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Global Warming Reshapes European Pyroregions

Luiz Felipe Galizia[1,2], Renaud Barbero[1], Marcos Rodrigues[3], Julien Ruffault[4], Francois Pimont[4], and Thomas Curt[1]

[1]INRAE, RECOVER, Aix-Marseille University, Aix-en-Provence, France, [2]AXA Climate, Paris, France, [3]Department of Geography and Land Management, University of Zaragoza, GEOFOREST-IUCA Group, Zaragoza, Spain, [4]INRAE, Ecologie des Forêts Méditerranéennes (URFM), Avignon, France

Key Points:

- This is the first study to project future changes in fire regimes on a pan-European scale
- Our projections point to an intensification and expansion of the most fire prone pyroregions in southern Europe under a warmer climate
- Limiting global warming would substantially reduce the expansion of the area at risk and the transition toward more intense fire regimes

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

L. F. Galizia,
luiz.galizia@gmail.com

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Author Contributions:

Conceptualization: Luiz Felipe Galizia, Renaud Barbero, Marcos Rodrigues, Thomas Curt
Formal analysis: Luiz Felipe Galizia
Methodology: Luiz Felipe Galizia, Renaud Barbero, Marcos Rodrigues, Julien Ruffault, Francois Pimont, Thomas Curt
Project Administration: Thomas Curt
Supervision: Renaud Barbero, Thomas Curt
Writing – original draft: Luiz Felipe Galizia

Abstract

Wildland fire is expected to increase in response to global warming, yet little is known about future changes to fire regimes in Europe. Here, we developed a pyrogeography based on statistical fire models to better understand how global warming reshapes fire regimes across the continent. We identified five large-scale pyroregions with different levels of area burned, fire frequency, intensity, length of fire period, size distribution, and seasonality. All other things being equal, global warming was found to alter the distribution of these pyroregions, with an expansion of the most fire prone pyroregions ranging respectively from 50% to 130% under 2° and 4°C global warming scenarios. Our estimates indicate a strong amplification of fire across parts of southern Europe and a subsequent shift toward new fire regimes, implying substantial socio-ecological impacts in the absence of mitigation or adaptation measures.

Plain Language Summary

Pyroregions represent the typical range of area burned, fire frequency, intensity, and seasonality that prevail in a region over long periods of time. Pyroregions are thus of great interest given their potential utility to determine regional fire patterns and foresee future alterations in response to global warming. Previous research has investigated the effects of global warming focusing on burned area and fire frequency, yet changes in fire regimes are often overlooked. In this paper, we examined the effects of global warming on pyroregions in Europe. We identified five large-scale pyroregions reflecting different fire regimes. Future climate projections indicated an increase in fire activity and subsequent expansion of fire prone pyroregions across parts of southern Europe under warmer and drier conditions. The most fire prone pyroregions presented a spatial expansion ranging respectively from 50% to 130% under 2° and 4°C global warming scenarios with potential impacts on society. Limiting global warming would substantially reduce the expansion of the fire prone pyroregions in Europe.

1. Introduction

Wildland fire research has been increasingly promoted in Europe in recent years to better understand the driving forces and identify regions at risk. Fire activity responds to multiple drivers among climate, vegetation, and human activities operating at different spatial and temporal scales (Bowman et al., 2020; Cochrane & Bowman, 2021; Zheng et al., 2021). While the relative influence of environmental and anthropogenic factors varies geographically, climate variability expressed through fuel availability and dryness has been shown to be the dominant driver of fire activity at broad spatio-temporal scales (Abatzoglou et al., 2018, 2021; Bedia et al., 2015; Jones et al., 2022). Climate influences fire activity primarily by controlling fuel abundance in fuel-limited regions, and by controlling fuel dryness in flammability-limited regions (Pausas & Paula, 2012) with more fire under warmer and drier conditions (Barbero et al., 2019; Rodrigues et al., 2021; Turco et al., 2017). Extreme fire seasons, featuring intense and large fires, as seen in 2016 in France (Ruffault et al., 2018), 2017 in Portugal (Turco et al., 2019), and 2021 in Greece (Giannaros et al., 2022) were indeed associated with intense droughts and heatwaves.

These fire climate conditions are widely thought to become more frequent and intense with global warming (Abatzoglou et al., 2019; Jones et al., 2022; Son et al., 2021). Previous research projected an increase in burned area (Amatulli et al., 2013; Dupuy et al., 2020; Pimont et al., 2022; Turco et al., 2018), fire frequency (Pimont et al., 2022; Vilar et al., 2021), fire intensity (Aparício et al., 2022), and fire size (Ruffault et al., 2020) alongside a lengthening of the fire season (Fargeon et al., 2020) in Europe, under a warmer climate. Yet, our understanding of the effects of global warming on fire has been limited to single fire-regime components, thereby ignoring how fire regimes might change in the future.

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Fire-regime components such as the frequency, intensity, seasonality, and size control the effects of fire on the landscape, collectively shaping the so-called pyroregions (Cochrane & Bowman, 2021; Morgan et al., 2001). Pyroregions are usually defined as broad spatio-temporal units sharing similar distributions of the aforementioned components (Krebs et al., 2010). In this sense, pyroregions provide a level of generalization that may aid in understanding fire regimes among both technical and non-technical audiences (Boulanger et al., 2013; Galizia et al., 2021a). Pyroregions are also useful tools for developing fire policies that aim to adapt burnable landscapes to future climate conditions (Cochrane & Bowman, 2021). While previous efforts have focused on delineating historical or current pyroregions (Archibald et al., 2013; Galizia et al., 2021a; Pausas, 2022; Rodrigues et al., 2020), little is known about their future changes in response to global warming. Here, we hypothesize that future climate change may not only increase burned area but also alter the current pyrogeography with a potential expansion of fire-prone regions and even the emergence of new fire regimes.

Drawing from a remote-sensing data set of individual fires, we developed a European pyrogeography based on a range of fire-regime components to better understand how, where and when global warming may reshape fire regimes across the continent. We built empirical models linking each fire-regime component with climate and environmental variables for the historical period, and future 2° and 4°C global warming scenarios. We then delineated the pyroregions based on a clustering of the simulated fire-regime components and examined how these pyroregions might change in the future.

2. Materials and Methods

2.1. Fire Data

We used the GlobFire (Artés et al., 2019) data, a daily remote sensing data set of individual fires built from the pixel-based burned area MODIS product MCD64A1 Collection 6 (Giglio et al., 2018) at 500-m resolution over the period 2001–2018. GlobFire provides information beyond the burned area MODIS product, such as the perimeter and spatial extent of each fire patch. GlobFire data set presented a reasonable agreement with ground-based fire data, especially for fires larger than 100 ha (Campagnolo et al., 2021; Galizia et al., 2021b). We excluded fire data located within artificial lands (i.e., agriculture and urban) using Corine land cover data (European Union, 2018) because they generally do not put ecosystems at risk. Additionally, we used daily fire radiative power (FRP) of pixel-based MODIS product MCD14ML (Giglio, 2006) at 1-km resolution over the period 2001–2018. The FRP measures the radiant energy released per unit time from vegetation biomass burning (Wooster et al., 2021) and has been extensively used as a proxy of fire intensity, as well as for assessing carbon emissions and smoke impact for human health (Archibald et al., 2013; Laurent et al., 2019; Marlier et al., 2019; Pausas, 2022). Following Laurent et al. (2019), we performed a spatio-temporal matching between FRP and GlobFire databases. To do so, both datasets were regridded at an annual timescale and 1-km resolution and excluded FRP pixels without individual fire data.

2.2. Climate Data

We used the observed fire-weather index (FWI) (Van Wagner, 1987) data version 4.0 from the C3S Climate Data Store (CDS; https://cds.climate.copernicus.eu/) at 25-km resolution over the period 1980–2018, given its strong correlations with fire activity across Europe (Bedia et al., 2015; Galizia et al., 2021a; Pimont et al., 2021). FWI was calculated using weather variables from the ECMWF ERA5 reanalysis data set (Vitolo et al., 2020). Simulated FWI were extracted from the CDS at 11-km resolution over the period 1980–2098 and computed using one regional climate model (RCA4) coupled with six global climate models (GCMs; Table S1 in Supporting Information S1) from the EURO-CORDEX (Jacob et al., 2014) initiative. The RCA4 is widely used to provide fine-scale climate information for impact studies in Europe (Kjellström et al., 2016). Given that much of the variability across models arises from GCMs, our approach should capture most of the uncertainty in future projections.

We regridded the projected FWI onto a common 25-km resolution grid and averaged both observed and projected FWIs onto an annual timescale. We bias-corrected the projected FWI by applying the equidistant quantile mapping (Li et al., 2010) method to each climate model. This ensures that the distributions of projected FWI matched the observed FWI while preserving future changes in FWI from this reference period. Using a delta change bias correction procedure yielded similar results (Figure S8 in Supporting Information S1). Note that we bias-corrected directly the FWI values to avoid an underestimation of extreme values when correcting first the individual meteorological variables (Jain et al., 2020). We then reaggregated observed and projected fire weather data onto a common 50-km resolution grid for fire modeling purposes (i.e., gather enough fires in each grid cell).

We estimated the global warming dates (2° and 4°C) for each climate model following the procedure described in Jacob et al. (2014). Global warming levels are largely independent of the choice of future emissions scenario and align with the Paris Agreement targets (Hausfather et al., 2022). They correspond to the period over which time-averaged global mean temperature (20-year window) reaches 2° and 4°C, compared to the "preindustrial" period 1881–1910 (Table S2 in Supporting Information S1). Finally, we computed the annual multimodel mean by taking the average of the FWI from the six climate models for each warming scenario.

2.3. Environmental Data

We used the Corine land cover data from Copernicus Land Monitoring Service (https://land.copernicus.eu/pan-european/corine-land-cover) at 100-m resolution from the period 2000–2018. We computed the land cover distribution as the percentage area of the 50-km grid cell covered by different vegetation and anthropogenic classes across Europe (Table S3 in Supporting Information S1). To account for land cover changes through time we computed land cover distributions averaging the Corine data set over the studied period. We omitted from our analysis grid cells with more than 80% of non-burnable land cover (i.e., anthropogenic lands), following Abatzoglou et al. (2019). Additionally, we retrieved topographic data from the GTOPO30 raster digital elevation model (https://earthexplorer.usgs.gov/) at 1 km resolution. We computed the topographic slope as the percent of rise in elevation calculated from the altitude layer and regridded onto a common 50-km resolution grid.

2.4. Fire-Regime Components

Fire-regime components represent the statistical fire characteristics that collectively shape the so-called pyroregions (Krebs et al., 2010). We aggregated daily fire data onto a 50-km grid at an annual timescale to compute six fire-regime components: burned area (in ha), number of fires (in n), percentage of large fires (fires >100 ha; in %), percentage of fires during the cool season (fires in November–April period; in %), length of fire period (in months), and fire intensity (in MW), following Galizia et al. (2021a) (see Table S3 in Supporting Information S1). These components were used in previous studies for the characterization of fire regimes (Pausas, 2022).

2.5. Modeling Fire-Regime Components

Statistical models linking climate and environmental conditions to fires have received much attention under the global warming context (Abatzoglou et al., 2021; Barbero et al., 2014; Pimont et al., 2021; Riviere et al., 2022; Turco et al., 2018, 2019). We sought here to develop individual statistical models for each fire-regime component to simulate historical and future fire activity in Europe. We used generalized additive models (GAMs), a supervised learning data modeling method (James et al., 2013) that allows nonlinear responses to explanatory variables to be estimated through different smoothed functions and distribution types. GAMs were extensively used to simulate fire-regime components, such as the area burned (Joseph et al., 2019; Pimont et al., 2021) and fire frequency (Ager et al., 2018; Preisler et al., 2008; Woolford et al., 2021). Each fire-regime component was simulated at the annual scale in a 50-km grid (1,663 grid cells × 18 years) with relevant explanatory variables, such as climate, land cover, topography, and grid coordinates (i.e., spatial effect) over the period 2001–2018 (Table S3 in Supporting Information S1). In order to deal with the large proportions of zeros and high variance in our data, we used Tweedie and negative binomial regression as GAMs to link the fire-regime components with explanatory variables (Wood et al., 2016). For more technical details about smoothing and GAMs, see Wood et al. (2016). Note that we assumed that the percentage of fires during the cool season will remain unchanged (i.e., stationary) in the future as no significant relationship was found between this variable and climate conditions or land cover types (Galizia et al., 2021a), indicating that these are generally intentional fires under control. For each fire-regime component model, we selected the most relevant explanatory variables based on a stepwise approach with a trade-off between accuracy and complexity of the models using the Akaike information criterion (AIC). Only variables with significant influence on a specific fire-regime component were selected. We simulated each fire-regime component under the historical period (2001–2018) and for two different global warming levels (2° and 4°C) considering the respective 20-year window of each model (Table S2 in Supporting Information S1). FWI was the only time-varying explanatory variable in the models, while the other land cover variables were hypothesized to remain stationary. We evaluated the predictive performance of the models with an independent data set. By excluding a test period of 5 years (~30% of the data) when computing the model parameters (Turco et al., 2018). We then compared model simulations with observations aggregated across temporal and spatial scales to assess how the models perform in practice. The goodness-of-fit between predictions and observations was measured with the root-mean-square error (RMSE), coefficient of determination (R^2), and its significance values (p) using cross-validation method.

2.6. Delineating the European Pyrogeography

We delineated the European pyrogeography based on the projections of temporally averaged fire-regime components at the grid cell level over both historical and future (20-year) periods. Identifying homogeneous regions allows a better understanding of the climatic forcing on fire activity. The pyrogeography was designed through a fuzzy version of the K-means clustering algorithm (Pal et al., 1996). This analysis aimed to connect grid cells into distinct spatially defined regions (i.e., clusters) having maximum internal similarity according to the six fire-regime components. This optimizes the reduction of the sum-of-square differences, that is, the total difference between each data unit and the cluster mean. Note that for this analysis all fire-regime components presented the same weight. Additionally, fuzzy clustering algorithms implemented here have the advantage over other clustering methods to provide the probability of each observation to belong to a specific cluster. Fire-regime components were first rescaled into Z-scores with a zero mean and a unit variance, as implemented in most clustering approaches (Galizia et al., 2021a; Rodrigues et al., 2020). We then used the Euclidean distance as a dissimilarity measure for clustering the fire-regime components into homogeneous units. The optimal number of clusters was determined using the highest-ranked number of clusters out of 30 statistical indices available in the nbClust *R* package (Charrad et al., 2014). Pyroregions were then characterized according to the observed distribution of fire-regime components, indicating the most influential patterns in terms of magnitude and variability. Finally, we computed the spatial agreement between the pyrogeography from observed and simulated fire-regime components.

2.7. Future Changes in the European Pyrogeography

We analyzed future changes in the spatial distribution of the pyrogeography with 2 and 4°C global warming levels. To assess the uncertainty of future climate projections, we simulated the pyrogeography using each climate model separately, and grid cells for which all models agreed on the simulated pyroregion were indicated with a dot. Additionally, we assessed the degree to which each grid cell is likely to belong to a specific pyroregion for each scenario with a probabilistic approach. We then computed the difference in pyroregions probability between each warming scenario and the historical period. Finally, we averaged probabilities across longitudes and smoothed the signal using a polynomial filter to assess future changes across a north-south gradient.

3. Results and Discussion

3.1. Modeling Fire-Regime Components

We built statistical models based on climate and environmental factors for five different fire-regime components: burned area, number of fires, percentage of large fires, length of fire period, and fire intensity. These models reproduced to a large extent fire-regime components at the grid-cell level (50-km at annual timescale) across the European continent (Table S1 in Supporting Information S1). When averaged temporally over the historical period (2001–2018), the spatial agreement between model outputs and observations ranged from an R^2 of 0.40–0.79 depending on fire-regime components (Figure 1a, Figure S1, and Table S1 in Supporting Information S1), partly owing to the presence of the spatial effect. When averaged spatially across the continent, interannual correlations were however much lower (R^2 ranged from 0.22 to 0.43) (Table S1 and Figure S2 in Supporting Information S1). This lower correlation between observations and simulations was expected due to the contrasted fire regimes within such a large domain and the stochasticity at play amongst fire seasons. This has however limited impact on our study given our objectives to reproduce the averaged fire-regime components over 20-year periods.

FWI was the dominant driver of all fire-regime components on such spatio-temporal scales (Figure 1b). For instance, burned area, fire intensity, length of fire period, and the number of fires were all positively correlated

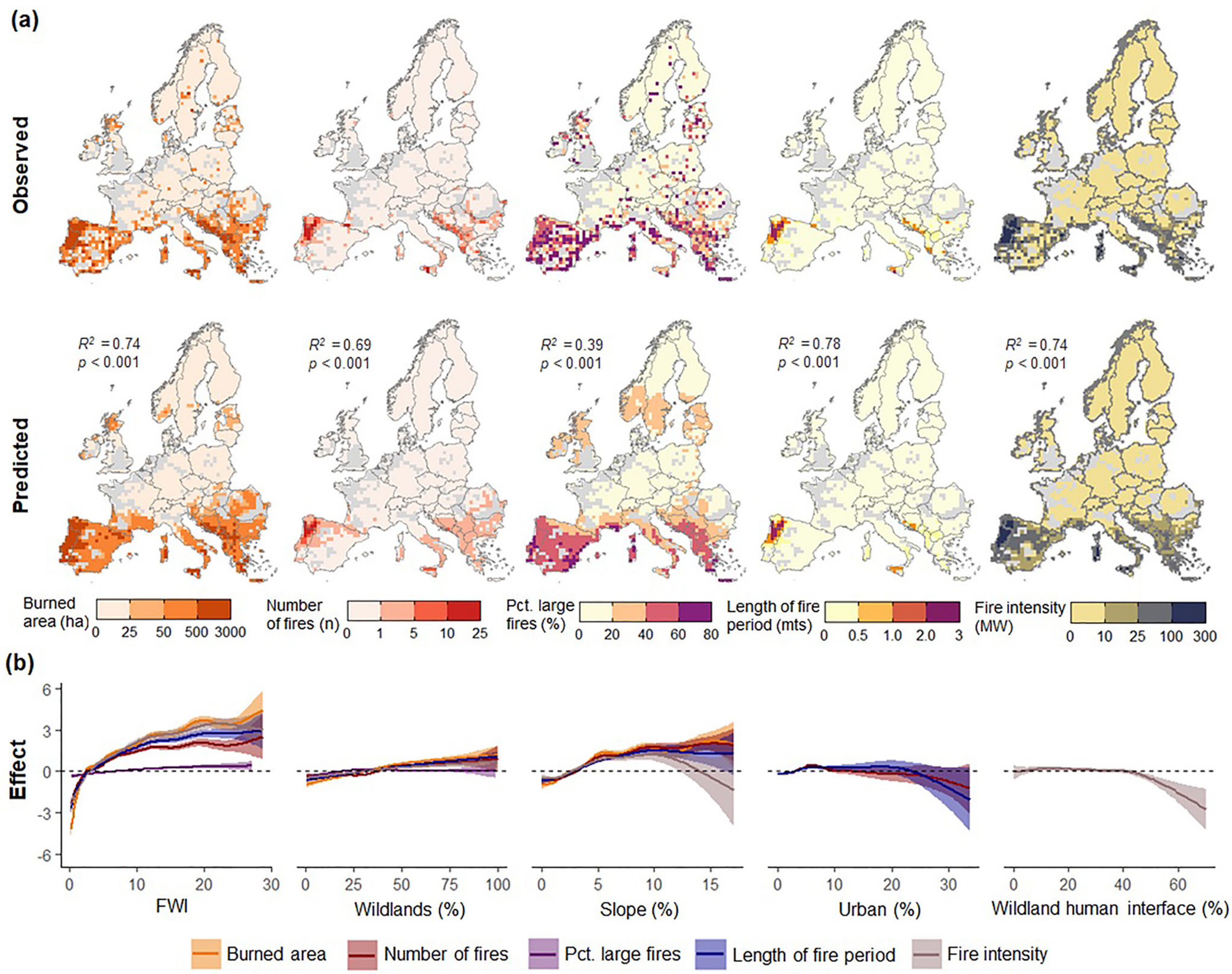

Figure 1. Fire-regime components and partial effects of the empirical fire models. (a) Observed and predicted burned area, number of fires, percentage of large fires, length of fire period, and fire intensity averaged over the historical period (2001–2018). *R*-squared (R^2) represents the spatial agreement with observations and significance level. Regions with more than 80% of non-burnable land cover are shaded in gray. Note the non-linear colorscales. Observed percentage of fires during the cool season is presented in Figure S3 in Supporting Information S1. (b) Response curves of the models showing the effects of fire-weather index, wildland cover (%), slope (%), urban cover (%), and wildland-human interfaces (%) on each fire-regime component. The shading shows the 95% confidence interval. Note that only predictor/predictand couples with significant responses are shown. For the spatial effect see Figure S4 in Supporting Information S1.

with annual FWI, in agreement with previous studies (Abatzoglou et al., 2018; Bedia et al., 2015; Ruffault et al., 2020), but their responses seem to level off beyond a certain threshold, as already observed at finer temporal and spatial scales (e.g., Pimont et al., 2021). Overall, environmental factors, such as wildland cover and topographic slope, were also positively correlated with fire activity as documented in previous regional studies (Boulanger et al., 2018; Pimont et al., 2021). Conversely, burned area and length of fire period were found to decrease in regions where urban land cover exceeds 20% due to the fragmentation of the landscape decreasing fuel continuity and load (Laurent et al., 2019). Interestingly, fire intensity also decreases at wildland human interface exceeding 40%, and at steeper slopes. Note that the use of the spatial effect (grid coordinates) improved the accuracy of the statistical fire models since this implicitly accounted for interactions among the explanatory variables, which were not explicitly modeled here.

3.2. Projecting Future Fire-Regime Components

We simulated each fire-regime component under both 2° and 4°C global warming periods (20-year window) using the multimodel mean of FWI computed from six paired GCM-RCMs projections while keeping the other

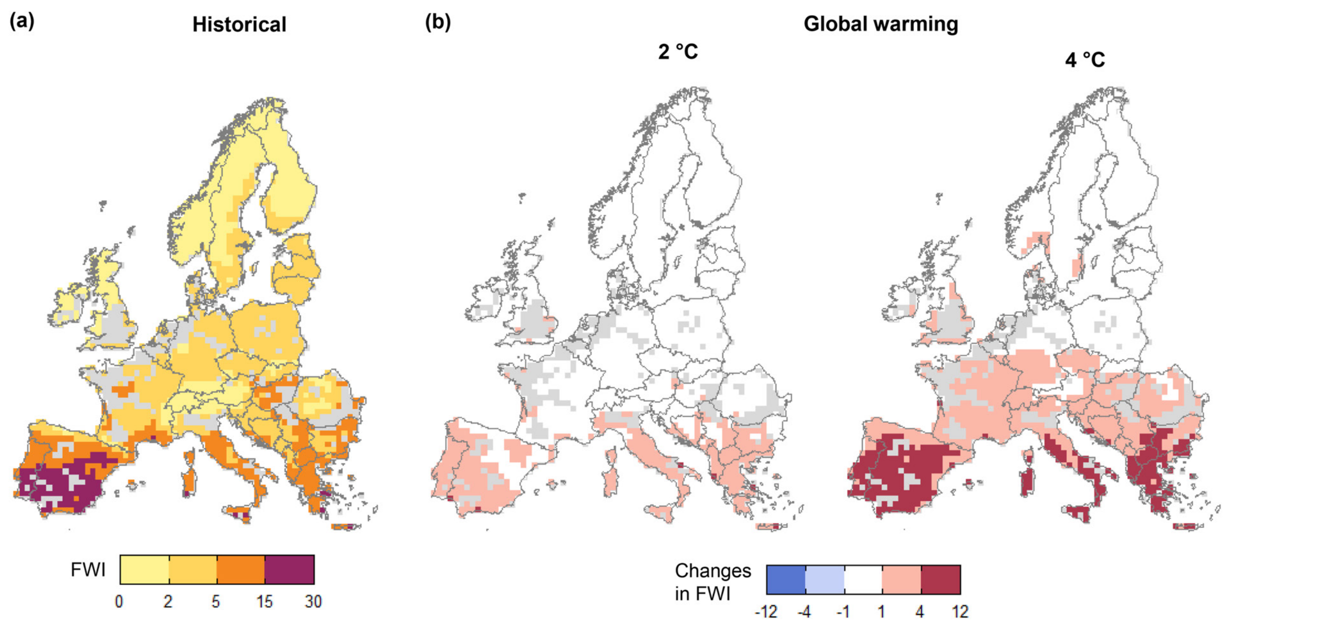

Figure 2. Observed fire-weather index (FWI) and future changes under different global warming levels. (a) Mean annual FWI during the historical period (2001–2018) and (b) absolute changes in the annual FWI multimodel mean with respect to the historical period in response to a 2° and 4°C global warming scenario.

predictors stationary (Figure 2 and Figure S9 in Supporting Information S1). As expected, FWI was projected to increase in response to global warming, with the highest changes in southern Europe and rather limited increases in northern Europe (i.e., >50°N). The increase of FWI is mainly related to substantial increases in temperature and decrease of relative humidity throughout Europe (Abatzoglou et al., 2018). Yet, projected changes in precipitation during the summer exhibit more distinct geographic variability with decreases in the Mediterranean (amplifying the temperature-induced FWI increase) and increases in northern Europe due to large-scale circulation changes (de Vries et al., 2022) thereby dampening the FWI increase (Bedia et al., 2015; Carnicer et al., 2022; Krikken et al., 2021).

At continental scale, all fire-regime components clearly increased with burned area, fire intensity and length of fire period showing the highest changes ranging from 30% increase under 2°C and up to 100% under the 4°C warming scenario (Table 1). This intensification of fire in a warmer world is projected to occur mostly across southern Europe (Figure 3). Regions such as the northwest of the Iberian Peninsula and the western Balkans presented substantial changes under the 2°C global warming scenario. Larger increases in fire activity were foreseen under the 4°C warming scenario, with a lengthening of the historical fire season by about 3 months in northern Portugal and western Balkans. Other regions, such as northern Spain, western Pyrenees, and southern Italy, showed substantial changes as well in that scenario. Similar to Turco et al. (2018), we found an increase in the

Table 1
Summary of Projected Changes in the Fire-Regime Components

	2°C global warming		4°C global warming	
	Absolute	Relative	Absolute	Relative
Burned area	87,373.30 (ha)	32.2%	275,621.20 (ha)	101.5%
Number of fires	217.00 (*n*)	21.7%	597.00 (*n*)	59.5%
Pct. large fires	0.80 (ppt)	3.5%	2.00 (ppt)	8.5%
Length of fire period	0.04 (mts)	28.2%	0.11 (mts)	80.7%
Fire intensity	3.20 (MW)	31.7%	9.60 (MW)	92.2%

Note. Changes of the spatial sum for burned area and number of fires and spatial mean for the other fire-regime components in absolute and relative (in %) values with respect to the historical period (2001–2018).

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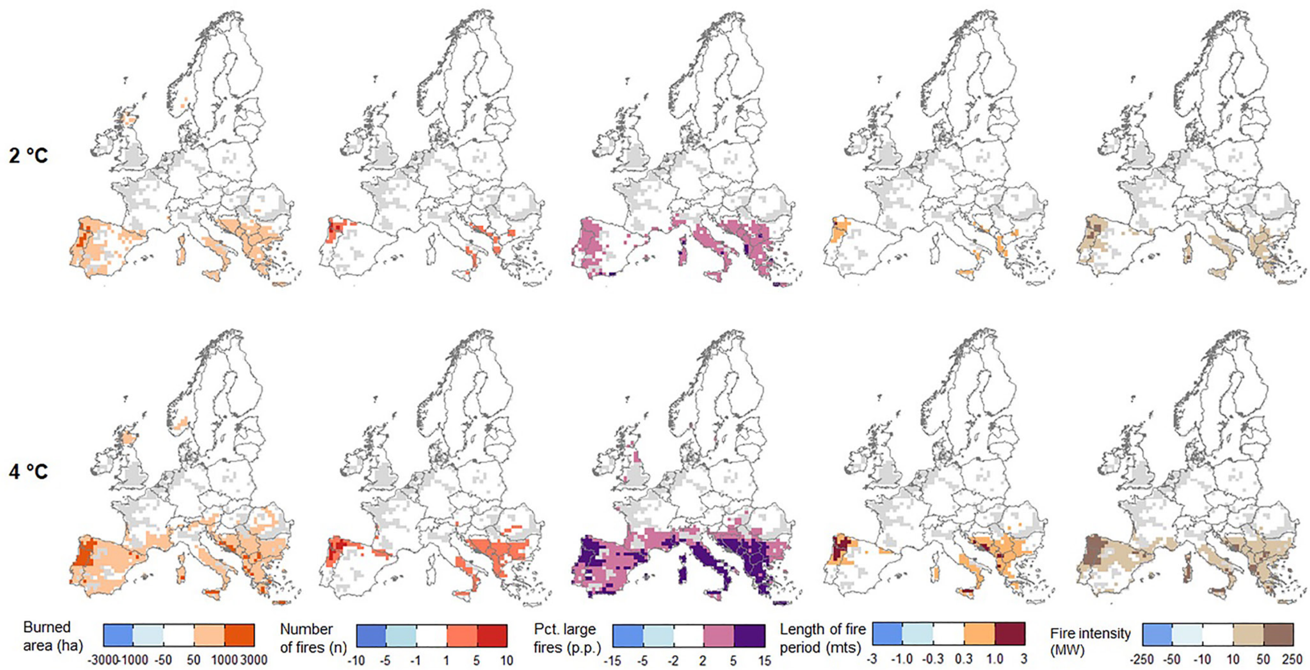

Figure 3. Changes in projected fire-regime components under different global warming levels. Absolute changes in projected fire-regime components in response to a 2° and 4°C global warming scenario with respect to the historical period (2001–2018).

burned area exceeding 50% across the northern Iberian Peninsula beyond a 2°C global warming level (Figure S5 in Supporting Information S1). Alongside the burned area, our analysis showed large increases in fire frequency, fire intensity, the length of fire season, and percentage of large fires. Yet, there was no notable increase in fire activity across central and northern Europe (i.e., >50°N) due to the limited change in FWI.

Although changes in fire-regime components are mostly expected across southern Europe due to the large signal of change in the FWI, the spatial patterns of changes did not entirely match those of the FWI (see Figures 2 and 3) as the climate-fire relation is mediated, on finer scales, by other bottom-up drivers.

3.3. Historical and Future European Pyrogeography

We then delineated the European pyrogeography based on a clustering of the temporally averaged fire-regime components over both the historical and future periods. We identified five different pyroregions representative of fire regimes prevailing in Europe (Figure 4). A Cool-season fire pyroregion (hereafter CSF) is characterized by moderate fire activity and a large percentage of very low-intensity fires occurring during the November–April period (Figure 4d). A Low fire-prone pyroregion (hereafter Low-FP) is characterized by very low fire activity and dominated by low-intensity fires. A Fire-prone pyroregion (hereafter FP) is characterized by moderate fire activity with moderate fire intensity, and a high proportion of large fires. A Highly fire-prone pyroregion (hereafter Highly-FP) features a high fire occurrence with high fire intensity and a long fire period. Finally, an Extremely fire-prone pyroregion (hereafter Extremely-FP) displays the highest fire incidence, fire intensity, and the longest fire period, characterizing the most fire-affected region in Europe. Note that FP, Highly-FP, and Extremely-FP presented a substantial percentage of cool-season fires (~10%), suggesting a bimodal fire season as seen in other regional analyses (Benali et al., 2017; Pimont et al., 2021). Conversely, in Low-FP, all fires occurred during the warm period.

Over the historical period, the CSF was scattered across Europe, including parts of the Alps, Pyrenees, Scotland, Romania, and the Baltics (Figure 4a). The Low-FP was found mostly across northern and parts of central Europe. The FP was identified mostly across Spain, southern Portugal, southern France, Italy, and parts of the Balkans. The Highly-FP was found in the northwestern part of the Iberian Peninsula, Sicily, and parts of the Balkans. Finally, the Extremely-FP was located mostly in northern Portugal. This historical pyrogeography built

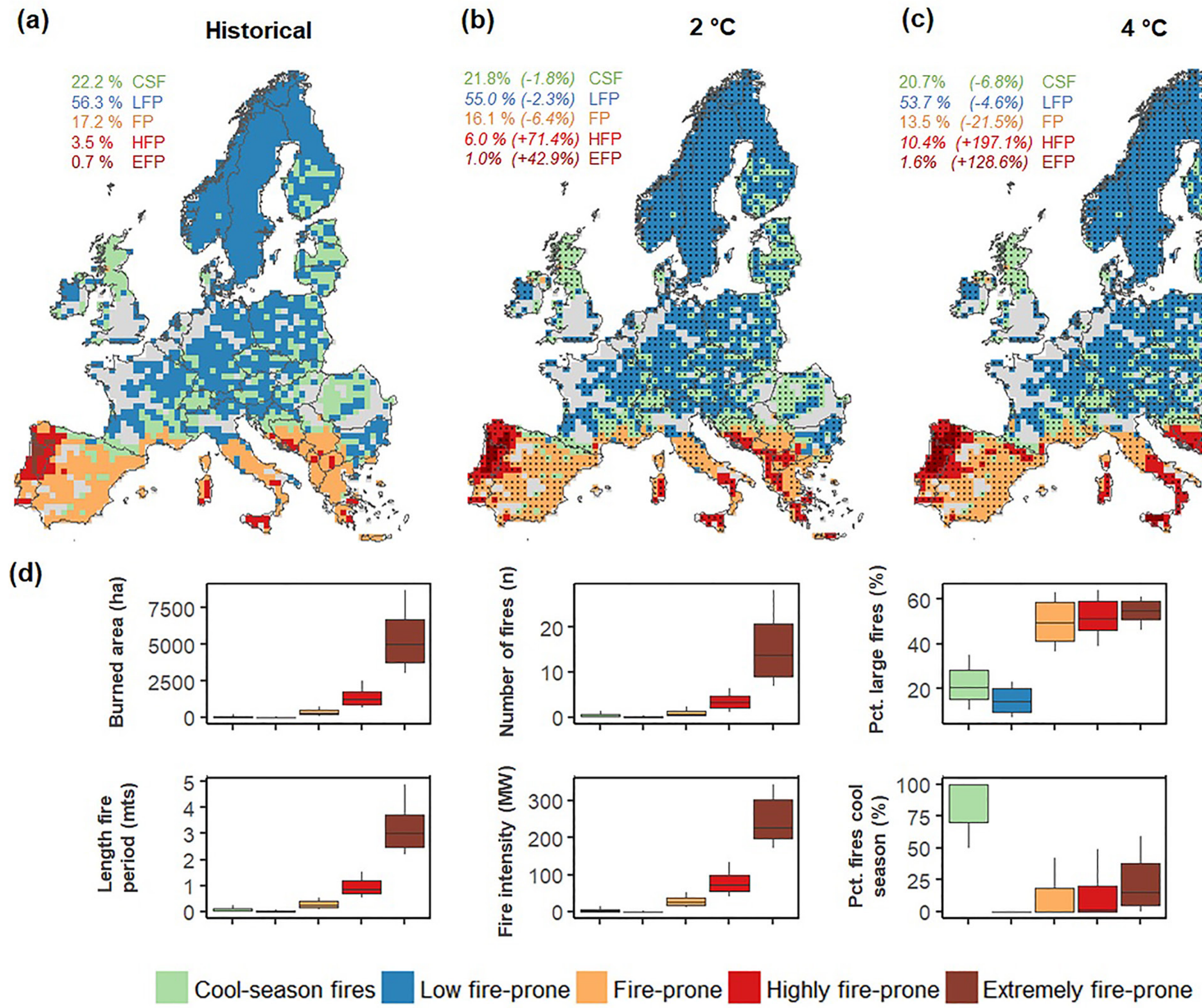

Figure 4. Historical and future pyrogeography under different global warming levels. Projected pyrogeography based on simulated fire-regime components for (a) the historical period (2001–2018), (b) the 2°, and (c) 4°C global warming scenarios. Values in the top left represent the relative extent of each pyroregion and relative changes (in %) in pyroregion extents among the scenarios. Dots indicate grid cells where the pyrogeography agrees with all individual climate model projections (d) Distribution of fire-regime components (i.e., median and interquartile range) in each pyroregion.

from modeled fire-regime components presented a reasonable spatial agreement (i.e., 86% of all grid cells were correctly classified) when compared with the pyrogeography built from observed fire-regime components (see Figure S6 in Supporting Information S1). Additionally, this pyrogeography exhibited spatial patterns in line with those reported in previous regional studies in southern Europe (Calheiros et al., 2021; Fréjaville & Curt, 2017; Moreno & Chuvieco, 2013; Rodrigues et al., 2020).

In the 2°C global warming scenario, the spatial extent of Highly-FP and Extremely-FP expanded by 71% and 43%, while Low-FP and FP decreased by ∼2% and 6%, respectively (Figure 4b). More acute changes arose with a 4°C warming, with Highly-FP and Extremely-FP increasing up to 197% and 129% in extent, while Low-FP, FP, and CSF decreased by ∼5%, 21%, and 7%, respectively (Figure 4c). In absolute terms, Highly-FP and Extremely-FP together increased by 116,410 km^2 in a 2°C warming and 324,285 km^2 in a 4°C warming. This represents an expansion of 1–3 times the size of Portugal. Overall, the main transitions occurred across southern Europe, with less fire-prone pyroregions (Low-FP and CSF) switching to more fire-prone pyroregions (FP and Highly-FP) and fire-prone (FP) switching to higher fire-prone pyroregions (Highly-FP and Extremely-FP), indicating an intensification of fire activity in regions already at risk (see Figure S7 in Supporting Information S1).

For a deeper understanding of future potential switches induced by climate change, we also examined, for each warming scenario, how the probabilities of grid cells to be classified in a given pyroregion may change (Figure 5).

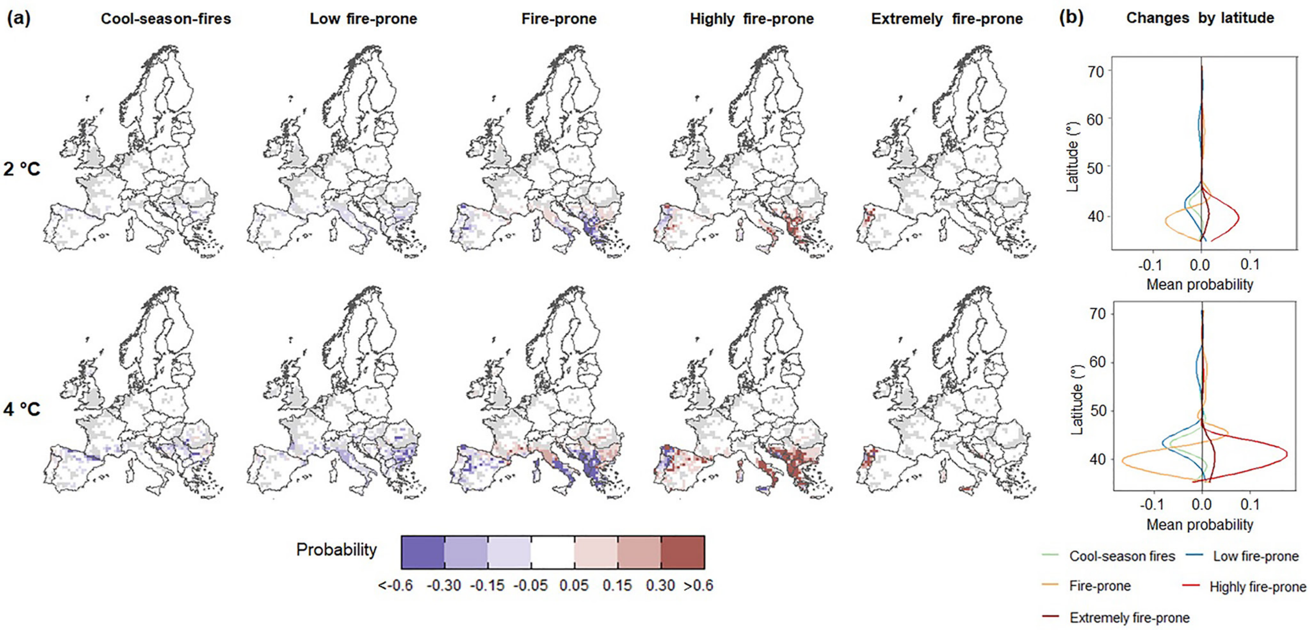

Figure 5. Changes in probability to belong to each pyroregion under different global warming levels. (a) Absolute changes in pyroregions probability were computed for each warming scenario with respect to the historical period (2001–2018). The probability of occurrence (0–1) indicates the degree to which grid cells belong to each pyroregion and (b) changes in the latitudinal average probability computed from weighted regression (smooth) across the latitudinal gradients for each warming scenario.

Unlike categorical changes (i.e., hard clustering) seen in Figure 4, which were mostly clumped in specific regions of southern Europe, large changes in the probability of pyroregions occurrence emerged along the northern edge of historically fire-prone regions (i.e., 40–45°N) (Figure 5b). We found an increased probability of FP regions expanding toward the north, while Highly-FP may expand to the east and south. However, future increases in FWI were too limited to trigger categorical changes in more mesic forested zones such as central and northern Europe.

Building upon previous studies projecting an increase in fire frequency and burned area across southern Europe due to global warming (Dupuy et al., 2020; Ruffault et al., 2020; Turco et al., 2018), our study provided two important new insights. First, we considered a range of fire-regime components, going beyond the single burned area metric examined in most studies. By including fire frequency, intensity, size distribution, and seasonality we presented different spatial patterns of fire that have been shown to shape collectively the pyroregions (Bowman et al., 2020; Krebs et al., 2010). For instance, we found that fire regimes in the southern Iberian peninsula were dominated by large but less frequent fires than in northern Portugal which featured the highest fire activity in Europe. In mountainous and/or traditionally agricultural regions, such as the Pyrenees, parts of the Alps, and Scotland, burned area can be substantial but originates mostly from cool-season fires due to human-related activities, which were not found to be related to climate conditions (Galizia et al., 2021a). Additionally, the magnitude of future changes was found to vary substantially across the fire-regime components (Figure S5 in Supporting Information S1). The highest changes were found in fire intensity and burned area, while changes in the number of fires were more limited. Second, we projected future changes in pyroregions in a spatially and temporally explicit approach at a pan-European level, relying on a statistical modeling framework able to reproduce historical patterns. Spatially and temporally explicit studies provide useful insights for fire management since they indicate where and when changes may occur (Boulanger et al., 2013; Rodrigues et al., 2020).

Our findings highlighted the importance of climate as a primary control of fire regimes, as observed in previous studies examining burned area (Abatzoglou et al., 2018; Jones et al., 2022; Rogers et al., 2020). The projected increase in frequency and persistence of compound dry-warm periods during the summer is projected to expand the Mediterranean climate (Ruffault et al., 2020), as well as the fire prone regions. Yet, our findings also indicated that climate alone cannot explain all the variation in fire regimes throughout Europe. Other factors, such as the location, land cover, urban cover and topography controlled to some extent fire regimes across space. Future changes projected in the European pyrogeography agreed with other studies indicating that most of the future increases are expected in the most fire-affected areas today (Carnicer et al., 2022; Jones et al., 2022; Pimont et al., 2022; Riviere et al., 2022). Additionally, our findings indicated that regions with a great extent of fuel available to burn in the transition zones (40–45°N) were more likely to shift toward a more fire prone regime in a warmer and drier climate.

This work extends previous regional or national studies that had delineated historical fire regimes across parts of Europe (Fréjaville & Curt, 2017; Resco de Dios et al., 2022; Rodrigues et al., 2021) and shows how global warming might alter fire regimes on a continental scale. We reported on a strong intensification and expansion of the most fire prone regions (Highly-FP and Extremely-FP) across southern Europe in a warmer world. This shed light on potential concerns raised by firefighting and fire management services, which were devised based on historical records or experiences (Taylor, 2020). An increase in the area burned, fire intensity, and lengthening of fire period up to 3 months in parts of the Balkans, northern Iberian Peninsula, Italy, and western France may overwhelm national fire suppression capacities. Historical observations alone may become insufficient to cope with fire in a warmer climate in some regions of Europe. In this sense, the pyrogeography developed here may help in prioritizing fire management and develop consistent risk mitigation strategies across pyroregions. Combined with fire danger forecasts, pyroregions can be seen as broad management units to mitigate the negative effects of fire. This may also facilitate country-to-country cooperation for fire management and suppression (Bloem et al., 2022) when pyroregions span geopolitical borders, fostering and strengthening partnerships among fire-affected regions within the European Union Civil Protection Mechanism. Finally, combining the pyrogeography with exposure and vulnerability maps would be the first step into a fire risk assessment on a pan-European scale.

The classification of fire-regime components into pyroregions is widely thought to capture the spatial heterogeneity of fire regimes providing a level of generalization that aids in understanding the fire patterns (Boulanger et al., 2013; Bowman et al., 2020). This implies using a coarse spatiotemporal resolution in order to identify persistent fire patterns (i.e., historical range of variability). However, fires are often characterized by many low-intensity events and a few high-intensity events responsible for most of the societal and ecological impacts (Le Breton et al., 2022). The latter is obviously masked in such coarse resolution analysis (Krebs et al., 2010). Our approach is thus likely to underestimate the occurrence of individual extreme fire events generally associated with specific meteorological conditions (Ruffault et al., 2020). Flash droughts and/or critical synoptic-scale fire weather conditions have been shown to facilitate the occurrence of extreme fire, features that are not evident in annual resolution (Barbero et al., 2019; Pimont et al., 2021). This may partly explain why interannual correlations were rather low to moderate, yet our results are broadly consistent with longer–term regional climate–fire relationships (e.g., Pimont et al., 2022). Additionally, climate projections are known to underestimate the observed trends in fire weather conditions across Europe (Jones et al., 2022). In this sense, our study should be viewed as a conservative estimate of the effect of climate change on fire regimes.

We note that the methodology developed here has some other limitations. First, we assumed that the percentage of cool-season fires will remain unchanged in the future. In Europe, cool-season fires are mostly related to anthropogenic activities, however, no correlation was found between those fires and anthropogenic variables over the historical period, hampering reliable projections. Second, we considered the environmental and human-related variables as stationary in our future simulations. Although the developed statistical models accurately simulated historical fire activity, our approach overlooks the impacts of future climate conditions on vegetation, as well as the effect of fire itself on fuel load (Hantson et al., 2016; Williams & Abatzoglou, 2016). Indeed, a warming climate may temper increases in fire activity by decreasing fuel availability in dry regions through aridification (Mauri et al., 2022; Pausas & Paula, 2012). Conversely, this may boost fire activity in other regions through transitions from forested systems to more flammable vegetation types (i.e., shrublands), or through increasing dead fuel from drought-induced forest diebacks (Liang et al., 2017; Masrur et al., 2022). Additionally, an increase in fuel accumulation due to systematic fire suppression (Moreira et al., 2020; Parisien et al., 2020) could exacerbate the signal of climate change on fire activity, particularly high-intensity fires. The impact of reburn could also decrease fuel availability consequently limiting future increase of fire activity in the most fire prone regions. The complex relationships between climate, vegetation and fire may thus challenge the realism of our purely statistical approach in future decades. To overcome these limitations, studies that explicitly account for interactions among fire, climate, vegetation, and anthropogenic factors have been implemented using dynamic global vegetation models (Hantson et al., 2016). Yet, such models often struggle to represent interannual variations in fire activity and observed trends (Forkel et al., 2019; Jones et al., 2022). Finally, previous research has shown that new fire suppression policies (e.g., Ruffault & Mouillot, 2015), as well as changes in human ignitions, population density, land use and landscape fragmentation may also reshape the functional climate-fire relationship (Kelley et al., 2019). In this sense, continued efforts are still needed to better understand the roles played by top-down climate and bottom-up environmental and anthropogenic factors in shaping current and future fire regimes across Europe.

4. Conclusions

This work is the first to project future changes in fire regimes on a pan-European scale. This is crucial in the context of global change since it provides a baseline to investigate temporal and spatial changes in fire regimes under different warming scenarios. Additionally, by examining future changes under policy-relevant warming levels of 2° and 4°C, we provided insights into how the success or failure of climate policies would translate to fire hazards in Europe.

We found a substantial increase in all fire-regime components across southern Europe in a future warmer climate, indicating a strong amplification of fire in regions already at risk. We showed that under global warming, pyroregions are likely to shift toward more fire prone regimes across parts of southern Europe, potentially triggering a wide range of ecological and socio-economic issues. Additionally, regions on the northern edge of historically fire-prone areas (i.e., 40–45°N) were found to be the most sensitive to a warming climate.

These projected changes have direct implications for both short-term risk management and long-term risk mitigation implemented by the European Union Civil Protection mechanisms, as well as climate adaptation across these regions. This notably includes increased community preparedness, optimized resource allocation (personnel and equipment), resource sharing, and enhanced fuel management. Policies based on a specified fire-regime target should help develop better fire prevention and suppression strategies supporting fire managers to minimize the negative impacts of fire.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All the data that support this study can be freely accessed using the websites or data repositories described below. The GlobFire data set of individual fires is available at https://doi.pangaea.de/10.1594/PANGAEA.895835. The fire radiative power from MODIS (MCD14DL) is available at https://earthdata.nasa.gov/firms. The Canadian FWI System indices from ERA5 reanalysis are available at https://doi.org/10.24381/cds.0e89c522 and from EURO-CORDEX climate projections are available at https://doi.org/10.24381/CDS.CA755DE7. The land cover data set is available at https://land.copernicus.eu/pan-european/corine-land-cover. The GTOPO30 global elevation data is available at https://doi.org/10.5065/A1Z4-EE71. Simulation outputs supporting this manuscript can be found at www.zenodo.org in the following repository: Data_support_Galizia_et_al_2023 (https://doi.org/10.5281/zenodo.7632099). All analyses, maps and plots were conducted using the R's framework for statistical computing, Version 4.1.0, available via https://cran.r-project.org/ (R Core Team, 2021).

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