

Rising wildfire risks in Europe fuelled by global warming

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Abstract

Recent extreme wildfires worldwide have raised concerns about the accelerating impacts of climate change. Assessing the socioeconomic impacts of wildfires is challenging due to uncertainties in risk drivers and observational records. Here, we implement a high-resolution data modelling framework to quantify fire season length, population exposure to fire weather, and wildfire economic damage in Europe for a range of global warming scenarios. Climate change is expected to lengthen the fire season across Europe, particularly in southern regions already prone to fire-conducive weather. While the south already faces extended periods of high fire danger, population in central and northern Europe will be increasingly exposed to adverse fire weather conditions. Present direct wildfire damages of €2.4 billion per year could nearly double with warming of 3°C or more. Mediterranean regions will bear the highest economic burden, with annual maximum damages reaching 5–10% of their regional economy. Our findings advocate for stringent climate mitigation, fire-resistant ecosystems, and resilient communities near fire-prone areas.

Main

Recent years have witnessed a series of catastrophic wildfire events across the globe ¹. In 2022, Europe faced the second largest burnt area on record ², while 500,000 ha were burnt in 2023 (4th largest annual total), including 96,000 ha in Greece during the largest individual wildfire ever mapped in Europe ³.

Wildfire disasters are complex phenomena, driven by the interplay between climatic, environmental and socioeconomic drivers ⁴. They are associated with highly anomalous fire weather conditions ⁵, which are compound events characterized by high temperatures, low humidity and strong winds ⁶. In many areas prone to wildfires, such as western North America, the Mediterranean, and southeast Australia, fire weather has become more frequent and severe in recent decades ^{7–9}. Global trends in burnt area, however, have declined ^{10,11}, while the frequency of extreme fires has increased 2.2-fold from 2003 to 2023 ¹². Accelerating climate change, with higher temperatures and prolonged periods of dryness, reduces moisture in vegetation and will increasingly prime landscapes to burn more regularly, severely, and intensely, especially in Boreal and Temperate zones ^{13,14}.

A number of studies have mapped the extent of fire-prone regions, fire season length, and fire danger based on fire weather indices ^{14–16}. Recently, machine learning techniques have been developed to estimate fire initiation, severity and burnt area extent by combining remotely sensed burn severity and burnt area information with a range of climate, biophysical and social variables ^{17,18}. Quantifying and projecting into the future the drivers and occurrence of wildfires, as well as their impacts, is essential to manage future fire hazard and avoid potential impacts.

Extreme wildfires with significant socioeconomic consequences are primarily found in suburban regions that are interspersed with flammable forests in the developed world ⁵. Currently, human elements are responsible for 96% of wildfire ignition in Europe, including inadequate forest management that can increase fuel accumulation and fire-proneness ¹⁹. The wildland-urban interface (WUI), where human and natural environments intersect, has expanded globally by 35.6% since 2000, owing largely to rapid urbanization. This has heightened the risk of wildfires, as evidenced by a substantial increase in small fires in these areas ²⁰.

Wildfires can have far-reaching and complex repercussions²¹, including direct assets damages, indirect and long-term economic effects²², health impacts²³, ecological damage²⁴ and loss of ecosystem services^{25,26}, including carbon capture²⁷. As a result, reported wildfire losses vary widely, depending on the type of impacts considered. In the US, average annual loss estimates range from \$3.3²⁸ to 370.5 billion²⁹ (2024 \$ values), where the higher estimates include the economic valuation of fire- and smoke-exposure related deaths. In Europe, average annual loss estimates range from €3 billion³⁰ to more than 20 billion when including indirect economic consequences²².

While a few local and regional quantitative wildfire risk assessments exist^{31–33}, evaluations of the socioeconomic implications at larger scales^{22,34} are rare due to data limitations. To date, no comprehensive overview of the socioeconomic risk posed by wildfires in the context of climate change is available for Europe.

In this article, we present a quantitative assessment of wildfire hazard and risk across 1366 regions of Europe, covering EU27, Norway, Switzerland, and the UK, for scenarios of 1.5, 2.0, 3.0 and 4.0°C global warming above preindustrial times. We use an ensemble of high-resolution bias-adjusted climate projections³⁵ to calculate the Canadian Fire Weather Index (FWI) for assessing fire season length and population exposure to fire weather in WUI. To address economic losses, we estimate burnt area (BA) using a random forest model that integrates historical satellite-derived BA data, climate projections, and biophysical and socioeconomic variables^{17,25}. Exposure is quantified through asset values in the BA from the HANZE database³⁶, with literature-based loss rates applied to estimate direct asset losses. Our economic loss estimates focus on direct asset losses, excluding suppression costs, health impacts, ecosystem damage, and indirect effects. In the quantification of direct economic damages we also account for uncertainty in the random forest model and damage appreciation (more details in Methods).

Fire season length in Europe with global warming

At present (1991-2020), the length of the fire season, defined as the number of days per year with high-to-very-extreme fire danger ($FWI \geq 21.3$)³⁷, varies greatly across Europe (Figure 1). While fire weather conditions in the northern countries only exceptionally exceed the high fire danger threshold, the fire season can last for over two months in the Mediterranean region, and in the most southern regions of Greece, Portugal, Spain, Cyprus and Malta, it can last up to four months. This pattern aligns with EFFIS fire statistics for Europe over the last two decades, with a disproportionally high share in Mediterranean countries³⁸. Yet, in recent years fires have also occurred in northern European regions, such as the extensive fires during summer of 2018 in Sweden, indicating that exceptionally dry and hot summers favour wildfires also in regions much less exposed to hazardous fire weather conditions³⁹.

With rising global temperature this north-south gradient is amplified. At 1.5°C global warming, the wildfire season in southern regions could extend by one to two weeks, highlighting their vulnerability to fire weather due to increased dry and hot summers, even under low emission scenarios⁴⁰. For higher levels of warming, the wildfire season could lengthen by 4 to 6 weeks, meaning that some regions could be exposed to high or more severe fire conditions for nearly half of the year. As temperatures rise, the fire season also prolongs for most regions south of 55° North. These findings are consistent with⁴¹ which suggests that increasing temperatures create climate conditions conducive to wildfire development. They also align with (El Garroussi et al., 2024), which identified similar patterns of change in fire season length in Europe under global warming by using a more extreme fire weather indicator. Our projections of a lengthened fire season are also supported by observational evidence that

fire activity has already significantly changed in southern and central regions of Europe, with the emergence of unprecedented long fire-prone summers ⁴². Regions in northern Germany and Poland, and the Baltic countries might experience a slight shortening of the fire season at 1.5°C warming, yet with further warming this trend is reverted, except for the Baltic countries and some regions in Scandinavia. In the north of Europe, rising temperatures favor fire conditions, but summer precipitation is expected to increase in many regions and there is no distinct change projected in extended dry spells ³⁹.

People living in wildland-urban interface exposed to fire danger

Approximately 45 [30.2 – 63.5] million Europeans who live in WUI are currently exposed to at least one week of high-to-very-extreme fire danger per year (Table 1), corresponding to 8.6% [5.7 – 12.1%] of Europe's population. The 90% confidence ranges shown in square brackets (see Table S1) illustrate the variability in the estimates due to differences in climate projections. Italy, Spain, France and Portugal show the highest absolute exposure, and collectively account for over 60% of the total population exposed to fire danger. In relative terms, Portugal, Croatia, Slovenia and Greece have the highest proportion of their population exposed, with rates of 35.6%, 22.7%, 22.1% and 20.0%, respectively. Exposure to fire danger, however, is not limited to the southern regions, with nearly three million people exposed each year in both Germany and Poland, more than 2 million in Romania, approximately 1.5 million in Hungary and 1.25 million in Bulgaria.

Climate change could expose an additional 1.4 million Europeans in the WUI to high fire danger at 1.5°C warming, and up to 15 million at 4°C. This represents a non-linear increase in exposure: 3.1% at 1.5°C and 33.0% at 4°C compared to the present climate. It must be noted that in most Mediterranean regions nearly all people residing in WUI are presently already exposed to fire danger for extended periods, resulting in a stable, or only slightly increased, population exposure with higher warming. The strongest absolute rise is projected for France, with at least 1 million more people in the WUI exposed per each degree Celsius of warming. At 4°C warming, several Central European countries, including Austria, Switzerland, Czechia, and Slovakia, could see up to 10% of their populations living near wildlands exposed to fire danger. Even in the UK, under these scenarios around 1 million people living in WUI would be exposed each year to high fire danger. In contrast, most northern European countries, such as Estonia, Latvia, Lithuania, Ireland, Norway, and Denmark, are expected to experience little to no change in population exposure under higher warming scenarios.

The exposure is highly sensitive to the type of urbanization, with more people exposed in rural settlements (embedded in WUI) than in urbanized areas. WUI coverage differs greatly between but also within countries of Europe ⁴³. Consequently, our estimates show high variability within countries (Figure S1). Areas with scattered and rural settlements, such as northern Spain, show higher shares of population exposed as most people are living in the proximity to burnable vegetation. In contrast, more urbanized and compact settlements, like those in south-western Spain, have fewer people living near wildland areas, reducing the population exposure.

Table 1. Number of people (in thousands) annually exposed to high fire danger for at least 7 days a year in EU27 countries, Norway, Switzerland and the UK. Estimates are based on today's population and considering climate conditions of 1991-2020 (PresC) and for GWLs of 1.5°C, 2.0°C, 3.0°C, and 4.0°C. Values present the mean estimate over the climate ensemble. Additionally, the table includes relative exposure as a percentage of the total population for each region. Detailed uncertainty ranges are provided in Table S1.

NUTS0	Absolute exposure (in thousands)					Relative exposure to the total pop. (%)				
	PresC	1.5C	2.0C	3.0C	4.0C	PresC	1.5C	2.0C	3.0C	4.0C
AT	595.6	617.7	659.0	866.9	986.4	6.70	6.90	7.40	9.70	11.00
BE	153.9	172.4	278.8	387.7	516.9	1.30	1.50	2.40	3.30	4.50
BG	1245.7	1245.7	1245.7	1245.7	1245.7	18.10	18.10	18.10	18.10	18.10
CH	278.7	324.1	425.6	757.7	960.3	3.20	3.80	4.90	8.80	11.10
CY	113.2	113.2	113.2	113.2	113.2	12.60	12.60	12.60	12.60	12.60
CZ	693.1	713.2	744.1	882.7	986.4	6.50	6.70	7.00	8.30	9.20
DE	2858.0	3186.1	3839.6	5451.5	6449.1	3.40	3.80	4.60	6.60	7.80
DK	54.9	57.5	65.4	78.3	110.3	0.90	1.00	1.10	1.30	1.90
EE	41.0	41.7	39.6	33.8	36.1	3.10	3.10	3.00	2.50	2.70
EL	2134.7	2134.7	2134.7	2134.7	2134.7	20.00	20.00	20.00	20.00	20.00
ES	8637.9	8882.1	9107.5	9548.0	9821.2	18.30	18.80	19.20	20.20	20.80
FI	227.7	262.4	241.4	259.4	309.0	4.10	4.70	4.40	4.70	5.60
FR	6528.5	7001.2	8027.1	9780.7	10954.2	9.90	10.60	12.20	14.90	16.70
HR	881.7	928.6	945.9	992.4	1048.6	22.70	23.90	24.30	25.50	27.00
HU	1419.3	1482.0	1503.8	1538.9	1651.4	14.60	15.30	15.50	15.80	17.00
IE	2.5	3.1	3.6	8.8	10.0	0.00	0.10	0.10	0.20	0.20
IT	9006.2	9211.1	9330.0	9633.1	9833.3	15.20	15.60	15.80	16.30	16.60
LT	90.7	82.8	89.0	74.8	91.6	3.20	3.00	3.20	2.70	3.30
LU	23.4	28.3	47.7	74.2	91.6	3.70	4.40	7.40	11.60	14.30
LV	71.1	68.0	71.0	58.8	65.2	3.80	3.60	3.80	3.10	3.50
MT	20.4	20.4	20.4	20.4	20.4	3.90	3.90	3.90	3.90	3.90
NL	169.9	195.9	250.4	353.9	478.7	1.00	1.10	1.40	2.00	2.70
NO	49.5	49.3	54.6	77.3	90.4	0.90	0.90	1.00	1.50	1.70
PL	2723.3	2348.9	2654.9	2952.6	3191.8	7.10	6.20	7.00	7.70	8.40
PT	3667.8	3762.0	3798.9	3823.3	3831.5	35.60	36.60	36.90	37.10	37.20
RO	2299.2	2416.4	2463.7	2601.4	2697.5	12.00	12.60	12.80	13.50	14.00
SE	258.7	274.9	300.6	327.4	383.5	2.50	2.60	2.90	3.10	3.70
SI	466.3	485.0	511.9	599.7	662.1	22.10	23.00	24.30	28.50	31.40
SK	435.6	445.4	455.7	522.5	572.8	8.00	8.20	8.40	9.60	10.50
UK	379.3	383.0	573.7	910.1	1216.7	0.60	0.60	0.90	1.40	1.80

TOTAL	45527.8	46937.1	49997.5	56109.9	60560.6	8.64	8.91	9.49	10.65	11.50
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Economic damages from wildfires

We estimate present (1991-2020) expected annual damage (EAD) due to wildfires in the EU27, Norway, Switzerland and the UK at €2.4 billion [0.6 - 7.8] (Table 2, Methods). The 90% confidence range on this estimate lies between €0.6 and €7.8 billion per year (Table S2), which relates to uncertainty in the estimation of BA, the damage appreciation and variability in the climate simulations. The large confidence interval is consistent with the wide variability of losses reported. The European Commission communicated economic losses of €2-3 billion per year for the EU ⁴⁴, while combining burned area information from the European Forest Fire Information System ⁴⁵ with a unit cost of around €10,000 per hectare burned resulted in an estimate of €4.1 billion in losses for 2023 ⁴⁶. An academic assessment based on economic panel data analysis, estimated an average yearly production loss of €13-21 billion for Southern Europe ²².

The highest present economic losses are estimated for Italy (€0.64 billion/year, 26.1% of the total), Spain (€0.52 billion/year, 21.0% of the total), Portugal (€0.46 billion/year, 18.8% of the total), France (€0.40 billion/year, 16.5% of the total), and Greece (€0.21 billion/year, 8.6% of the total), together contributing to more than 90% of the total damage for the study area.

With increasing global warming, EAD for the study area is projected to rise from €2.8 [0.7-9.4] billion at 1.5°C to €5.1 [1.3-16.4] at 4.0°C global warming, or more than a doubling compared to present. In the most southern countries, including Portugal, Spain, Greece, Cyprus and Malta, despite a considerable lengthening of the season with dangerous fire weather conditions, direct damages from wildfires are not expected to grow strongly or can even slightly decrease with higher warming. This counterintuitive pattern can be attributed to heightened aridity, which restricts vegetation growth and consequently diminishes biomass, ultimately reducing the availability of fuel and a decrease in the extent of burnt areas. Similar mechanisms have been already observed over the period 1979–2018 in southern Europe ²⁵. An analysis of observed climate and fire data from 1970 to 2007 indicates that in a typical Mediterranean environment, increased fuel flammability due to global warming is offset by the indirect effects of climate on fuel structure, such as less favourable conditions for fine-fuel availability and fuel connectivity ⁴⁷. Other studies also show the negative effects of an amplification of aridity on biomass ⁴⁸.

The aridity effect on biomass is less pronounced for Italy and France and their estimated EAD steadily grows with global warming and could exceed €1 and €0.8 billion per year for 4°C, respectively. The largest absolute damage under this scenario, however, is projected for Germany at €1.24 billion per year, more than an order of magnitude larger compared to present damages. Large relative increases in damages are projected for most other European countries, except for Ireland, Norway, Sweden and Estonia, yet for all countries apart from Bulgaria EAD remains below €100 million per year.

Aggregated over the whole study area or at country level the damage estimates remain fairly low compared to the size of the economy (represented by the gross domestic product, GDP). At regional level, however, impacts can become more substantial relative to the economic scale. Present EAD expressed as a share of regional GDP (using the Nomenclature of territorial units for statistics classification level 3, or NUTS3) exceeds 0.1% in 75 NUTS3 regions, predominantly located in the Mediterranean (Figure 2). The relative economic impact is largest in regions of Greece and Portugal, with annual damages ranging between 0.3 and 0.6% of GDP, while also in some Spanish and Italian regions present impacts exceed 0.2% of GDP. With increasing warming the number of NUTS3 regions

that are expected to experience annually damages exceeding 0.1% (0.2%) of GDP grows steadily, corresponding to 90 (53), 100 (55), 125 (71) and 163 (81) regions for 1.5, 2, 3 and 4°C, respectively. At 1.5°C and 2°C warming, additional southern regions in Spain, Italy, France, Croatia, and Bulgaria are also affected. As warming intensifies, an increasing number of regions more northward will face higher fire damages and in some regions of Germany and Hungary impacts will also exceed 0.1% of GDP. On the other hand, the effect of fuel limitation due to increasing aridity in the most southern regions results in rather stable impacts.

Our EAD estimates represent the damage that would occur in any given year if damages from all wildfire probabilities and magnitudes were spread out equally over time. Maximum annual damages (MAD) estimated for each region for baseline climate and the GWLs (Figure 2) show that wildfire impacts at the time of the event, however, can be substantially larger. For 74 (33) regions MAD exceeds 5% (10%) of regional GDP at present, which increases to 89 (40), 107 (58), 121 (59) and 138 (78) regions for 1.5, 2, 3 and 4°C, respectively. The largest relative economic shocks are projected for regions of Greece and Portugal, followed by Mediterranean regions of France, Italy, Croatia and Bulgaria, and as warming rises also for rural regions in Germany, Hungary and Poland. In some regions, this could possibly affect long term economic growth ⁴⁹.

Table 2. Expected annual damage (EAD) (in € million, 2020 values) by country and aggregated over the study area for present climate conditions (1991-2020, PresC) and climate under scenarios of 1.5°C, 2.0°C, 3.0°C and 4.0°C global warming.

NUTS0	PresC	1.5C	2.0C	3.0C	4.0C
AT	0.95	4.41	6.72	27.27	78.66
BE	0.14	0.16	0.36	1.07	2.76
BG	29.08	42.30	62.06	126.78	168.09
CH	1.23	1.70	5.89	28.05	57.49
CY	36.71	30.72	30.66	27.02	25.55
CZ	2.28	1.91	3.14	7.04	21.18
DE	98.08	127.21	189.18	568.14	1232.77
DK	0.02	0.06	0.06	0.12	0.26
EE	0.04	0.06	0.10	0.07	0.03
EL	212.22	239.02	246.07	273.82	258.93
ES	516.20	553.85	597.80	567.51	568.41
FI	0.95	1.47	1.75	4.42	9.78
FR	403.81	457.76	522.68	690.68	863.83
HR	22.57	31.17	35.85	46.16	56.27
HU	5.19	10.99	13.79	30.53	56.65
IE	0.47	0.46	0.40	0.94	0.50
IT	640.89	764.31	808.32	951.57	1009.28
LT	0.01	0.01	0.08	0.23	0.32
LU	2.03	2.13	2.96	5.33	16.93
LV	0.05	0.05	0.09	0.23	0.12
MT	0.66	0.77	0.67	0.82	0.63
NL	5.03	4.28	8.57	41.31	77.48
NO	1.18	1.16	1.11	1.29	1.27
PL	0.28	0.36	1.16	11.28	49.37
PT	462.39	468.64	475.47	498.59	520.53
RO	1.62	3.06	4.44	7.55	13.21
SE	1.88	1.86	1.82	1.77	1.94
SI	0.87	2.26	2.99	5.36	10.30
SK	0.25	1.52	3.36	13.16	29.82
UK	0.27	0.27	0.23	0.93	3.78
TOTAL	2447.2	2753.7	3027.6	3938.9	5135.9

Discussion

This study provides a first comprehensive pan-European analysis of wildfire hazard and risk in regions of Europe for a range of global warming scenarios. We used the Canadian FWI as an index for fire danger, but a number of other indices are available. While the Canadian FWI emerged as the most reliable indicator in a study of the French Mediterranean, relying exclusively on fire-weather indices may not always be the best choice for predicting fire danger ⁵⁰. Estimates of WUI depend on methodological choices, including the definition of WUI and distance thresholds for wildland and urban areas, as well as discrepancies in the type, quality, and temporal dimensions of the input data. Our WUI estimates are in the range of those obtained in reference studies for Europe (Figure S2).

We estimated population exposure to fire danger using present population and WUI. Population in Europe is projected to decline throughout this century ⁵¹, especially in rural areas, aligning with observations of contemporary strong rural depopulation ⁵². On the other hand, continued land abandonment, especially in Mediterranean and Eastern European countries, can result in greater vegetation around settlements, while the expansion of secondary home developments in rural areas is driving settlements deeper into wildland regions ⁴³. While the fire season will intensify and lengthen in most regions of Europe, the local interplay between these demographic drivers will determine the actual amount of people and settlements exposed to fire danger.

The occurrence and scale of fires are influenced by a variety of other elements than weather conditions conducive to fires, including ignition sources, available fuel, and socio-economic factors. We used a random forest (RF) model ^{17,25} trained on satellite-derived burnt area data in combination with land use statistics of mapped wildfire events to predict the probability and extent of burnt area. The RF model incorporates a suite of climate, environmental and landscape metrics as predictors. We further acknowledge the unpredictability of wildfires due to the stochastic component driven by human activities. This is accounted for by incorporating population density as predictor, which has been found to be strongly correlated with the occurrence of wildfires ⁵³. Although predicting fire initiation and burnt areas remains very challenging and is inherently uncertain, in Europe models that incorporate both climatic and human predictors demonstrated better predictive capacity than models based only on human variables ¹⁸.

The scale of fires and the impacts they cause further depend on factors such as fire suppression ¹⁰, land and fuel management ⁵⁴, and asset characteristics ⁵⁵, with reported asset destruction rates in burnt areas varying between 10 to more than 90% (see SI). Here we used a central loss rate estimate with a range around it derived from literature, but regional variability in construction and building standards could strongly affect local impacts. Socioeconomic vulnerability to climate-related hazards has declined globally over the last decades ⁵⁶. Conversely, forest vulnerability to wildfires has risen in recent decades, especially in southwestern Europe, reflecting a decline in their resilience ^{17,57}. We assumed static vulnerability in our assessment, but continuing efforts to increase fire protection, prevention and suppression, improve ecosystem resistance (e.g., forest structure and species variety), and build fire-resilient human communities ⁵⁸ will likely mitigate future risks of wildfires.

Risks from wildfires go beyond population exposure to fire danger and direct damages to assets quantified here. Direct exposure to flames and heat can result in injuries or fatalities, while exposure to smoke and fine particulate matter can lead to health issues, even at far distances ⁵⁹. The destruction of productive capital, reduction in labour supply, or disruption of transport systems can impact other economic activities across connected supply chains ⁶⁰. While some wildfires may have beneficial functions for ecosystems ⁶¹, they result in a wide range of

environmental impacts and can lead to vast carbon emissions suppressing the carbon uptake capacity of forests⁶². Our estimates should therefore be interpreted as conservative estimates of overall wildfire losses.

Despite these limitations, our pan-European analysis of wildfire danger, population exposure and economic losses under climate change scenarios fills a significant gap in existing research. We show that climate change will lengthen fire seasons, expose more people to wildfire danger and result in higher direct damages, but with large spatial variability across regions of Europe, reflecting the complex interplay of local factors, including vegetation, fuel conditions, human activities, economic wealth, and climate change. Future research should focus on improving the prediction of fire occurrence and burnt areas, the quantification of vulnerability, and the evaluation of the effectiveness of adaptation measures.

Methods

Modelling framework

We assessed wildfire hazard and risk by evaluating fire season length, population exposure to dangerous fire conditions within the Wildland-Urban Interface and wildfire economic damages. We quantify wildfire danger and impacts for climate representative of the recent past (1991-2020, baseline) and climate corresponding to global warming levels (GWLs) of 1.5, 2, 3 and 4°C above preindustrial temperature. The Paris Agreement explicitly considers the warming scenarios of 1.5°C and 2°C, while higher levels of warming are anticipated by the end of the 21st century if appropriate mitigation strategies are not implemented⁶³.

We consider an ensemble of 10 bias-adjusted regional climate projections for the RCP4.5 and RCP8.5 scenarios from the EURO-CORDEX initiative (Dosio, 2016; Jacob et al., 2014), where RCPs represent different greenhouse gas concentration trajectories. We use the time sampling method adopted in AR6⁶⁴ to identify climate conditions at specific Global Warming Levels (GWLs). This approach assumes that wildfire hazard at a given GWL can be inferred from transient climate projections using a 30-year period centred on the year the targeted GWL is achieved. This technique allows us to decouple climate conditions from the timing of reaching a specific GWL and evaluate the impact of climate stressors at various GWLs on present or future societies. The influence of the pathway on fire-related hazards is relatively insignificant compared to the variability between climate models, allowing us to combine RCP4.5 and RCP8.5 projections into a single ensemble without losing significant information⁶⁵. Supplementary Table S3 presents the climate models used and the year at which the GWLs are exceeded. Given that the climate simulations extend up to 2100, if a warming level is reached post-2085, we adopt the fixed period 2071-2100 instead. Wildfire conditions for the baseline, 1.5, and 2°C warming are derived from an ensemble of 20 members, whereas the ensemble projections for 3 and 4°C warming are derived from ensembles of 11 and 10 members, respectively, as 9 out of 10 RCP4.5 climate simulations do not reach 3°C warming and none reach 4°C.

We focus on the effect of climate change on wildfire impacts using static exposure and vulnerability due to the significant uncertainty surrounding assumptions about socioeconomic developments over extended time periods, particularly at a high spatial resolution^{66,67}. Wildfire hazard and impacts were calculated for all climate realizations and we report ensemble average estimates and the 90% confidence interval defined by the second highest and second lowest estimate in the ensemble.

The analysis covers the 27 countries of the European Union (EU) plus Norway, the United Kingdom, and Switzerland. Wildfire danger and impacts are estimated for 1366 regions, corresponding to administration units defined in the Nomenclature of Territorial Units for Statistics (NUTS), at the finest level (NUTS 3) ⁶⁸.

The subsequent sections provide more details on the quantification of fire hazard, exposure and risk.

Fire season length

As indicator of fire danger we used the Canadian Forest Fire Weather Index (FWI), one of the most commonly utilized indices for analysing the effect of climate variability and change on fire behaviour. The FWI is used for modelling fire season length due to its effectiveness in capturing climate change impacts on fire dynamics ¹⁶. It considers the impact of fuel moisture and weather conditions on fire behaviour ⁶⁹. The components were calculated at 0.11 degree resolution (of the climate projections) for each of the climate realizations using daily projections of temperature, relative humidity, wind speed, and precipitation. The length of the fire season was determined by analysing the number of days per year with high-to-very-extreme fire danger ($FWI > 21.3$) ³⁷, and we report the average values over the respective 30-year time windows for the baseline and GWLs.

Population living near wildland exposed to fire danger

Population exposure was quantified as the number of individuals residing in the Wildland-Urban Interface (WUI) who are exposed to high-to-very-extreme fire danger levels ($FWI > 21.3$) for more than seven days per year.

To delimit WUI areas, we used the geospatial processing method proposed by ⁷⁰. It first identifies artificial and flammable areas, then considers a buffer zone around them, and finally identifies WUI areas as the overlapping between the two buffered zones. Artificial areas were identified based on built-up data from the Global Human Settlement built-up surface product for the year 2020 at 100m resolution ⁷¹. The built-up threshold to classify urban grid cells typically ranges from 0% to 20% of the pixel built-up ⁷²⁻⁷⁴. In our study, we adopted a 5% threshold, considering any value greater than 5% as an urban pixel. To identify fuel areas we used land use for the year 2020 at 100 m resolution from the Historical Analysis of Natural Hazards in Europe (HANZE) project ³⁶. We considered the land use (LU) classes 3.11 (broad-leaved forest), 3.12 (coniferous forest), 3.13 (mixed forest), 3.23 (sclerophyllous vegetation) and 3.24 (transitional woodland-shrub). In European countries, the buffer distances considered around urban settlements range from 50 to 200 meters, while those around areas covered with woody vegetation range from 100 to 400 meters. Here, a buffer distance of 200 meters from artificial land and 400 meters from fuel areas was implemented.

Published studies present a broad range of WUI extent estimates across Europe, from approximately 3% to 22% ^{43,70,75}. Variability in these estimates arises from different methodological approaches, including varying definitions of WUI, thresholds, and buffer areas, as well as discrepancies in the type, quality, and temporal aspects of the input data, and geographical coverage. We estimate that 21.2% of European land (1.01 million km² within the EU27 countries, Norway, Switzerland and the UK) can be characterized as WUI. This is consistent with the findings of ⁷⁵, who reported that 22.1% of land within the same region can be classified as WUI. Fig. S2 shows a country-scale comparison of our estimates with the available pan-European analyses.

We used the JRC-GEOSTAT Population Grid 2018 ⁷⁶ at 100m resolution to identify people living in WUI. This was then combined with information on fire season length (at 0.11 degree spatial resolution) calculated above to obtain

estimates of the number of people living close to wildland and exposed to at least seven days of high fire danger per year. Population exposure was aggregated to NUTS3 and country scale. We report the average values over the respective 30-year time windows for the baseline and GWLs.

Economic impacts

The procedure to estimate economic losses due to wildfires consists of two main parts. In the historical part we combine observed (or reanalysis) data on potential drivers of wildfires with reported wildfire impact metrics to derive a predictive model of fire occurrence and impacts. In the projection part, we apply the model to the climate simulations to estimate wildfire impacts for the baseline (1991-2020) and GWLs of 1.5, 2, 3 and 4°C.

The extreme wildfires global database indicates that wildfires deemed economically or socially devastating are primarily concentrated in suburban areas where flammable forests merge with developed regions⁵. We therefore implemented a set of Random Forest (RF) models developed in earlier studies (Forzieri et al., 2021; Forzieri et al., 2024) to predict forest burnt areas based on climate, vegetation and landscape features. Climate predictors in the RF simulations include annual values of key climatic variables (e.g., temperature, precipitation, snow), their long-term averages, the FWI, and indicators of extremes (e.g., maximum wind speed, Standardized Precipitation Index, Annual Moisture Index). Vegetation parameters include biomass, tree height, tree age, tree density and Leaf Area Index. Landscape predictors include population density, slope, evenness, homogeneity and elevation. The RF models were tailored for major plant functional types (PFTs), including broadleaved deciduous (BrDc), broadleaved evergreen (BrEv), needleleaf deciduous (NeDc), and needleleaf evergreen (NeEv). The values for the variables are derived from ERA5⁷⁷, satellite data and other observational sources^{17,25}. The RF models were trained over the period 2000-2017 against more than 15,000 records of fires from the European Forest Fire Information System (EFFIS, <https://effis.jrc.ec.europa.eu/>). When applied to the projections, only climate drivers were treated as dynamic in accordance to the GWL scenarios. In contrast, vegetation and landscape features were kept constant at present values. Temporal biomass changes are not explicit predictors but are partially captured through climate feature changes and the vegetation-climate interplay in RF models. The RF model provides as output for each simulation year the expected annual fraction burnt (EAFB) of forest at pixel level (with 0.1 degree of the climate projections). We quantify uncertainty using the standard deviation of predictions across 500 trees in the RF model (see S2 Supplementary Information).

To include fire-prone lands beyond forests, we computed statistics for all flammable land use classes affected by historical wildfires. We used the Rapid Damage Assessment (RDA) from EFFIS (JRC-EC) to estimate burnt areas in Europe. This daily satellite-based product uses the MODIS sensor (on board of Terra and Aqua satellites) with a spatial resolution of 250 m. Small burnt scars (< 30 ha) are generally not provided and final burnt areas are refined through visual interpretation. To mitigate fire date uncertainties (especially before 2007), we used the dataset from⁷⁸ to identify the start and end fire dates. Data access and further information at <http://effis.jrc.ec.europa.eu>. We therefore overlaid burnt-area polygons of each wildfire for the period 2000 to 2022 from EFFIS with the 100m gridded HANZE LU map³⁶. From the 44 LU classes in HANZE, we selected those that collectively accounted for 99% of the total burnt area in the study region. These include: transitional woodland-shrub (19.6%), moors and heathland (12.0%), natural grasslands (10.9%), sclerophyllous vegetation (10.9%), broad-leaved forest (10.0%), non-irrigated arable land (6.1%), sparsely vegetated areas (5.3%), land principally occupied by agriculture (5.1%), coniferous forest (4.6%), mixed forest (3.0%), pastures (2.3%), complex cultivation patterns (2.2%), inland marshes (2.2%), peat bogs (1.4%), olive groves (1.3%), agro-forestry areas (0.7%), annual crops associated with permanent crops (0.5%), discontinuous urban fabric (0.3%), vineyards (0.3%), and fruit trees and berry plantations (0.3%).

We calculated statistics for flammable LU classes at various geographical aggregation levels: NUTS3, NUTS2, NUTS1, and NUTS0, as well as for the study region. For each flammable LU category the fraction of area burnt to its total area was computed, averaged over all fires reported in the period 2000-2022 in that region. In projection mode, EAFB for forests simulated by the RF models was translated into EAFB for other flammable LU categories based on historical shares under the assumption that these are region-specific. So when sufficient observations of burnt areas were available at NUTS3 level during the observation period, the most detailed historical statistics were employed for the extrapolation to other flammable LU classes in the projections. When data were not available at NUTS3, the extrapolation was based on statistics at a higher NUTS level. Figure S3 shows for each region the level at which statistics were used in this process. Consequently, we produced annual estimates of EFAB for each flammable LU class at NUTS3 level. This method is based on two assumptions: first, that wildfires need to affect forests (otherwise the model would not detect burnt areas), and second, that fire behaviour is consistent with historical statistics across different flammable LU classes.

We used the EFFIS (JRC-EC) observed burnt-areas data product to validate our results. In Figure S4, we present a side-by-side evaluation of the estimated and observed burnt areas, aggregated at the country level, over the period 2000-2022. The estimated burnt areas shown are the mean of the climate ensemble.

The value of exposure in estimated burnt areas was appraised using the fixed asset value dataset from HANZE ⁷⁹ as economic metric, available at 100 m spatial resolution and expressed in €2020 values. This represents the maximum economic value that can be potentially damaged due to direct contact with fire. The degree to which damage actually occurs in burnt areas, however, depends strongly on the economic, social and political context of the communities exposed ⁸⁰, and studies that have analysed wildfire vulnerability for the built environment are limited ⁸¹. Reported impacts from recent fire events show that damage to fixed assets in the burned areas varies widely, with damage rates from below 10 to 90% of exposed asset values (see S1 in Supplementary Information).

Acknowledging that not all fixed assets are equally vulnerable to fire, and that actual losses vary based on fire intensity and the inherent resilience of each asset, we recognized the need for a simplified approach to assess economic risk. We therefore adopted as vulnerability for fixed assets a damage ratio of 50% of the asset value. This is consistent with observations from the very recent Palisades fire in California, where in January 2025 approximately 55% of structures exposed to fire were destroyed ⁸². Our methodology, therefore, takes a pragmatic approach by assuming a 50% vulnerability rate, which enables us to conduct a pan-European economic risk analysis. This is in line with other studies with similar data resolution constraints ⁸³, and highlights the need for more detailed data to refine future assessments. Based on the reported damage rates we further implement 25 and 75% damage ratios to account for uncertainty in the damage loss ratio.

We estimated economic damages at NUTS3 level by combining the estimated burnt areas (EAFB) of each flammable LU class, exposure (FA) values within each LU class, and vulnerability (assuming uniform loss rate of FA in burnt areas). Economic losses were estimated with annual time step for each climate projection. We used the mean value of the climate ensemble as our central estimate. We quantify uncertainty around our mean estimate accounting for uncertainty in the different steps of the impact assessment (see details in S2 Supplementary Information). Economic damages are expressed in €2020 values.

Declarations

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Competing interests

The authors declare no competing interests.

Disclaimer

The views expressed are purely those of the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Authors' contribution

Conceptualization, D.G., L.F.; Methodology, D.G., L.F.; Formal Analysis, D.G., L.F., C.M.; Validation, D.G., L.F., G.F., C.M; Data Curation, D.G., L.F., G.F., A.D., C.M; Writing - Original Draft Preparation, D.G., L.F., Writing - Review & Editing, D.G., L.F., G.F., C.M, A.D., A.C, P.B.

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Figures

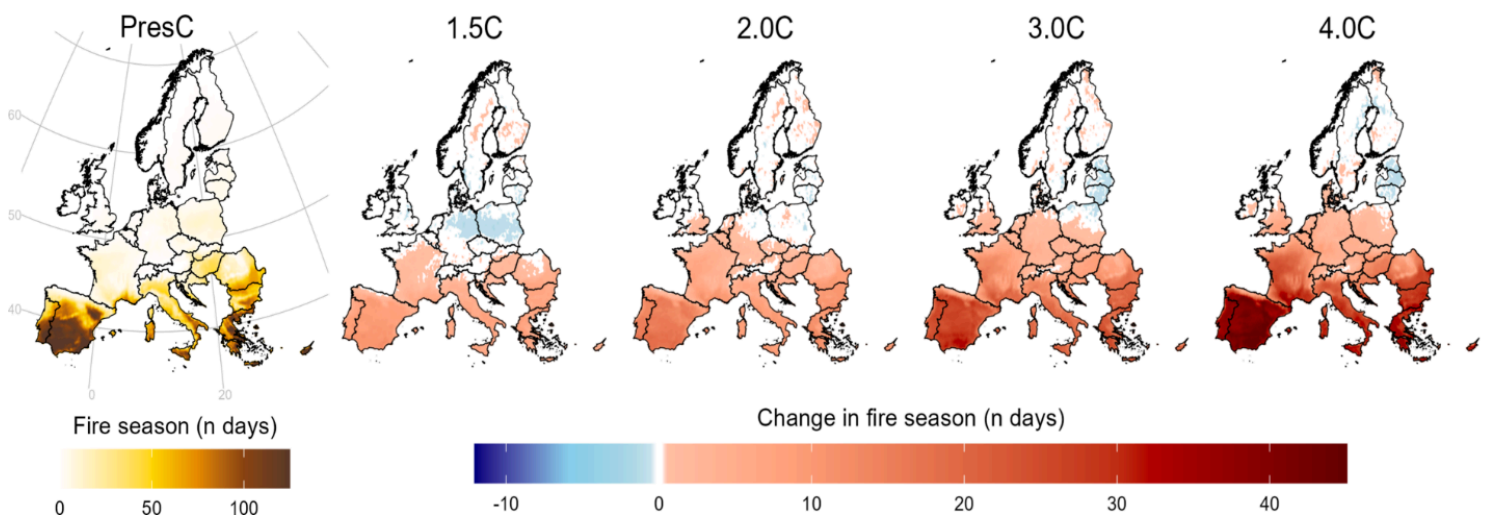


Figure 1

Mean fire season length for present (1991-2020) climate conditions (PresC) and change in fire season length compared to PresC for different global warming levels. Fire season length is expressed as the number of days per year with high-to-very-extreme fire danger ($FWI \geq 21.3$). Values refer to the mean estimates across the ensemble of climate simulations.

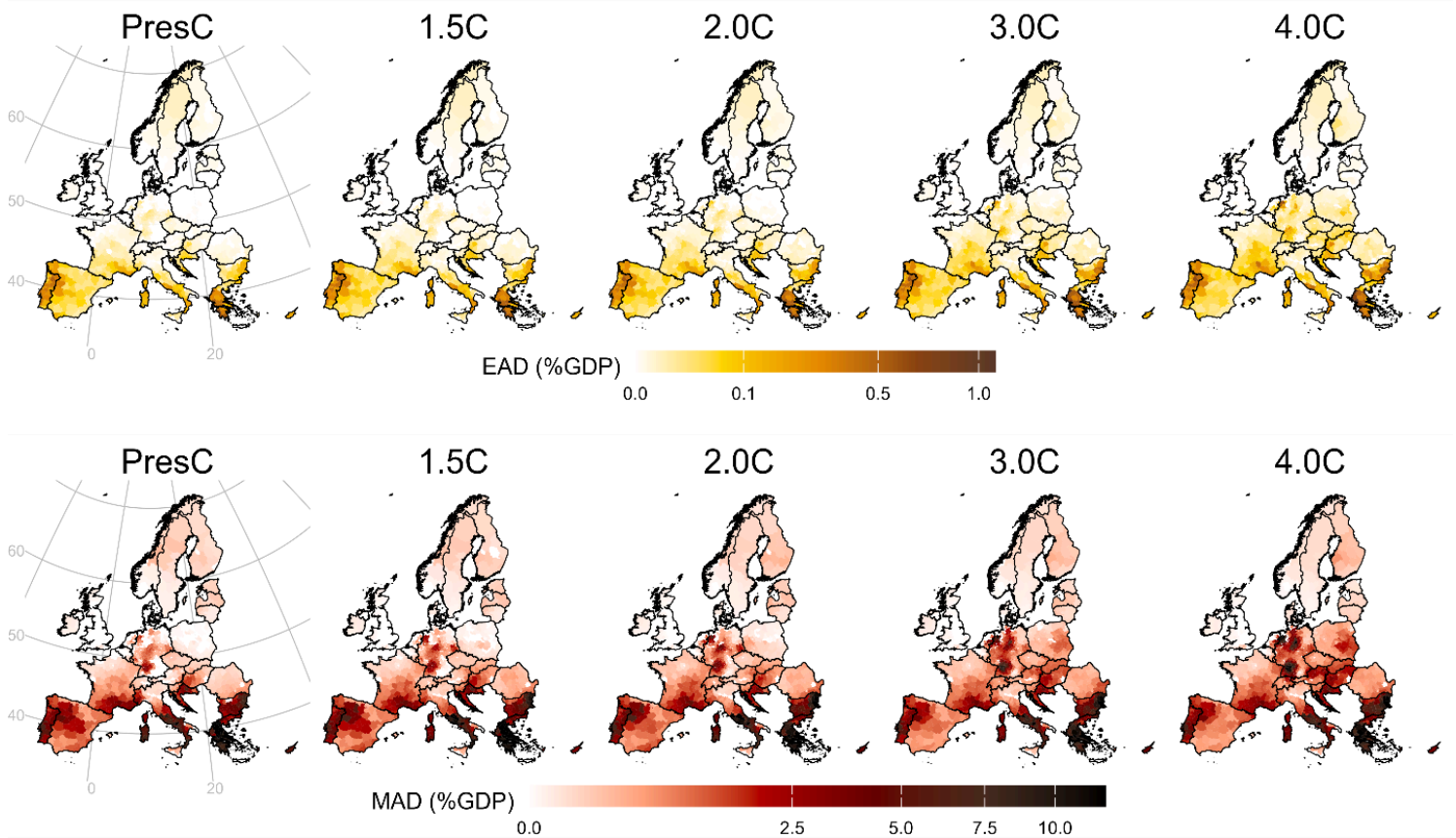


Figure 2

Expected annual damage (EAD) and Maximum annual damages (MAD) by NUTS3 region for present climate conditions (1991-2020, PresC) and climate under scenarios of 1.5°C, 2.0°C, 3.0°C, and 4.0°C global warming. EAD and MAD are expressed as a share of regional Gross Domestic Product (%GDP) of 2020 economy.

Supplementary Files

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