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Abstract

Anticipating future fire activity at global and regional scales is critical in a changing climate. Indeed, fire seasons are expected to lengthen and fire prone areas are expected to expand, but the magnitude, location and timing of such increases remain uncertain. Moreover, an intensification is expected during the core of the fire season of already fire-prone regions. However, quantifying seasonal and spatial impacts of climate change on fire activity is challenging. Here, we projected future fire activities in Southern France using the Firelihood model. This Bayesian probabilistic model operates on a daily basis in 8-km pixels, allowing to analyze both seasonal and spatial distributions of fire activities in a framework integrating stochasticity. Projections were computed for 13 GCM-RCM couples under two RCP scenarios (4.5 and 8.5), assuming that the only factor of change in future fire activity was the daily fire weather. The fire season was defined as the period with fire-activity level higher than the level of the 15th of July of the present period. The fire-prone region corresponded to locations with fire-activity levels higher than the 2nd level of a 5-level fire-activity scale derived from numbers of fires larger than 1ha, 100ha (N1ha and N100ha) and burnt areas (BA).

Simulations under RCP8.5 show that large increases in fire activity should be expected from the mid-century and that the rate of increase should then accelerate, leading to more than three-fold increases for number of fires larger than 100ha by the end of the century. In particular, all metrics except N1ha increased faster than the mean FWI and even the mean DSR. Such increases were partly caused by a massive seasonal lengthening from 42-43 days to up to 100 days, almost equally distributed between spring and autumn. However, the intensification during the present fire season was found to contribute slightly more to the overall increase than the lengthening itself. For example, for N100ha, the intensification would represent a 200 % increase in fire activity with respect to the present seasonal reference, whereas the lengthening outside of the present season would represent +190%. The fire prone area would increase by 140%, shifting from 28 to 67% of the regional total area. However, the intensification inside the already fire-prone region was found to contribute more to the increase than to the spatial expansion. For example, for N100ha, the intensification would represent a 183% increase with respect to the present fire-prone regional reference, whereas the expansion outside of this area would represent +101%.

These drastic increases provide a good indication of the potential lengthening of the fire season, spatial expansion and intensification of future fire activities under RCP 8.5, all three being importantly concerned, but dominated by intensification. Expanding and lengthening suppression policies may allow to mitigate projected increases, but the intensification of fire activity during the core of the fire season overwhelm current fire suppression capacities.

1. Introduction

Anticipating future fire activity at global and regional scales is critical in a changing climate. Indeed, burnt areas have already increased across parts of the globe over the last decades and are expected to keep growing over the century (Abatzoglou and Williams 2016; Amatulli et al. 2013), as the potential for large fires (Barbero et al. 2015; Ruffault et al. 2020). Fire seasons are expected to lengthen and fire prone areas are expected to expand (Flannigan et al. 2013), but the magnitude, location and timing of such increases remain uncertain, especially in the Mediterranean area. Moreover, an intensification is expected during the core of the fire season of already fire-prone regions, which should become more severe (Dong et al. 2022; Senande-Rivera et al. 2022). Quantifying those changes remain challenging at the regional scale, because of the complex interactions between climate, meteorology, vegetation, humans, and fires. In particular, disentangling seasonal lengthening and spatial expansion from intensification has been seldom addressed.

Here, we estimated future fire activities in Southern France with climatic projections of simulations of the *Firelihood* model. This region has already showed an increase in fire danger mostly attributed to anthropogenic climate change, resulting in drastic increase in the frequency of heat waves, as observed in 2003 (Barbero et al. 2020). The Bayesian probabilistic model allowed to analyze both future seasonal and spatial distributions of fire activities in a framework accounting for stochasticity. Thanks to 300 replications of potential future activities, fire activity metrics were used to compute the expansion, the lengthening and the intensification of future fire activities under two RCP scenarios (4.5 and 8.5).

2. Methods

Fire activity were simulated with *Firelihood*, a probabilistic Bayesian framework designed and validated for stochastic modeling of summer fire activity (number and size) in southeastern France (Pimont et al. 2021). The occurrence of escaped fires (i.e. number of fires larger than 1ha) is modelled through a space-time Poisson process simulating the number of fires occurring in each 8km-pixel and day of year. For each fire, its burnt area (fire size in ha) is assigned by sampling from the estimated distribution of burnt area in each pixel and day. Explanatory variables are the FWI, which summarizes the influence of fire weather on daily fire danger, and the Forest area as a landscape factor representing exposition to wildfire danger. Here, the fire size model was slightly improved, thanks to the inclusion of spatial effects operating at NUTS3 level, to improve the accuracy of spatial predictions.

Present and future FWI were estimated from weather data derived from 13 climate models of the EURO-CORDEX initiative for RCPs 4.5 and 8.5, which were developed for IPCC Assessment Reports and representative of the currently most-likely radiative forcing trajectories. 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 activity, which represent both the distributional uncertainty associated with stochastic processes and the statistical uncertainty from the estimation of model parameters. Such replications allow to compute fire occurrences and sizes in each pixel × day through different fire metrics of numbers of fire larger than certain thresholds (N1ha, N10ha, N100ha, N1000ha) and burnt areas (BA).

To analyse seasonal variations, fire metrics were aggregated by day of year and the fire season was computed for the whole area for three periods (2000-2019, 2040-2059 and 2080-2099). We selected the 15th of July (day of year 196) as the reference date of the present period (2000-2019), as it corresponds to the beginning of the fire season in agreement with considerations of operational services. This reference date was used to identify a reference level for each fire activity metric, which was subsequently used for determining the end of the fire season of the present period, as well as future fire-prone periods. Intensification and lengthening were quantified as the percentages of additional future fire activities with respect to those of the present fire season, occurring respectively inside and outside of the present season.

To analyse spatial variations, fire metrics were aggregated by pixels to determine the fire distributions for three periods (2000-2019, 2040-2059 and 2080-2099) on a yearly basis. In order to facilitate interpretation, fire activity metrics (N1ha, N100ha and BA) were classified according to three different levels corresponding to low, moderate, high, very high and extreme fire activities, by means of "k-means" clustering. We defined the present extent of the present fire-prone region as regions where the fire activity level is at least moderate, so that the expansion corresponds to pixels that would shift from low to moderate levels. The intensification and expansion were quantified as the percentages of additional future fire activities with respect to those of the already fire-prone region, occurring respectively inside and outside of this region.

3. Results and discussion

Firelihood allowed to distinguish the effects of projected climate on several fire metrics, as represented in Figure 1. For RCP 4.5, the increase factor remained limited to 1.6 folds, with a saturation after 2040. Similar results were observed for RCP8.5.5 until 2040, but the increase factor reached between 2.1 and 3.4 folds for respectively 1 ha and 100 ha fires near the end of the century. 1000 ha fires and burnt areas increased slightly slower than 100 ha-fires, which is explained by a steeper response to FWI for 100 ha than for larger fire size, especially in the 20-35 range (Pimont et al. 2021; Fig. 3b). This could reflect that landscape factors, such as fuel continuity or natural barriers (Mediterranean Sea, riparian zones) induce a constraint on the development of very large fires. Another explanation could be some limitations in the FWI for rating consistently the fire danger in Southern France, as already pointed out in Pimont et al. (2021). For all fire activity metrics, the increase was faster than the one of the mean FWI (1.76 folds) and even DSR (2.2), except for 1ha fires which increased slower than the DSR. This is an important result, as the mean DSR -also called SSR- is often used to estimate the difficulty to control fires and seasonal length (Flannigan et al. 2013).

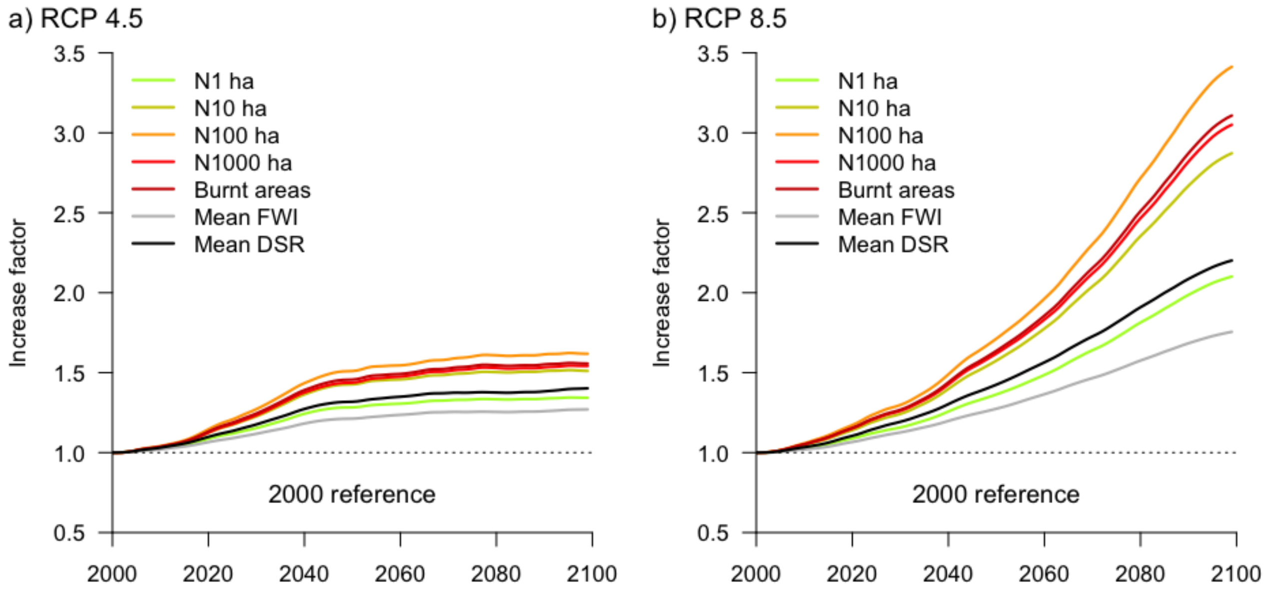

Figure 1- Trends in fire activity metrics under a) RCP 4.5 and b) RCP 8.5

Future expected fire activity increased for all days of the warm season (between day 148 and 309, Fig. 2), with a greater absolute increase in summer than in spring and fall. These increases translate into the lengthening of the fire season, as well as into the intensification of the fire activities during the present fire season. The lengthening was roughly equally distributed between spring and fall, differing by only a few days. Such a symmetric lengthening is expected in other temperate ecoregions, contrary to other regions where the fire season typically ends with the arrival of monsoonal precipitation (Barbero et al. 2015; Dong et al. 2022). The worse increases (RCP8.5 in 2090) were observed for N100ha and BA, showing +56 days by the end of the century. With respect to fire activities occurring during the present fire season, an increase by roughly 180-200% should be expected from intensification for N100ha and BA. With respect to the same reference, an increase by 180-190% is expected for new fire activity occurring during the lengthening period. The intensification in N1ha was slightly smaller than lengthening.

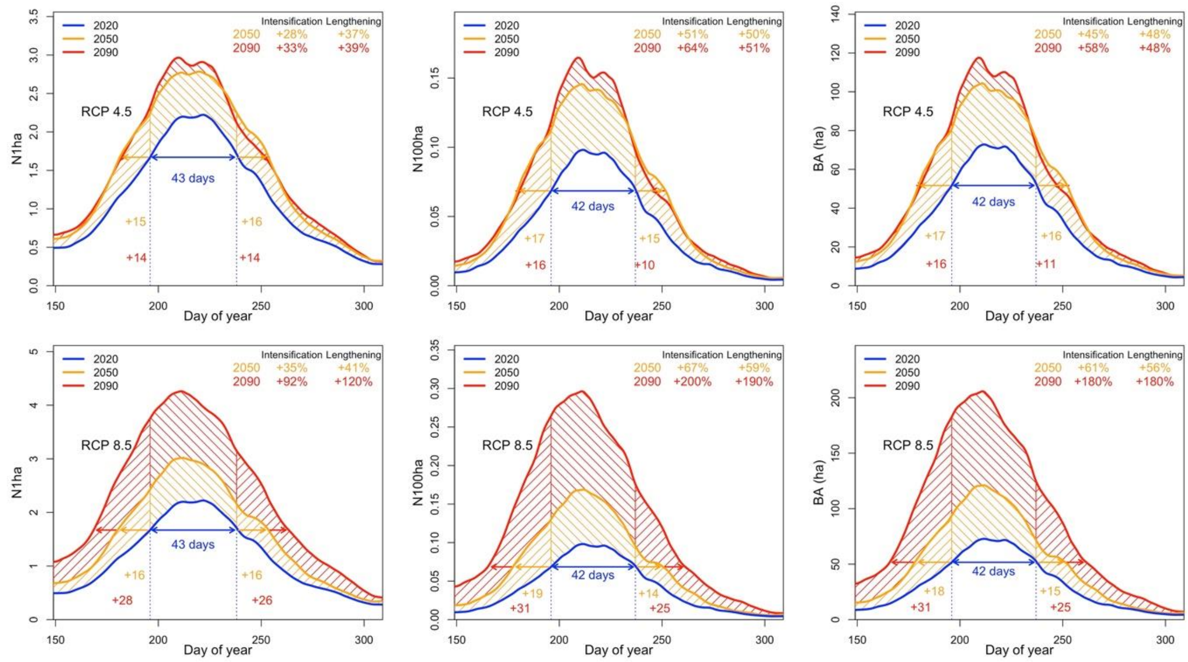

Figure 2- Seasonal lengthening and intensification for 1ha fires (N1ha), 100ha fires (N100ha) and burnt areas (BA) for RCP 4.5 (up) and 8.5 (down). Downward and upward hatches correspond to respectively the intensification and the lengthening of the fire season. There are expressed in percentages of the metric sum with respect to the present fire season.

Fire activity maps derived from the five levels are plotted in Fig. 3 for the three different periods and scenario RCP 4.5 and 8.5. The fire prone region should expand from 28% to 45% and 67% of the region of interest, with a strong expansion in the western part of the region. A potential expansion in Corsica and eastern parts was apparently more limited, probably because of mountainous barriers. As a result, the major part of expected increase was related to intensification in fire prone areas, which was roughly twice as large as the part related to expansion, despite of the large spatial expansion (Table 1). These spatial projections of fire activity were consistent with expected trends in FWI in France, which anticipate a strong heat-induced increase in fire danger in the French already fire-prone region (Fargeon et al. 2020).

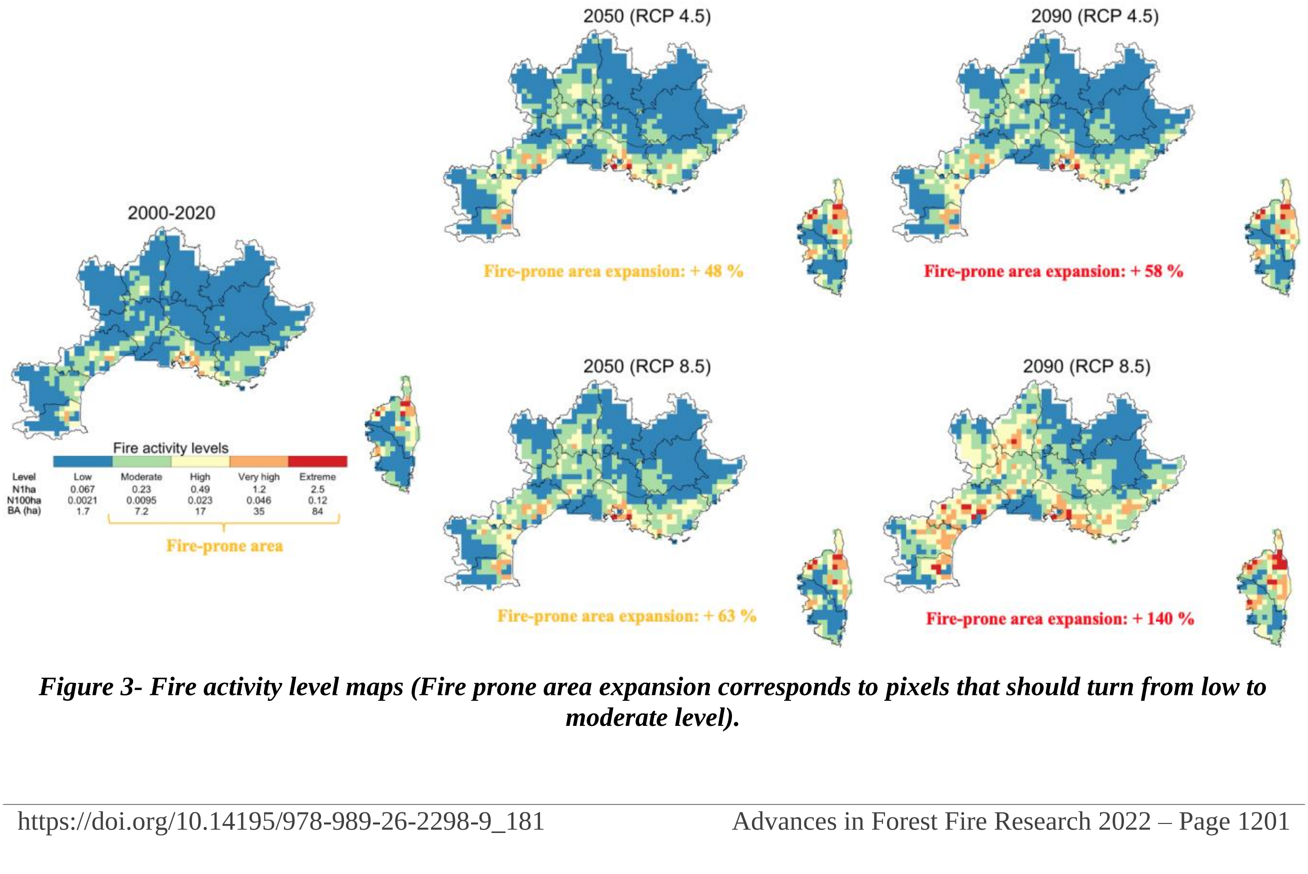

Figure 3- Fire activity level maps (Fire prone area expansion corresponds to pixels that should turn from low to moderate level).

Table 1- Percent fire activity changes due to the intensification and the expansion (Expressed in percentages of the metric sum over the fire-prone area for the present period).

RCP	Period	Fire metric	Intensification	Expansion
4.5	2050	N1	+30%	+14%
		N100	+54%	+21%
		BA	+48%	+20%
	2090	N1	+32%	+17%
		N100	+58%	+26%
		BA	+52%	+25%
8.5	2050	N1	+34%	+18%
		N100	+64%	+29%
		BA	+57%	+27%
	2090	N1	+90%	+52%
		N100	+183%	+101%
		BA	+162%	+93%

This study assumed that everything but climate remained equal, an assumption common to many projection studies, but which becomes questionable facing such large changes and long-term perspective. Land use and land cover could be included in the modelling framework of Firelihood (Castel-Clavera et al. 2022), but projecting future values for these variables remains challenging even if scenarios are becoming available. Moreover, even if fire return intervals remained quite large in 8-km pixels, local reburns can be frequent (Ganteaume and Barbero 2019), so that the increasing impact of fire-activity on fuel structure should be accounted. Finally, the expansion, lengthening and intensification were estimated assuming that suppression and prevention will remain identical. Expanding and lengthening management may allow to mitigate projected increases, at the cost of significant expansion of these policies. The intensification could be even more problematic, as suppression might be more frequently overflowed by simultaneous escaped fires (N1ha) and large fire events (N100ha).

4. Conclusion

These drastic increases provide a good indication of the potential lengthening of the fire season, spatial expansion and intensification of future fire activities under RCP 8.5, all three being importantly concerned, but dominated by the intensification in the case the spatial expansion. Lengthening and expansion might be mitigated by an expansion of the fire prevention and suppression policies, but the intensification might raise most operational concerns.

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