Increasing lifetime exposure to extreme fire weather under climate change in Europe

R. Pietroiusti[1*], J. Hetzer[2], M. Turco[3], A. Laridon[1], Q. Lejeune[1], S. Prudencio Montaño[1], D. Paprotny[4,5,6], W. Thiery[1]

[1]Vrije Universiteit Brussel, Department of Water and Climate, Brussels, Belgium [2]Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt am Main, Germany [3]Department of Physics, Regional Campus of International Excellence (CEIR) Campus Mare Nostrum, University of Murcia, Murcia, Spain [4]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany [5]Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin, Poland [6]Baltic Climate Centre, University of Szczecin, Szczecin, Poland

*Author to whom any correspondence should be addressed. **E-mail:** rosa.pietroiusti@vub.be

Keywords: fire weather, fire weather index, lifetime exposure, projections, Europe, Portugal

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Abstract

Climate change increases fire weather globally. Hot, dry and windy conditions raise the likelihood of fires igniting and spreading and make suppression more challenging. With further warming, fire weather is projected to intensify across Europe, yet implications for today's young generations remain unclear. Here, we analyse lifetime exposure to extreme fire weather across Europe using an ensemble of bias-adjusted and downscaled global climate models. To this end, we developed *dem4cli*, an open-source Python package that integrates demographic data into climate hazard assessments. We find younger generations are projected to be disproportionately exposed compared to older generations across all warming pathways, while also benefitting most from ambitious mitigation. Across Europe, individuals born in 2025 are projected to experience, on average, around 3 additional years of exposure to extreme fire weather compared to those born in 1950, corresponding to an 80% increase, with larger increases in Southern and Eastern Europe. Focusing on Portugal, under current policies, people born in 2025 are projected to experience nearly twice the exposure compared with those born in 1950, and up to 2.5 times more in the most exposed regions of northeastern Portugal. Under a 1.5°C pathway, lifetime exposure is substantially reduced. Each additional degree of global warming by 2100 adds around 270 days of extreme fire weather to the lifetime exposure of a person born in Portugal in 2025. These results reveal pronounced intergenerational inequalities in exposure to fire weather and underscore the urgency of ambitious mitigation to limit cumulative exposure for younger generations.

1 Introduction

Climate change is driving increases in fire weather across the world [81, 2, 36, 35]. Hotter and drier conditions dry fuels, increasing the likelihood of ignition and enabling faster fire spread that is more difficult to suppress [1].

Across Europe, wildfires present a risk for populations. In the summer of 2025 over 1 Mha burned in the European Union, breaking records since 2006, when European Forest Fire Information Service (EFFIS) satellite-based estimates began. Fires particularly affected Spain, Portugal [64, 45] and Southeastern Europe [46], causing dozens of casualties and hundreds of injuries. Previous active fire seasons occurred in 2017, which recorded the second-highest burned area after 2025, and in 2021-2023 [40, 41, 42, 38], with highly impactful fires affecting Greece [37], Portugal [78, 62] and Turkey [37]. Much of this fire activity is concentrated in the Mediterranean, which accounts for the majority of burned area in Europe [29, 39] and is among the most fire-affected regions worldwide [36].

Within this region, Portugal stands out as the European country most affected by wildfires, with over 100,000 ha burned annually on average in the past two decades and the highest proportion of national territory burned each year [20]. Portugal is home to some of the most fire-prone regions in Europe [26]. Severe wildfire events in 2017, 2024 and 2025 caused multiple fatalities, and injured dozens to hundreds of people [78, 62, 47, 64].

Fire activity emerges from the interplay between vegetation characteristics, climatic variability, and human management. Nonetheless, studies have shown that climatic conditions exercise a dominant influence on the interannual variability of fire activity in many parts of the world, including the Mediterranean [56, 80, 3, 36]. Fire weather is projected to increase across Europe with further warming, and to expand into areas previously rarely exposed to high levels of fire danger [32, 22]. In the Mediterranean, climatic conditions are projected to become hotter and drier, with warming amplified during summer and precipitation declines projected in all seasons [15, 33, 14]. Such changes would increase fire activity in an already fire-prone region [79], recognized as a climate change hotspot [15, 51, 16].

While it is clear that fire danger will increase in Europe with further warming, the intergenerational implications of this have not been explored. Today's children have little responsibility for past emissions, yet they will be disproportionately exposed to the impacts of climate change over their lifetimes and will bear much of the responsibility for mitigation efforts to limit future warming and associated risks [63, 82]. Intergenerational inequity associated with climate change is rarely quantified in terms of differences in lifetime exposure to projected climate hazards, thus such aspects are rarely incorporated into assessments on the relative desirability of different mitigation pathways, despite their relevance for evaluating the long-term societal implications of climate policy.

Here, we assess how exposure to extreme fire weather may differ across the lifetimes of different generations. Fire weather is represented using the Canadian Fire Weather Index (FWI) under policy-relevant global warming pathways ranging from 1.5°C to 3.5°C of warming by 2100. We combine projections from state-of-the-art global climate model (GCM) simulations, statistically downscaled to 0.1° resolution, with data on population density and life expectancy.

We build on previous studies that have estimated intergenerational inequity in exposure to climate extremes [76, 28], for the first time carrying out analysis at subnational level, updating demographic data, and improving the method used to emulate regional climate response to policy-relevant stylized warming pathways. We merge our developments into *dem4cli*, a new flexible open-source Python package that can be used to estimate age-specific and lifetime exposure to any climate hazard.

In Section 2 we describe our data and methods, and in Section 3 we present results for Europe and then focus on Portugal, given its relevance as one of Europe's most fire-prone countries.

2 Methods

2.1 Fire weather data and definition of extreme fire weather days

To study fire-prone weather conditions, we use the Fire Weather Index (FWI), a dimensionless measure of meteorological fire danger that integrates temperature, humidity, wind, and precipitation, and accounts for antecedent conditions influencing fuel dryness and flammability [87, 19, 90, 11]. We use daily FWI values from Hetzer et al. [32], calculated from six CMIP6 global climate models (GCMs) under historical forcings and four Shared Socioeconomic Pathway (SSP-RCP) scenarios for 1950–2100 (Table S1). Input variables were statistically downscaled and bias-adjusted against ERA5-Land over 1985–2014. We additionally use ERA5-Land FWI for 1985–2014 from Hetzer et al. [32] to compare reanalysis and model trends. All data are bilinearly interpolated to a regular 0.1° grid to match gridded population data.

We define "extreme fire weather days" as days exceeding a local 95th percentile of FWI, calculated over the reference period 1985–2014, following Abatzoglou, Williams, and Barbero [2] and Quilcaille et al. [61]. By construction, this corresponds to approximately 18 extreme days per year during the reference period (Figs. S1-S2).

We additionally present results for two classes based on absolute magnitude thresholds, defined by the EFFIS fire danger forecast service as "very high" (38≤FWI<50) and "extreme" (FWI≥50) fire danger [13]. Due to its rarity, we include the "very extreme" fire danger class, introduced in 2021 (FWI≥70), within the "extreme" danger class.

2.2 Dem4cli: a flexible package to estimate age-specific and lifetime exposure to climate hazards

We present *dem4cli*, a new Python package that allows to integrate demographic and climate data to estimate age-specific and lifetime exposure to climate hazards, building on previous studies [76, 28, 59]. Lifetime exposure is defined as the cumulative number of hazard occurrences experienced by individuals born in a given year and location over their lifetime (Fig. A1). The package allows analyses at national and subnational scales (NUTS2 and NUTS3 in Europe), supports user-provided climate or impact model ensembles, and allows for using high-resolution climate data. Compared to earlier studies, we update demographic datasets, refine the emulation of climate responses to better isolate the forced signal, revise stylized warming pathways, and add flexibility for user-defined regions and hazard datasets. A full description of *dem4cli* is provided in Supplementary Text S1.

2.3 Estimating lifetime exposure to extreme fire weather days

Using *dem4cli*, we estimate lifetime exposure to extreme fire weather for individuals born between 1950 and 2025 in Europe under stylized warming trajectories reaching 1.5°C to 3.5°C by 2100.

2.3.1 Construction of stylized global warming trajectories We construct 21 stylized global mean temperature (GMT) trajectories reaching 1.5–3.5°C in 2100 at regular 0.1°C intervals (Fig. A1). Following Grant et al. [28], we construct these by linearly interpolating global warming pathways obtained from the IPCC AR6 Scenario Explorer [6] for 2000–2100. These are extended backward using AR6-assessed GMST observations for 1950–1999 [33, 34, 48], smoothed with a 21-year moving average to remove natural variability, and extended beyond 2100 using linear extrapolation of the final decade.

2.3.2 Remapping input simulations to emulate local impacts in stylized trajectories We emulate regional climate responses using a GMT-mapping approach based on Thiery et al. [76] and Grant et al. [28], which assumes that the local forced response of a climate indicator primarily depends on global warming level [31, 60]. First, for each input GCM simulation (Section 2.1, Table S1), we derive annual grid-cell counts of extreme fire weather days and the corresponding annual GMT anomaly timeseries. Both are smoothed using a 21-year moving average to isolate the forced response. As the FWI data are bias-adjusted, we rebase each model's GMT such that mean warming over 1985–2014 matches ERA5 warming relative to 1850–1900 (i.e., 0.74°C). Then, we match each simulation's GMT timeseries to the target trajectories by identifying, separately for each target trajectory and simulation, the year in the simulation with the closest GMT anomaly. This produces a remapping "recipe" (year-to-year mapping), which is applied to reconstruct spatial patterns of extreme fire weather along each target trajectory based on original input simulations across SSP-RCP pathways. Simulations are only used if the absolute GMT difference never exceeds 0.2°C, ensuring consistency between input and target warming levels. Consequently, colder trajectories (e.g., 1.5°C) are informed by a larger ensemble than higher-warming trajectories.

2.3.3 Estimating lifetime exposure For each region and year, exposure is calculated as the population-weighted average number of extreme fire weather days, thus accounting for spatial population distribution within each region. Lifetime exposure is then obtained by summing annual exposure from birth to death, including fractional exposure in the final year.

We use gridded population data from the COMPASS project [54], updated in this study to align with the latest SSP v3.2 projections [86, 44, 43], at 0.1° resolution. These are derived by spatially disaggregating national population estimates from United Nations World Population Prospects (UNWPP) [83] and SSP projections. Life expectancy data are taken from UNWPP 2024. Following previous studies [76, 28], we estimate life expectancy at birth conditional on survival to age 5 and convert period life expectancy to cohort life expectancy, accounting for improvements in life expectancy, by adding 6 years, based on Goldstein and Wachter [27].

We conduct the analysis at national, NUTS2, and NUTS3 levels using the 2016 NUTS classification [23]. A total of 1440 NUTS3 and 313 NUTS2 regions are included after excluding regions too small to be resolved at the climate data resolution. For Kosovo and Bosnia and Herzegovina, only national-level results are provided. Results are also aggregated to IPCC AR6 regions based on centroid location.

This framework enables comparison of lifetime exposure across birth cohorts, regions, and warming pathways. The emulation approach allows us to quantify changes in exposure per degree of warming and across policy-relevant scenarios. The 1.5–3.5°C range reflects plausible future warming outcomes under a range of policy and climate sensitivity scenarios [84, 12], while ensuring sufficient simulations available for robust emulation.

We report lifetime exposure as total time and fraction of lifetime exposed. Additionally, we estimate the increase in exposure per degree of warming by fitting an ordinary least squares regression to ensemble mean results.

3 Results

3.1 Increasing lifetime exposure to extreme fire weather in Europe

We project lifetime exposure to extreme fire weather in Europe at national and sub-national NUTS2 and NUTS3 levels (Figs. 1, S5, S6). Lifetime exposure increases for younger birth cohorts and with global warming (Fig. 1). The largest increases occur in Southern and Eastern Europe, and parts of Western and Central Europe.

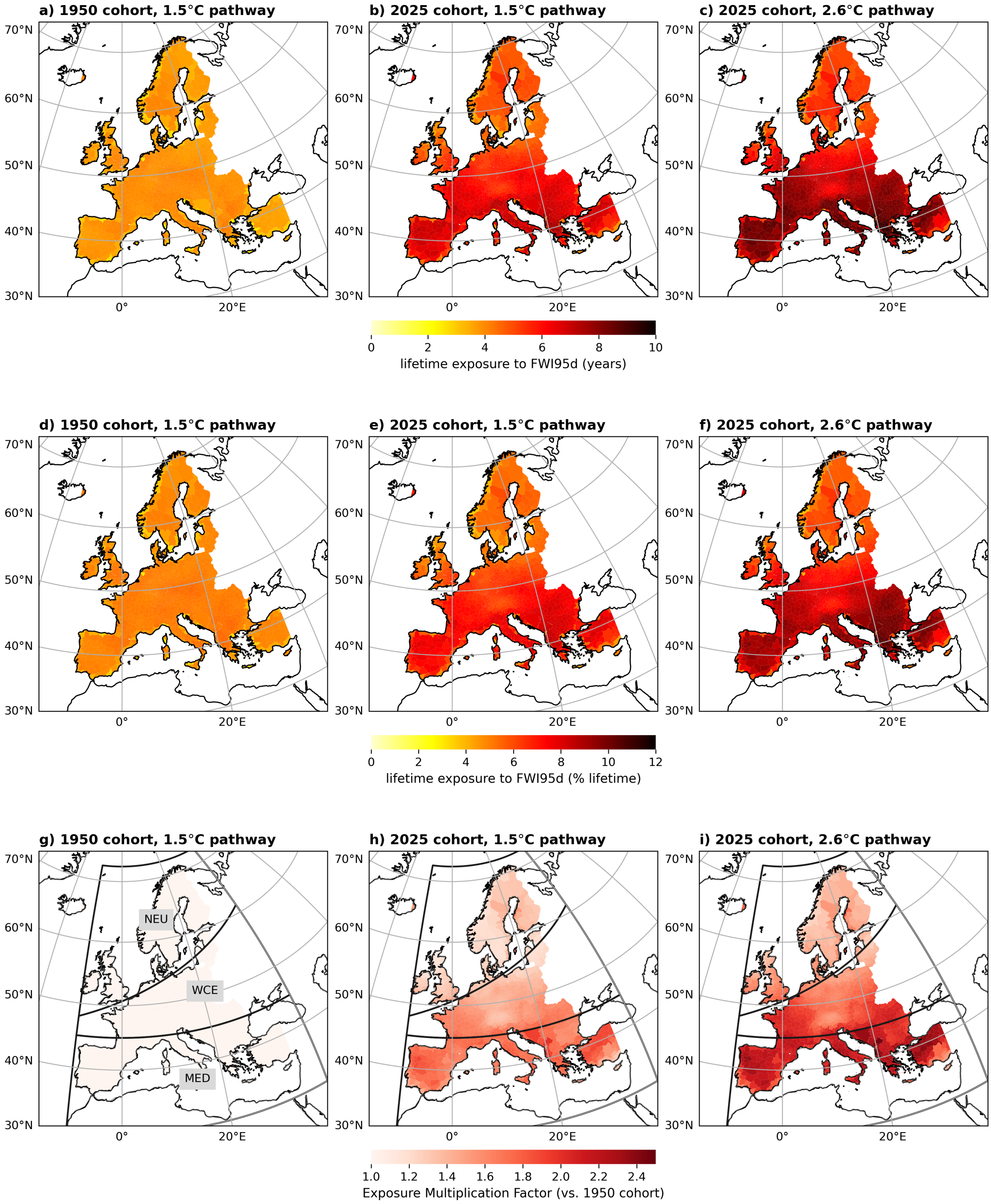

Figure 1. Lifetime exposure to extreme fire weather days (FWI95d) in Europe, at NUTS3 level. Number of years exposed (a-c), percentage lifetime exposed (d-f) and exposure multiplication factors relative to the 1950 birth year (g-i), for people born in 1950 (a, d, g) and 2025 (b, c, e, f, h, i) under 1.5°C (a, b, d, e) and 2.6°C (c, f) warming pathways. Multi-model mean is shown. See Figs. S5-S6 for the results at the country and NUTS2 level. Results for all countries, NUTS2 and NUTS3 regions are included in tabular format as Supplementary Data.

We find little variation in the lifetime exposure of people born in 1950 across warming scenarios. At the NUTS3 level, they are exposed to 0.5-4.3 years (1-6% of lifetime, multi-model mean, range across regions) of extreme fire weather regardless of the scenario (Fig. 1a,d).

For the 2025 birth year, exposure varies strongly across regions and scenarios. Under a scenario that reaches 1.5°C in 2100, lifetime exposure ranges from 0.6-6 years (1-7% of lifetime) in Northern Europe, 2.4-7.2 years (3-8% of lifetime) in Western and Central Europe, and 1.5-7.7 years (2-9% of lifetime) in Southern Europe. In a 2.6°C scenario, corresponding to the median expected end-of-century warming under current policies in the latest assessment of the United Nations Emissions Gap Report [84], this increases strongly, with exposure rising to 0.7-7.4 years (1-8% of lifetime) in Northern Europe, 2.9-8.6 years (3-10% of lifetime) in Western and Central Europe, and 1.6-9.5 years (2-11% of lifetime) in Southern Europe (Fig. 1c,f).

Young generations experience substantially more extreme fire weather than older ones. Across NUTS3 regions, individuals born in 2025 face on average 3 additional years (2.3 - 3.8, multi-model mean ± 1 SD) of exposure compared to those born in 1950 under current policies, corresponding to an 80% (64 - 96%) increase in exposure (Fig. 1i). In some regions in Southern Europe, differences exceed five years, corresponding to an increase by a factor of up to 2.5 (2.1 - 2.9, Figs. 1i). The largest increases occur in regions of Turkey, Italy, southwestern France, the Iberian Peninsula, Greece, and the Balkans (Fig. 1i).

Aligning current policies with the 1.5°C Paris Agreement target reduces exposure in all regions (Fig. 1). Exposure for the 2025 birth cohort decreases by 1.3 (0.5 - 2, multi-model mean ± 1 SD) years on average across Europe, 0.9 (0.1 - 0.7) years in Northern Europe, 1.3 (0.3 - 2.3) years in Western and Central Europe, 1.6 (1.0 - 2.2) years in Southern Europe, with reductions exceeding 2 years in the most affected regions in Southern Europe.

When considering definitions of fire danger using the absolute magnitude thresholds adopted by EFFIS for fire danger forecasts [21], we find very high fire danger ($38 \leq \text{FWI} < 50$) is concentrated in Southern Europe, particularly in the Iberian Peninsula, Turkey, Greece, Italy, Southern France and Eastern Europe (Fig. A2a-c). The strongest increases in lifetime exposure are projected in Iberia, Greece, Italy, Western France and Eastern Europe, (Fig. A2d–e). In these regions, people born in 2025 experience up to 4 percentage points more of their lifetime exposed than those born in 1950 under a 1.5°C pathway, and up to 5 percentage points more under a 2.6°C pathway. While locally more constrained than very high fire danger, we find very large increases in the frequency of extreme fire danger ($\text{FWI} \geq 50$), in the order of up to 7 additional years of lifetime exposure for people born in 2025 relative to those born in 1950 (6-7 additional percentage points of lifetime), in particular in inland Iberia and Turkey, where static or slightly decreasing frequencies of very high fire danger (Fig. A2d-e) are more than compensated by increases in extreme fire danger (Fig. A3).

3.2 Increasing lifetime exposure to extreme fire weather in Portugal

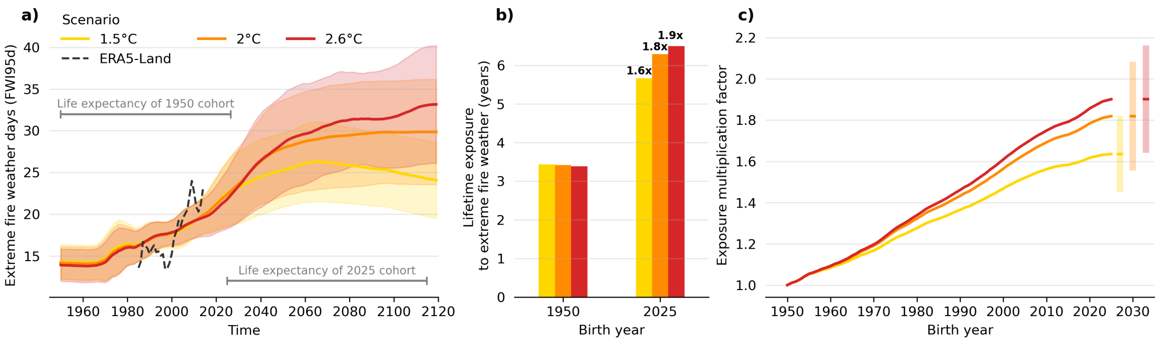

Figure 2. (a) Area-weighted average number of extreme fire weather days crossing the FWI95p threshold in Portugal. Results are shown for three scenarios leading to 1.5°C, 2°C and 2.6°C of warming in 2100, and for ERA5-Land in the 1985-2014 period. Data is smoothed with a 10-year moving average with a minimum window size of 1 year. By definition, 18 extreme fire weather days per year occur in the reference period 1985-2014. (b) Lifetime exposure to extreme fire weather expressed as number of years, for people born in 1950 and 2025 in Portugal. Exposure multiplication factors are indicated above the bars and express the relative lifetime exposure of the 2025 birth year compared to the 1950 birth year. (c) Exposure multiplication factor relative to the lifetime exposure of the 1950 birth year for birth years from 1950 to 2025 in Portugal, smoothed with a 5-point moving average. In all panels, full lines represent the multi-model mean, and uncertainty spans ± one standard deviation across models.

We analyse projections of extreme fire weather (FWI95d) in Portugal, one of Europe's most fire-prone countries. We find an increase in the number of extreme fire weather days experienced on average in Portugal across all assessed warming scenarios (Fig. 2a). These increase from 14 (12–16) days per year in 1950–1970 to 25 (21–29) days under 1.5°C, 30 (24–36) days under 2°C, and 32

(26–38) days under a 2.6°C pathway by 2100. Under current policy projections extreme fire weather days in Portugal are thus expected to more than double relative to the 1950–1970 period.

In terms of lifetime exposure, we find people born in 1950, who have a life expectancy of approximately 76.4 years, experience approximately 3.4 years of their lives under extreme fire weather conditions, with little variation across scenarios (Fig. 2b). Children born in 2025, who have a mean life expectancy of 89.7 years, experience 5.7 years of their life under extreme fire weather conditions in a 1.5°C pathway, 6.3 years in a 2°C pathway and 6.5 years in a 2.6°C pathway (Fig. 2b).

The 1.5°C warming pathway we assess is a low-overshoot pathway that limits warming to 1.5°C in 2100 after a peak of approximately 1.6°C in the 2060s. This warming pathway corresponds to the most ambitious category of mitigation pathways assessed in the IPCC AR6 (i.e., C1), which limit warming to 1.5°C with no or limited overshoot [34, 65]. Even under this pathway, which implies immediate ambitious global coordinated climate mitigation action [34], people born in 2025 in Portugal are projected to experience 60% more extreme fire weather days than people born in 1950 (Fig. 2b). With global warming reaching 2°C and 2.6°C in 2100, children born in 2025 in Portugal are projected to experience respectively 80% and 90% more extreme fire weather compared to people born in 1950 (Fig. 2b).

In all warming scenarios, the youngest generations will experience the highest lifetime exposure to fire danger. However, the difference between warming scenarios is also most striking for younger generations (Fig. 2c). This implies that the youngest generations would also have the most to gain from ambitious mitigation. Limiting warming in line with the Paris Agreement target of 1.5°C would reduce the lifetime exposure of Portuguese individuals born in 2025 to extreme fire weather by approximately one year (1.1 (0.5-1.6) years) compared to current policies (Fig. 2b).

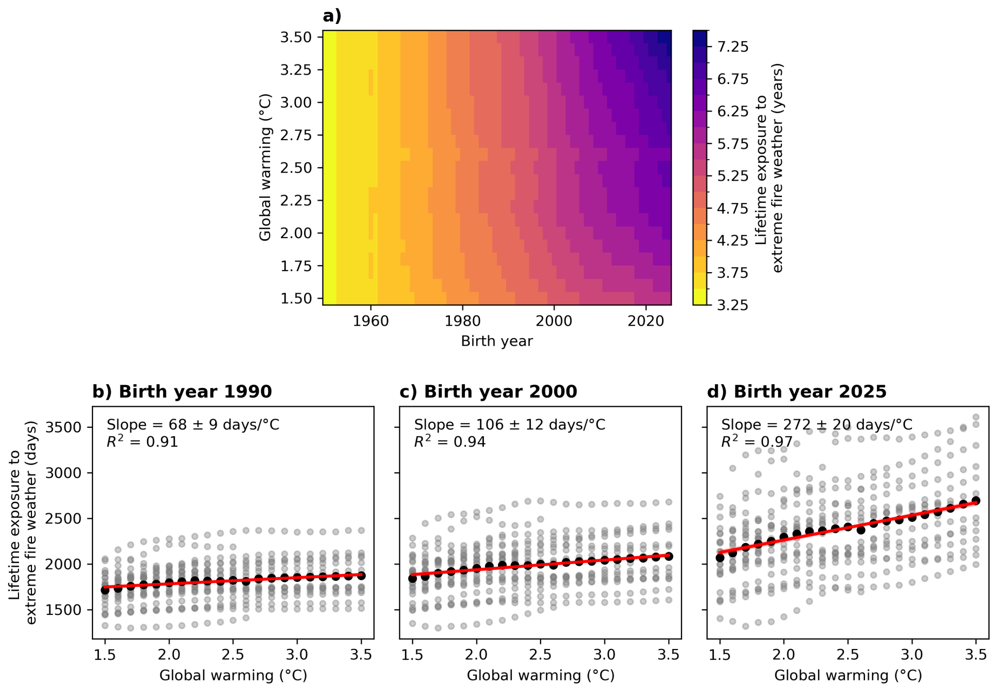

Figure 3. Lifetime exposure to extreme fire weather in Portugal under global warming trajectories reaching 1.5°C to 3.5°C in 2100. (a) Years of lifetime exposed for people born in Portugal between 1950 to 2025 under warming pathways from 1.5°C to 3.5°C in 2100. Multi-model mean results are shown. (b-d) Additional lifetime exposure per degree of global warming for people born in (b) 1990, (c) 2000, (d) 2025, calculated based on a linear regression of the lifetime exposure against global warming in 2100. Ordinary least squares regression is carried out on the ensemble mean (black dots), individual remapped simulations are shown for context (gray dots). The slope of the linear regression indicates the additional days of lifetime exposure per degree of end-of-century warming (days/°C). Results for more birth years in Portugal in Table A2, and for all countries in Table A3. Results for all NUTS3 regions in Portugal in the Supplementary Materials (Table **??**), and for all countries, NUTS2 and NUTS3 regions, and birth years, in the Supplementary Data.

We find that, for each birth year, lifetime exposure to extreme fire weather increases approximately linearly with global mean warming in 2100 (Fig. 3). This means we can estimate the exposure that every additional fraction of a degree of end-of-century warming adds. Based on ordinary least squares estimation on the ensemble mean, we find that each degree of warming in 2100 adds approximately 272 days (± 20 days, $R^2 > 0.9$) of extreme fire weather to the life of someone born in 2025 in Portugal, 106 days (± 12, $R^2 > 0.9$) for someone born 2000 and 68 days (± 9, $R^2 > 0.9$) for someone born in 1990 (Fig. 3b-d, see results for all countries in Table A3). As in previous results, the sensitivity to higher warming is highest for the youngest generations.

When considering EFFIS fire danger forecast absolute thresholds [21] (Figs. A2-A3), we find that in Portugal, each additional degree of warming by 2100 adds 248 days (± 16 days, $R^2 > 0.9$) of very high fire danger ($38 \leq FWI < 50$) to the lifetime exposure of someone born in 2025, and 88 days (± 7 days, $R^2 > 0.9$) of extreme fire danger ($FWI \geq 50$).

3.3 Sub-national variation in increasing lifetime exposure to extreme fire weather in Portugal

Analysing projections at the NUTS3 level in Portugal, we find that lifetime exposure to extreme fire weather is projected to increase across the whole country, with the greatest increases in the Northeast (Norte and Centro regions), especially inland where oceanic influence is limited (Fig. 4, left). While people born in 1950 experience 4-5% (multi-model mean, range across regions) of their lifetime in extreme fire weather conditions, with little variation across scenarios, we find people born in 2025 projected to live 5-8% of their lifetime exposed across regions in a 1.5°C scenario, 5-9% in a 2°C scenario and 5-10% under current policies (Fig. 4, left).

Across regions, we find people born in 2025 are projected to experience 40-90% more extreme fire weather during their lifetime than people born in 1950 in a 1.5°C pathway (Fig. 4, right), 50% more to 2.1 times as much in a 2°C scenario and 50% more to 2.4 times as much in a current policies pathway, with the highest increases in the Northeast (Fig. 4, right).

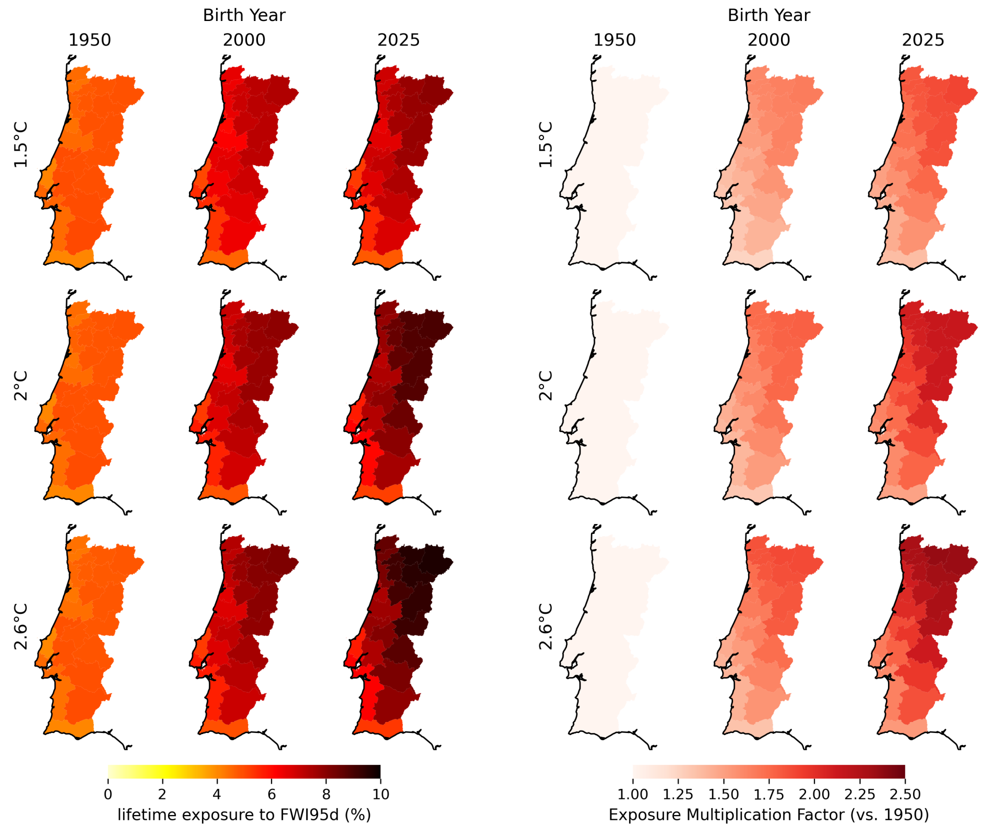

Figure 4. Percentage of lifetime exposed to extreme fire weather (FWI95d, left). Exposure multiplication factor relative to the lifetime exposure of the 1950 birth year (right). Results are shown at the NUTS3 level of Portugal for people born in 1950, 2000 and 2025, under 1.5°C, 2°C and 2.6°C warming pathways. Multi-model mean is shown.

We focus on one region as a case study, Leiria, located in the coastal part of the Centro region, as this region was heavily affected in recent fire seasons, notably in 2017 (Fig. S4c-d). Here, we find people born in 1950 are projected to live approximately 3.8 years of their life in extreme fire weather conditions (Fig. 5). People born in 1999 are projected to live 50% more time in these conditions (5.5 years) in a 1.5°C pathway and 60% more (5.9 years) in a current policies pathway

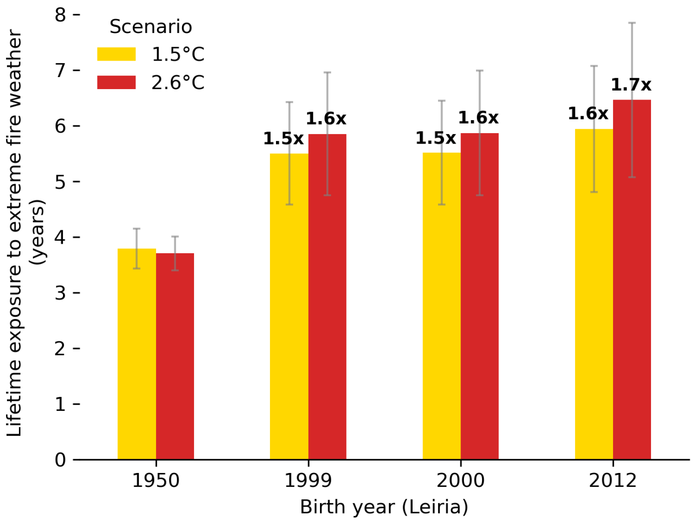

Figure 5. Lifetime exposure to extreme fire weather (FWI95d) in the NUTS3 region of Leiria, Portugal. Results are shown for people born in 1950, 1999, 2000 and 2012, under 1.5°C and 2.6°C warming pathways. Multi-model mean plus and minus one standard deviation is shown. Multiplication factors express the multi-model mean relative exposure of each birth year compared to the 1950 birth year under the same pathway.

(Fig. 5). Children born in 2012 are projected to live respectively 60% more (5.9 years) and 70% more time (6.5 years) in extreme fire weather conditions than people born in 1950 in 1.5°C and 2.6°C pathways (Fig. 5).

4 Discussion and Conclusions

Our results show that, irrespective of the warming pathway, climate change is increasing lifetime exposure to extreme fire weather for young generations across Europe. However, both the magnitude of the increase and the resulting intergenerational disparity in exposure are greater under higher warming pathways. Under a current policies scenario, projected to lead to 2.6°C of warming by 2100 [84], the youngest generations in Europe are expected to experience on average 3 additional years of exposure compared to their older counterparts. Limiting warming to 1.5°C reduces the exposure of younger generations, for instance cutting the exposure of people born in 2025 in Portugal by over a year relative to current policies. Although some degree of intergenerational inequity is committed due to past emissions and plausible future pathways, there remains scope to reduce future inequities through ambitious mitigation.

Our findings have implications for intergenerational justice, as we show that younger generations, who have contributed least to historical emissions, are projected to bear a disproportionate share of future exposure to extreme fire weather. Such analyses can inform the arguments of youth climate justice movements and legal initiatives asking for more ambitious climate action [63, 55].

We find the largest projected increases in exposure for young people in Southern Europe, a region that is already highly fire-prone (Fig. 1) [26, 25]. This is in line with previous research [25, 2, 32], and has been linked to projections of hotter and drier conditions in the Mediterranean [25, 33, 15, 14] and longer fire seasons [4]. Together with the high impacts of recent fire events in Southern Europe [64, 78, 46], our findings raise concerns for the region and underline the growing importance of effective land and fire management and preventative measures in fire-prone areas, together with climate mitigation.

Portugal has emerged as one of the most fire-prone countries in Europe [20, 26, 47, 64]. We found a pronounced increase in lifetime exposure to extreme fire weather projected for young people in Portugal, with the largest increases in the Northeast (Fig. 4), which is already today one of the most fire-prone regions in Europe [26, 25, 77, 64]. While the Southern Alentejo region experiences the highest absolute fire weather values due to a drier and hotter climate (Fig. S1), wildfires mostly affect the forested Central and Northern regions [11] (Fig. S4a-b). Historical patterns of high fire risk and projected increases in fire weather raise concerns on heightened fire danger for communities and ecosystems in these areas. Our findings are in line with previous research that has projected high increases in fire weather [10, 4] and activity [25, 8] in the Northwest of the Iberian Peninsula, associated with projections of strong increases in summer maximum temperatures [10, 9, 51, 14] and possible declines in summer precipitation [10, 72].

Using absolute magnitude indicators of fire danger classes, we find very high and extreme fire danger is concentrated in Southern Europe, where baseline climates are hotter and drier. Increases in lifetime exposure to these classes are highest in Southern Europe, but occur in other parts of the continent under higher warming pathways (Figs. A2-A3).

With *dem4cli* we present a new community Python package that can be used to estimate exposure, including age-specific and lifetime exposure to any climate hazard. This package expands on previous research [76, 28], increasing the robustness in the emulation approach and flexibility for user-defined analyses. The lifetime exposure method allows to compare the projected exposure to climate hazards of people in different locations and born in different years, at national and sub-national scales, along policy-relevant warming pathways.

Several aspects of this study could be improved through further research. First, we study fire weather, namely the hot-dry-windy meteorological conditions that are conducive to the initiation and spread of fires, not actual fire occurrence. Other factors such as vegetation, land cover and management, and human factors are important in determining the occurrence and spread of fires [11, 53, 56], and mediate the local sensitivity of fires to climatic conditions [57, 3]. Nonetheless, the FWI has been shown to be a good proxy of fire danger in many locations [3, 36] including Europe [25, 26, 19, 24], the Mediterranean [19, 89] and Portugal [11]. Moreover, we do not consider vegetation–climate feedbacks that could alter pyroregion structure and fire–weather relationships [57, 8]. However, given uncertainties in process-based fire models [75, 36, 5] and future projections of biogeography, land use, and management [17], projections of meteorological fire danger remain valuable.

Second, we use an ensemble of bias-adjusted and statistically downscaled simulations from the latest state-of-the-art CMIP6 GCMs [32]. Future studies could use a larger ensemble of GCMs, or dynamically downscaled simulations [10]. The previous generation of GCMs, CMIP5 underestimated FWI trends in the Mediterranean [36], while global and regional climate models underestimate warming over Europe in the historical period [88, 68, 71, 33], meaning our results could be conservative.

Finally, we use an emulation approach to model the regional response to policy-relevant global warming pathways. By using a GMT-mapping approach, we assume that the GMT-to-hazard relationship is path-independent and that the hazard magnitude and regional response depends mainly on GMT. This is supported for various indicators [31, 66, 73, 30] and similar reasoning is applied in other emulation approaches [7, 70, 74, 69, 60], but we note that this might be less applicable in overshoot or temperature stabilisation scenarios [58, 67, 52, 49, 50], or where climate is strongly affected by aerosol concentrations or land use changes [18, 85]. Future work could specify different relationships before and after peak warming in the context of overshoot, and could increase policy relevance by emulating exposure under emission pathways, instead of warming pathways.

In conclusion, our results show that exposure to extreme fire weather accumulates over decades, creating substantial risk for today's young generations across their lifetimes. Policy decisions on emission reductions taken today will shape the exposure to hazardous conditions of children and of future generations. By explicitly considering lifetime exposure in risk assessments, this study helps clarify the long-term consequences of climate change and highlights the benefits of prevention compared with the costs of delayed action. Our results show that every fraction of warming avoided reduces the burden on young generations across Europe by lowering their lifetime exposure to extreme and dangerous fire weather. Climate change mitigation should therefore be understood as a preventative policy to protect the health and safety of today's young generations.

5 Appendix

5.1 Appendix Tables

Table A1. List of GCMs, ensemble members and experiments used in this study. All data was bias adjusted and statistically downscaled against ERA5-Land prior to calculation of the FWI, as described in [32].

GCM	Ensemble member	Experiments
ACCESS-CM2	r1i1p1f1	historical, ssp126, ssp245, ssp370, ssp585
CNRM-ESM2-1	r1i1p1f2	”
CanESM5	r1i1p1f1	”
EC-Earth3	r1i1p1f1	”
MPI-ESM1-2-HR	r1i1p1f1	”
MRI-ESM2-0	r1i1p1f1	”

Table A2. Additional days of extreme fire weather (FWI95d) experienced per degree of end-of-century warming (days/°C), in Portugal, for selected birth years. Best estimate ± 95% confidence interval. For results for all birth years see Supplementary Data Excel files.

Birth year	Days/°C	R^2
1990	68 (± 9)	0.91
1999	103 (± 12)	0.94
2000	106 (± 12)	0.94
2010	162 (± 15)	0.96
2012	174 (± 15)	0.96
2020	231 (± 18)	0.97
2025	272 (± 20)	0.97

Table A3. Additional days of extreme fire weather (FWI95d) experienced per degree of end-of-century warming (days/°C), for selected birth years and all countries. Best estimate ± 95% confidence interval. All $R^2 \geq 0.79$. For results for all birth years, NUTS2 and NUTS3 regions see Supplementary Data files.

Country	1990	2000	2010	2025
Albania	119 (± 10)	196 (± 12)	290 (± 14)	477 (± 18)
Algeria	58 (± 7)	123 (± 9)	198 (± 11)	333 (± 14)
Andorra	139 (± 12)	229 (± 18)	336 (± 22)	511 (± 25)
Austria	82 (± 12)	135 (± 16)	199 (± 19)	317 (± 24)
Belarus	58 (± 6)	94 (± 9)	160 (± 14)	249 (± 18)
Belgium	126 (± 16)	206 (± 20)	289 (± 24)	432 (± 34)
Bosnia and Herzegovina	102 (± 9)	212 (± 12)	311 (± 15)	510 (± 19)
Bulgaria	117 (± 10)	200 (± 10)	309 (± 10)	514 (± 12)
Croatia	85 (± 9)	156 (± 11)	245 (± 13)	410 (± 18)
Cyprus	26 (± 4)	45 (± 5)	68 (± 5)	107 (± 6)
Czechia	68 (± 11)	112 (± 17)	167 (± 22)	270 (± 28)
Denmark	79 (± 9)	129 (± 12)	183 (± 14)	264 (± 17)
Estonia	23 (± 5)	58 (± 10)	106 (± 13)	177 (± 15)
Faroe Islands	20 (± 3)	27 (± 5)	35 (± 6)	46 (± 8)
Finland	41 (± 5)	71 (± 8)	107 (± 9)	161 (± 10)
France	117 (± 13)	192 (± 18)	277 (± 22)	431 (± 28)
Germany	95 (± 11)	158 (± 15)	222 (± 18)	338 (± 24)
Greece	125 (± 5)	204 (± 5)	297 (± 6)	473 (± 8)
Hungary	78 (± 11)	130 (± 17)	202 (± 21)	336 (± 25)
Iceland	108 (± 8)	154 (± 10)	198 (± 13)	263 (± 18)
Ireland	72 (± 13)	111 (± 18)	153 (± 23)	220 (± 29)
Isle of Man	44 (± 8)	64 (± 12)	82 (± 16)	107 (± 21)
Israel	38 (± 5)	55 (± 6)	76 (± 6)	113 (± 5)
Italy	108 (± 9)	187 (± 10)	279 (± 12)	448 (± 15)
Kosovo (under UNSC res. 1244)	130 (± 12)	219 (± 13)	327 (± 16)	542 (± 23)
Latvia	29 (± 4)	66 (± 7)	117 (± 11)	191 (± 13)
Libya	34 (± 4)	51 (± 5)	71 (± 6)	117 (± 6)
Liechtenstein	85 (± 9)	142 (± 13)	207 (± 16)	321 (± 19)
Lithuania	53 (± 6)	91 (± 9)	145 (± 13)	223 (± 17)
Luxembourg	116 (± 16)	200 (± 21)	297 (± 27)	457 (± 34)
Malta	14 (± 1)	24 (± 2)	38 (± 3)	58 (± 4)
Montenegro	118 (± 10)	188 (± 12)	290 (± 15)	479 (± 20)
Morocco	50 (± 7)	83 (± 11)	131 (± 14)	219 (± 18)
Netherlands	111 (± 12)	176 (± 15)	243 (± 18)	353 (± 26)
North Macedonia	133 (± 10)	216 (± 11)	327 (± 14)	535 (± 21)
Norway	57 (± 3)	91 (± 5)	127 (± 6)	179 (± 8)
Poland	66 (± 10)	112 (± 15)	168 (± 20)	258 (± 24)
Portugal	68 (± 9)	106 (± 12)	163 (± 15)	272 (± 20)
Republic of Moldova	67 (± 9)	136 (± 14)	224 (± 19)	388 (± 23)
Romania	90 (± 13)	167 (± 16)	271 (± 19)	449 (± 19)
Russian Federation	31 (± 3)	53 (± 5)	104 (± 10)	177 (± 14)
San Marino	144 (± 11)	239 (± 16)	357 (± 19)	548 (± 21)
Serbia	100 (± 9)	168 (± 9)	275 (± 11)	466 (± 14)
Slovakia	85 (± 17)	131 (± 22)	197 (± 27)	321 (± 33)
Slovenia	91 (± 9)	159 (± 12)	252 (± 16)	417 (± 23)
Spain	113 (± 9)	185 (± 11)	281 (± 13)	448 (± 14)
Sweden	62 (± 8)	107 (± 11)	156 (± 12)	236 (± 13)
Switzerland	97 (± 11)	161 (± 16)	237 (± 20)	376 (± 25)
Tunisia	44 (± 4)	79 (± 5)	125 (± 7)	221 (± 11)
Türkiye	103 (± 6)	176 (± 7)	270 (± 7)	435 (± 8)
Ukraine	61 (± 8)	108 (± 12)	200 (± 16)	343 (± 19)
United Kingdom	98 (± 16)	155 (± 21)	214 (± 26)	312 (± 33)

5.2 Appendix Figures

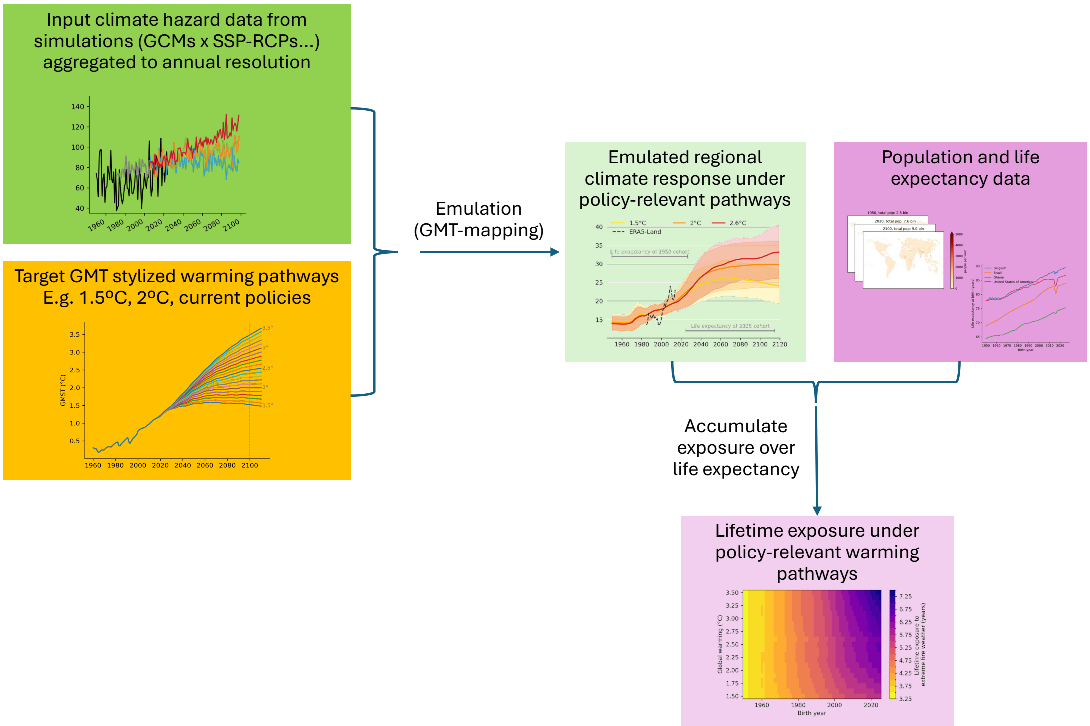

Figure A1. Lifetime exposure methodology available within *dem4cli*. User-provided climate hazard simulations aggregated to annual resolution are provided as input (green) and are remapped using a GMT-mapping approach to emulate the climate response under user-defined stylized warming trajectories (yellow). In this study we create the stylized trajectories by combining historical multi-dataset GMT time series from AR6 with projections from the AR6 Scenario Explorer projections, to construct 21 stylized pathways that in 2100 reach GMT anomalies ranging from 1.5°C to 3.5°C at regular intervals of 0.1°C. The GMT-mapping results in emulated regional climate response under the target warming pathways (light yellow), which can then be combined with data on population density and lifetime exposure to calculate lifetime exposure across regions (e.g. countries or sub-national units) for each birth year (light purple). See Methods and Supplementary Text S1.

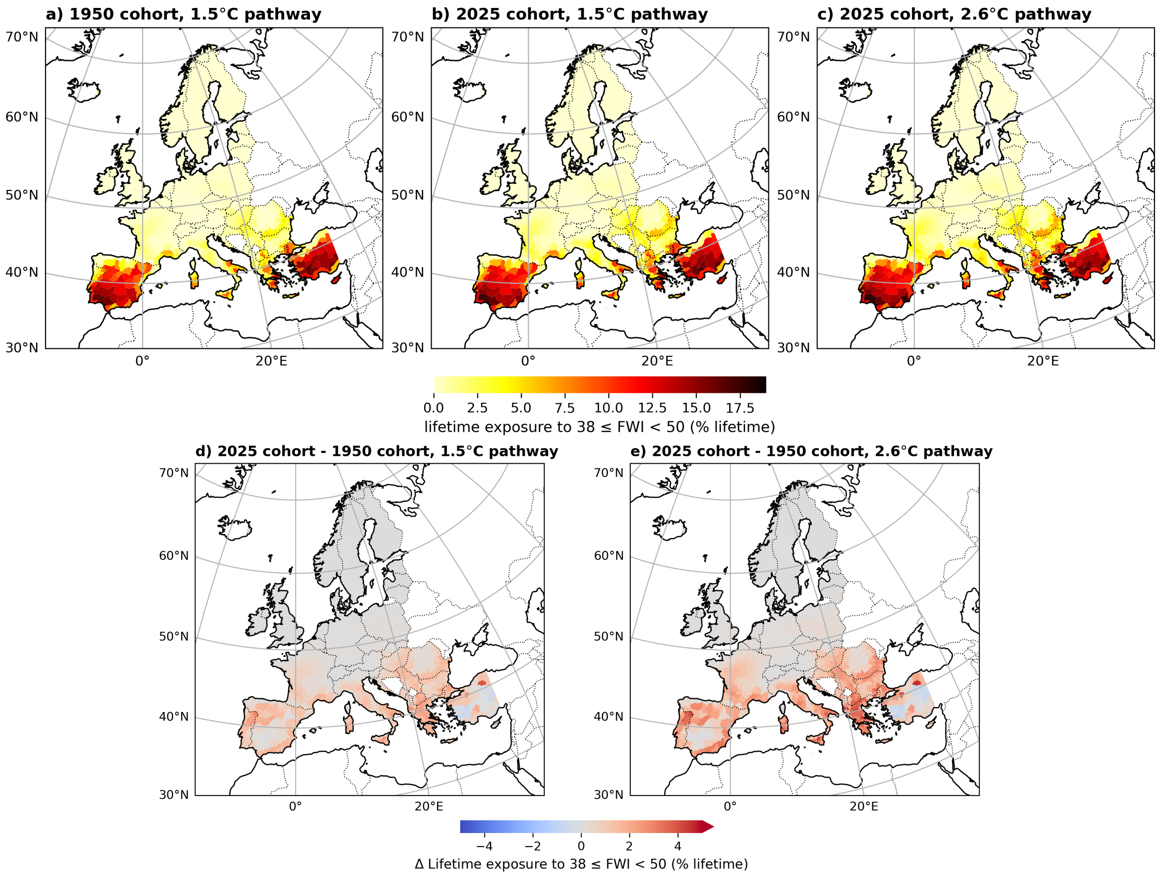

Figure A2. Lifetime exposure to very high fire danger days based on an absolute magnitude EFFIS threshold ($38 \leq$ FWI < 50) in Europe, at NUTS3 level. Percentage lifetime exposed (a-c) for people born in 1950 (a) and 2025 (b, c) under 1.5°C (a, b) and 2.6°C (c) warming pathways. Change in percentage of lifetime exposed to very high fire danger days between 1950 cohort and 2025 cohort under 1.5°C (d) and 2.6°C (e) warming pathways. Multi-model mean is shown.

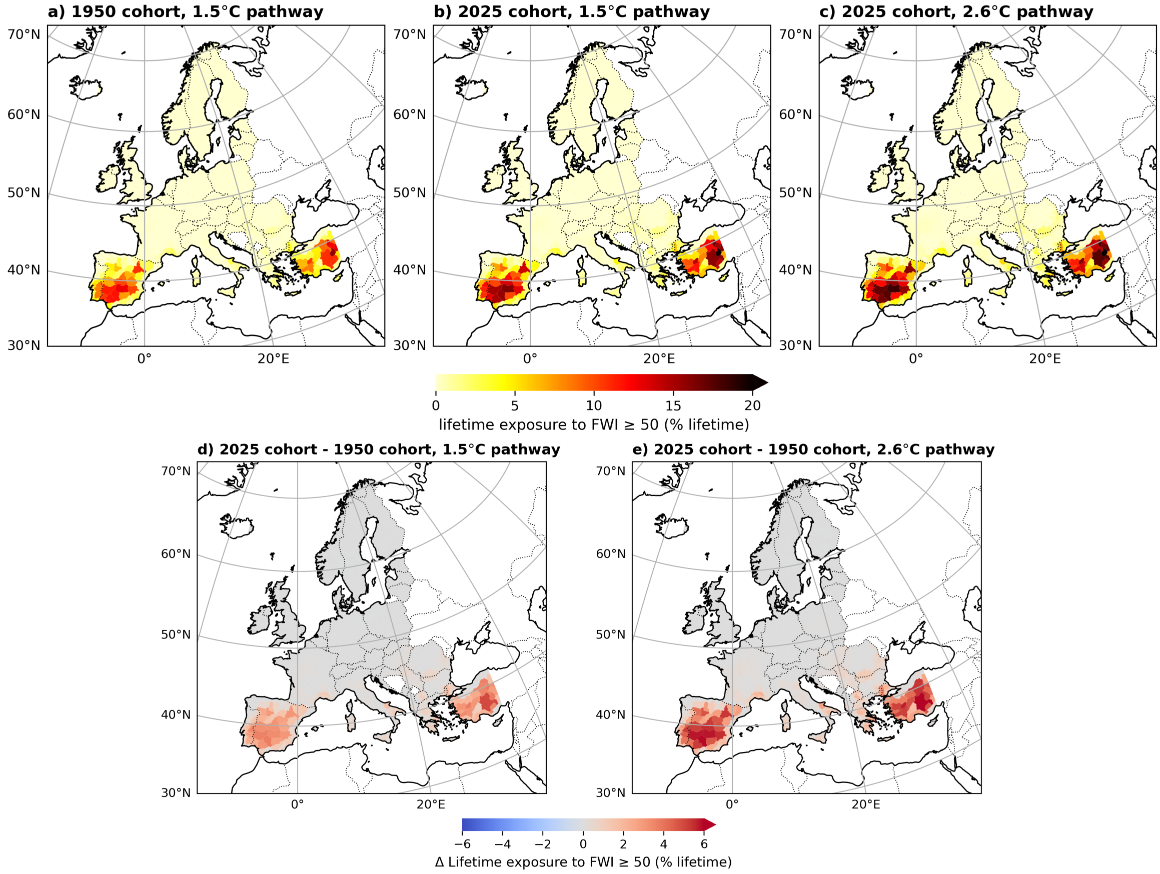

Figure A3. Lifetime exposure to extreme fire danger days based on an absolute magnitude EFFIS threshold (FWI $\geq$ 50) in Europe, at NUTS3 level. Percentage lifetime exposed (a-c) for people born in 1950 (a) and 2025 (b, c) under 1.5°C (a, b) and 2.6°C (c) warming pathways. Change in percentage of lifetime exposed to very high fire danger days between 1950 cohort and 2025 cohort under 1.5°C (d) and 2.6°C (e) warming pathways. Multi-model mean is shown.

Funding
R.P. acknowledges funding from the VUB Research Council EUTOPIA inter-university PhD grant (OZRIFTM12). D.P. acknowledges support from the European Union's HORIZON research and innovation action programme through project "Compound extremes attribution of climate change: towards an operational service" (COMPASS, grant no. 101135481). M.T. acknowledges funding by the Spanish Ministry of Science, Innovation and Universities through the Ramón y Cajal Grant Reference RYC2019-027115-I and through the project ONFIRE, Grant PID2021-123193OB-I00, funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe". Q. L. acknowledges support from the Wellcome Trust (grant no. 309498/Z/24/Z). W.T. acknowledges funding from the European Research Council (ERC) under the Horizon Framework research and innovation programme of the European Union (grant agreement no. 101076909; ERC Consolidator Grant LACRIMA).

Author contributions
Conceptualization: RP, WT. Methodology: RP, WT, JH, MT, QL. Software, visualization, validation: RP, AL, QL. Data curation: RP, JH, DP. Supervision: WT. Investigation, formal analysis, writing—original draft: RP. Writing—review & editing: RP, JH, MT, AL, QL, SPM, DP, WT. Funding acquisition: RP, WT.

Data availability
Dem4cli is publicly available here: https://github.com/rosapietroiusti/dem4cli/. All code necessary to reproduce the analyses and figures is available here: https://github.com/rosapietroiusti/fwi-portugal. All data to reproduce the analyses is publicly available. Fire weather index data is available here: https://zenodo.org/records/12095573. Burned area data are available via the European Forest Fire Information System – EFFIS (https://forest-fire.emergency.copernicus.eu) of the European Commission Joint Research Centre. Life expectancy data and cohort size data are available from the UN Wold Population Prospects 2024 (https://population.un.org/wpp/). Gridded population data are publicly available here: https://doi.org/10.5281/zenodo.17572467. Country shapefiles are publicly available via Natural Earth. European NUTS-level shapefiles are publicly available via Eurostat (https://ec.europa.eu/eurostat/web/gisco/geodata/statistical-units/territorial-units-statistics).

Supplementary data
Supplementary Data tables are associated with this article. These provide (a) additional lifetime exposure to extreme fire weather days per end-of-century degree of warming for each birth year, country, NUTS2 and NUTS3 region in Europe, (b) lifetime exposure to extreme fire weather (number of years) for all birth years under warming pathways leading to 1.5°C, 2°C, 2.6°C end-of-century warming, for all countries, NUTS2 and NUTS3 regions in Europe.

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Supplementary Materials for "High-resolution lifetime exposure to extreme fire weather: projections for Portugal and Europe"

R. Pietroiusti[1], J. Hetzer[2], M. Turco[3], S. Prudencio Montaño[1], A. Laridon[1], Q. Lejeune[1], D. Paprotny[4], 5, W. Thiery[1]

[1]Vrije Universiteit Brussel, Department of Water and Climate, Brussels, Belgium [2]Senckenberg Biodiversity and Climate Research Centre (SBiK-F), Frankfurt am Main, Germany [3]Department of Physics, Regional Campus of International Excellence (CEIR) Campus Mare Nostrum, University of Murcia, Murcia, Spain [4]Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam, Germany [5]Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin, Poland

E-mail: rosa.pietroiusti@vub.be

Supplementary Text

S1 *Dem4cli*: a flexible package to estimate age-specific and lifetime exposure to climate hazards

We present *dem4cli*, a flexible Python package that can be used to combine demographic and climate data to estimate population exposure to any climate hazard, including estimating age-specific and lifetime exposure. This module updates and expands on methodologies developed in previous studies that estimated age-specific and lifetime exposure to climate hazards at the country or gridscale [32, 9, 24]. *Dem4cli* can be used to estimate total population exposure and age-specific population exposure to climate hazards in a specified time window or warming level, and lifetime exposure under different policy-relevant global warming pathways.

Estimating lifetime exposure consists in calculating the number of times individuals born in different locations and years will experience a given climate hazard or impact during their lifetime (Fig. A1). *Dem4cli* allows to estimate lifteime exposure under different stylized global warming trajectories by emulating the regional climate response to these warming pathways, based on a user-provided ensemble of climate or impact model simulations using any user-defined polygon. Built-in functions are available for calculating lifetime exposure at the national level and at subnational levels across Europe based on the NUTS classification, including larger (NUTS2) and smaller (NUTS3) regions. Overall, *dem4cli* facilitates the inclusion of state-of-the-art population and demographic data in climate risk assessments.

Compared to previous lifetime exposure studies [32, 9], with *dem4cli* we (i) update population and demographic data to use the latest available state-of-the-art datasets and (ii) improve the method used to emulate projected changes in climate extreme indicators for different GMT trajectories to better isolate the forced signal. We also incorporate new features which include (iii) the possibility of carrying out lifetime exposure analysis at sub-national administrative levels, (iv) for user-specified regions rather than globally, and (v) using high resolution climate data. Finally, (vi) we add flexibility for users to provide climate hazard datasets coming from any global or regional climate model projection as input, and (vii) provide some ancillary pre-processed package data with the aim of facilitating further analyses by users.

In the following sections, we describe the demographic input data used in *dem4cli*, as well as the exposure estimation methodologies and the new features available in the package.

S1.1 Demographic data

Dem4cli uses country-level data on life expectancy and population size per age group, as well as gridded population data.

Life expectancy data are obtained from the United Nations World Population Prospects 2024 (UNWPP; UNDESA [33]). Data are available per country, expressed as years left to live for exact ages and calendar years. The data consist of reconstructions from 1950 to 2023 and projections from 2024 onward. *Dem4cli* uses life expectancy data for people born from 1950 to 2025, under medium fertility assumptions for the projections. Life expectancy at birth includes the probability of dying in the first years of life, which can substantially shorten life expectancy estimates. Because child mortality rates vary considerably between countries with different income levels, life expectancy at birth is less comparable across countries. Therefore, following Thiery et al. [32] and Grant et al. [9], we estimate life expectancy at birth conditional on survival beyond early childhood. Specifically, we use the best estimate of life expectancy expressed as years remaining at age 5 and add 5 years to obtain life expectancy at birth. Moreover, to account for changes in life expectancy during an individual's lifetime, we convert period life expectancy to cohort life expectancy by adding 6 years, following the lag theory described in [8]. We note that state-of-the-art life expectancy projections do not account for potential impacts of climate change on mortality [10].

Country-level data on population size per age group are obtained from UNWPP 2024 [33] in the standard settings of *dem4cli*. These data are available for exact ages and calendar years, for reconstructions until 2023 and medium fertility assumptions thereafter, and are consistent with the life expectancy data. Alternatively, to explore the effect of different demographic dynamics in the future, users can choose to use reconstructions and projections of country-level population size per age group developed within the framework of the Shared Socioeconomic Pathways (SSPs). In particular, *dem4cli* allows users to explore the implications of SSP1, SSP2 and SSP3, which, respectively, represent low, middle and high fertility scenarios. The SSPs and demographic data are described in K.C. et al. [17], Riahi et al. [28], and K.C. and Lutz [15]. We use the latest available version of the data (v3.2), updated for the Scenario Model Intercomparison Project as part of the Coupled Model Intercomparison Project phase 7 (ScenarioMIP-CMIP7; Van Vuuren et al. [35] and K.C. et al. [17, 16]). We note that the medium fertility projections of UNWPP are broadly comparable with those under SSP2.

Gridded population data used in *dem4cli* are an updated version of the data produced within the COMPASS project and described in Paprotny [21]. These data are derived by spatially disaggregating national population estimates from UNWPP [33] and national SSP-based population projections [35, 17] by using external gridded population datasets. Gridded data are obtained from the Global Human Settlement Layer [14, 23], backward-extended using population from HYDE [19], and extended into the future using population projections from Wang, Meng, and Long [37]. All datasets are harmonized, as described in Paprotny [21]. Compared to the data described in Paprotny [21], in this study national totals in the gridded data were updated to align with those of the most recent SSP v3.2 projections. The data are made available for *dem4cli* users as population counts under SSP1, SSP2 and SSP3, at a spatial resolution of 0.1° and 0.5° on regular grids, allowing users to run lifetime exposure calculations at both resolutions. We note users can also run analyses at lower spatial resolution by coarsening the gridded population data. Under default *dem4cli* settings, gridded population data under the SSP2 scenario are used for projections, as it represents a medium fertility scenario broadly comparable with the UNWPP medium fertility projections used for life expectancy estimates.

S1.2 Country and sub-national borders

Dem4cli allows users to estimate lifetime exposure at country level or at sub-national administrative units. Ancillary package data includes country borders from Natural Earth at a spatial resolution of 10 meters, as well as subnational borders at the coarser NUTS2 and smaller NUTS3 levels for Europe at a spatial resolution of 20 meters [7].

S1.3 Stylized warming trajectories

Lifetime exposure can be calculated for any user-defined global warming pathway, which is used as a target to emulate regional responses from available input climate model simulations under a wider range of policy-relevant warming pathways (See Section S1.4). *Dem4cli* includes built-in functionalities to derive stylized global warming pathways from the Intergovernmental Panel for Climate Change (IPCC) Sixth Assessment Report (AR6) Scenario Explorer archive of global warming timeseries produced by Integrated Assessment Models coupled with Simple Climate Models (IAM-SCMs) [2]. This built-in functionality follows the methodology in Grant et al. [9], using the full Scenario Explorer archive to select a subset of warming pathways that are representative of different levels of peak warming. These are then linearly interpolated to obtain a set of stylized warming trajectories that reach user-defined regularly-spaced warming levels in 2100.

In this study, and in the default *dem4cli* configuration, we define 21 stylized warming trajectories that in 2100 reach GMT temperatures ranging from 1.5°C to 3.5°C at regular 0.1°C intervals (Fig. A1). The Scenario Explorer archive provides projections for the period 2000–2100. For the historical period 1950–1999, we use the multi-dataset global mean surface temperature (GMST) observational time series assessed in AR6 [12, 13, 18]. Prior to analysis, this time series is smoothed using a 21-year rolling mean to remove natural variability and ensure consistency with the Scenario Explorer projections. GMT time series from climate models correspond to global surface air temperature (GSAT), whereas observational estimates are based on GMST (a blend of sea surface and land air temperatures). However, AR6 IAM–SCM projections were aligned to match assessed observed warming in the historical period 1995–2014, ensuring consistency between these time series [18, 13, 12]. We therefore refer to both generically as GMT, expressed as anomalies relative to 1850–1900.

Finally, *dem4cli* includes options to extend stylized warming pathways past 2100 to span the full life expectancy of people born in 2025. By default, in *dem4cli* this is done by extending the linear trend of the last 10 years of data, but options for alternative post-2100 assumptions are available.

Constructing these stylized trajectories allows us to quantify how lifetime exposure changes for incremental increases in end-of-century global warming and to compare outcomes across different warming pathways. The selected end-of-century temperature range in this study, from 1.5°C to 3.5°C, represents plausible warming outcomes under different policy and climate sensitivity scenarios [34, 6]. Restricting our upper bound to 3.5°C ensures that enough input simulations are available to emulate higher warming outcomes, thus limiting sampling artefacts between warming trajectories. Nonetheless, we note that higher warming outcomes are possible under unambitious policy and high climate sensitivity scenarios [34]. We thus note that our results could be too conservative to estimate the full range of possible outcomes under such scenarios.

S1.4 Remapping input simulations to emulate local impacts in stylized global warming trajectories

To emulate the regional climate response to policy-relevant stylized global warming trajectories, input model simulations are remapped in *dem4cli* using a GMT-mapping approach [32, 9]. In this study, the input model simulations are annual counts of exceedances of the FWI thresholds obtained from GCMs and described in Section 2.1. Users can provide annual data from any climate or impact model simulation, representing the annual count of event occurrences at each grid cell, or binary annual occurrence data. The corresponding annual GMT time series of the input climate model simulation is also necessary, and can be either provided by the user or obtained from the ancillary package data provided with *dem4cli* (see below).

Using a GMT-mapping emulation approach consists in matching global warming in input simulations with global warming in target trajectories [32, 9]. This assumes that the local forced response of a climate indicator of interest to global climate change mostly depends on the global warming level. This is an assumption which is well verified in many cases, including for fire weather [11, 26].

Prior to remapping simulations, the original GMT trajectories of the input model simulations are smoothed, by default with a 21-year moving average, or with a different window size defined by users. Users also have the option to align the GMT timeseries of input model simulations on a common baseline period and adding a common anomaly value, for users working with bias-adjusted climate hazard data, with GMT input timeseries derived from the original simulations prior to bias adjustment.

Then, the GMT timeseries of the input simulations are matched to the target stylized GMT trajectories, to obtain a GMT-mapping 'recipe'. Namely, for each year in a target trajectory we identify the year in the smoothed GMT anomaly timeseries of a given input simulation that has the closest GMT anomaly value. This is repeated for each input simulation, so that we obtain as many lists of pairs of years (i.e., remapping recipes) as input simulations are available. This procedure is applied separately for each input simulation and each GMT anomaly stylised trajectory. We then apply the obtained recipe to remap the regional climate hazard or impact data from each input simulation. Concretely, for each year in a given target trajectory we reconstruct the spatially explicit changes in the indicator of interest by selecting its values in an input simulation, for the corresponding year indicated by the recipe. We apply an exclusion criteria, whereby we only use an input simulation to remap a given target trajectory if the absolute difference in GMT value never exceeds 0.2°C, or a different user-specified value. This ensures that low-warming SSP-RCP simulations are not used to emulate high-warming stylized pathways, which include global warming values never reached in the original input simulations. This remapping approach implies that the effective ensemble size is generally larger for colder target stylized trajectories (e.g., 1.5°C), since low-warming input simulations (e.g., SSP1–RCP2.6) do not reach the high GMT levels associated with warmer stylized trajectories (e.g., 3.5°C).

We note that prior to remapping, the input climate hazard data, already preprocessed to annual resolution (e.g., annual count of exceedances), is also smoothed, by default with a 21-year moving average, although this can be modified by users. This option is new in *dem4cli* relative to previous studies [32, 9]. We implement this to remove internal variability and focus on the forced climate response, and find that this improves the robustness of emulation results. Since we study exposure over the lifetimes of individuals, it is justified to focus on the forced response, as year-to-year variability is smoothed out when aggregating over lifetimes. This is similar to emulation approaches applied in RIME [3] and RIME-X [30]. Nonetheless, we note that this approach does not allow us to focus on exceptional or record-breaking individual years, where interannual variability is an important factor. Studying extreme years would require emulation approaches that explicitly reproduce interannual variability, such as STITCHES [31] or MESMER [25, 20, 1], and could be an avenue for further lifetime exposure research.

All functions necessary to carry out the GMT-mapping emulation are available in *dem4cli*. We provide options for users, including the possibility to specify the size of the smoothing window applied to GMT timeseries and the climate hazard data, to use different target stylized global warming trajectories, and to provide any input climate or hazard data. In the ancillary data we additionally provide pre-processed annual GMT timeseries from one ensemble member each of all models included in the CMIP6 archive, to facilitate users running their own analyses.

S1.5 Lifetime exposure calculation across stylized warming trajectories

We estimate the lifetime exposure of an average member of the population of a given region under different stylized trajectories. Regions can be any user-defined polygons in shapefile format. *Dem4cli* includes built-in functionalities to calculate exposure at country scale globally and at NUTS2 and NUTS3 subnational level for Europe.

For each input simulation, we first aggregate the hazard or impact data spatially. Specifically, we estimate the exposure of an average individual in each region for each model year by calculating a population-weighted average of the climate hazard data. This approach accounts for the spatial distribution of people within a region by weighting climate hazard values by population exposure, and also captures temporal changes in population distribution over time. The resulting population-weighted average represents the exposure experienced by an average individual in the region in a given year.

Then, for each birth year and region, we aggregate the exposure of an average individual across their lifetime. To this end, we sum the exposure from their year of birth until their year of death, accounting for fractional exposure in the last year of life (as life expectancy is a decimal number). Overall, the lifetime exposure methodology allows for comparison of expected exposure to climate hazards across locations, birth cohorts, and warming pathways, at national and sub-national scales.

S1.6 Additional functionalities available in dem4cli

Dem4cli additionally allows to process results as area-weighted averages for each region, instead of computing population exposure. These area-weighted time series can also be remapped following the GMT-mapping method. If the input data is provided as annual exceedance counts, this results in a time series of the average number of events experienced annually in the region under the target warming trajectories. If the input data is provided as annual binary occurrence data, this results in a time series of the fraction of land exposed to a given hazard in the region.

Moreover, while not applied in this study, *dem4cli* can also be used to estimate age-specific exposure to climate hazards for a given time-window or warming level, as in Pietroiusti et al. [24]. In this case, we assume that age groups follow the spatial distribution of the total population within each country. Specifically, the national fraction of the population in each age group is applied uniformly across all grid cells within the country at each time step. We do not account for sub-national detail on age structures as granular data is unavailable for the full time period 1950-2100, but note that this could be an avenue for further development of *dem4cli*. Age-specific exposure can then be calculated at the grid scale and aggregated globally, as in Pietroiusti et al. [24], or for user-defined regions.

S2 Decomposing the influence of climate change and increasing life expectancy on exposure differences

We find that longer lifetime exposure times are primarily driven by climate change, with a smaller contribution from increased lifespan. We estimate what part of the higher exposure of young people is due to life expectancy increases for Portugal by holding exposure constant to the average exposure in the period 1950-1970, corresponding to approximately 14 (12-16) extreme fire weather days per year (Fig. 2a), and allowing life expectancy to vary. We find increases in life expectancy are responsible for 190 (163-217) days of additional exposure of the 2025 birth year compared to the 1950 birth year. Climate change since 1950-1970 is responsible for the remaining difference in exposure, corresponding to 1.7 (1.0-2.4) years of additional extreme fire weather exposure in a 1.5°C scenario, 2.4 (1.4-3.3) years in a 2°C scenario, and 2.6 (1.6-3.6) in a 2.6°C scenario, for the 2025 birth year compared to the 1950 birth year. This corresponds to 74% (64-84%) of the difference in lifetime exposure in a 1.5°C scenario, 79% (69-89%) in a 2°C scenario, and 82% (77-88%) in a 2.6°C scenario. Life expectancy increases are responsible for the remaining 18-26% of the difference across scenarios.

We thus find that climate change is the more important driver of the disproportionate exposure of younger generations, and is responsible for over three fourths of the difference in exposure between generations across all assessed scenarios. However, this estimate is conservative because it does not capture the full influence of climate change since pre-industrial times, as the frequency of extreme fire weather days in 1950-1970 was already influenced by anthropogenic warming.

S3 Supplementary analysis on fire weather and burned area relationship in Portugal

We conduct a supplementary analysis to characterize the relationship between burned area and fire weather in Portugal. Burned area data for Portugal are obtained from the EFFIS database for the period 1980-2020 at the subnational NUTS3 level (Nomenclature of Territorial Units for Statistics, an EU regional classification) [29]. These are data reported by national authorities to EFFIS and thus exclude small fires that are included in satellite-derived burned area datasets. We identify the temporal and spatial distribution of the years with the highest burned area in the country at NUTS2 and NUTS3 level, on average in the 1980-2020 period and in the high-impact 2017 year [27].

Burned area temporal patterns at the national scale are then compared with annual average FWI during the fire season (June-September) calculated from ERA5 reanalysis data [36] at the national level in Portugal. ERA5-derived data are used for this analysis these are available for the same period as the burned area data.

While fire weather by design only reflects the meteorological risk of fire, we note through this supplementary analysis that there is a good temporal correlation between summertime FWI and burned area over Portugal, especially in years with high fire activity (Fig. S3). We therefore conclude that high FWI values, whether defined in relative or absolute terms, are a relevant indication of fire danger over Portugal, in agreement with previous literature [5].

From the analysis of burned area data we find that while the Southern Alentejo region in Portugal experiences the highest absolute fire weather values due to a drier and hotter climate (Fig. S1) it is not the region most affected by wildfires historically, which instead mostly affect the more forested Central and Northern regions [5] (Fig. S4a-b). This has been linked to a more agricultural land cover, a drier climate that limits fuel build-up [22, 4], forest types resistant to fires and populations being more concentrated in urban centers, which reduces ignition probabilities [5] in the Southern parts of Portugal, relative to the North and Northeastern parts of the country.

Supplementary Figures

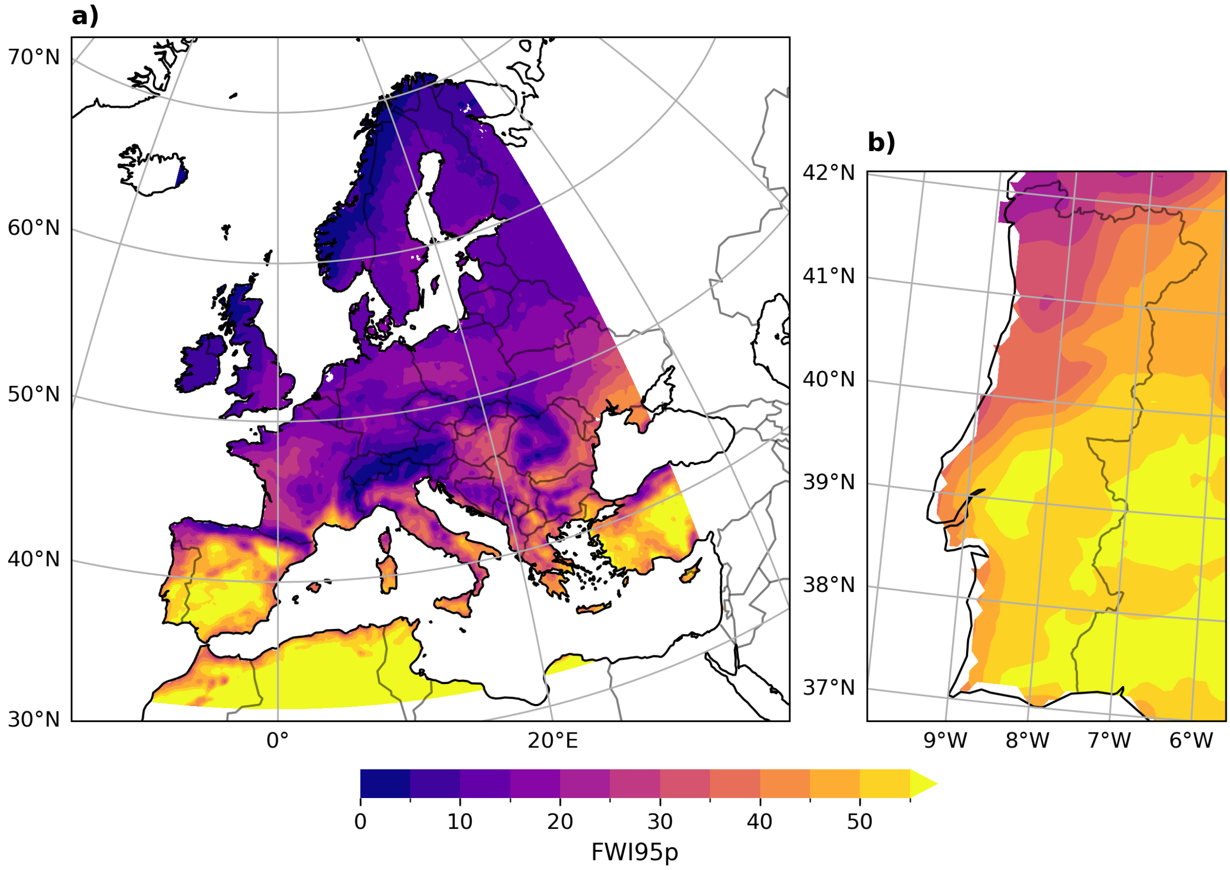

Figure S1. Absolute value of FWI corresponding to the 95th percentile from the 1985-2014 reference period (FWI95p), computed from ERA5-Land in Europe (a) and Portugal (b).

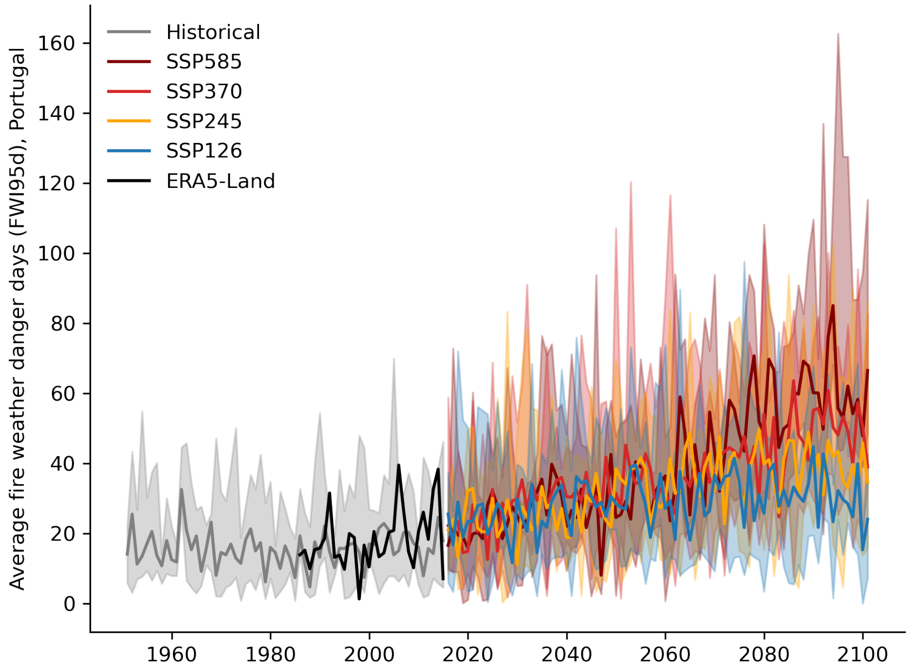

Figure S2. Average number of days crossing the 95th percentile of FWI per year (FWI95d) in Portugal, from bias-adjusted and downscaled GCM simulations used in this study, forced under historical, SSP126, SSP245, SSP370 and SSP585 experiments, and from ERA5-Land reanalysis. Multi-model median and range is shown.

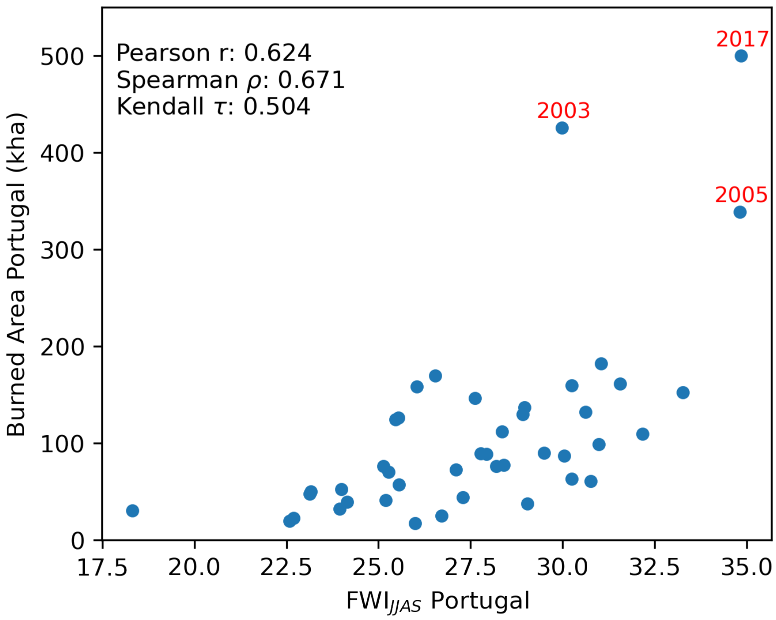

Figure S3. Correlation between total yearly burned area and mean summer (June-September) FWI in Portugal, for the period 1980-2020, with top three burned area years highlighted. Burned area data for Portugal are obtained from the EFFIS country-reported database for the period 1980-2020 at the subnational NUTS3 level [29]. FWI data is from ERA5 reanalysis [36]. Correlation values shown are Pearson's r, Spearman's ρ and Kendall's τ.

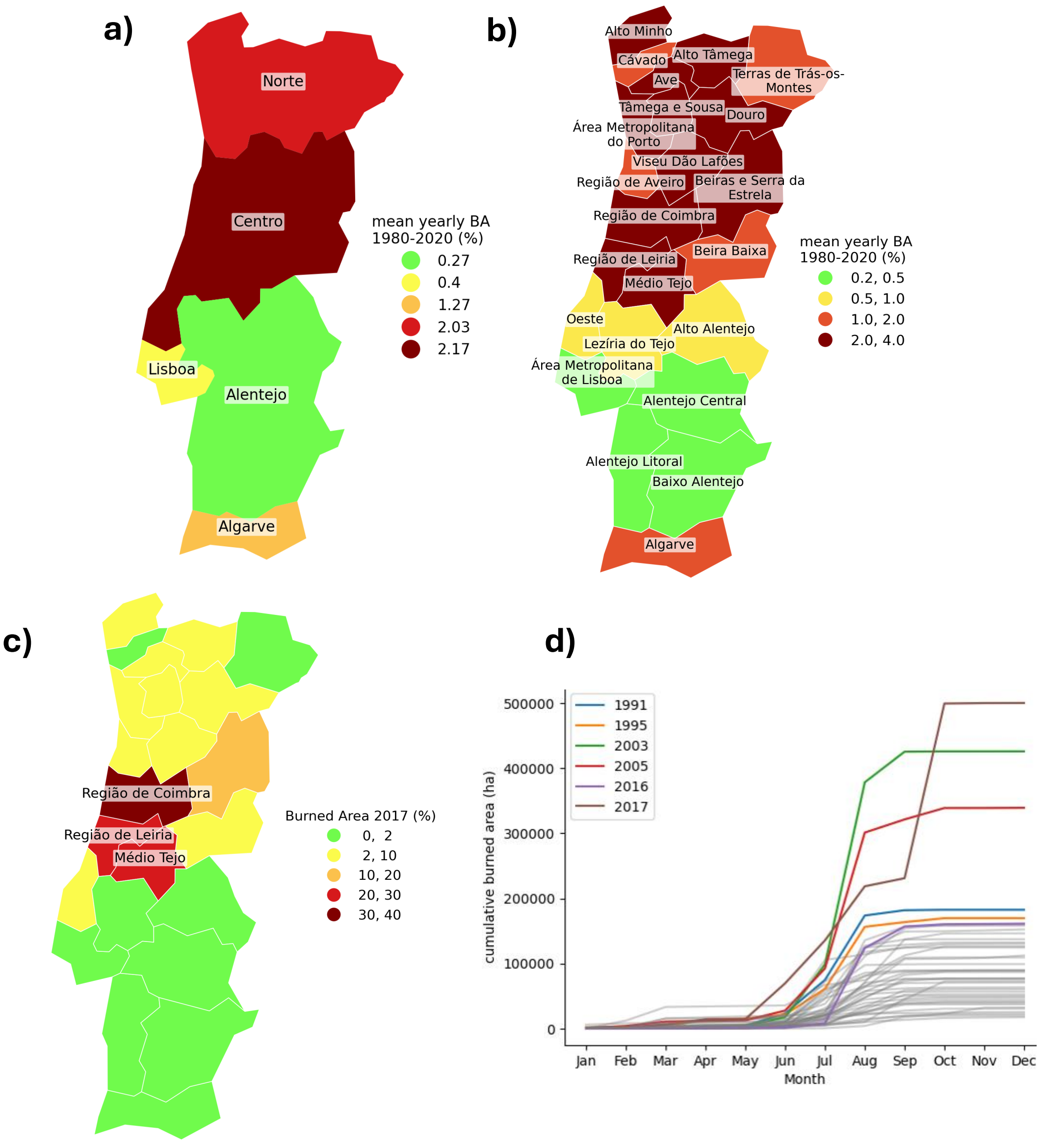

Figure S4. Burned area spatial patterns in Portugal. Average percentage of burned area (BA) in Portugal in the period 1980-2020 in each NUTS2 region (a) and NUTS3 region (b). (c) Percentage of BA in 2017 in each NUTS3 region, with top three regions highlighted. (d) Cumulative BA in Portugal for each year 1980-2020, with top five years highlighted. BA data for Portugal are obtained from the EFFIS database for the period 1980-2020 at the subnational NUTS3 level [29].

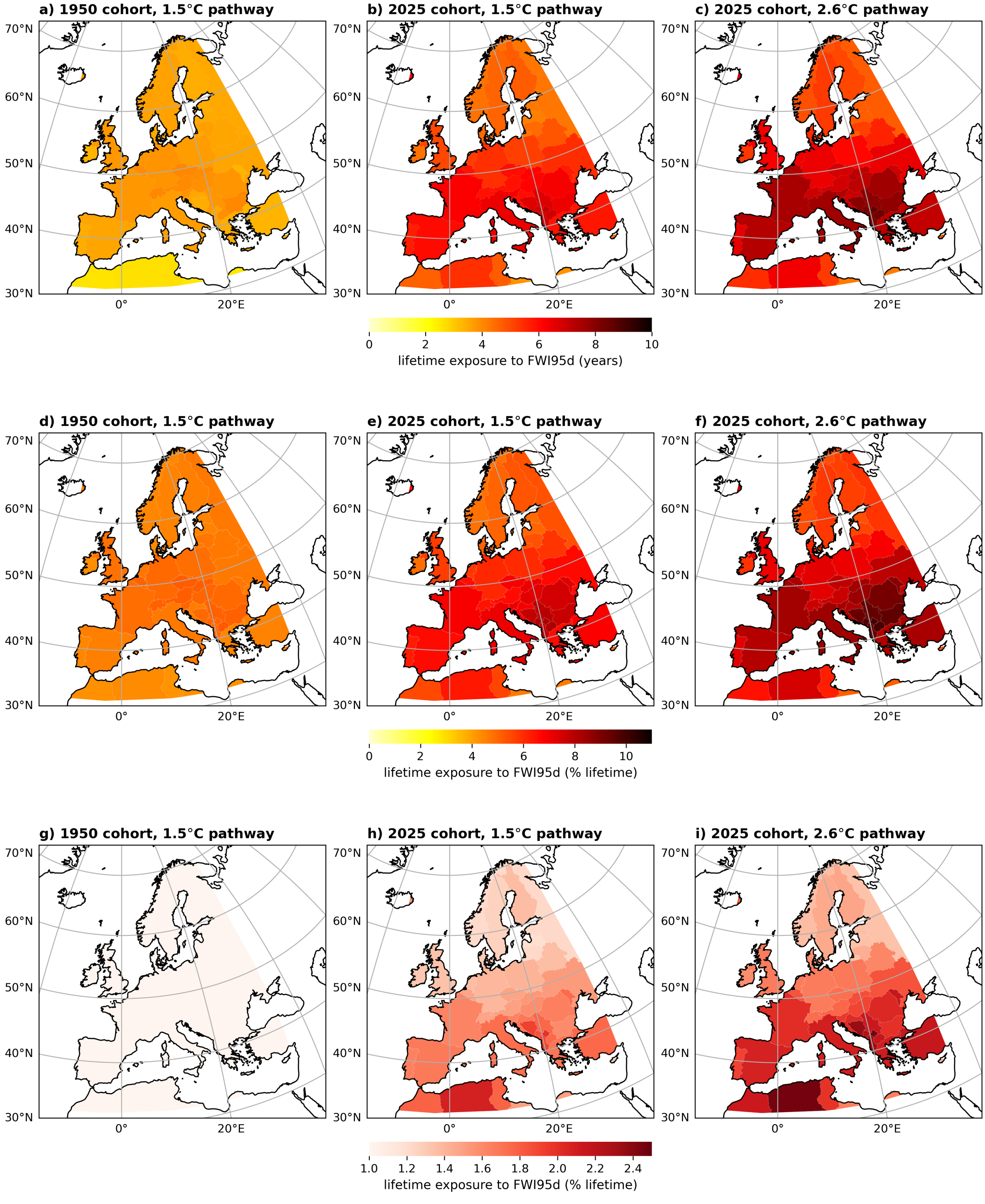

Figure S5. As Fig. 1, at the country level. Lifetime exposure to extreme fire weather days (FWI95d) in Europe. Number of years exposed (a-c), percentage lifetime exposed (d-f) and exposure multiplication factors relative to the 1950 birth year (g-i), for people born in 1950 (a, d, g) and 2025 (b, c, e, f, h, i) under 1.5°C (a, b, d, e) and 2.6°C (c, f) warming pathways. Multi-model mean is shown.

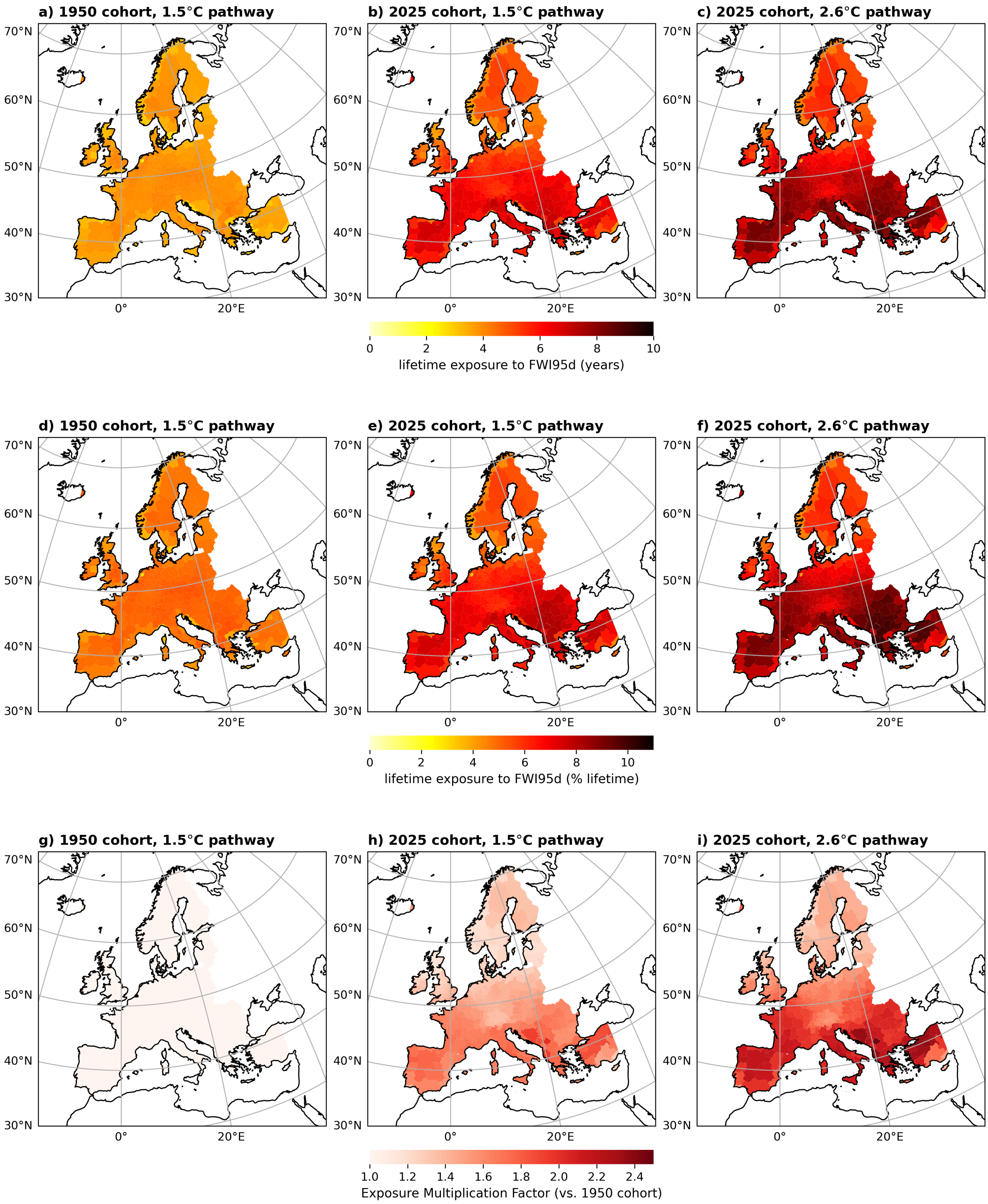

Figure S6. As Fig. 1, at the NUTS2 level. Lifetime exposure to extreme fire weather days (FWI95d) in Europe. Number of years exposed (a-c), percentage lifetime exposed (d-f) and exposure multiplication factors relative to the 1950 birth year (g-i), for people born in 1950 (a, d, g) and 2025 (b, c, e, f, h, i) under 1.5°C (a, b, d, e) and 2.6°C (c, f) warming pathways. Multi-model mean is shown.

Supplementary Tables

Table S1. Additional days of extreme fire weather days (FWI95d) experienced per degree of end-of-century warming, in Portugal at NUTS3 level, for selected birth years. Best estimate ± 95% confidence interval. For results for all birth years and countries see Supplementary Data Excel files.

Region	1990	1999	2000	2010	2012	2025
Alto Minho (PT111)	128 (± 11)	202 (± 13)	208 (± 13)	313 (± 18)	335 (± 19)	501 (± 24)
Cávado (PT112)	123 (± 10)	192 (± 13)	198 (± 13)	297 (± 17)	317 (± 18)	474 (± 24)
Ave (PT119)	135 (± 12)	210 (± 14)	216 (± 14)	324 (± 18)	346 (± 19)	515 (± 25)
Área Metropolitana do Porto (PT11A)	99 (± 10)	153 (± 13)	157 (± 13)	238 (± 17)	255 (± 18)	388 (± 25)
Alto Tâmega (PT11B)	140 (± 13)	223 (± 15)	230 (± 15)	350 (± 19)	375 (± 20)	559 (± 23)
Tâmega e Sousa (PT11C)	127 (± 12)	196 (± 14)	202 (± 14)	305 (± 18)	326 (± 19)	490 (± 25)
Douro (PT11D)	127 (± 13)	202 (± 15)	208 (± 15)	319 (± 19)	341 (± 19)	514 (± 23)
Terras de Trás-os-Montes (PT11E)	132 (± 12)	214 (± 14)	221 (± 14)	341 (± 17)	365 (± 18)	549 (± 21)
Algarve (PT150)	44 (± 8)	60 (± 11)	62 (± 11)	88 (± 13)	94 (± 13)	137 (± 15)
Oeste (PT16B)	29 (± 8)	43 (± 10)	45 (± 10)	71 (± 13)	78 (± 14)	132 (± 18)
Região de Aveiro (PT16D)	76 (± 10)	116 (± 12)	119 (± 13)	182 (± 17)	195 (± 18)	305 (± 26)
Região de Coimbra (PT16E)	70 (± 11)	108 (± 14)	111 (± 14)	174 (± 19)	187 (± 20)	298 (± 27)
Região de Leiria (PT16F)	53 (± 13)	82 (± 16)	85 (± 16)	136 (± 21)	148 (± 22)	244 (± 28)
Viseu Dão Lafões (PT16G)	108 (± 13)	167 (± 15)	172 (± 16)	264 (± 19)	283 (± 20)	433 (± 25)
Beira Baixa (PT16H)	102 (± 15)	158 (± 19)	163 (± 19)	252 (± 23)	270 (± 24)	413 (± 27)
Médio Tejo (PT16I)	62 (± 13)	95 (± 17)	98 (± 17)	158 (± 21)	172 (± 22)	280 (± 28)
Beiras e Serra da Estrela (PT16J)	117 (± 14)	183 (± 17)	188 (± 17)	288 (± 20)	309 (± 21)	466 (± 23)
Área Metropolitana de Lisboa (PT170)	36 (± 9)	49 (± 12)	50 (± 12)	76 (± 15)	82 (± 16)	136 (± 20)
Alentejo Litoral (PT181)	46 (± 11)	66 (± 14)	68 (± 14)	103 (± 17)	111 (± 17)	173 (± 20)
Baixo Alentejo (PT184)	74 (± 14)	113 (± 18)	116 (± 19)	178 (± 22)	191 (± 22)	291 (± 24)
Lezíria do Tejo (PT185)	45 (± 11)	69 (± 14)	71 (± 14)	115 (± 17)	125 (± 18)	208 (± 24)
Alto Alentejo (PT186)	87 (± 17)	133 (± 21)	137 (± 21)	214 (± 25)	231 (± 26)	358 (± 30)
Alentejo Central (PT187)	73 (± 16)	112 (± 20)	115 (± 20)	181 (± 23)	196 (± 24)	307 (± 27)

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