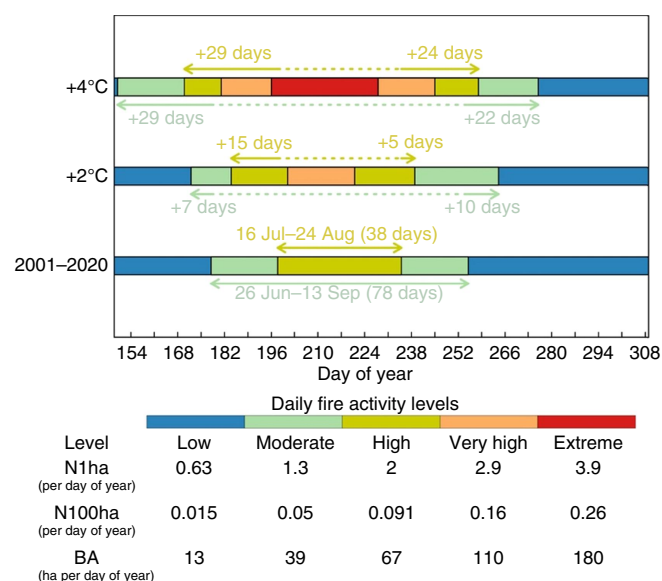
Fig. 6. Seasonal distribution of fire activity levels for the 2001–2020 reference, +2 and +4°C global warming scenarios. Fire season length and high fire season length respectively correspond to number of days with daily fire activity levels at least moderate and at least high. Lengthening in number of days at the beginning and end of the reference season was computed for +2 and +4°C. Daily fire activity metrics per day of year corresponding to each level are indicated below the colour bar.

imply that the major part of future increases in fire activity would occur outside the historical fire niche.

Fig. 7a shows anomalies of N100ha, partitioned inside and outside the historical fire-prone region. Approximately two-thirds of climate change-induced large fires would occur from intensification inside the historical fire region (which covers only 28% of the territory), whereas only one-third would be caused by the spatial expansion of the fire-prone region. Moreover, one-third would occur within the historically highly fire-prone region, which covers 8% of the territory (Fig. 7c). This shows that the intensification inside the current fire niche, more than its spatial expansion, would be responsible for future increases in fire activity.

Fig. 7b, d show the anomalies of N100ha during days corresponding to historical fire and high fire seasons. Approximately half of the increases in large fires would occur from intensification during the historically high fire season, between 16 July and 24 August. Only 15% of increases would occur outside the historical fire season, before 26 June or after 13 September. Similar results were obtained for N1ha and BA (Supplementary Figs S4, S5), highlighting that lengthening would not be the major cause of increases in regional fire activity.

For more details regarding the distribution of historical and future fire activity metrics, the spatial and seasonal distributions of N1ha, N100ha, BA are reported in Supplementary materials.

Discussion

In this study, we projected regional fire activity in southeastern France, assessed the potential extension of the historical spatial-temporal fire niche (i.e. the expansion of fire-prone regions and the lengthening of fire seasons) and quantified the distribution of climate-induced fire activity inside and outside the fire niche. Our results suggest that fire activities are expected to dramatically increase in this region, up to +160% for BA and +180% for the number of large fires under the +4°C scenario. Although a significant extension of the spatial and temporal fire niche is predicted, our results highlighted that approximately two-thirds of the additional fire activity induced by global warming would be caused by an intensification inside the historical fire-prone region. Below, we discuss these results and their implications for the understanding of future fire regimes and fire management in southeastern France.

Projected trends in fire activity metrics

The projected increases in fire activity metrics were larger in relative terms than the projected changes in mean FWI and DSR – except for 1 ha fires (Fig. 3). This suggests that the mean seasonal DSR (also called SSR, seasonal severity rating), often used to estimate the difficulty to control fires and season length (Flannigan *et al.* 2013), and more generally assessments based on mean FWI (e.g. Chatry *et al.* 2010) could underestimate the effect of climate change on fire activity.

Furthermore, we found that the fastest growing metric is the number of fires larger than 100 ha, which is consistent with the steeper response to FWI of the probability to exceed 100 ha than for other thresholds (e.g. 1000 ha), especially in the 20–35 range (Pimont *et al.* 2021; Fig. 3b). One could have expected that larger fires and BA would increase the most. This may reflect that landscape factors, such as fuel continuity or natural barriers (Mediterranean Sea, riparian zones) induced a constraint on the development of very large fires. This constraint could be reduced in the future with the wildland expansion caused by agricultural abandonment (Abadie *et al.* 2018), which could increase fuel continuity.

Our study projects larger relative increases than a previous continental study (Amatulli *et al.* 2013), which projected a 129% increase in BA in Mediterranean France between 1985 and 2004 and the end of the 21th century under scenario A2, corresponding to +13% per decade. This is much lower than the +24% per decade projected in the present study under the RCP8.5 during 2010–2090. Such a deviation is not surprising as the two studies differ in many ways (climate models, temporal resolution, reference period, etc.). It is important to note, however, that the reference 'historical' BA used in Amatulli *et al.* (2013) – 20 200 ha for 1985–2004 – was much higher than in the present study
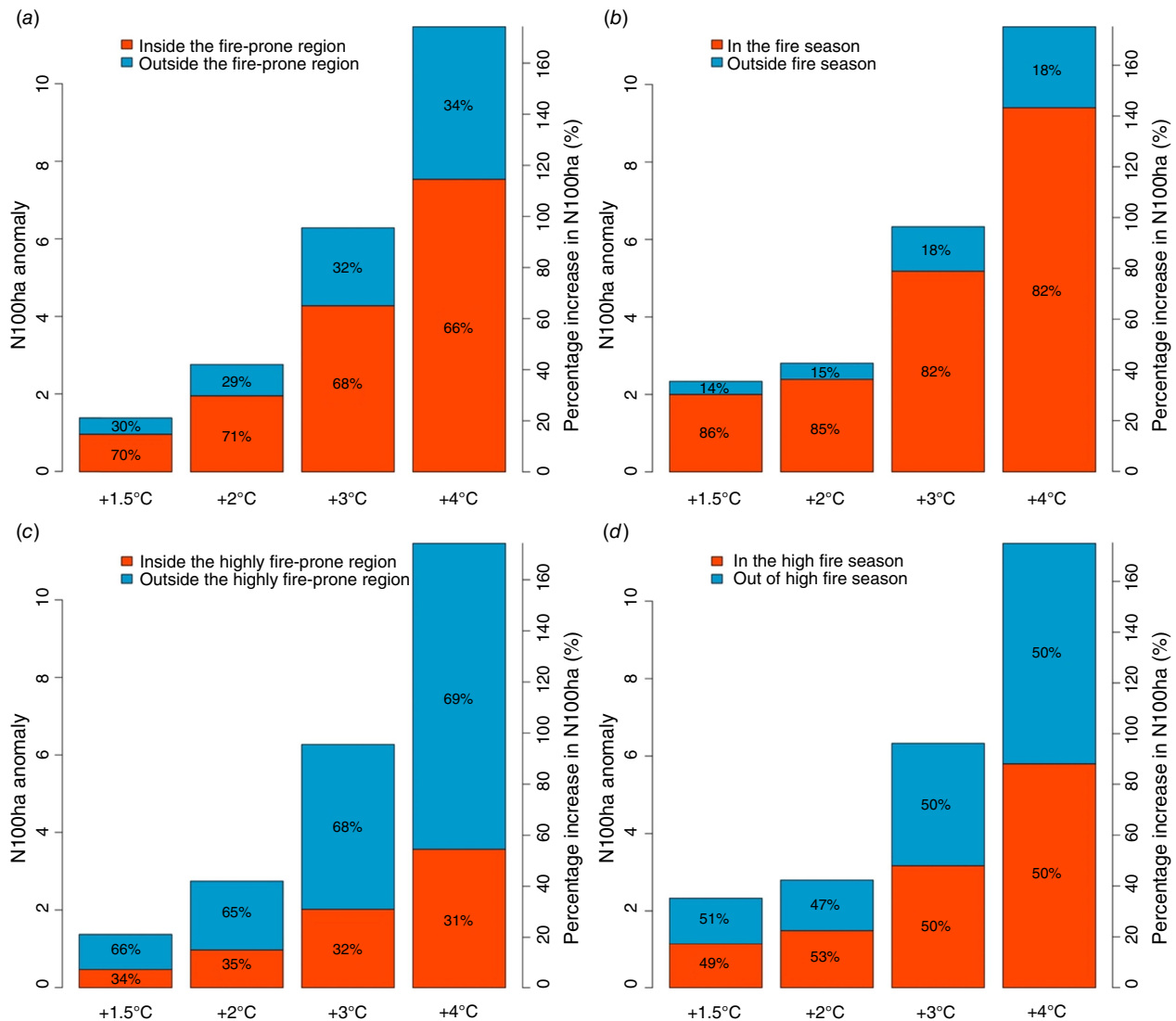
Fig. 7. Anomalies in number of large fires N100ha with respect to the historical fire niches: (*a*) spatial distribution inside and outside the historically fire-prone region; (*b*) seasonal distribution in and beyond the historical fire season; (*c*) spatial distribution inside and outside the historically highly fire-prone region; (*d*) seasonal distribution in and beyond the historical high fire season. Same figures are provided for N1ha and BA in Supplementary Figs S3, S4.

(5010 ha for 2004–2019). This large discrepancy is primarily due to a drastic reduction in fire activity in the last decades after 1990, and then after 2003 (Supplementary Table S4). In the present study, all fire activity metrics would have been twice higher if we had used fire weather relationships corresponding to the period 1995–2003 (Pimont *et al.* 2021). This strong sensitivity of absolute projections to reference periods when atmosphere–fire relationships change rapidly shows that they should be considered with caution and that comparisons based on relative increase per decade are more consistent (Dupuy *et al.* 2020). Besides, compared with monthly or yearly correlative fire models, we expect our modelling framework to better account for the impact of marginal daily increases in fire

weather and days with extreme fire weather than a mean state of seasonal forcing variables (Williams and Abatzoglou 2016), and for the critical interactions between human factors and fire weather (Balch *et al.* 2017), represented here through efficient spatial effects.

At regional scales such as southeastern France, uncertainty in fire activity pertaining to climate change are high, in agreement with previous studies (e.g. Boulanger *et al.* 2018). The approach of emission scenarios at selected time horizons (used in Amatulli *et al.* 2013) showed higher uncertainty than by global warming levels (used in Turco *et al.* 2018), as shown in Fig. 2. Such levels align with climate policies and provide insights into risk avoidance and the potential benefits of meeting international climate

agreements. However, they induce uncertainties regarding the time frame, limiting the implications of impacts studies for adaptation policies. Moreover, our results show that uncertainties in fire activity metrics – although reduced – remain quite high at regional scales, despite the forced convergence of global predictions. These points suggest that the two approaches are complementary.

Spatiotemporal extension of the wildfire niche

A much larger part of the southeastern zone would be exposed to wildfire, with the fire-prone region increasing from 28% of the territory to 45% in 2050 and 67% in 2090 (in RCP 8.5; Supplementary Fig. S2). We found higher increases inside the fire niche, which seems consistent with projections for the whole of France (Fargeon *et al.* 2020), which reported the highest increase in fire danger in already fire-prone regions.

Our high fire season (16 July–24 August) was consistent with operational perceptions that report intense suppression activities typically starting on average mid-July. Attaining +4°C of global warming would lengthen such a high fire season from 17 June to 16 September. This lengthening concerns both the beginning and the end of the period, being even slightly more marked at the beginning. Such a two-ended lengthening is expected in many temperate ecoregions, in contrast to other regions where the fire season typically ends with the arrival of monsoonal precipitation, and little lengthening is observed at the end of the season (Barbero *et al.* 2015; Dong *et al.* 2022). Half of the additional fire activity generated by global warming would occur during the historical high fire season, demonstrating a significant intensification between 16 July and 24 August.

Implications

Whereas fire projection studies generally focus on the projections of fire activity metrics (Amatulli *et al.* 2013; Turco *et al.* 2018), our study provides estimates of how the increase will translate into an extension of the fire niche and how the increase will be distributed with respect to the historical fire niche.

Indeed, the extension of the spatiotemporal fire niche and intensification within have important and distinct implications for fire management.

First, the spatial expansion of the niche would reach large areas where wildfires have been very rare. Preparedness for wildfires (forest management, firefighting equipment, culture of risk) is less developed in these areas than where the fire risk is historically higher (near Mediterranean Coast). A reanalysis of past trends in fire activity suggests that the observed increase in fire weather has already resulted in a deterioration of the operational response in the western part of this area, historically less prone to fire that the eastern part (Castel-Clavera *et al.* 2022). This could indicate that the

consequences of the future expansion could be amplified with respect to the historical fire niche, especially if a very significant expansion of prevention and control policies is not conducted.

Second, the lengthening of the fire season projected in our simulations would require prevention and suppression services to maintain their vigilance over a much longer period of time. This raises the issue of fatigue, which is already suspected to increase large fire potential according to operational staff. This is all the more important as large increases in fire season lengths are projected for +2°C, which would occur soon (near 2040) according to climate models (Supplementary Table S2).

Third, most fire activity induced by climate change will occur within the historical niche, which means more simultaneous fires to catch before escape as well as more large fires to manage. In particular, a few hot spots covering less than 2% of the region are projected to see extreme spatial fire activity levels for +4°C. Also, extreme seasonal levels – hence extreme days for regional operations – will emerge above this global temperature increase to represent one-third of the fire season. The present projections assume that the efficiency of current prevention and control policies will not deteriorate in an environment with more fires, higher fire intensity and a longer fire season. Moreover, other regions of France and of Europe would also experience an intensification or expansion (Turco *et al.* 2018), limiting the reallocation of additional and sustainable resources to southeastern France and to use the European Union (EU) Civil Protection mechanisms in the extreme days, as already observed with synchronous increase in fire danger in the USA (Abatzoglou *et al.* 2021a). It is therefore likely that fire suppression will not be sufficient to limit the impacts of fires and new approaches will have to be considered.

Limitations and future developments

Our estimates for future fire activity suffer from several limitations, which will be the subject of future research directions. First, we assumed that the fire–climate relationship remains constant over time, whereas strong shifts have been observed in southeastern France (Ruffault and Mouillot 2015; Evin *et al.* 2018; Pimont *et al.* 2021; Castel-Clavera *et al.* 2022). However, the regional changes in prevention and suppression policies are not easily translated into quantitative metrics (Castel-Clavera *et al.* 2022) or projected by current models. Second, our model relied on rating fire danger with the FWI, which is not fully consistent (Pimont *et al.* 2021). In particular, seasonal cycles of FWI and fire activity show a time lag at both ends of the fire season, which was empirically corrected in *Firelihood* (seasonal effect), but whether this empirical correction would hold in the future remains unclear. It is important to note, however, that on-going analyses suggest that the FWI would be the

most efficient fire danger index among those currently available to rate the danger in southeastern France. A final limitation was that reburns were not explicitly considered. Even if fire return intervals remained quite long in 8-km pixels, local reburns can be frequent (Ganteaume and Barbero 2019). This impact was implicitly accounted for in the model, but the impact of reburn could change with a tripling of burnt areas and ultimately limit fuel availability. Future methodological developments could help to account for this phenomenon (e.g. Abatzoglou *et al.* 2021*b*), especially for applying our methodology to locations with more frequent reburns.

Supplementary material

Supplementary material is available online.

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Author affiliations

[A]URFM, INRAE, Domaine Saint Paul, Site Agroparc, 84000 Avignon, France.

[B]BioSP, INRAE, Avignon, France.

[C]RECOVER, INRAE, Aix-en-Provence, France.