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Europe faces up to tenfold increase in extreme fires in a warming climate

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This study quantifies how changes in temperature and precipitation would influence the intensity and duration of extreme fires across Europe. The analysis explores the impact of a range of climate change projections on fire events compared to a baseline of fire danger, using a 30-year ERA5 reanalysis. The results show that areas in southern Europe could experience a tenfold increase in the probability of catastrophic fires occurring in any given year under a moderate CMIP6 scenario. If global temperatures reach the +2 °C threshold, central and northern Europe will also become more susceptible to wildfires during droughts. The increased probability of fire extremes in a warming climate, in combination with an average one-week extension of the fire season across most countries, would put extra strain on Europe's ability to cope in the forthcoming decades.

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INTRODUCTION

Wildfires are an essential ecological component in flammable ecosystems, and about 3% of the land area is burned every year^{1–3}. While natural in origin, fire activity has been used for millennia by cultural and economic activities and to fulfill human desires to modify the landscape^{4,5}. In Europe, 96% of all ignitions are caused by human activity, either intentionally or accidentally⁶. A large proportion of these fires are then suppressed to protect human lives and property⁷. The spread and intensity of wildfires are predominantly influenced by weather conditions, vegetation, and topography, regardless of the initial source of ignition.

In recent years, there has been a surge of destructive wildfires⁸, causing social disruptions and substantial economic losses⁹. Three of the worst fire years in terms of burnt area in Europe have occurred in the past six years since records began in 1980. In southern Europe, the total burnt area in 2021 was 391,736 ha, nearly double the previous year's total and the highest since 2017. A shift in the scale and persistence of wildfires globally can be observed over the last 40 years^{10,11}. Wildfires are occurring in new places because of increased vegetation flammability¹². They happen outside the traditional fire season^{13,14} and are much more intense^{15,16}. A small number of high-intensity wildfires, often called megafires¹⁷, produce most of the recorded burned areas (~97%)^{18,19}. Their secondary impacts include erosion²⁰, deforestation^{21,22}, depletion of carbon stocks^{23,24}, and they pose a threat to human safety and infrastructure^{25,26}. These events are also of particular importance to wild-land fire management. Rapidly spreading fires are difficult to suppress and often have catastrophic impacts. No firefighting methods can fully cope with megafires, and these are often left to burn until natural extinction takes place²⁷.

While several studies have examined climate-induced regional trends in fire danger^{17,28–35}, a comprehensive quantitative analysis of how temperature and precipitation, both in isolation and combination, contribute to a change in the probability of extreme wildfire events at a pan-European scale remains limited. In this study, we address this research gap by performing a sensitivity analysis of how changes in precipitation and temperature influence fire danger. We use the fire weather index (FWI)³⁶

calculated from the ECMWF fifth generation climate reanalysis (ERA5)³⁷ to construct two-dimensional impact response surfaces (IRS) to quantify how temperature and precipitation variation will likely change fire extremes in Europe. FWI is an estimation of potential fire behavior and intensity based on prevailing weather conditions. Its calculation is based on daily weather variables, including air temperature and precipitation, and it is the most widely used metric for estimating fire weather globally, both operationally³⁸ and in research^{15,39}. While FWI does not directly express a measure of fire activity, it has been shown to correlate with burned areas, especially for significant events (burnt area > 10,000 hectares), and to indicate the effort required to suppress a fire once ignited^{40–43}. Thus, one can anticipate an increased likelihood of extreme fires as extreme fire weather events become more frequent, regardless of the specific location where a fire might start. This correlation relies on the assumption of relative stability in fire ignitions. Most fires in Europe are ignited because of human behavior, and this behavior is not likely to change in the near future. We also assume that there will be no significant changes in fire suppression measures or land use, which could otherwise weaken the correlation between extreme FWI values and the occurrence of extreme fires. Control measures will face increasing challenges as fire risk escalates in extensive European areas⁴⁴ and landscape transformations—such as rural abandonment—have led to increased fuel availability for burning⁴⁵. Given these assumptions, the utilization of the output from the latest generation of Global Climate Models participating in the sixth phase of the Coupled Model Intercomparison Project (CMIP6), in conjunction with the FWI, has proven to be a valuable tool for comprehending the forthcoming alterations in fire weather patterns linked to a shifting climate⁴⁶.

The area of focus in this study is a latitudinal gradient spanning three specific regions in mainland Europe, as delineated by the Intergovernmental Panel on Climate Change (IPCC, 2022) (Fig. 1). The three regions are projected to undergo variations in temperature and precipitation, characterized by warmer and drier summers in southern and central Europe (SEU and CEU) and warmer and wetter winters in northern Europe (NEU).

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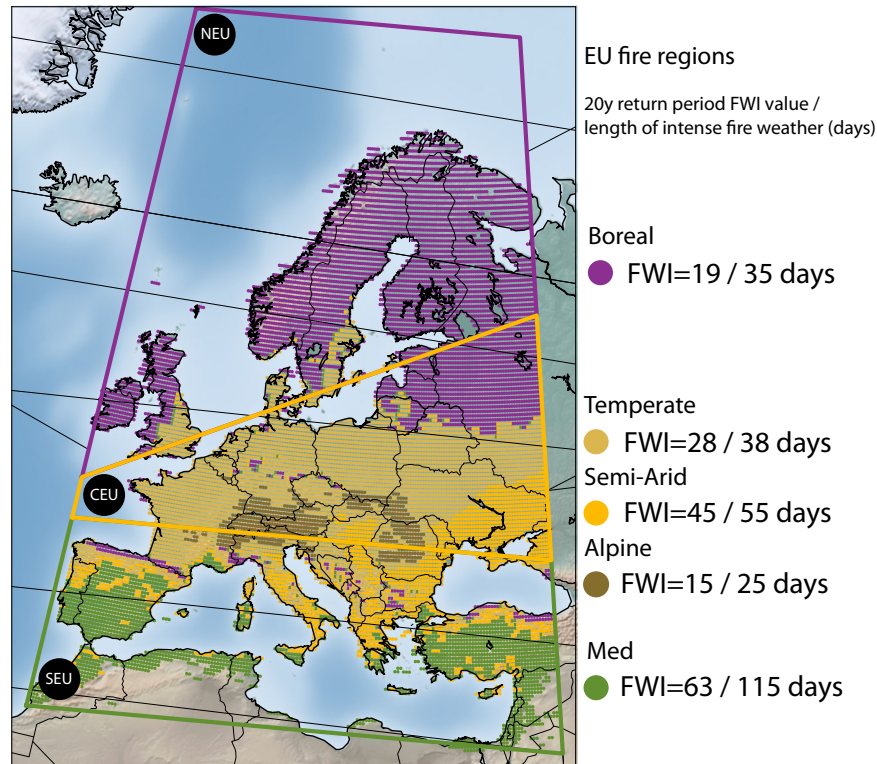


Fig. 1 Extreme fire conditions in Europe under the current climate expressed in terms of (1) FWI value associated with extremes defined as a 20-year return period event and (2) average fire seasonal length defined as the number of days above half 20-year return period event. Five areas (boreal, temperate, semi-arid, alpine, and Mediterranean) of similar fire season duration and intensity have been identified, looking at the historical daily summer record of FWI value over the period 1981–2010. Some areas classified as boreal are not geographically in the boreal region, but since they display a similar FWI pattern, they are bundled together with the boreal region. The boundaries of the three European IPCC regions (NEU-northern Europe, CEU-central Europe and SEU-southern Europe; (IPCC, 2022)) are overlaid upon the five cluster regions to contextualize and facilitate the comparison of projected seasonal changes. These five areas exhibit varying levels of extreme fire danger in the current climate, as indicated by the 20-year return period value. They also display distinct duration of the fire season. FWI reaches higher intensity in arid and semi-arid areas than in temperate, boreal and alpine regions. The fire season is much longer in the Mediterranean than in other identified fire regions in Europe. Projected changes in temperature and precipitation will affect these five fire regions differently because of the latitudinal dependence of the seasonal changes projected in the three European IPCC regions.

The CMIP6 simulations under a moderate Shared Socio-economic Pathway (SSP) scenario (SSP2-4.5) anticipate an average annual temperature rise in Europe of 2 °C in the short-term (2036–2065) and 3 °C in the long-term (2070–2099) (Supplementary Table 2). Under the more extreme SSP4-8.5 scenario, the increase could reach 4 °C. Such temperature rises, particularly when coupled with reduced precipitation, could significantly alter landscape flammability across Europe. The proposed IRS study quantifies the expected shifts in extreme fire probability in response to a range of projected temperature and precipitation changes. This analysis not only enhances our understanding of current and future fire risks but also aids in identifying European regions at high risk of catastrophic fires. Additionally, it offers a framework to assess the impact on the coping capacities of nations in a warmer climate.

RESULTS

Fire extremes in Europe under current and future climate change

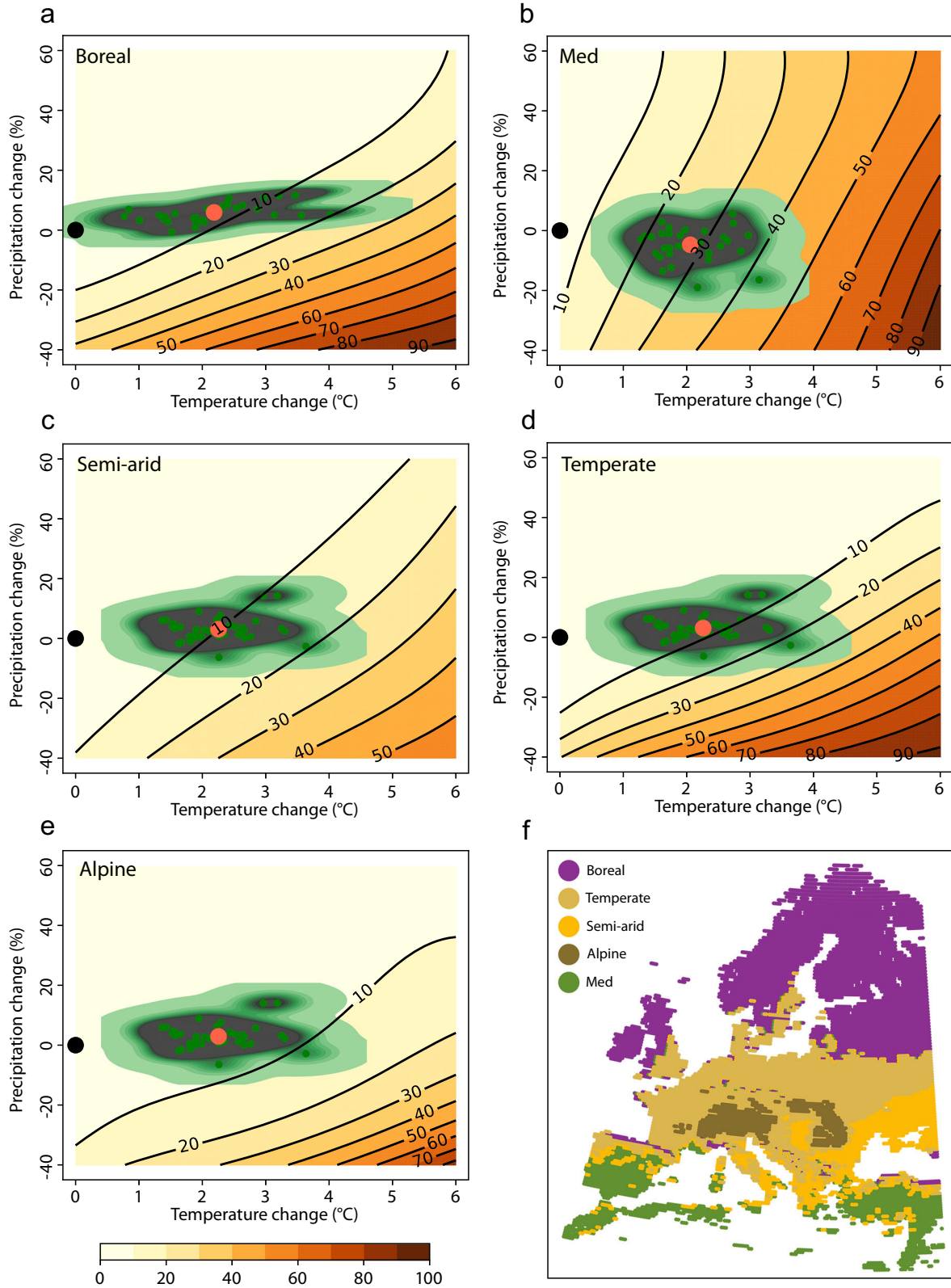
The initial step of the analysis involved assessing regional variations in landscape flammability and the prevalence of fire-prone conditions across Europe, considering different climatic zones. A cluster analysis of historical daily simulations (1981–2010) of FWI during the active fire season (April–October) calculated using the ERA5 reanalysis³⁷ revealed five distinct

regions (Fig. 1): boreal, temperate, semi-arid, alpine, and Mediterranean (MED). The identified regions represent areas of similar fire season length and intensity.

In the second step, the definition of an extreme fire event was established for each cluster. Specifically, an extreme event was characterized as corresponding to the FWI value expected to be observed once in 20 years, on average. The intensity of events at this level is assumed to be severe, potentially escalating into megafires. The 20-year return period differs significantly among the previously identified five regions. In the MED fire region, an FWI value of 63 represents the 20-year return period. This implies that between 1981 and 2010, there was a 5% probability of observing an FWI value equal to or greater than 63 in any given year (Fig. 1). However, a much smaller value of FWI denoted a 20-year return period in the boreal (FWI = 19) and alpine regions (FWI = 15).

The duration of the average fire season in different parts of Europe is also considered and defined as the number of days when FWI exceeds half the value of the 20-year return period threshold. Currently, the MED region is experiencing four months of fire weather conditions. This duration is as much as four times longer than the boreal, temperate and alpine regions and two times longer than the semi-arid regions of central Europe.

After identifying the intensity of extreme fire events as an FWI value corresponding to a 20-year return period and defining duration as the number of days above half of this threshold, we



used these parameters as a reference under the current climate scenario. We then computed the exceedance probabilities in various future climate scenarios, assessing the likelihood of surpassing these established thresholds. This analysis aimed to quantify potential changes in the intensity and duration of

extreme fire weather due to climate change. This assessment was conducted using IRS, where weather variables driving fire events are systematically altered, and the response in fire weather is depicted through surfaces representing combined changes (Figs. 2, 3).

Fig. 2 Probability, in %, of extreme fire danger under projected temperature and precipitation changes in Europe. Two-dimensional impact response surfaces (IRS) illustrating the probability, in %, of extreme fire danger under projected temperature and precipitation changes in Europe. The black dot represents the baseline scenario, where there is a 5% probability in any given year of experiencing a 20-year return period event as observed in the present climate (1981–2010). The curves outline projected changes in the probability of such an event for the five identified regions with homogeneous fire regimes: **a** Boreal, **b** Mediterranean **c** Semi-arid, **d** Temperate, and **e** Alpine. These projections are based on incremental simulations considering temperature changes from 0 to +6 °C and total precipitation changes from -40% to +60% relative to the annual mean with a monthly adjustment based on future projections of changes to the inter-annual variability. Overlaying the IRS curves are density probability functions in green, representing the projected temperature and precipitation from CMIP6 SSP2-4.5 multi-model simulations for the short-term scenario (2036–2065). The red dot denotes the mean value of these projected outcomes. **f** The map aids in identifying the five fire regions. A full explanation of the methodology is given in “Derivation of incremental curves from CMIP6 multi-model projections”. The IRS curves with superimposed CMIP6 multi-model simulations for the SSP2-4.5 long-term scenario (2070-2099) are provided in Supplementary Fig. 2.

The projected temperature and precipitation changes derived from CMIP6 multi-model simulations for the scenario SSP2-4.5 were used to calculate the likelihood of observing these changes in the short-term (Figs. 2, 3) and toward the end of the century (Supplementary Figs. 2, 3). The IRS was employed to directly link climate change outputs with potential impacts on the target variable (fire intensity and duration). The CMIP6 multi-model simulations consistently indicate comparable changes in precipitation across the five climate regions, while temperature changes exhibit greater variability among these regions. However, compared to temperature projections, the changes in precipitation are more uncertain⁴⁷. This increased uncertainty arises from the significant spatial and temporal variability of precipitation, along with the complexity of atmospheric processes. Challenges in accurately modeling the hydrological cycle and cloud dynamics further contribute to this uncertainty. The NEU region exhibits significant variability in projected temperature increase, whereas precipitation shows relatively minor deviations compared to the current climate, with some climate models even suggesting an increase.

The impact of temperature changes on the probability of high FWI events varies across the five identified regions (Fig. 2). Arid regions, such as MED, exhibit a heightened sensitivity to temperature fluctuations, with a one-degree Celsius increase in temperature nearly doubling the likelihood of an extreme fire event. Precipitation decrease has a less pronounced impact. A 20% increase in total precipitation is required to counterbalance the effects of one-degree warming. A similar trend, albeit less pronounced, is evident in the semi-arid region of central Europe. In contrast, boreal, temperate and alpine regions display a distinct pattern whereby the increase in extreme fire events will be observed when temperature increases beyond the 2 °C threshold. Only beyond this point does a one-degree increase in temperature result in a twofold increase in the probability of extreme events.

In boreal and temperate regions (Fig. 2a, d), a 20% reduction in precipitation is expected to double the probability of extreme fire weather from its current 5% to 10%. In these regions, the impact of temperature changes on FWI is less pronounced. The increased probability of observing extreme events is accompanied by an extension of the fire season in Europe, with a nearly uniform 10-day increase observed when the mean temperature reaches +2 °C. However, the impact of this extension varies across European countries. Northern European countries are expected to witness a nearly 30% rise in the number of days requiring fire assistance, whereas southern European countries will experience a more moderate 8% increase (Fig. 3).

In the MED region, the majority of projections indicate a drying trend (Figs. 2, 3). However, the IRS analysis suggests that the potential of extreme fire risk in this region is primarily driven by temperature changes with limited sensitivity to changes in precipitation. This can be attributed to the region's already dry conditions during summer, where further drying may have a limited impact on exacerbating the already high fire-prone conditions. Notably, any increase in temperature is expected to

raise the probability of extreme fire occurrences in the future. While this analysis does not explicitly consider fuel moisture, it is important to note that in arid regions, elevated temperatures result in a higher partial vapor pressure deficit, which intensifies evaporation from soil and evapotranspiration from plants, ultimately reducing soil moisture and causing vegetation to become drier. Consequently, these conditions can increase the likelihood of the ignition and spread of fires due to the greater availability of dry fuels.

Considering CMIP6's most likely scenario (denoted as a red dot in Figs. 2, 3) in both short- and long-term projections, the projected impact of climate change on landscape susceptibility to extreme fires varies across the five European regions (Fig. 4a, b). In most regions, about two-thirds (66%) of the landscape is predicted to have a 5–10% probability of such events in the short-term. However, the MED region is likely to face higher risks, with 40% of its area showing a 10–15% likelihood. Approximately 11% of the MED region could see extreme fire probabilities between 20% and 25%, while 5% might experience a 25–50% likelihood of extreme fires. By 2100, the extent of areas with a medium risk is expected to increase across all five regions. In the MED region, the area facing a medium risk is projected to triple, and in the other four regions, it is projected to double from 6% to 12%.

CMIP6's most likely climate projections indicate an extended fire season duration across Europe (Fig. 4c, d). In the MED region, the fire season is expected to increase by at least one week, with one-fifth of this region potentially experiencing an extension of the fire season by 20 days by the end of the century (Fig. 4d). Similarly, the northern part of Europe is projected to experience a prolongation of the fire season by approximately one week. These projections consider changes in temperature and precipitation in isolation. However, a study by³⁴ highlights the significance of maximum daily vapor pressure deficit in predicting fire activity. This study suggests that if the effect of moisture is considered, the fire season could extend beyond what our current analysis indicates.

An increase in the probability of extreme fires is expected to strain nations' capacities to cope with the fire risk, particularly if it affects extensive areas. Climate risk information must be actionable to be useful for decision-makers. To expand on this, we assessed the spatial extent of the enhanced probability of extreme fires in short- and long-term scenarios (Fig. 5a), along with the extended periods of fire-prone weather (Fig. 5b).

Our analysis indicates that more than half of Europe's total land area is expected to witness a doubling of the probability of extreme fire events, increasing from 5% to 10%. Moreover, specific regions will experience localized hotspots marked by a tenfold increase in the probability (from the current 5% to 50% under the most likely CMIP6 scenario).

The MED region, encompassing eastern Turkey, Greece, southern Italy, the Iberian Peninsula, southern France, and northern Africa, is projected to experience the most significant rise in fire risk (see Fig. 5). Additionally, a heightened risk zone extends along the Atlantic coastline of central and northern Europe. In contrast,

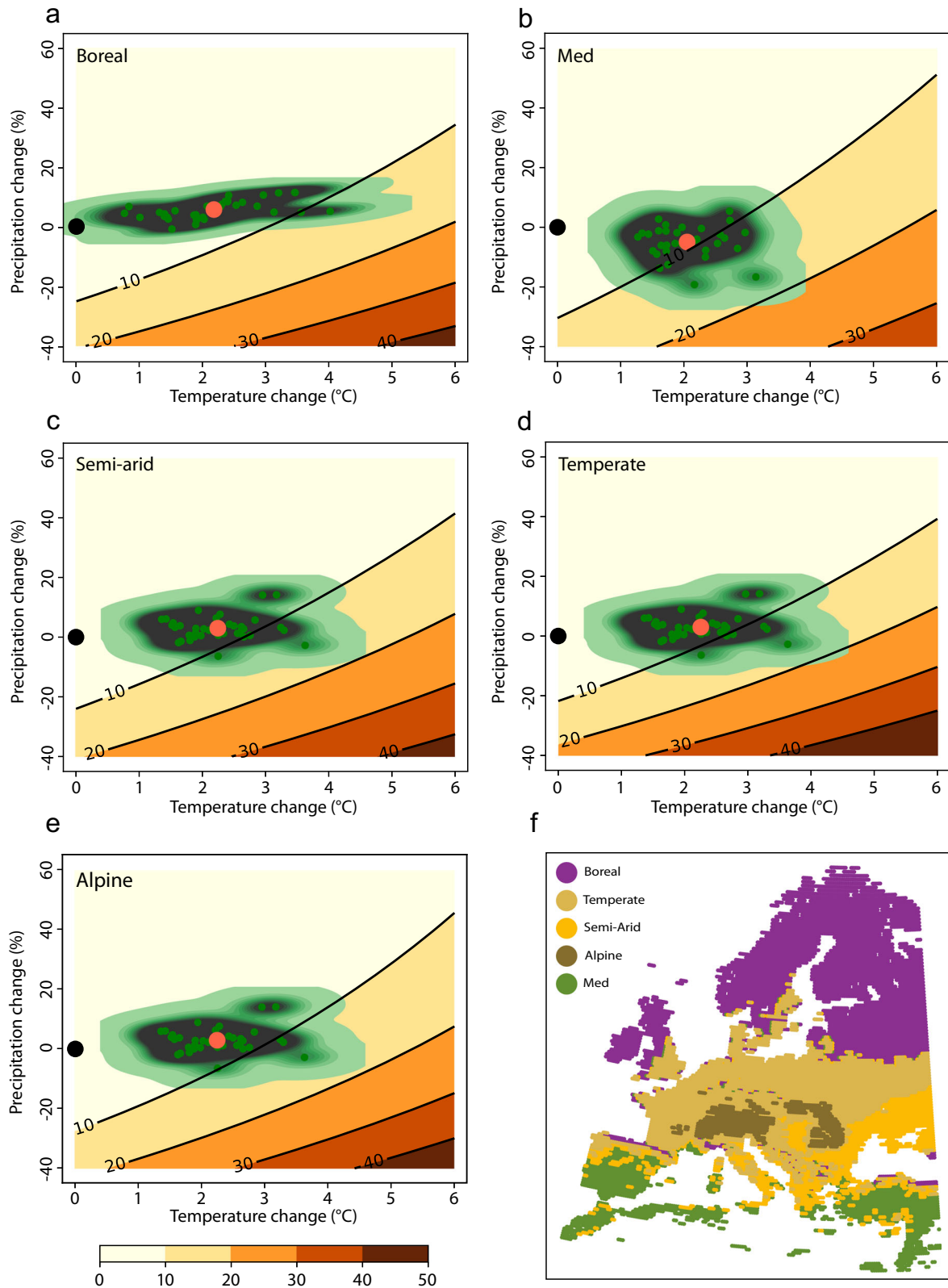


Fig. 3 Lengthening in days of fire season under projected temperature and precipitation changes in Europe. Same as Fig. 2, but for the excess in the days when fire assistance capability is employed. The length of the fire season is defined as the number of days above half the 20-year return period FWI value for **a** Boreal, **b** Mediterranean **c** Semi-arid, **d** Temperate, and **e** Alpine. The baseline climate refers to a 30-year simulation (1981–2010) of daily FWI estimations from historical simulations³⁷ and is indicated as a null increment marked with a black dot to highlight current conditions. Superimposed on the IRS curves, the projected temperature and precipitation CMIP6 SSP2-4.5 multi-model simulations for the short-term scenario (2036–2065) are shown as a density probability function in green, with the red dot identifying the most likely projected outcome. **f** The map helps identifying points belonging to each fire region. The CMIP6 multi-model output for the SSP2-4.5 long-term (2070–2099) scenario is provided in Supplementary Figure 3.

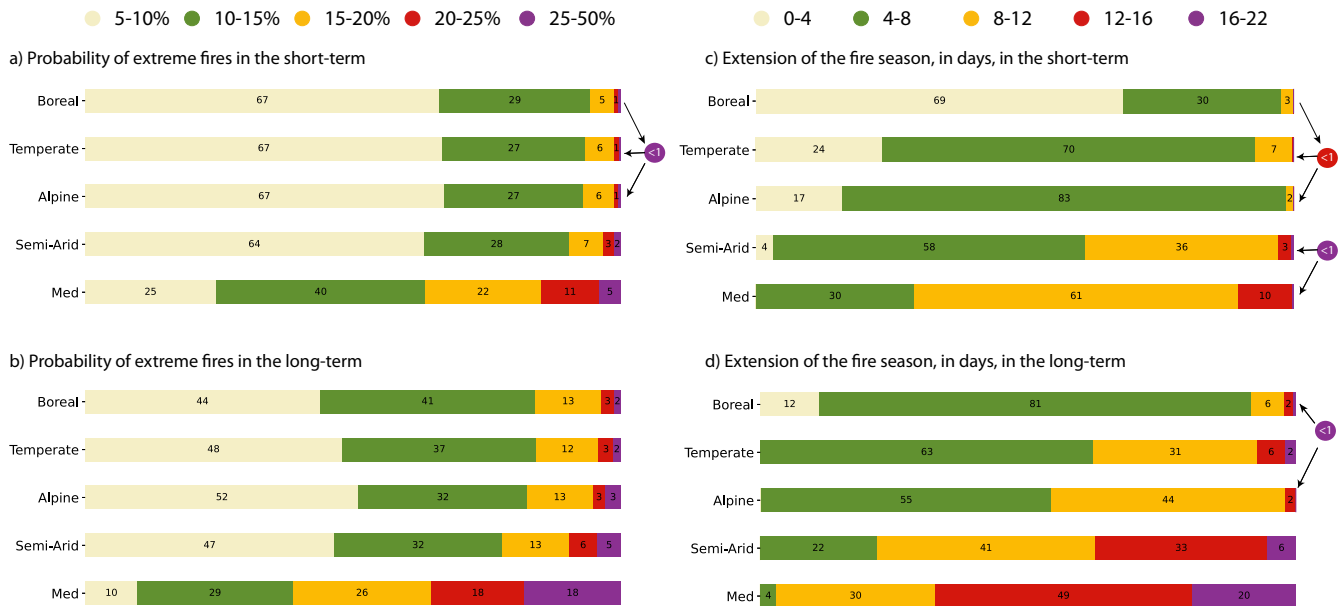


Fig. 4 Expected extent in the increased probability of extreme fires and the length of the fire season in the coming decades. Analysis of the proportion of land in the five fire regions showing **a** short-term and **b** long-term amplification in the probability of occurrence of an extreme fire event, along with **c** short-term and **d** long-term extension of the fire season. The statistics are constructed using the most likely projected outcome of the CMIP6 multi-model simulations for all points within each region and grouping them according to their increased probabilities. 50% of Europe will experience at least a doubling in the probability of an extreme event.

northern Europe shows the least pronounced increase in risk. In most parts of this region, the expected maximum increase is 20% (shifting from one event every 20 years to one every five years). However, it is crucial to note that the boreal area is highly susceptible to changes in precipitation, and prolonged drought periods during the fire season can result in catastrophic consequences for this region.

In the short-term, the fire season is projected to be extended by 12–16 days in the Iberian Peninsula, eastern Spain, southern France, Greece, and western Turkey, while central Europe is expected to experience an increase of 4–8 days (Fig. 5). In the long-term, central Europe will see a modest increase of an additional four days, but the MED region, encompassing North Africa, eastern Spain, southern France, eastern Greece, and western Turkey, is anticipated to undergo a substantial escalation in fire duration, with increases ranging from 12 to 22 days. This trend indicates that, by the end of the century, up to 18% of southern Europe's land area could be subjected to catastrophic fire events as frequently as every other year. Furthermore, climate projections reveal an emerging pattern of increased vulnerability to extreme fires in previously less affected regions of southern Europe (Fig. 5).

DISCUSSION

Projected climate change, which encompasses changes in temperature and precipitation, is anticipated to have an impact on the occurrence of extreme fire events. In this study, we specifically concentrate on extreme fire weather conditions since they are known to be the primary drivers behind most large fire events⁴⁸. Our investigation focuses on assessing the heightened likelihood of extreme fires occurring in Europe by analyzing the probability of observing FWI values equivalent to a 20-year return period in the current climate under future climate conditions. Although the FWI is not a direct measure of fire activity, it is closely linked to the environmental conditions conducive to fire development. This correlation is particularly pronounced for extreme events that span large areas, implying a strong

connection between extreme fire weather and the probability of extreme fires.

Our analysis shows that there will be a substantial increase in the probability of these conditions developing under a broad spectrum of climate change conditions. Fires that develop at FWI larger than 50 (the current climate 20-year return period values of the MED and semi-arid regions) can transition into megafires. The consequences of these fires can be catastrophic, as demonstrated by recent events in Europe and worldwide. Notably, the Pedrógão Grande fire, which developed in Portugal⁴⁹ in 2017, caused 66 casualties and triggered a change in the way fire suppression is managed by European member states across the European Union⁵⁰. In recent years, a sharing mechanism known as RescEU has been implemented, providing a communal pool of resources, such as an expanded fleet of firefighting planes and ground forces, to enhance firefighting capabilities.

Fires that ignite at FWI around 20 are usually manageable through effective suppression actions. Even though the probability of a 20-year return period event is increasing in Europe's temperate, boreal, and alpine regions, the likelihood of observing megafires in these regions, even under extreme projected climate changes, remains limited in absolute terms. However, a country's coping capacity is often proportional to the frequency of extreme events. In 2018, when FWI reached its 20-year return period value, Scandinavia witnessed a substantial, albeit manageable, number of forest fires. These conditions were able to swamp the limited national resources. By the end of that year, a total area of 20,000 hectares had burned. This unprecedented event stunned the population and marked the worst fire year on record for northern Europe⁵¹.

The findings of this study highlight the MED region as experiencing the most pronounced impact in terms of increased fire extremes (Figs. 2–5). This is a direct consequence of the projected increase in temperature and decrease in precipitation over the fire season. Further, the IRS-based sensitivity analysis showed that the boreal and temperate cluster regions are very sensitive to changes in precipitation (Fig. 2a, d). In these regions, even areas that are typically less susceptible to fires may see an

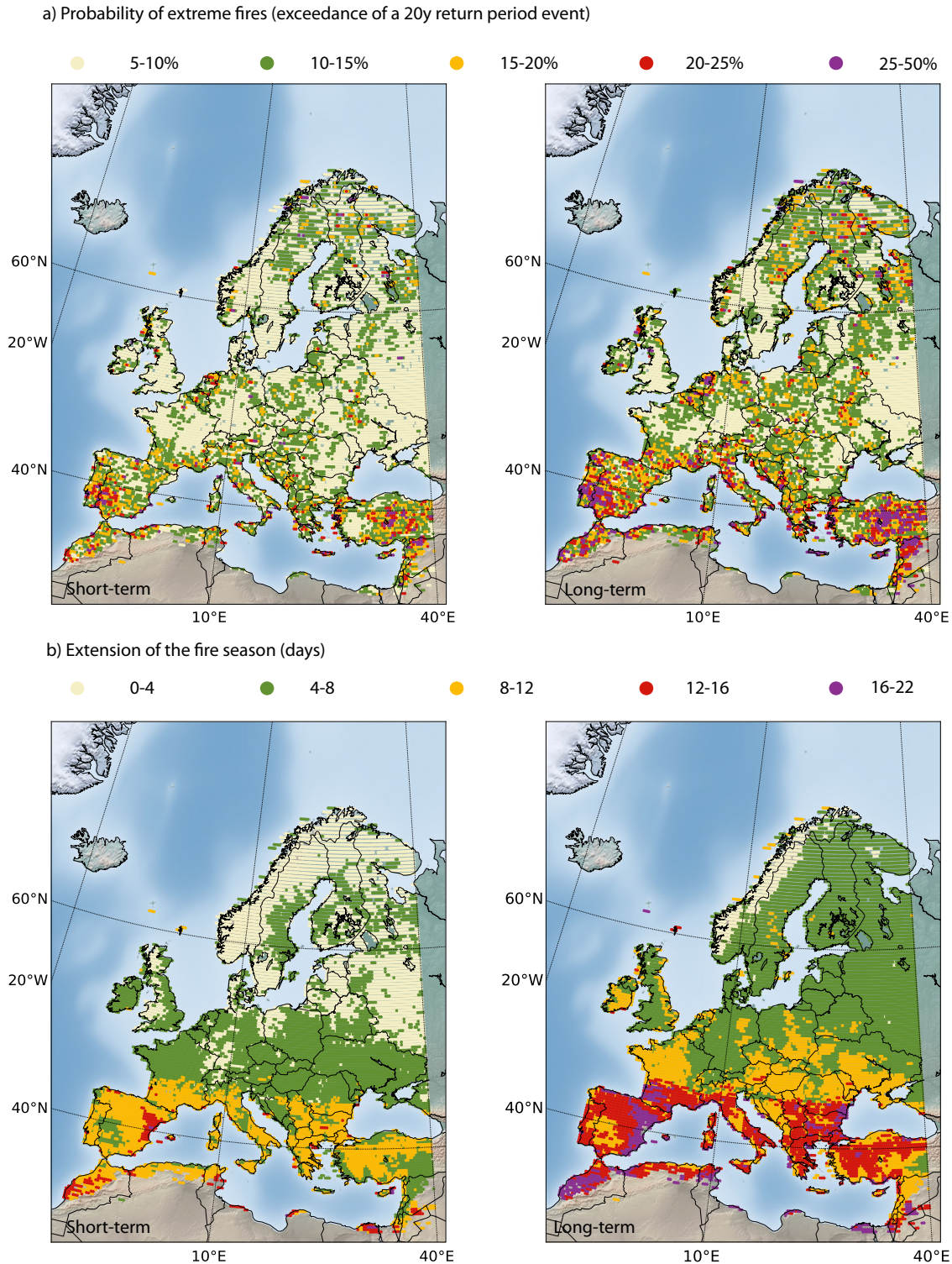


Fig. 5 Maps of increased probability for extreme fires and extension on the length of the fire season in the coming decades. **a** Projected changes in the probability of extreme fire events and **b** Expansion of the fire season in Europe. The left column represents the short-term period (2036–2065), while the right column represents the long-term period (2070–2099). The statistics are derived from the most likely outcomes projected by the CMIP6 multi-model simulations. The points are grouped within each region based on their increased probabilities for extreme events and extended fire season duration. The analysis reveals that more than 50% of Europe is expected to experience at least a twofold increase in the probability of extreme events, accompanied by a minimum extension of the fire season by five days by the end of the century.

extension in the duration of fire-prone weather conditions. This effect can be exacerbated by the projected increase in fire ignitions, driven by climate-induced rises in lightning activity⁵². As a result, it is likely that even European boreal and temperate regions, which are expected to experience a moderate increase in fire extremes, will still confront a future marked by more frequent and intense wildfires.

Future increases in the drivers of wildfires caused by climate change are expected to be highly challenging to mitigate. They will impose additional burdens on the European community in managing future fire risks. RescEU is considered the EU's response to the need to efficiently offset the consequences that the predicted increase in these events can have. RescEU has proven to reduce the number of casualties by increasing the efficiency and the costs of suppression actions⁵³. To a certain extent, investigating suppression capabilities can reduce the realized impacts⁴⁴. This study, however, indicates that large parts of Europe will experience double the likelihood of these events happening, and some parts of southern Europe could experience a ten-fold increase in the probability of extreme fire weather (see also^{54,55}).

The entire European continent will experience a lengthening of the fire season. Under these conditions, a tipping point can be reached due to the high costs of suppression strategies and the increased difficulties in dampening high-impact trajectories when these have an exponential growth^{7,56,57}. In recent years, the recorded increase in megafires has already called for a paradigm shift to increase efforts toward mitigation rather than extinction measures^{58,59}. Without mitigation, climate change is expected to increase the economic costs of fire suppression and may lead to fire seasons that overwhelm fire suppression agencies⁶⁰. Although wildfire management is adapting to the new reality, more may be required in the future, given the extent of changes in extreme fire weather expected in Europe in future decades.

In this study, it is pertinent to acknowledge that our analysis does not account for vegetation dynamics, specifically the process of post-fire vegetation recovery. While we assume a minor change in the availability of fuel, it should be noted that if fuel availability were to diminish significantly, fire activity would be impeded, irrespective of the FWI conditions. Furthermore, this analysis presumes the absence of substantial climate change mitigation efforts, which, if enacted, could substantially alter the anticipated patterns and severity of fire activity in relation to changing FWI scenarios. Future research should consider incorporating vegetation dynamics under different climate scenarios to provide a more comprehensive understanding of the complex relationship between climate change and wildfires.

METHODS

Data

The analysis was conducted using reanalysis data from ERA5 and global climate change projections from the CMIP6 multi-model dataset. ERA5 refers to the Fifth Generation of the European Reanalysis dataset produced by ECMWF and disseminated through the Copernicus Climate Data Store⁶¹. Reanalysis combines historical observations with advanced numerical weather prediction models to create a consistent and continuous representation of the Earth's atmosphere over a specific period. ERA5 provides high-resolution, three-dimensional atmospheric data. It covers the entire globe with a spatial resolution of approximately 31 km and is available from 1940 to near-real-time with a latency of 2 months.

In our assessment of how changes in temperature and precipitation are likely to impact extreme fires in Europe, we overlaid the CMIP6 projections for comparison. The CMIP6 multi-model simulations, employing the SSP2-4.5 scenario⁶², provided a framework for examining potential future climates characterized

by moderate greenhouse gas emissions mitigation and intermediate socio-economic development. Thirty-six commonly used climate models listed in Supplementary Table 1 were used. This study included multiple climate models to encompass various climate scenarios and enhance the reliability of our findings.

Fire weather index

To produce the historical daily FWI data outlined in this study, the global ECMWF Fire Forecast (GEFF) model⁴¹ forced by ERA5 data was used³⁷. The dataset is available through the Copernicus Climate Data Store⁶¹. The study period spanned from 1981 to 2010, covering 30 years.

The FWI assesses potential fire danger by integrating key meteorological factors such as temperature, humidity, wind speed, and precipitation, providing a quantitative measure of landscape flammability. Our analysis has presumed a correlation between FWI and observed fire activity. However, the strength of this correlation varies significantly based on the specific environmental conditions and ecosystems under study. In areas where fire activity is predominantly limited by the availability of fuel, the link between FWI and fire occurrences tends to be weaker. This indicates that fire initiation relies more on the presence of flammable materials rather than solely on weather conditions^{38,41,63}. Nevertheless, our analysis focuses on extreme fire weather scenarios where this correlation becomes notably stronger. During such conditions, the combination of high FWI values, dry weather, and strong winds creates an environment conducive to large and uncontrollable fires. Notably, certain regions only experience extreme fires when FWI values exceed a specific threshold. Recognizing these nuances and limitations is crucial when employing FWI as a proxy for fire activity, and our discussion section provides a comprehensive analysis of these results.

Return periods

We calculated the 20-year return periods of FWI to identify unusual fire conditions. Return periods are not commonly used in fire management. However, it is a common concept in other natural hazard assessments, such as flood and drought forecasting, to evaluate the rarity and intensity of a specific event. It is a statistical concept expressing the likelihood of an event occurring within a specified period. For example, a return period of 20 years denotes the value which would occur on average once in 20 years or with a probability of 5% in any given year. It is important to note that while the return period provides an average estimate, actual occurrences can be irregular and less predictable.

Return period, denoted as R , was computed using the Weibull's formula as given below⁶⁴:

$$R = \frac{n + 1}{m}, \quad (1)$$

where n is the total number of years of record and m is the rank of the maximum annual simulated FWI values when arranged in descending order. The probability of exceedance of FWI values is the reciprocal of the return period.

In our analysis, the twenty-year FWI return period serves as a critical threshold to assess the future risk of extreme fire weather events. We aim to evaluate how the probability of reaching or surpassing this threshold might shift under various climate scenarios. By establishing the current climatic conditions as a baseline, where the FWI threshold is met with a 5% probability each year, we project changes in this probability with altered temperature and precipitation changes.

Clustering fire regimes over Europe

The k-means clustering algorithm⁶⁵ was used to cluster fire regimes across Europe. The analysis focused on the FWI time series data, from 1981 to 2010. The k-means clustering algorithm is a commonly used unsupervised machine learning technique that partitions data into K clusters based on their similarities.

Formally, clustering involves partitioning the set of observations \mathcal{L} into K disjoint sets $\mathcal{L}_1, \dots, \mathcal{L}_K$ by returning labels indicating the index of the class of membership of each observation. This algorithm requires prescribing the number of clusters K . The latter can be prescribed manually based on the user's knowledge or estimated from a selection criteria such as the silhouette criterion⁶⁶.

The k-means algorithm partitions the n observations into K clusters in which each observation belongs to the cluster with the nearest mean. It seeks to minimize the variance within the clusters:

$$\operatorname{argmin}_{\mathcal{L}_1, \dots, \mathcal{L}_K} \sum_{k=1}^K \sum_{i \in \mathcal{L}_k} \left\| \tilde{\mathbf{y}}^{(i)} - \mu_k \right\|_2, \quad (2)$$

where $\mu_k = \|\mathcal{L}_k\|^{-1} \sum_{i \in \mathcal{L}_k} \tilde{\mathbf{y}}^{(i)}$ is the empirical mean of $\tilde{\mathbf{y}}$ in cluster \mathcal{L}_k .

The k-means clustering method was applied to the FWI time series data, covering the extended fire season from April to October in the northern hemisphere. An additional factor was added by calculating the product of the maximum FWI value and the FWI range ($\max^*(\max - \min)$) to account for fire intensity. The silhouette criterion was utilized to establish the optimal number of clusters for the k-means algorithm, evaluating the similarity of data points within clusters compared to those in neighboring clusters. This facilitated the identification of the most significant clusters in the dataset. Lastly, manual adjustments were made to refine the cluster definitions derived from the k-means analysis, ensuring an accurate representation of fire risk patterns and trends.

Derivation of incremental curves from CMIP6 multi-model projections

To evaluate the impact of climate change on fire events in Europe, the average inter-annual change signal, based on monthly means, in temperature and precipitation was derived from the CMIP6 multi-model simulations. The scenario SSP2-4.5 was used in this study because of its moderate emission trajectory, which we assume is a realistic response to the main atmospheric drivers (temperature and precipitation). To address the coarse resolution of the CMIP6 models, an upsampling approach was employed using ERA5 historical data. To compensate for the CMIP6 models' coarse resolution, we applied an upsampling technique utilizing ERA5 historical data. This approach involved converting the CMIP6 models' monthly outputs into daily values, achieved by integrating the more detailed resolution offered by the ERA5 dataset.

The forcing curves, shown in Supplementary Fig. 1, were derived by perturbing daily temperature (T) and precipitation (P) from ERA5 reanalysis over the control period 1980–2010 using monthly factors. These factors were calculated from the climate change signals in the CMIP6 multi-model simulations and integrated with mean annual perturbations. The perturbation for temperature T was constructed as an additive factor, varying from 0 °C to 6 °C with an increment of 1 °C, added to the projected temperature under the SSP2-4.5 climate scenario. The perturbation for precipitation was constructed as a multiplicative factor, ranging from 0.6 to 1.6 with an increment of 0.2. The analytical formulation of the incremental curves can be

expressed as follows :

$$T(i) = T_p(i) + X_t(\bar{T}_{scen}(j) - \bar{T}_{ctl}(j)), \quad (3)$$

$$P(i) = P_p(i) \left(\frac{\bar{P}_{scen}(j) \cdot X_p}{\bar{P}_{ctl}(j)} \right), \quad (4)$$

where T is temperature, P precipitation, X is the perturbation factor, i time (days), p projected values, \bar{T}_{scen} future scenario projection of monthly mean temperature, \bar{T}_{ctl} control period simulation of monthly mean temperature for j month of the year (Similar denotations for mean monthly precipitation). The methodology follows⁶⁷. The resulting forcing data were then used to calculate FWI to create the impact response surfaces (see below section).

Impact response surfaces

IRS are an effective way to display an environmental system's sensitivity to climate change⁶⁸. The two-dimensional IRS facilitate the concurrent examination of two primary drivers affecting a single dependent variable. This approach enables a sensitivity analysis of the dependent variable, highlighting the influential forcing variables. In our case, the feature was the 20-year return period of FWI and the length of the fire season, expressed as days above half the 20-year return period. The exceedance probability is estimated through a frequency analysis of the feature over the training period. The final impact response curves are then plotted as point-wise exceedance probabilities for each perturbation, and continuous curves are interpolated between the points. This approach facilitates the identification of critical thresholds or tipping points beyond which the variable of interest may experience rapid or nonlinear changes. Additionally, the IRS methods aid in recognizing potential synergistic or antagonistic effects between the drivers, thereby informing adaptive management strategies and policy interventions.

Density-based probability of climate change projections

The shared socioeconomic pathway 2 (SSP2-4.5) scenario was considered to explore potential future developments in human society, the economy, and the environment, as well as their implications for greenhouse gas emissions and climate change. The SSP2-4.5 scenario is designed to represent a world with moderate challenges in terms of mitigation and adaptation to climate change.

Thirty-six distinct climate models (Supplementary Table 1) were considered to capture a wide range of potential future climate outcomes. This methodology emphasizes the importance of considering various factors and uncertainties, including greenhouse gas emissions, climate sensitivity, and natural climate variability. The results of these ensemble simulations form the basis for developing probability density functions (PDFs) of future climate variables, mainly temperature and precipitation.

DATA AVAILABILITY

The baseline FWI data utilized in this study are accessible at the Copernicus Climate Data Store, available at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview>. The CMIP6 datasets can be downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6?tab=doc>. Furthermore, the ERA5 reanalysis data used in this study are available at the Copernicus Climate Data Store, accessible at <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview>. The perturbed FWI simulations data⁶⁹, used for constructing the impact response surfaces, are available from a public Zenodo repository (<https://doi.org/10.5281/zenodo.10458186>).

CODE AVAILABILITY

The Global ECMWF Fire Forecast (Geff) fire model used to perform the simulations is accessible through the ECMWF Git repository at <https://git.ecmwf.int/projects/CEMSF/repos/geff/browse>. All additional codes needed to perform the analyses are available upon reasonable request from the corresponding author.

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AUTHOR CONTRIBUTIONS

F.W., S.E.G. and F.D.G. were responsible for conceptualization. S.E.G. and C.B. undertook data creation and model experimentation. S.E.G. and F.D.G. conducted the model analysis. F.W., S.E.G. and F.D.G. developed the methodology. F.D.G. and S.E.G. were responsible for visualization. F.D.G. and S.E.G. wrote the original draft and all other authors reviewed and edited the final manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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