

Anthropogenic warming shifted southwestern Europe into fire-weather conditions exceeding operational suppression thresholds

Marc Lemus-Canovas

`marc.lemus@bsc.es`

Barcelona Supercomputing Center <https://orcid.org/0000-0002-0925-3827>

Victor Resco de Dios

University of Lleida <https://orcid.org/0000-0002-5721-1656>

Katherine Grayson

Barcelona Supercomputing Center

Matias Olmo

Barcelona Supercomputing Center

Diego A. Campos

Barcelona Supercomputing Center

Irene Fidalgo

Barcelona Supercomputing Center

Carolyn Daher

Barcelona Supercomputing Center

Francisco Doblas-Reyes

BSC <https://orcid.org/0000-0002-6622-4280>

Article

Keywords:

Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11052030/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: There is **NO** Competing Interest.

Anthropogenic warming shifted southwestern Europe into fire-weather conditions exceeding operational suppression thresholds

Marc Lemus-Canovas¹, Victor Resco De Dios², Katherine Grayson¹, Matías Olmo¹, Diego Campos¹, Irene Fidalgo-Castanon¹, Carolyn Daher¹ & Francisco J. Doblas-Reyes^{1,3}

¹Earth Sciences Department, Barcelona Supercomputing Center (BSC), Barcelona, Spain.

²Department of Forest and Agricultural Science and Engineering, University of Lleida, Lleida, Spain.

³Institució Catalana de Recerca i Estudis Avançats (ICREA), Barcelona, Spain

Abstract

Anthropogenic climate change is increasing wildfire hazard worldwide, however how this growing risk will impact suppression efforts remains poorly quantified. Existing attribution studies have largely focused on meteorological fire danger, without assessing whether warming shifts fire-weather conditions beyond operational thresholds at which wildfire suppression becomes progressively ineffective. Here we combine global kilometer-scale simulations, constrained by spectral nudging to reproduce observed large-scale atmospheric circulation under 1950-like climate (Counterfactual), current climate (Factual) and +2 K climate states, with empirical relationships between the Fire Weather Index, potential fireline intensity and expected operational suppression categories to quantify how anthropogenic warming altered the August 2025 wildfire crisis in the northwestern Iberian Peninsula. August 2025 simultaneously recorded the highest fire weather index values and largest burned area of the 1985–2025 record across the study region. We find that, relative to a 1950-like climate, present-day warming increased the spatial extent and persistence of fire-weather conditions associated with extreme wildfire events that render suppression virtually impossible ($>10,000 \text{ kW m}^{-1}$), with the exposed area increasing by 0.47 Mha (3.9%), while a +2 °C warmer climate further increased it by 0.92 Mha (7.6%). Consequently, exposure of protected areas, population and the wildland–urban interface to well beyond suppression capacity fire-weather conditions increased substantially. Our findings demonstrate that anthropogenic climate change is not simply increasing wildfire hazard, but progressively increasing the likelihood of the extreme wildfire events that significantly reduce opportunities for effective suppression.

Introduction

Anthropogenic climate change is increasing wildfire hazard across many fire-prone regions through hotter temperatures, more frequent droughts and increasingly severe fire weather (Jain et al., 2022; Jones et al., 2022; Liu et al., 2022). Yet wildfire disasters emerge not simply because weather favours ignition success and fire spread, but because fire behaviour exceeds the operational capacity of suppression systems. Wildfire suppression is inherently governed by operational thresholds: as fireline intensity increases, opportunities for successful direct attack rapidly diminish, containment probability declines, and wildfire impacts can escalate sharply (Alexander, 2002; Plucinski, 2019; Tedim et al., 2018; Castellnou et al., 2019). Recent studies have further shown that relatively modest increases in fire weather can produce disproportionately large increases in escaped fires and burned area once these thresholds are exceeded (Wotton et al., 2017; Reimer et al., 2019). Consequently, a key challenge is no longer simply determining whether anthropogenic climate change is increasing fire danger, but whether it is progressively shifting landscapes towards fire-weather conditions associated with extreme wildfire events that burn beyond suppression capacity (i.e., typically when fireline intensity exceeds $10,000 \text{ kW m}^{-1}$ and cannot be extinguished through human intervention (Tedim et al. 2018)).

Over the last decade, event attribution has demonstrated that anthropogenic climate change has increased the likelihood and intensity of extreme fire weather across many regions of the world (Kirchmeier-Young et al., 2019; Wixson & Cooley, 2023). These studies have largely followed two complementary approaches: risk-based attribution, which quantifies how climate change alters the likelihood or intensity of an observed event, and climate storylines, which explore how a specific event could unfold under alternative climate states (Shepherd et al., 2018). Recent risk-based attribution studies, for example, concluded that human-induced warming greatly increased the intensity of the exceptional fire-weather conditions experienced during the 2025 southwestern European wildfire crisis (Keeping et al., 2026). Among the different approaches used to construct physical climate storylines, spectral nudging has emerged as a useful technique for generating dynamically consistent simulations (Van Garderen et al., 2021; Sánchez-Benitez et al., 2022; John et al., 2026). By constraining the large-scale atmospheric circulation towards reanalysis while allowing thermodynamic processes and mesoscale variability to evolve freely, spectral nudging allows the thermodynamic contribution of anthropogenic warming to be isolated while preserving the dynamical characteristics of the event. This provides a physically consistent basis for assessing how climate change may alter event-specific impacts and risks, while enabling “what-if” experiments that explore how the same event could unfold under different plausible climate states, providing information directly relevant to adaptation and risk management. Applying spectrally nudged storylines to the Mediterranean summer of 2025, van Garderen et al. (2026) showed that anthropogenic warming robustly increased the Fire Weather Index (FWI) across the Mediterranean, primarily through increased temperature and, regionally, reduced relative humidity and precipitation. The recent development of kilometre-scale, coupled global IFS–FESOM simulations within the European Union’s Destination Earth initiative (DestinE ClimateDT; Doblas-Reyes et al., 2026; Hoffmann et al., 2023; Wedi et al., 2022) provides a new opportunity to apply such dynamically consistent storylines across large domains under counterfactual (1950-like climate), present-day and warmer climate states (John et al., 2026).

Despite these advances, an important gap remains between climate attribution and operational wildfire management. Existing attribution studies have almost exclusively quantified changes in meteorological fire hazard, typically represented by the Canadian FWI. Although FWI effectively

characterizes surface meteorological fire danger, it does not linearly translate into the operational constraints faced by wildfire suppression efforts. Fireline intensity (FLI), in contrast, is widely used as an operational indicator of suppression difficulty because increasing fire intensity progressively constrains suppression opportunities (Alexander, 2002; Alexander & Cruz, 2012). In practice, empirical relationships between FWI and potential FLI enable meteorological fire danger to be translated into operationally meaningful suppression conditions (Palheiro et al., 2006; Tedim et al., 2018). Recent works further indicate that climate change is progressively increasing the frequency of conditions under which suppression becomes less effective, contributing to more escaped fires, longer-duration events and growing pressure on firefighting resources (Moreira et al., 2020; Tymstra et al., 2020). These changes have implications beyond fire suppression itself, as increasingly severe fire conditions can expose larger areas of human settlements, protected ecosystems and the wildland–urban interface (WUI) to potentially damaging fire behaviour. Previous studies have documented substantial wildfire exposure of communities and protected areas under extreme fire weather (Alcasena et al., 2021; Rodrigues et al., 2022; Resco de Dios et al., 2025) and projected increasing fire intensity across fire-prone WUI under global warming (Cunningham et al., 2025). Moreover, human exposure can increase even where burned area remains stable or declines, emphasizing that changes in fire hazard alone do not fully capture their societal consequences (Seydi et al., 2025; Torres-Vázquez et al., 2026). However, no attribution study has explicitly combined counterfactual climate simulations, operational suppression thresholds, and spatially explicit exposure to determine how anthropogenic warming changes the number of people and extent of ecosystems and WUI exposed to operationally critical fire-weather conditions.

The unprecedented wildfire crisis that affected southwestern Europe during the summer of 2025 provides an exceptional test bed to address this challenge. By the end of August, nearly one million hectares had burned across Europe, representing the largest seasonal burned area on record (Fig. 1a), with more than half concentrated within only ~2% of the European Union land area in the north-western Iberian Peninsula (Sanchez-Hernandez et al., 2026). Multiple large wildfires developed simultaneously under exceptional meteorological conditions, causing fatalities, mass evacuations, severe ecological impacts and the first activation of the European Civil Protection Mechanism in Spain (DGPCCE, 2026). Studies published in the aftermath of the event have characterised it as an indicator of ongoing shifts in European fire regimes, associated with exceptional fire weather, rapid fuel desiccation, flash-drought development, widespread nocturnal fire activity and multiple simultaneous large fires that challenged suppression operations (Sánchez-Hernández et al., 2026; Resco de Dios et al., 2026). Complementary analyses further highlighted the combined influence of meteorological conditions, vegetation characteristics and fuel continuity in explaining the exceptional burned area and fire severity across the north-western Iberian Peninsula (Beltrán-Marcos et al., 2026; Quintero et al., 2026; Novo & Fernandez, 2026). Together, these studies provide a comprehensive understanding of the climatic and environmental drivers of the event, but they leave unanswered a fundamental operational question: did anthropogenic warming push large areas into fire-weather conditions associated with fireline intensities exceeding operational suppression thresholds?

Here we address this question by combining kilometre-scale spectrally nudged climate storylines with high-resolution fire-weather analyses and empirical relationships between FWI, potential fireline intensity and operational suppression thresholds. We first quantify how anthropogenic warming altered the spatial extent and persistence of fire-weather conditions corresponding to progressively higher operational fireline-intensity thresholds. Secondly, we assess how these

changes modified the exposure of populations, protected areas, and the WUI. Our framework extends climate attribution beyond conventional hazard metrics and provides a practical basis for understanding how global warming is reshaping wildfire risk and informing adaptation in an era of increasingly extreme wildfire activity.

Results

The August 2025 wildfire crisis occurred under unprecedented fire-weather conditions

The August 2025 wildfire episode in northwestern Iberian Peninsula (NW-IP) was exceptional in both fire-weather severity and burned area. August 2025 recorded simultaneously the highest monthly mean FWI and the largest August burned area within the NW-IP domain over the 1985–2025 record (Fig. 1a), highlighting the concurrence of unprecedented fire-weather conditions and wildfire activity. By the end of August, cumulative burned area across Spain and Portugal exceeded half of the total area burned across Europe in 2025 (Fig. 1a, inset), illustrating the disproportionate contribution of the Iberian Peninsula to the European fire season. The exceptional fire-weather conditions were also spatially coherent with wildfire occurrence: August 2025 FWI ranked first across much of the NW-IP domain relative to the 1985–2025 record, with the highest-ranked areas closely overlapping the concentration of large fire perimeters (Fig. 1b). Notably, all megafires (>10,000 ha) ignited between 8th and 15th August occurred within or in close correspondence with areas experiencing the highest FWI values during summer 2025 across the NW-IP domain ([Supplementary Fig. 1](#)).

The exceptional fire activity coincided with widespread anomalies in the meteorological and land-surface conditions conducive to fire weather (Fig. 1c–f). The episode was characterized by enhanced atmospheric evaporative demand, with positive vapour pressure deficit (VPD) anomalies reaching +0.4 (std: ± 0.2) kPa, together with substantial deficits in root-zone soil moisture (RZSM) ($-0.02 \pm 0.02 \text{ m}^3\text{m}^{-3}$) and accumulated summer (JJA) precipitation across much of the affected region ($-43.0 \pm 25.3 \text{ mm}$). These abovementioned anomalies were consistent with the exceptionally high fire weather, with FWI exceeding the 1985–2024 climatological mean by up to +9.2 (± 3.4) units across the NW-IP domain (Fig. 1f).

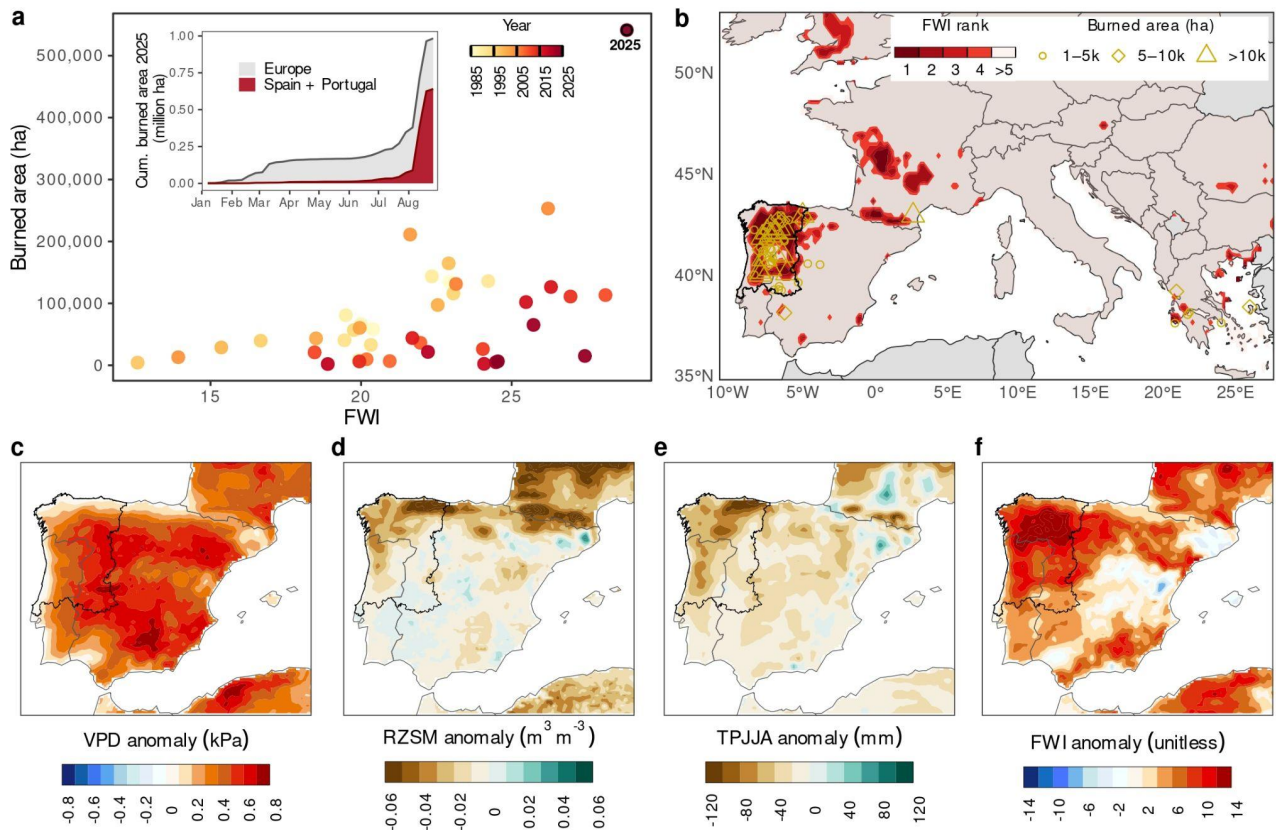


Figure 1 | Exceptional fire-weather conditions during the August 2025 northwestern Iberian wildfire crisis. (a) Relationship between August burned area and August-mean Fire Weather Index (FWI) across the NW-IP domain (darkest domain in **b**) for 1985–2025, with August 2025 highlighted in bold contour. The inset shows the 2025 cumulative burned area until the end of August across Spain and Portugal compared with the corresponding European Union total. **(b)** Spatial rank of August-mean FWI in 2025 relative to August values over 1985–2025, overlaid with August 2025 fire perimeters scaled according to burned area. **(c–f)** Mean anomalies in vapor pressure deficit (VPD), 10-m wind speed, root-zone soil moisture (RZSM), total precipitation of June, July and August (TPJJA), and FWI during August 2025 relative to the 1985–2024 climatological mean.

Warming increased the extent and persistence of fire weather beyond suppression capacity

To quantify how anthropogenic warming altered the operational severity of the August 2025 wildfire episode, we first characterized changes in August daily maximum FWI—corresponding to August 15th, See [Supplementary Fig. 1](#)—using the standard EFFIS fire-danger classes (Low to Very Extreme; Fig. 2a). We then translated FWI into potential fireline intensity (FLI) using an empirical FWI–FLI relationship and classified the resulting values into operational suppression-difficulty categories following [Tedim et al. \(2018\)](#): fairly easy ($<500 \text{ kW m}^{-1}$), moderately difficult ($500\text{--}2,000 \text{ kW m}^{-1}$), very difficult ($2,000\text{--}10,000 \text{ kW m}^{-1}$), virtually ineffective ($10,000\text{--}30,000 \text{ kW m}^{-1}$) and ineffective ($>30,000 \text{ kW m}^{-1}$) (see [Materials and Methods](#)). The FWI classes and FLI-based suppression categories therefore provide complementary information: the former characterize meteorological fire danger based on statistical distributions, whereas the latter translate these conditions into their potential implications for wildfire suppression. Compared with the Counterfactual storyline, representative of a cooler 1950 climate (See [Materials and Methods](#) Section for further details), present-day conditions (Factual) significantly shifted fire weather towards higher FWI classes and more severe suppression regimes across the NW-IP domain, while a +2K warming further amplified this response (Fig. 2a). After translating FWI into potential FLI, areas exceeding the operational thresholds of $10,000$ and $30,000 \text{ kW m}^{-1}$ —corresponding to virtually ineffective and ineffective suppression conditions, respectively—expanded progressively

from Counterfactual to Factual and +2K (Fig. 2a). The area exceeding $10,000 \text{ kW m}^{-1}$ increased by 0.47 Mha (3.9%) from Counterfactual to Factual and by a further 0.92 Mha (7.6%) from Counterfactual to +2K storylines, while the corresponding increases above $30,000 \text{ kW m}^{-1}$ were 0.40 Mha (4276.5%) and 1.72 Mha (18334.9 %), respectively. As noted, conditions exceeding this last threshold were virtually absent under the Counterfactual storyline, but emerged under the Factual one, and expanded sharply under +2K. This emergence and rapid expansion of the least effective operational category indicate that anthropogenic warming pushed substantial portions of NW-IP into a fire-weather regime associated with ineffective suppression conditions.

These shifts were consistent with systematic changes in the underlying meteorological components, including higher temperature, lower relative humidity and an increasing precipitation deficit, whereas changes in wind speed remained highly uncertain, as shown by the low member agreement ([Supplementary Fig. 2](#)). Complementary indicators averaged over 8–15 August 2025—the period encompassing the ignition of most megafires—revealed a spatially coherent intensification of atmospheric and land-surface dryness, characterised by increasing VPD and declining root-zone soil moisture, with these responses becoming progressively more pronounced with increasing warming ([Supplementary Fig. 3](#)).

Anthropogenic warming altered not only the spatial extent but also the temporal persistence of operationally critical fire-weather conditions throughout August 2025 (Fig. 2b). Under the Factual storyline, the proportion of the study area experiencing the two worst operational FLI categories remained consistently above the Counterfactual simulation for most of August, whereas the +2K storyline further increased both the extent and persistence of these conditions. In contrast, the very difficult suppression category progressively shrinks under warmer storylines, reflecting a systematic transition towards conditions where direct wildfire suppression becomes increasingly ineffective. Note that the moderately difficult suppression category shows only minor differences across the storylines (Fig. 2b) and is particularly widespread along the coastal fringe, reflecting the spatial distribution of the associated FWI values (Fig. 2a).

These results demonstrate that anthropogenic warming fundamentally altered the operational difficulty of the August 2025 wildfire episode by expanding and prolonging fire-weather conditions beyond critical suppression thresholds. This shift raises the likelihood that larger portions of the landscape experience conditions under which wildfire suppression is severely constrained, providing the basis for assessing changes in societal and environmental exposure.

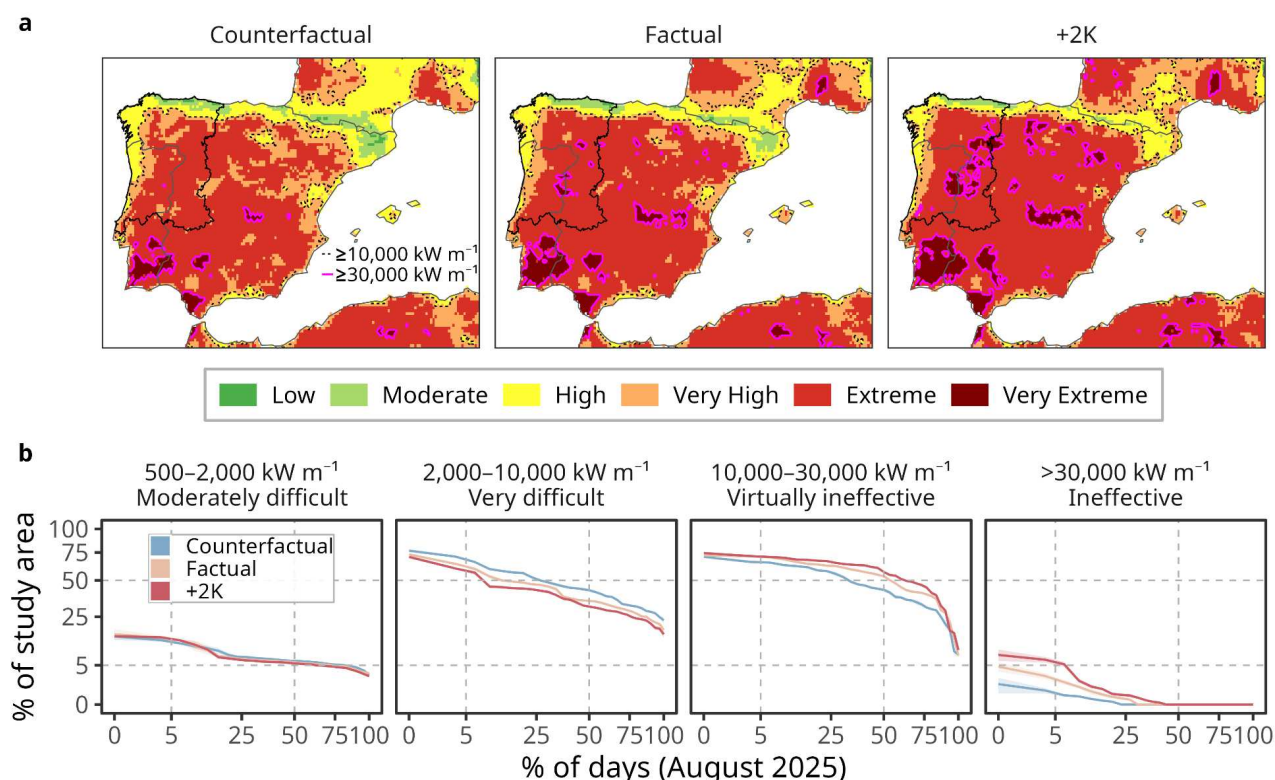


Figure 2 | Climate change increased the spatial extent and persistence of operationally critical fire-weather conditions. (a) Maximum Fire Weather Index (FWI) for the Counterfactual, Factual, and +2K storyline simulations during August 2025. The colour shading indicates the EFFIS FWI danger classes, whereas black dashed and magenta isolines show the $> 10,000$ and $> 30,000$ kW m⁻¹ potential fireline intensity (FLI) suppression thresholds derived from the empirical FWI–FLI relationship of Palheiro et al. (2006), respectively. (b) Duration curves showing the percentage of the study area exceeding each operational FLI category throughout August 2025 in the northwestern Iberian Peninsula (NW-IP).

Operationally critical fire weather increased societal and environmental exposure

The expansion of operationally critical fire-weather conditions was accompanied by substantial increases in the exposure of both protected areas and population during the peak of the August 2025 wildfire episode (Fig. 3). Protected areas were particularly affected by the transition towards the highest potential FLI suppression categories (Fig. 3a, left panel). Exposure of protected areas to the two highest FLI categories ($>10,000$ kW m⁻¹) increased substantially under anthropogenic warming. When considered together, these categories increased by approximately 0.13 Mha (12%) under the Factual storyline and by a further 0.22 Mha (21%) under the +2 K storyline relative to the Counterfactual. The increase was particularly pronounced in the most severe category ($>30,000$ kW m⁻¹), where exposure increased by 0.07 Mha (380%) under Factual and by a further 0.14 Mha (780%) under +2 K. These increases were accompanied by a reduction of -0.12 Mha (29%) and -0.19 Mha (47%) in protected-area exposure to the very difficult suppression category (2,000–10,000 kW m⁻¹) under Factual and +2 K, respectively relative to the Counterfactual simulation, reflecting a redistribution of protected landscapes from conditions within suppression capacity towards more operationally challenging fire-weather regimes.

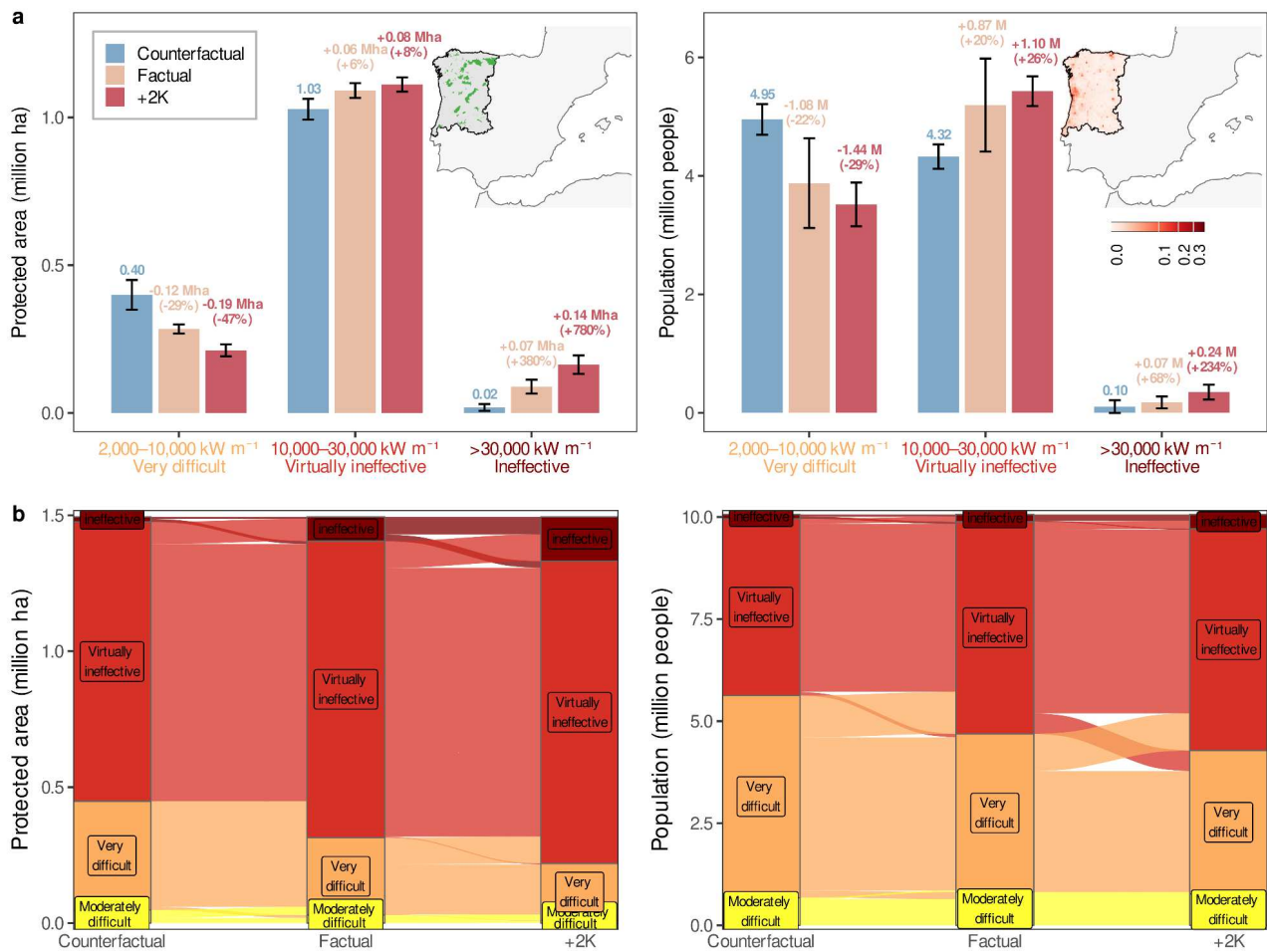


Figure 3 | Anthropogenic warming increased the exposure of people and protected areas to operationally critical fire-weather conditions. (a,b) Exposure of population and protected areas to operational maximum fireline-intensity (FLI) suppression categories during August 2025 wildfire daily peak under the Counterfactual, Factual, and +2K storyline simulations. Bars represent the ensemble mean sum of ha exposed and error bars indicate $\pm$ standard deviation across storyline members. **(c,d)** Sankey diagrams showing transitions in exposed population and protected-area extent between operational FLI suppression categories from the Counterfactual to Factual (left) and from Factual to +2K (right) storyline simulations. Flow widths are proportional to the amount of exposed population or protected-area extent undergoing transitions between suppression categories.

Population exposure showed the same overall response (Fig. 3a, right panel). The number of people exposed to the highest FLI suppression categories increased relative to the Counterfactual simulation and increased further under the +2K storyline, whereas exposure to lower-severity categories declined. In the most severe category ($>30,000 \text{ kW m}^{-1}$), anthropogenic warming increased population exposure by 0.07 million people (68%) under the Factual storyline, with a further increase of 0.24 million (234%) under the +2 K storyline relative to the Counterfactual. When the two most extreme suppression categories ($>10,000 \text{ kW m}^{-1}$) were considered together, population exposure increased by 0.94 million (21%) under Factual and by 1.34 million (30%) under +2 K relative to the Counterfactual storyline. These increases were accompanied by a comparable reduction in exposure to the very difficult suppression category ($2,000\text{--}10,000 \text{ kW m}^{-1}$), which decreased by -1.08 million and -1.44 million people under Factual and +2 K, respectively, compared with the Counterfactual simulation.

Anthropogenic warming redistributed protected areas and populations towards increasingly severe suppression regimes (Fig. 3b). In the Counterfactual, Factual and +2 K storylines, respectively, 70%, 79% and 85% of the total protected-area extent within NW-IP was exposed to fire-weather conditions exceeding the suppression-capacity threshold ($>10,000 \text{ kW m}^{-1}$). Population exposure showed a similar increase, with 44.2%, 53.6% and 57.6% of the total NW-IP population exposed to these conditions under the three storylines, respectively. Most transitions occurred from the very difficult ($2,000\text{--}10,000 \text{ kW m}^{-1}$ for protected areas and population exposure, respectively) to the virtually ineffective ($10,000\text{--}30,000 \text{ kW m}^{-1}$) category, and from the virtually ineffective to the ineffective ($>30,000 \text{ kW m}^{-1}$) category, whereas transitions in the opposite direction were comparatively rare. This progressive redistribution explains the marked increase in exposure to the most operationally constrained fire-weather conditions.

To assess the implications for areas where people and flammable vegetation coexist, we extended the exposure analysis to the WUI, focusing on intermix WUI, the dominant WUI configuration across the study region, characterized by interspersed buildings and wildland vegetation (Fig. 4). Anthropogenic warming increased the extent of both forest and grassland intermix WUI exposed to potential fire line intensities exceeding $10,000 \text{ kW m}^{-1}$, the threshold above which fire suppression becomes virtually ineffective. Compared with the Counterfactual storyline, exposed forest WUI increased by approximately 0.11 Mha (11.6%) under Factual and by 0.20 Mha (20.2%) under +2k storylines, while grassland WUI showed a similar response but less pronounced, increasing by 0.06 Mha (5.5%) and a further 0.11 Mha (10.5%), respectively. Areas consistently exceeding this threshold across all five ensemble members also expanded from Counterfactual to Factual and +2K, indicating a robust spatial increase in WUI exposure under warming (Fig. 4a).

Warming also increased the spatial continuity of WUI exposure (Fig. 4b). The number of contiguous exposed forest WUI clusters larger than 500 ha increased from 193 under the Counterfactual to 205 under the Factual and 219 under the +2K storylines, with increases also evident for larger cluster sizes. Clusters exceeding 2,000 ha increased from 35 to 38 and 40, respectively, while those exceeding 5,000 ha increased from 14 to 16 and 17. Grassland WUI exhibited a comparable response, with exposed clusters larger than 1,000 ha increasing from 122 under Counterfactual to 124 under Factual and 135 under +2K, and those exceeding 2,000 ha increasing from 46 to 48 and 50. These results indicate that warming increased not only the overall extent of WUI exposed to conditions severely constraining fire suppression, but also the occurrence of large, spatially contiguous exposed areas.

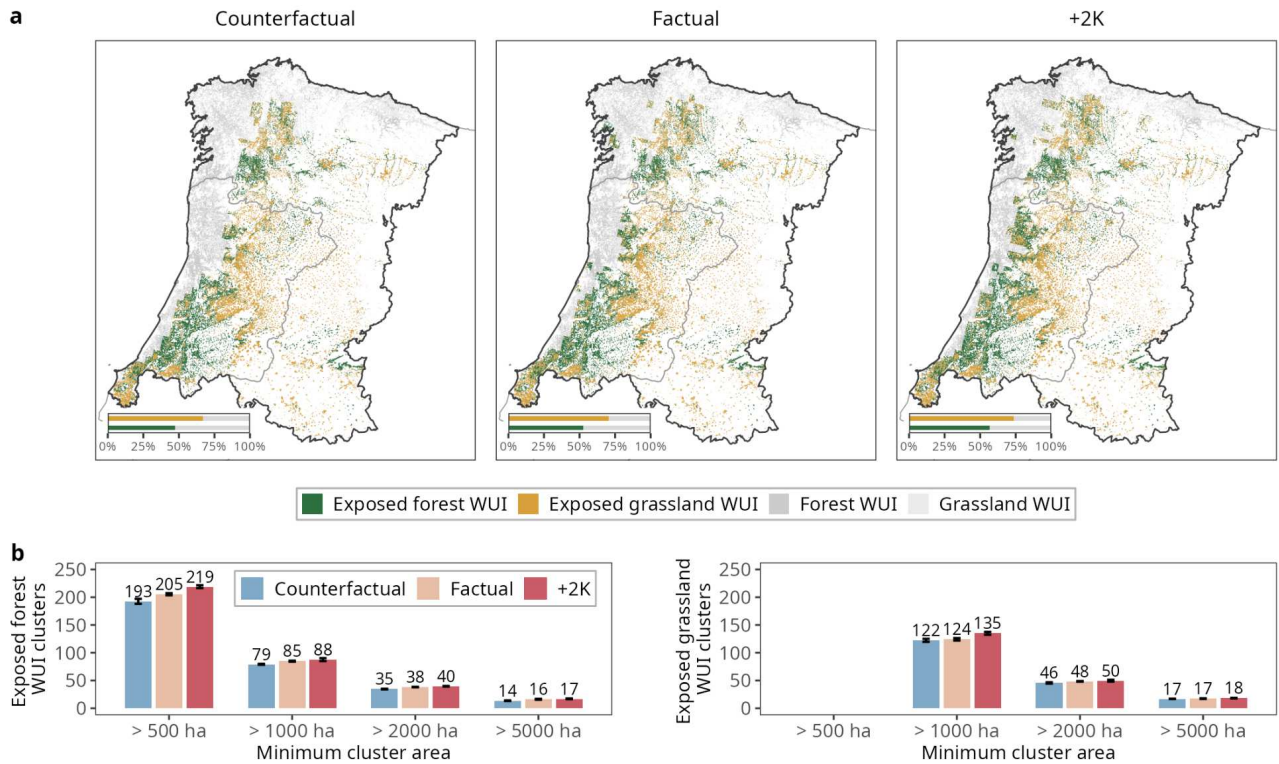


Figure 4 | Warming increases both the extent and spatial continuity of WUI exposed to fire-weather conditions corresponding to the virtually ineffective suppression category. (a) Maps show forest and grassland wildland–urban interface (WUI) exposed to potential fireline intensities $>10,000 \text{ kW m}^{-1}$, corresponding to virtually ineffective fire-suppression conditions, during the daily peak of the August 2025 wildfire episode under the Counterfactual, Factual and +2K storylines. Grey colours represent the total forest and grassland WUI extent, whereas green and yellow indicate exposed forest and grassland WUI, respectively. Mapped exposed areas correspond to locations consistently classified as exposed by all five ensemble members. Insets show the percentage of exposed forest and grassland WUI relative to their total extent. **(b)** Bar plots quantify the number of contiguous exposed forest and grassland WUI clusters exceeding minimum areas of 500, 1,000, 2,000 and 5,000 ha. Bar heights represent the ensemble mean across the five ensemble members, and error bars show the standard deviation across members.

Discussion

Our results show that anthropogenic warming during the August 2025 northwestern Iberian wildfire crisis systematically shifted fire weather towards conditions exceeding operational suppression thresholds. This extends previous attribution studies, which have primarily quantified anthropogenic influences through changes in meteorological indicators such as the FWI, vapour pressure deficit, fuel aridity or burned area (Gauthier & Bevacqua, 2026; Nogherotto et al., 2026; Turco et al., 2026). While these metrics provide robust measures of wildfire hazard, they do not directly assess how climate change affects the operational conditions under which wildfires can be suppressed. This distinction is important because suppression effectiveness is inherently threshold-dependent, varies non-linearly with fire weather, and it declines rapidly once fireline intensity exceeds critical levels (Wotton et al., 2017; Tymstra et al., 2020). Our findings therefore complement previous evidence of increasing conditions exceeding suppression thresholds and the growing limitations of suppression-centred strategies under warmer climates (Wotton et al., 2017; Whitman et al., 2022; Schoennagel et al., 2017; Moreira et al., 2020). They provide evidence from an observed European wildfire crisis that climate change is progressively narrowing the window of conditions under which successful suppression remains possible.

Our study also illustrates the value of storyline approaches for operational climate-risk assessments. Although these approaches have only recently begun to be applied to wildfire impacts ([Corning et al., 2024](#)), expressing these simulations through operational suppression thresholds substantially enhances their practical relevance. Rather than describing abstract changes in fire-weather indices, this framework quantifies how climate change alters the conditions associated with extreme wildfire events that increasingly challenge suppression, providing a physically consistent basis for exploring how comparable events may unfold under alternative climate states. The exceptional conditions observed during the August 2025 crisis should therefore not necessarily be interpreted as a one-off anomaly. The 2025 season itself was characterised by record-breaking fire intensity, an increasing contribution of very large fires, and the expansion of fire activity into previously less fire-prone high-altitude areas ([Resco de Dios et al., 2026](#)). The recurrence of severe wildfire conditions across southwestern Europe during the 2026 fire season further highlights the possibility that fire-weather conditions previously considered unprecedented may become increasingly recurrent under continued warming. Across all exposure metrics, additional warming consistently expanded both the spatial extent and persistence of the highest fireline intensities associated with increasingly challenged suppression categories, suggesting that future wildfire emergencies are increasingly likely to occur under conditions where opportunities for successful initial attack are substantially reduced.

Beyond intensifying fire weather itself, our results show that anthropogenic warming systematically redistributes the exposure of ecological and societal assets towards fire-weather conditions exceeding operational suppression thresholds. This shift is particularly relevant because it affects assets where wildfire consequences are disproportionately high. Recent studies have shown that climate change is progressively increasing the exposure of populations and ecosystems to wildfire hazard through the growing overlap between fire-prone conditions and human or ecological assets ([Pietrojusti et al., 2026](#); [Torres-Vazquez et al., 2026](#); [Seydi et al., 2025](#)). Importantly, the consequences of this shift may extend beyond increased exposure alone. Areas and communities historically less frequently exposed to such severe fire-weather conditions may also be particularly vulnerable to these emerging regimes, as their landscapes, infrastructure and preparedness strategies may not have been designed to cope with fires occurring under conditions that increasingly constrain direct suppression ([Alcasena et al., 2019](#)). The systematic increase observed across protected areas is particularly concerning given their role in conserving biodiversity, carbon stocks and other ecosystem services, whereas the corresponding shift across WUI landscapes implies that more communities and infrastructure may be exposed—and potentially vulnerable—under conditions where direct suppression becomes increasingly ineffective. Combined with the growing synchronization of extreme fire-weather conditions across Europe ([Yin et al., 2026](#); [Torres-Vázquez et al., 2025](#)), these changes may increasingly challenge the availability of suppression resources and emergency response capacity during severe wildfire seasons. These findings reinforce calls for a transition from suppression-centred wildfire policy towards integrated fire management strategies that combine fuel management, landscape resilience and adaptation ([Moreira et al., 2020](#); [Oliveras Menor et al., 2025](#)).

Several limitations should nevertheless be acknowledged. First, the relationship between FWI and fireline intensity is empirical and represents expected operational fire behaviour rather than simulated fire dynamics. Consequently, our analysis should be interpreted as quantifying changes in meteorological conditions associated with different suppression regimes rather than predicting realised fire intensity. Second, FWI does not capture atmospheric instability and dry pyroconvection, which are processes that could multiply FLI in extreme wildfire events and, in

consequence, we may have underestimated future changes in effective suppression ([Castellnou et al., 2024](#); [Resco de Dios et al., 2022](#)). Third, the storyline framework isolates the climatic component of the event and does not account for concurrent changes in fuels, vegetation, land management, ignition sources or suppression strategies, all of which influence wildfire outcomes ([Curt and Fréjaville, 2018](#); [Kreider et al., 2024](#)). Moreover, the strong spectral nudging used to preserve the observed large-scale circulation substantially limits changes in atmospheric dynamics across the storylines ([Campos et al., 2026](#); [Grayson et al., 2026](#)). This is appropriate for isolating the thermodynamic contribution of anthropogenic warming, but means that our results do not capture the potential influence of climate-change-driven changes in atmospheric circulation on fire-weather conditions. Fourth, although the FWI was bias-corrected against ERA5-Land to ensure a more realistic representation of absolute fire-danger conditions, a small positive residual bias remains, which may lead to a slight overestimation of the estimated changes ([Supplementary Fig. 4–5](#)). This bias might arise from a precipitation underestimation encountered in the IFS-FESOM simulations ([Destination Earth, 2026](#)) and in this work as well ([Supplementary Fig. 6](#)). Finally, although operational suppression thresholds provide a more management-oriented representation of wildfire hazard, actual suppression effectiveness ultimately depends on additional factors including accessibility, available resources, fire behaviour and tactical decisions ([Rodríguez y Silva et al., 2014](#); [Wotton et al., 2017](#)), which have not been analysed.

Overall, our findings suggest that one of the most important consequences of anthropogenic climate change may not simply be the intensification of fire weather itself, but the progressive loss of opportunities for effective wildfire suppression. Incorporating operational suppression thresholds into event attribution therefore offers a complementary framework that directly connects climate science with the realities of wildfire management.

Materials and methods

Climate storyline simulations

In this study, we analyse spectrally nudged climate storyline simulations performed with the coupled global climate model IFS–FESOM ([John et al., 2026](#)) within the Destination Earth Climate Digital Twin (ClimateDT) initiative ([Wedi et al., 2022](#); [Doblas-Reyes et al., 2026](#)). The modelling framework couples the Integrated Forecasting System (IFS, cycle 48r1; ECMWF, 2023), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), for the atmosphere, land surface and waves, with the Finite volume Sea Ice–Ocean Model (FESOM2, version 2.5), developed by the Alfred Wegener Institute. Simulations spanning from 2017 to 2025 were performed using the ClimateDT configuration ([Rackow et al., 2025](#)), with an atmospheric horizontal resolution of approximately 9 km (TCo1279) and 137 vertical levels. The ocean component uses 70 vertical levels and an unstructured NG5 mesh, with horizontal resolution ranging from approximately 12 km in the tropics to 4.5 km in dynamically active and polar regions ([Danilov et al., 2017](#); [Scholz et al., 2019](#)).

The simulations are constrained through spectral nudging following [Sánchez-Benítez et al. \(2022\)](#). Large-scale atmospheric vorticity and divergence are nudged towards ERA5 reanalysis between 700 and 100 hPa for spatial scales up to wavenumber T60, using a one-hour e-folding relaxation time. This approach constrains the simulations to closely reproduce the observed large-scale atmospheric circulation while allowing mesoscale and local-scale processes to evolve freely ([John et al., 2024](#)). The storyline framework therefore enables the same synoptic evolution associated with the August 2025 wildfire episode to be reproduced under different thermodynamic climate

backgrounds, allowing the influence of anthropogenic warming on fire-weather conditions to be isolated.

We compare three climate storylines: Counterfactual, Factual, and +2K:

- Counterfactual: represents a cooler climate by prescribing 1950 boundary conditions and fixed CMIP6 historical forcing, thereby approximating the climate conditions that would have prevailed in the absence of most subsequent anthropogenic warming.
- Factual: represents the present-day climate (2017-2025) and uses transient forcing following SSP3–7.0.
- +2K: represents a future climate approximately 2 K warmer than pre-industrial conditions, corresponding approximately to the climate state projected around 2040. It uses CMIP6 SSP3–7.0 forcing fixed at 2040 conditions and is initialized from the coupled IFS–FESOM nextGEMS simulation on 1 January 2040 ([Rackow et al., 2025](#)).

Because all three storylines are constrained towards the same observed large-scale atmospheric circulation, differences among them provide a physically consistent estimate of how the meteorological conditions associated with the August 2025 wildfire episode respond to different levels of global warming.

Each storyline simulation is represented by a five-member ensemble. The first member corresponds to the original simulation, in which spectral nudging remains continuously active. The four additional members were generated by temporarily disabling spectral nudging from 1st of January 2017 for one to four days, respectively, before reactivating it. This procedure allows small perturbations to develop and grow while subsequently constraining the simulations towards the same observed large-scale atmospheric evolution.

Meteorological and fire-related data

The August 2025 wildfire episode was characterized using burned-area data from the European Forest Fire Information System (EFFIS). EFFIS seasonal statistics were used to compare cumulative burned area through August 2025 across Spain and Portugal with the corresponding European total. Historical August burned area within the NW-IP domain for 1985–2025 was obtained from the reconstructed burned area time series of [Sanchez-Hernandez et al. \(2025\)](#), which integrates the EFFIS burned area database with the higher-resolution EFFIS Sentinel-2/MODIS product available from 2016 onwards.

Fire-weather conditions were placed in a historical context using daily FWI from the Copernicus Emergency Management Service historical fire-danger dataset ([CEMS, 2019](#)), derived from ERA5 at 0.25° spatial resolution. For each year from 1985 to 2025, FWI was averaged over August and across the NW-IP domain and compared with the corresponding August burned area. The exceptional nature of the 2025 event was further evaluated by calculating August-mean FWI at each grid cell and ranking the 2025 value against the corresponding August values over 1985–2025. Spatially explicit EFFIS fire perimeters were used to examine the spatial correspondence between historically exceptional fire-weather conditions and the location and size of the fires exceeding 1,000 ha.

Meteorological conditions associated with the event were characterized using the variables required to calculate FWI, together with vapour pressure deficit (VPD) and root-zone soil moisture (RZSM). FWI input variables comprised 2-m air temperature, relative humidity and 10-m wind

speed at 12:00 UTC, together with daily accumulated precipitation. VPD was derived from 2-m air temperature and 2-m dew-point temperature, whereas 10-m daily mean wind speed was calculated from the zonal and meridional 10-m wind components. RZSM was derived from volumetric soil water content by integrating the first three soil layers (0–7, 7–28 and 28–100 cm), representing soil moisture conditions over the upper 1 m of the soil column. ERA5-Land (Muñoz-Sabater et al., 2021) was used for the observational characterization of the 2025 event (Fig. 1), while the corresponding IFS–FESOM variables were used to characterize the three climate storylines. Details of the FWI calculation and subsequent derivation of fireline intensity are provided in the following section.

Fire Weather Index and fireline intensity estimation

The Canadian Fire Weather Index (FWI) (Van Wagner, 1987) was calculated daily for each ClimateDT storyline and ensemble member by means of the cffdrs R package (Wang et al., 2017). FWI was derived through the sequential calculation of the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI) and Build-Up Index (BUI). The FWI was calculated continuously from 1 January 2018 to 31 August 2025, with the first six months used as a spin-up period to minimise the influence of initial conditions before the analysis period. Because our analysis relies on absolute fire-danger classes, simulated FWI was bias-corrected against the same indicator calculated from ERA5-Land using quantile delta mapping (QDM) implemented in the MBC R package (Cannon, 2026). The bias correction was calibrated independently for each Factual ensemble member against ERA5-Land using daily summer (June–August) FWI over 2018–2025, employing the full empirical sample of 720 daily values to estimate the quantile distributions. Reducing the quantile resolution to 100 empirical quantiles produced virtually identical results. The resulting member-specific transfer functions were then applied consistently to the corresponding Counterfactual, Factual and +2K storyline ensemble members for summer 2025. This approach corrects systematic biases in the absolute FWI distribution while preserving the climate-change signal (Cannon et al., 2015; Casanueva et al., 2020) between storylines, as demonstrated by the nearly unchanged FWI differences among Cont, Hist and Tp2K before and after bias correction over the NW-IP (Supplementary Fig. 4-5). However, a slight positive bias in FWI remained after bias correction.

To translate meteorological fire danger into a metric with direct operational relevance for fire behaviour and suppression difficulty, FWI was converted to potential fireline intensity (FLI) using the empirical relationship developed by Palheiro et al. (2006) (See supplementary Fig. 7):

$$FLI = 8.071 \text{ FWI}^{1.940}$$

where FLI is expressed in kW m⁻¹. This relationship was empirically derived for *Pinus pinaster* stands, whose mapped distribution encompasses approximately 70% of the NW-IP domain (Supplementary Fig. 8). Nevertheless, the relationship provides an estimate of potential, rather than realized, fireline intensity, as actual fire behaviour also depends on local fuel characteristics and load, fuel moisture, topography, and fire dynamics (Pausas and Keeley, 2021).

Potential FLI values were classified into operational suppression-difficulty categories adapted from Tedim et al. (2018): fairly easy (<500 kW m⁻¹), moderately difficult (500–2,000 kW m⁻¹), very difficult (2,000–10,000 kW m⁻¹), virtually ineffective (10,000–30,000 kW m⁻¹), and ineffective (>30,000 kW m⁻¹). The corresponding FWI thresholds were obtained by inverting the Palheiro et al. (2006) relationship and applied directly to the bias-corrected daily FWI fields. Conventional EFFIS

FWI classes (low, moderate, high, very high, extreme and very extreme) were additionally used to provide a standardized fire-weather reference. The relationship between the FWI and FLI can be found in [Supplementary Fig. 7](#).

Changes in the spatial extent and persistence of operational fire-weather conditions were evaluated over the FWI daily peak in August 2025 ([Supplementary Fig. 1](#)), which was on the 15th of August. Note that wildfires starting by the 14th and 15th of August ended up burning more than 126,000 ha with a total of 5 simultaneous megafires in the NW-IP ([Resco-De Dios et al., 2026](#)). For each operational threshold, storyline, and ensemble member, we calculated the fraction of the NW-IP study area exceeding the threshold on each day. Area–duration exceedance curves were then constructed by determining, for each affected-area fraction, the percentage of days during August 2025 in which at least that fraction of the study domain exceeded the corresponding threshold. This provides a joint measure of the spatial extent and temporal persistence of operationally challenging fire-weather conditions. Calculations were performed independently for each ensemble member and summarized using the ensemble mean and standard deviation.

Exposure analysis

Exposure to operationally challenging fire-weather conditions was quantified for population, protected areas, and wildland–urban interface (WUI) areas across the NW-IP study domain. For each storyline and ensemble member, we determined the daily maximum operational FLI suppression category reached at each grid cell during August 2025 and overlaid these fields with spatially explicit exposure datasets. Population, protected areas and WUI were kept fixed across the three storylines, allowing changes in exposure to be attributed solely to changes in fire-weather conditions rather than to changes in the distribution of exposed elements.

Population exposure was extracted from the 1-km JRC-ESTAT Census Population Grid 2021 ([Batista et al., 2024](#)). Protected areas were obtained from the October 2025 release of the World Database on Protected Areas ([UNEP-WCMC and IUCN, 2026](#)). We considered terrestrial protected areas, excluding sites with a designation status of “Proposed” or “Not reported” as in ([Resco De Dios et al. 2026](#)). Both products were regridded to the spatial resolution of the storyline simulations using nearest-neighbour resampling. To characterize how warming altered the severity of exposure, we tracked transitions between operational suppression categories from Counterfactual to +2K storylines. For each spatial unit, population or protected-area extent was assigned to its category of origin and destination, allowing transitions towards higher or lower suppression-difficulty regimes to be quantified. These transitions were visualized using Sankey diagrams using the R package “ggalluvial” ([Brunson, 2020](#)).

WUI exposure was assessed using the global 10-m WUI dataset of [Schug et al. \(2023\)](#), representative of 2020. The dataset was resampled to 100-m spatial resolution using nearest-neighbour resampling to reduce computational requirements while retaining a fine spatial resolution. We separately considered forest/shrub/wetland intermix and grassland intermix WUI. Exposure was defined as WUI area experiencing potential FLI $>10,000 \text{ kW m}^{-1}$ during the FWI peak in August 2025, corresponding to the threshold above which fire-suppression conditions become virtually ineffective. For each storyline and ensemble member, we calculated the exposed area and its fraction relative to the total extent of each WUI type within the study domain. To identify areas of robust exposure, the spatial maps retained only WUI locations exceeding this threshold consistently across all five ensemble members. We further assessed whether warming altered the spatial continuity of WUI exposure. Contiguous WUI areas exceeding $10,000 \text{ kW m}^{-1}$

were identified independently for each storyline and ensemble member and grouped into spatial clusters. Cluster area was then calculated, and the number of exposed clusters exceeding minimum sizes of 500, 1,000, 2,000, and 5,000 ha was quantified separately for forest/shrub/wetland and grassland WUI.

Code and Data availability

The climate storyline simulations used in this study were accessed through the Destination Earth Climate Change Adaptation Digital Twin via the Polytope platform (<https://platform.destine.eu/services/service/polytope/>). Historical Fire Weather Index (FWI) data were obtained from the Copernicus Emergency Management Service (CEMS) historical fire-danger dataset (<https://ewds.climate.copernicus.eu/datasets/cems-fire-historical-v1?tab=overview>). ERA5-Land data used for FWI bias correction were obtained from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land?tab=overview>). Burned-area data and fire perimeters were obtained from the European Forest Fire Information System (EFFIS) (<https://forest-fire.emergency.copernicus.eu/apps/effis/statistics/seasonaltrend>). Gridded population data were obtained from Eurostat GISCO population grids (<https://ec.europa.eu/eurostat/web/gisco/geodata/population-distribution/population-grids>), and protected-area boundaries from the World Database on Protected Areas (WDPA) (<https://www.protectedplanet.net/en/thematic-areas/wdpa?tab=WDPA>). Wildland–urban interface data were obtained from the Global Wildland–Urban Interface (WUI) 2020 dataset (<https://silvis.forest.wisc.edu/globalwui/>). The spatial distribution of *Pinus pinaster* was obtained from EUFORGEN (<https://www.euforgen.org/species/pinus-pinaster>). The main codes used to perform the analyses and produce the figures presented in this study are available at <https://gitlab-earth.bsc.es/mlemus/fwi-fli-threshold-storylines>

Acknowledgements

M.L-C acknowledges a Beatriu de Pinós postdoctoral grant from the Government of Catalonia (2024BP00091). M.O and K.G are funded by the AI4Science PN070500 fellowship within the “Generación D” initiative, Red.es, Ministerio para la Transformación Digital y de la Función Pública, for talent attraction (C005/24-ED CV1). The work presented in this paper has been produced in the context of the European Union’s Destination Earth Initiative and relates to tasks entrusted by the European Union to the European Centre for Medium-Range Weather Forecasts implementing part of this Initiative with funding by European Union. Views and opinions expressed are those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. We acknowledge the EuroHPC Joint Undertaking (JU) for awarding this project access to the EuroHPC supercomputer LUMI and MareNostrum5 through a EuroHPC JU Special Access call.

References

- Abatzoglou, J. T., Williams, A. P. & Barbero, R. Global Emergence of Anthropogenic Climate Change in Fire Weather Indices. *Geophysical Research Letters* **46**, 326–336 (2019).
- Alexander, M. E. Fire behaviour as a factor in forest and rural fire suppression. In *Forest Fire Research & Wildland Fire Safety* (ed. Viegas, D. X.) (Millpress, Rotterdam, 2002).
- Alcasena, F. J., Ager, A. A., Bailey, J. D., Pineda, N. & Vega-García, C. Towards a comprehensive wildfire management strategy for Mediterranean areas: Framework development and implementation in Catalonia, Spain. *Journal of Environmental Management* **231**, 303–320 (2019).
- Alcasena, F. *et al.* Assessing Wildfire Exposure to Communities and Protected Areas in Portugal. *Fire* **4**, 82 (2021).
- Alexander, M. E. & Cruz, M. G. Interdependencies between flame length and fireline intensity in predicting crown fire initiation and crown scorch height. *International Journal of Wildland Fire* **21**, 95–113 (2012).

- Batista, F., Freire, S. & Pigaiani, C. JRC-ESTAT Census Population Grid 2021. European Commission, Joint Research Centre <https://doi.org/10.2905/JRC.VP18KXG> (2024).
- Beltrán-Marcos, D., Calvo, L. & Fernández-Guisuraga, J. M. Environmental drivers of burned area and fire severity during the 2025 extreme fire season in the NW Iberian Peninsula. *fire ecol* **22**, 27 (2026).
- Brunson, J. ggalluvial: Layered Grammar for Alluvial Plots. *JOSS* **5**, 2017 (2020).
- Campos, D. A. *et al.* The October 2024 extreme precipitation event over Valencia: storyline attribution of the synoptic-scale thermodynamic drivers. *Weather and Climate Dynamics* **7**, 1153–1171 (2026).
- Cannon, A. J., Sobie, S. R. & Murdock, T. Q. Bias Correction of GCM Precipitation by Quantile Mapping: How Well Do Methods Preserve Changes in Quantiles and Extremes? <https://doi.org/10.1175/JCLI-D-14-00754.1> (2015) doi:[10.1175/JCLI-D-14-00754.1](https://doi.org/10.1175/JCLI-D-14-00754.1).
- Cannon, A. J. MBC: Multivariate Bias Correction of Climate Model Outputs. (2026).
- Casanueva, A. *et al.* Testing bias adjustment methods for regional climate change applications under observational uncertainty and resolution mismatch. *Atmospheric Science Letters* **21**, e978 (2020).
- Castellnou, M. *et al.* Empowering strategic decision-making for wildfire management: avoiding the fear trap and creating a resilient landscape. *fire ecol* **15**, 31 (2019).
- Castellnou, M., Bachfischer, M., Bover, M. M. & De Arellano, J. V.-G. Dry pyroclouds promote longer-lasting extreme wildfire events intensification. Preprint at <https://doi.org/10.21203/rs.3.rs-4053550/v1> (2024).
- CMES. Fire danger indices historical data from the Copernicus Emergency Management Service. ECMWF <https://doi.org/10.24381/CDS.0E89C522> (2019).
- Corning, S. N. *et al.* Flammable futures—storylines of climatic impacts on wildfire events and palm oil plantations in Indonesia. *Environ. Res. Lett.* **19**, 114039 (2024).
- Cunningham, C. X., Abatzoglou, J. T., Ellis, T. M., Williamson, G. J. & Bowman, D. M. J. S. Wildfires will intensify in the wildland-urban interface under near-term warming. *Commun Earth Environ* **6**, 542 (2025).
- Curt, T. & Frejaville, T. Wildfire Policy in Mediterranean France: How Far is it Efficient and Sustainable? *Risk Analysis* **38**, 472–488 (2018).
- Danilov, S., Sidorenko, D., Wang, Q. & Jung, T. The Finite-volume Sea ice–Ocean Model (FESOM2). *Geosci. Model Dev.* **10**, 765–789 (2017).
- Destination Earth. Climate Digital Twin User Guide. DestinE Platform. https://platform.destine.eu/services/documents-and-api/doc/?service_name=climate-dt-user-guide (2026).
- Dirección General de Protección Civil y Emergencias (DGPCE). Informe anual de incendios forestales 2025. Ministerio del Interior, Gobierno de España (2026).
- Garderen, L. V., Fay, D. L. F., Dietz, V., De Berg, W. J. V. & Feser, F. Storyline attribution of fire weather during the 2025 Mediterranean summer. Preprint at <https://doi.org/10.21203/rs.3.rs-9252889/v1> (2026).
- Gauthier, E. & Bevacqua, E. Human-induced climate change intensifies spatially compounding fire weather extremes across European countries. *npj Nat. Hazards* **3**, 39 (2026).
- Grayson, K. *et al.* Reconstructing storm Gloria in a changing climate using physical storylines. *npj Nat. Hazards* **3**, 14 (2026).
- Haas, O., Prentice, I. C. & Harrison, S. P. Wildfires on a changing planet. *Nat Commun* **17**, 1599 (2026).
- Hoffmann, J. *et al.* Destination Earth – A digital twin in support of climate services. *Climate Services* **30**, 100394 (2023).
- Jain, P., Castellanos-Acuna, D., Coogan, S. C. P., Abatzoglou, J. T. & Flannigan, M. D. Observed increases in extreme fire weather driven by atmospheric humidity and temperature. *Nat. Clim. Chang.* **12**, 63–70 (2022).

- John, A. *et al.* Global Kilometer-Scale Climate Storylines Using Spectral Nudging. *J Adv Model Earth Syst* **18**, e2025MS005326 (2026).
- Jones, M. W. *et al.* Global and Regional Trends and Drivers of Fire Under Climate Change. *Reviews of Geophysics* **60**, e2020RG000726 (2022).
- Keeping, T. R. *et al.* Attribution of The Record Breaking 2025 European Fire Season to Climate Change. Preprint at <https://doi.org/10.5194/egusphere-2026-1193> (2026).
- Kirchmeier-Young, M. C., Gillett, N. P., Zwiers, F. W., Cannon, A. J. & Anslow, F. S. Attribution of the Influence of Human-Induced Climate Change on an Extreme Fire Season. *Earth's Future* **7**, 2–10 (2019).
- Kreider, M. R. *et al.* Fire suppression makes wildfires more severe and accentuates impacts of climate change and fuel accumulation. *Nat Commun* **15**, 2412 (2024).
- Liu, Z., Eden, J. M., Dieppois, B. & Blackett, M. A global view of observed changes in fire weather extremes: uncertainties and attribution to climate change. *Climatic Change* **173**, 14 (2022).
- Moreira, F. *et al.* Wildfire management in Mediterranean-type regions: paradigm change needed. *Environ. Res. Lett.* **15**, 011001 (2020).
- Muñoz-Sabater, J. *et al.* ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. *Earth System Science Data* **13**, 4349–4383 (2021).
- Nogherotto, R., Raffaele, F., Giuliani, G. & Coppola, E. Has the fire weather index emerged? Insights from global and regional climate models. *Weather and Climate Extremes* **51**, 100861 (2026).
- Novo, A. & Fernández, C. A multi-scale analysis of vegetation and soil burn severity drivers during the 2025 wildfire season in NW Spain. *GIScience & Remote Sensing* **63**, 2724597 (2026).
- Oliveras Menor, I. *et al.* Integrated fire management as an adaptation and mitigation strategy to altered fire regimes. *Commun Earth Environ* **6**, 202 (2025).
- Palheiro, P. M., Fernandes, P. & Cruz, M. G. A fire behaviour-based fire danger classification for maritime pine stands: Comparison of two approaches. *Forest Ecology and Management* **234**, S54 (2006).
- Pausas, J. G. & Keeley, J. E. Wildfires and global change. *Frontiers in Ecol & Environ* **19**, 387–395 (2021).
- Pietrojusti, R. *et al.* Increasing lifetime exposure to extreme fire weather under climate change in Europe. Preprint at <https://doi.org/10.31223/X5ZZ0R> (2026).
- Plucinski, M. P. Contain and Control: Wildfire Suppression Effectiveness at Incidents and Across Landscapes. *Curr Forestry Rep* **5**, 20–40 (2019).
- Quintero, N., Viedma, O. & Moreno, J. M. Protected and non-protected areas burned at a similar fire severity within the 2025 megafires in Spain. *fire ecol* **22**, 101 (2026).
- Rackow, T. *et al.* Multi-year simulations at kilometre scale with the Integrated Forecasting System coupled to FESOM2.5 and NEMOv3.4. *Geoscientific Model Development* **18**, 33–69 (2025).
- Reimer, J., Thompson, D. K. & Povak, N. Measuring Initial Attack Suppression Effectiveness through Burn Probability. *Fire* **2**, 60 (2019).
- Resco De Dios, V. *et al.* Convergence in critical fuel moisture and fire weather thresholds associated with fire activity in the pyroregions of Mediterranean Europe. *Science of The Total Environment* **806**, 151462 (2022).
- Resco De Dios, V. *et al.* Protected areas as hotspots of wildfire activity in fire-prone Temperate and Mediterranean biomes. *Journal of Environmental Management* **385**, 125669 (2025).
- Resco De Dios, V. *et al.* Record-breaking wildfire intensity and nocturnal spread during the extreme 2025 wildfire season in Southwestern Europe: causes and impacts. Preprint at <https://doi.org/10.64898/2026.06.15.732327> (2026).

- Rodríguez Y Silva, F., Molina Martínez, J. R. & González-Cabán, A. A methodology for determining operational priorities for prevention and suppression of wildland fires. *International Journal of Wildland Fire* **23**, 544–554 (2014).
- Rodrigues, M. *et al.* Drivers and implications of the extreme 2022 wildfire season in Southwest Europe. *Science of The Total Environment* **859**, 160320 (2023).
- Sánchez-Benítez, A., Goessling, H., Pithan, F., Semmler, T. & Jung, T. The July 2019 European Heat Wave in a Warmer Climate: Storyline Scenarios with a Coupled Model Using Spectral Nudging. <https://doi.org/10.1175/JCLI-D-21-0573.1> (2022) doi:[10.1175/JCLI-D-21-0573.1](https://doi.org/10.1175/JCLI-D-21-0573.1).
- Sánchez-Hernández, G. *et al.* Record-Breaking 2025 European Wildfires Concentrated in Northwest Iberia. *Global Change Biology* **31**, e70649 (2025).
- Schoennagel, T. *et al.* Adapt to more wildfire in western North American forests as climate changes. *Proc. Natl. Acad. Sci. U.S.A.* **114**, 4582–4590 (2017).
- Scholz, P. *et al.* Assessment of the Finite-volume Sea ice-Ocean Model (FESOM2.0) – Part 1: Description of selected key model elements and comparison to its predecessor version. *Geosci. Model Dev.* **12**, 4875–4899 (2019).
- Schug, F. *et al.* The global wildland–urban interface. *Nature* **621**, 94–99 (2023).
- Shepherd, T. G. *et al.* Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change* **151**, 555–571 (2018).
- Tedim, F. *et al.* Defining Extreme Wildfire Events: Difficulties, Challenges, and Impacts. *Fire* **1**, 9 (2018).
- Teymoor Seydi, S. *et al.* Increasing global human exposure to wildland fires despite declining burned area. *Science* **389**, 826–829 (2025).
- Torres-Vázquez, M. Á. *et al.* Large increase in extreme fire weather synchronicity over Europe. *Environ. Res. Lett.* **20**, 024045 (2025).
- Torres-Vázquez, M. Á. *et al.* Assessing decadal changes in human exposure near wildfires in a Mediterranean region. *Sci Rep* **16**, 5827 (2026).
- Turco, M. *et al.* The emerging human fingerprint on global extreme fire weather. *Sci. Adv.* **12**, eadx9845 (2026).
- Tymstra, C., Stocks, B. J., Cai, X. & Flannigan, M. D. Wildfire management in Canada: Review, challenges and opportunities. *Progress in Disaster Science* **5**, 100045 (2020).
- UNEP-WCMC & IUCN. Protected Planet: The World Database on Protected Areas (WDPA). <https://www.protectedplanet.net/en/thematic-areas/wdpa> (2026).
- van Garderen, L., Feser, F. & Shepherd, T. G. A methodology for attributing the role of climate change in extreme events: a global spectrally nudged storyline. *Natural Hazards and Earth System Sciences* **21**, 171–186 (2021).
- Van Wagner, C. E. Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forestry Service, Forestry Technical Report 35 (1987). <https://ostrnrcan-dostnrcan.canada.ca/handle/1845/228434>
- Wang, X. *et al.* cffdrs: an R package for the Canadian Forest Fire Danger Rating System. *Ecol Process* **6**, 5 (2017).
- Wedi, N. *et al.* Destination Earth: High-Performance Computing for Weather and Climate. *Comput. Sci. Eng.* **24**, 29–37 (2022).
- Whitman, E., Parks, S. A., Holsinger, L. M. & Parisien, M.-A. Climate-induced fire regime amplification in Alberta, Canada. *Environ. Res. Lett.* **17**, 055003 (2022).
- Wixson, T. P. & Cooley, D. Attribution of Seasonal Wildfire Risk to Changes in Climate: A Statistical Extremes Approach. *Journal of Applied Meteorology and Climatology* **62**, 1511–1521 (2023).

Wotton, B. M., Flannigan, M. D. & Marshall, G. A. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environ. Res. Lett.* **12**, 095003 (2017).

Yin, C. *et al.* Increasing synchronicity of global extreme fire weather. *Sci. Adv.* **12**, eadx8813 (2026).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [supplementary.pdf](#)