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Forest fire danger extremes in Europe under climate change: variability and uncertainty

PESETA III project - Climate Impacts and Adaptation in Europe, focusing on Extremes, Adaptation and the 2030s. Task 11 - Forest fires. Final report

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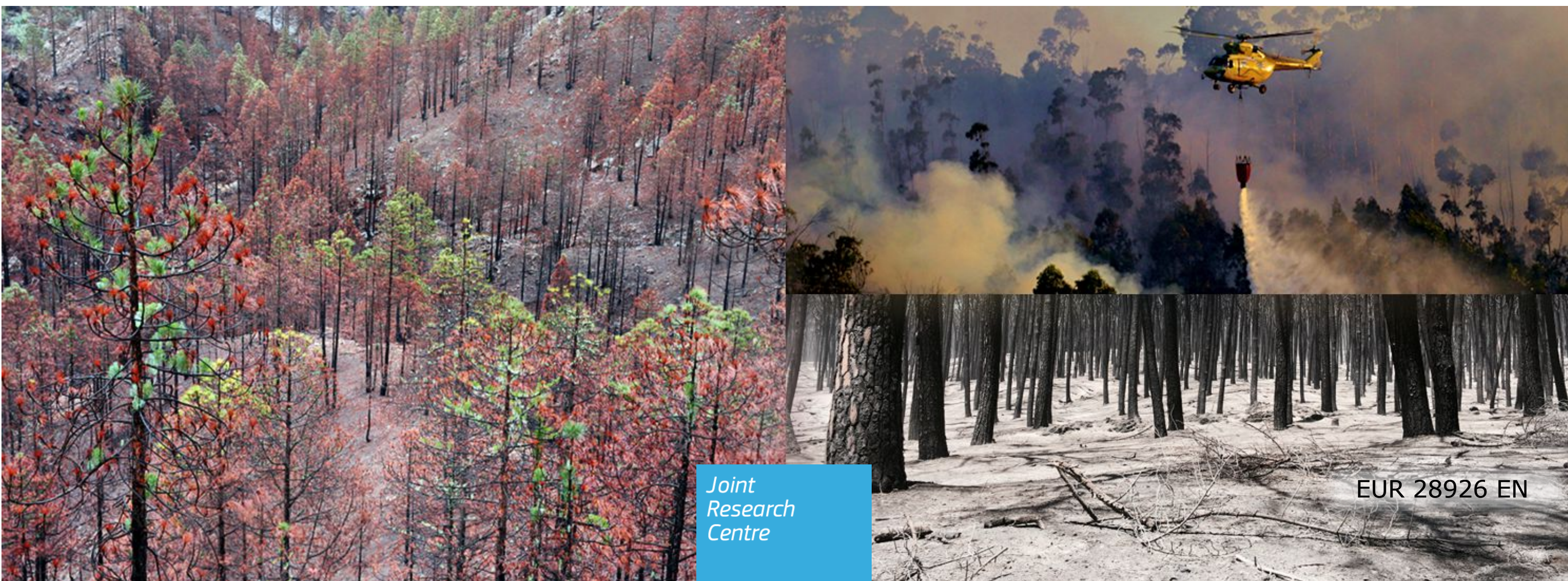

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Contents

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Images in the front cover: Left: wildfire in Gran Canaria, Canary Islands, Spain – adapted from an image authored by Tony Hisgett (CC-BY) https://preview.tinyurl.com/flickr-hisgett-2278903947. Top right, wildfire in Galicia, Spain – adapted from an image authored by Gabriel González (CC-BY) https://preview.tinyurl.com/flickr-gaby1-9754895414. Bottom right, wildfire in the Mount Vesuvius, Italy, 2017 – adapted from an image authored by Carlo Mirante (CC-BY) https://preview.tinyurl.com/flickr-crocieristi-35118297614.

Executive summary

▸ Scope

Forests cover about 215 million ha in Europe and an additional 36 million ha are covered by other wooded lands; this is over a third of the total land area. In recent years, large forest fires have repeatedly affected Europe, in particular the Mediterranean countries. In 2010 alone, wildfires were responsible for the damage of 0.5 million ha in the forests over the European continent [1, 2].

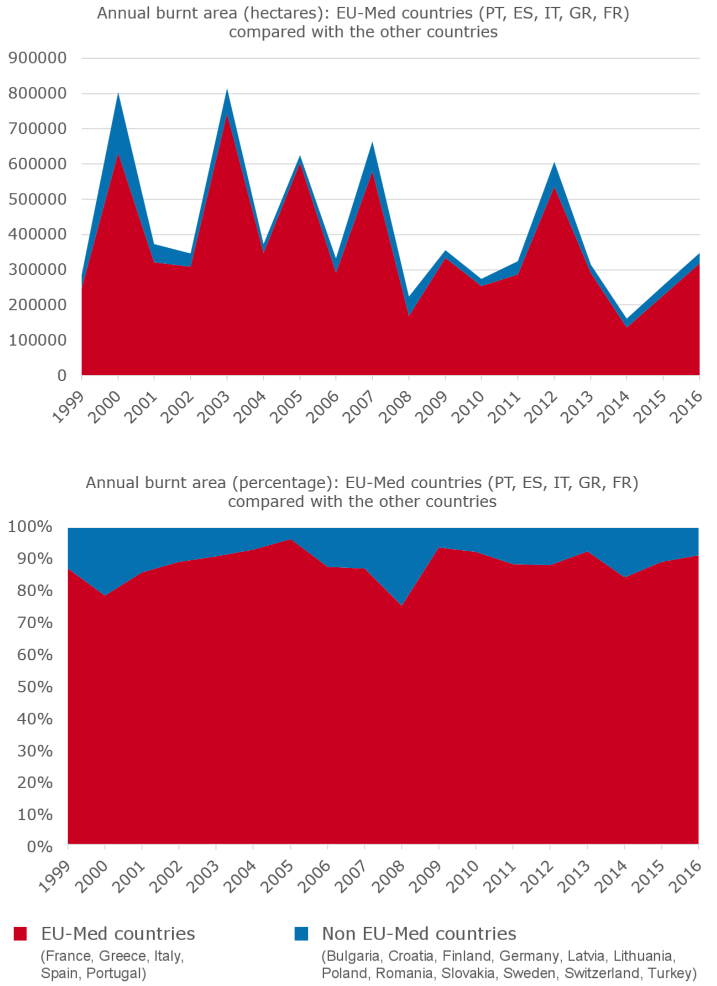


Figure 1: Annual burnt area of five EU-Med countries (France, Greece, Italy, Portugal, Spain) and of 12 other countries (Bulgaria, Croatia, Finland, Germany, Latvia, Lithuania, Poland, Romania, Slovakia, Sweden, Switzerland, Turkey). **Top**: total annual hectares burnt for the EU-Med and the other countries. **Bottom**: percentage of burnt area per year, where 100 % represents the total annual burnt area of al the 17 countries. More details may be found in Figure 4 and Figure 5.

Data available for specific countries highlight wildfire variability in time and space. In the current year 2017, in November the cumulated annual burnt area of Portugal, Spain, and Italy alone exceeded 0.8 million ha[1]. Figure 1 shows a comparison between the annual burnt area in five EU-Med countries (Portugal, Spain, Italy, Greece, and France) and in another 12 countries, where the variability of the fire damage is evident with years in which the weather conditions contributed to amplify the impact. In addition to the direct damage caused by fires, wildfire disturbances to forest resources may interact with biological invasions such as emerging plant pests and diseases [1, 3, 4].

For example, forests stressed by drought may be more vulnerable to insect attack, which in turn leads to large numbers of dead trees that are susceptible to fire. Temperature and drought stress have been correlated at regional scale with both abiotic and biotic disturbances (damage by wildfire and bark-beetle attacks [5, 6, 7]). Under climate change, the hazard will become higher than present, which means adaptation strategies are needed to avoid an increase in the devastating effects of forest fires on ecosystem functioning and biodiversity.

[1]See footnote 3.

▸ Assumptions

A number of factors contribute to forest fire occurrence, in particular weather and climate influence a network of other factors. For example, the moisture content of leaves on the ground's surface and of the deeper layers of organic matter: dryer or wetter surfaces can change the potential spreading of a fire, and also the ease of ignition; while the moisture level in the deeper layers reverberates into several aspects of soil and vegetation fuel. Climate variables such as wind speed are also important because they can affect the rate at which a fire might spread following ignition. Fire danger is influenced by weather in the short term, and by climate and its changes when considering longer time intervals.

In this work, the emphasis is on the direct influence on fire danger of weather and climate. However, other factors, such as vegetation conditions and composition, as well as human behaviour, are also important and affect the occurrence of fires in complex ways. Although the state of knowledge at the European scale for these aspects of fire danger is still qualitative and incomplete, it is possible to summarise core or emerging components of the heterogeneous information by offering a reasoned overview.

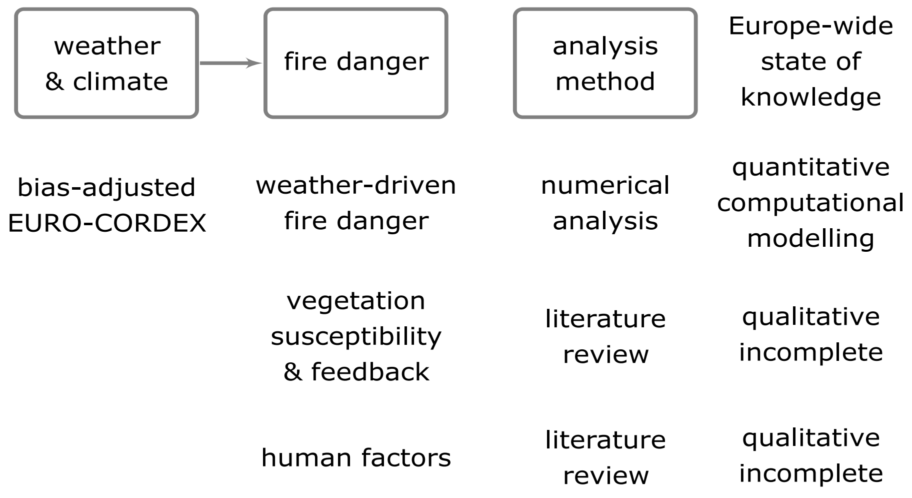
▸ Scenarios used

For the proposed climate analysis at the continental scale, a high-emission scenario was considered following the corresponding concentration trajectory adopted in the Fifth Assessment Report by the IPCC [8, 9, 10, 11]. The scenario focuses on a Representative Concentration Pathways (RCP) for which radiative forcing increase throughout the 21st century up to reach a high value (an approximate level of 8.5 W per m^2) by end of the century.

Even among predictions based on the same climate change scenario, different climate models predict variable climate patterns. The fire danger analysis was based on a regional downscaling of five global circulation models by means of three regional climate models (EURO-CORDEX downscaled climate data), with a further refinement of the simulated patterns of temperature and precipitation (bias-adjustment). Combined with the nonlinear relationship between climate and weather-driven fire danger, the variability of the five scenario instances resulted in a nonnegligible uncertainty in the estimated patterns of fire danger. However, considerable agreement among models was found over several European regions where fire danger is predicted to increase.

▸ Methodology and limitations

Several factor affecting fire danger are here considered. Concerning the direct influence on fire danger of weather and climate, particular attention is dedicated to how extreme weather patterns may evolve under climate change, through a robust analysis of fuel moisture and fire danger climate extremes. Literature reviews have been made of both the role of vegetation and forests (whose types, species composition and potential interaction with fires and other disturbances in Europe are quite variable [12, 13, 14, 15]), and the human component in the occurrence of wildfires, which is shown to have a role in a majority of cases.



A standardised index of weather-driven fire danger The Canadian Fire Weather Index (FWI) system is designed to provide a uniform numerical rating of the relative fire potential, by dynamically combining the information from local temperature, wind speed, relative humidity, and precipitation values. If a daily time series for each of these weather data variables is available, the system can process either actual observations or future simulated estimates.

The system relies on an array of six components which transform the input data into intermediate quantities that are then used to estimate the final aggregated index. Three of the components describe the state of the fuel (litter and organic layers, from the surface to the deeper levels of the soil) and the others are related to fire behaviour (rate of spread, intensity). The final index FWI is a standard aggregated numerical rating of fire intensity which takes into account the other components. The FWI system is standardised to consider the behaviour of a reference fuel type (mature pine stand), irrespective of other factors affecting fire danger such as the topography and the actual or future fuel details [16]. It is thus well suited to support harmonised comparisons between different regions, and different time intervals in the same region, to highlight the role of the varying climate in the resulting component of fire danger that is driven by weather.

Mitigating the uncertainty in fire damage data In addition to fire danger analysis under climate change, this work is also meant to contribute a systematic revision of available data to support future studies on climate-driven fire damage in Europe. The fire data considered in this work comprises monthly total burnt areas (excluding purely agricultural fires) for Portugal, Spain, Italy, Greece and the Mediterranean region of France, extracted from the EFFIS fire database which stores records of individual fire events. These five countries account for around 85 % of the total burnt area in Europe each year (Figure 1). As part of the data validation process, the data were compared with the official total figures reported annually by the same countries [17, 18, 19, 20, 21, 22] and gaps in the data for some years were identified for two countries. Estimates for the missing data were made using the known annual totals and allocating monthly proportions based on the patterns observed in years when the data were complete. This work establishes the necessary foundation for any future research to detect a robust relationship between fire danger and damage in the Mediterranean Europe.

Other sources of uncertainty, limitations There are a number of sources of uncertainty in wildfire modelling, as fire occurrence may additionally be linked with other, non-climatic factors that are also likely to change in the future. For example, while fires in Europe are mostly linked with human causes, there is a negative trend between observed mean fire size and population density [23, 24, 25]: fires near densely populated regions tend to be extinguished faster. There are also negative trends concerning cropland cover (possibly connected with landscape fragmentation [26]). Given the challenge of reliably projecting population, land use and cover, and their associated uncertainty under climate change scenarios, these relationships are difficult to assess.

▸ Main findings

Variability in rainfall, temperature, wind and humidity as a result of climate change – under the scenarios considered – will mean that the fuel moisture of deep layers of wood, leaves, soil and other organic matter on the ground will be affected (Figure 2). Around the Mediterranean region, climate change reduces fuel moisture levels from present values. The region becomes drier, making the weather-driven danger of forest fires higher. Furthermore, areas exhibiting low moisture extend further northwards from the Mediterranean than present, as a result of climate change. The area of high fuel moisture surrounding the Alps in the present climate decreases in size with climate change. Although the projected declines in moisture for Mediterranean countries are smaller with mitigation that limits global warming to 2 °C, relative to the high emissions scenario, moisture levels are still predicted to be lower than at present.

There is a clear north-south pattern of deep fuel moisture variability across Europe in the two climate change scenarios. It is a pattern also projected in another PESETA III study that investigated the impact of climate change on soil moisture levels, by using a hydrological model [27]. Since the focus here is on assessing a standardised response of fuel and fire danger to climate, that model is not used here, which indicates that the pattern is consistent across the different applications which consider ground moisture, aridity and drought indices in PESETA III [27, 28, 29, 30].

Whilst there is some uncertainty in the magnitude of the effect of climate change, it is clear that the danger of forest fires driven by weather increases with climate change around the Mediterranean (Figure 3). The three countries with the highest danger are Spain, Portugal and Turkey. Greece, part of central and southern Italy, Mediterranean France, and the coastal region of the Balkans also show an increasing danger both in relative and absolute terms.

Areas at moderate danger from forest fires are pushed north by climate change, up to central Europe. There is relatively little change in fire danger as directly driven by weather due to climate change across northern Europe.

To complement the fire danger climatic analysis, a literature review is summarised on the response, resilience and adaptation potential of vegetation, plant communities and ecosystems to changing fire danger and fire regimens. Human causes of forest fires are also reviewed, as well as forest management measures to mitigate their impact.

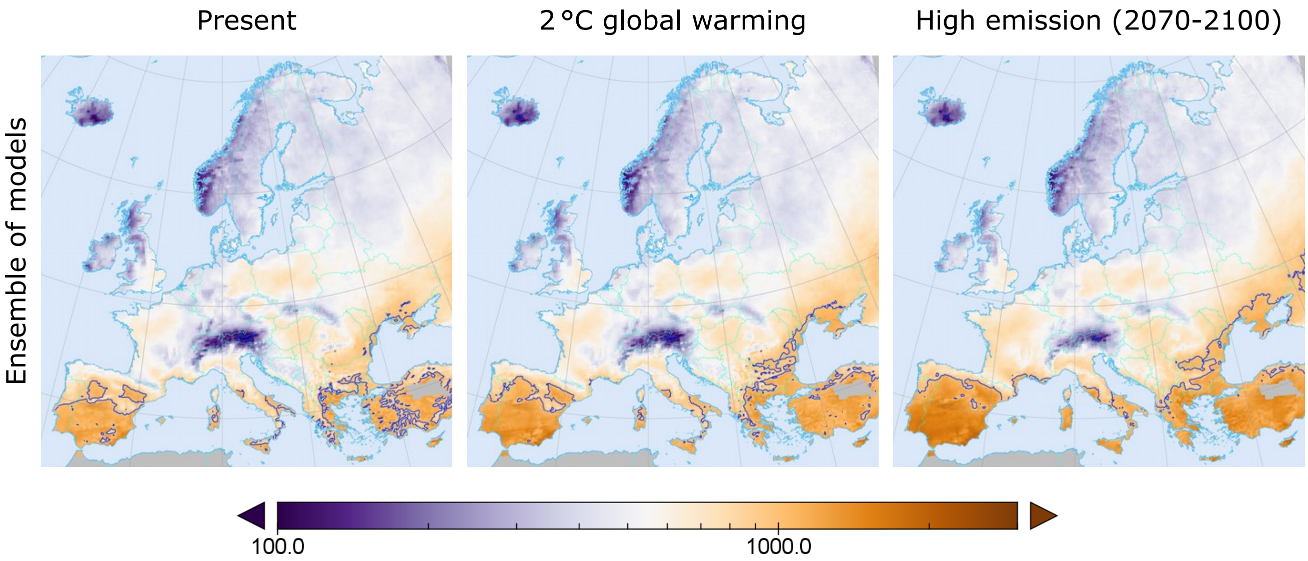


Figure 2: Seasonal drought effects on fuel moisture of the deeper layer of more compact organic matter in the ground, as estimated by a specific component of the Canadian Forest Fire Weather Index system (FWI) in present, and under two climate change scenarios. Contour lines denote corresponding orders of magnitude on the logarithmic scale (10, 100, 1000). Median values across five climate models. More details may be found in Figure 10.

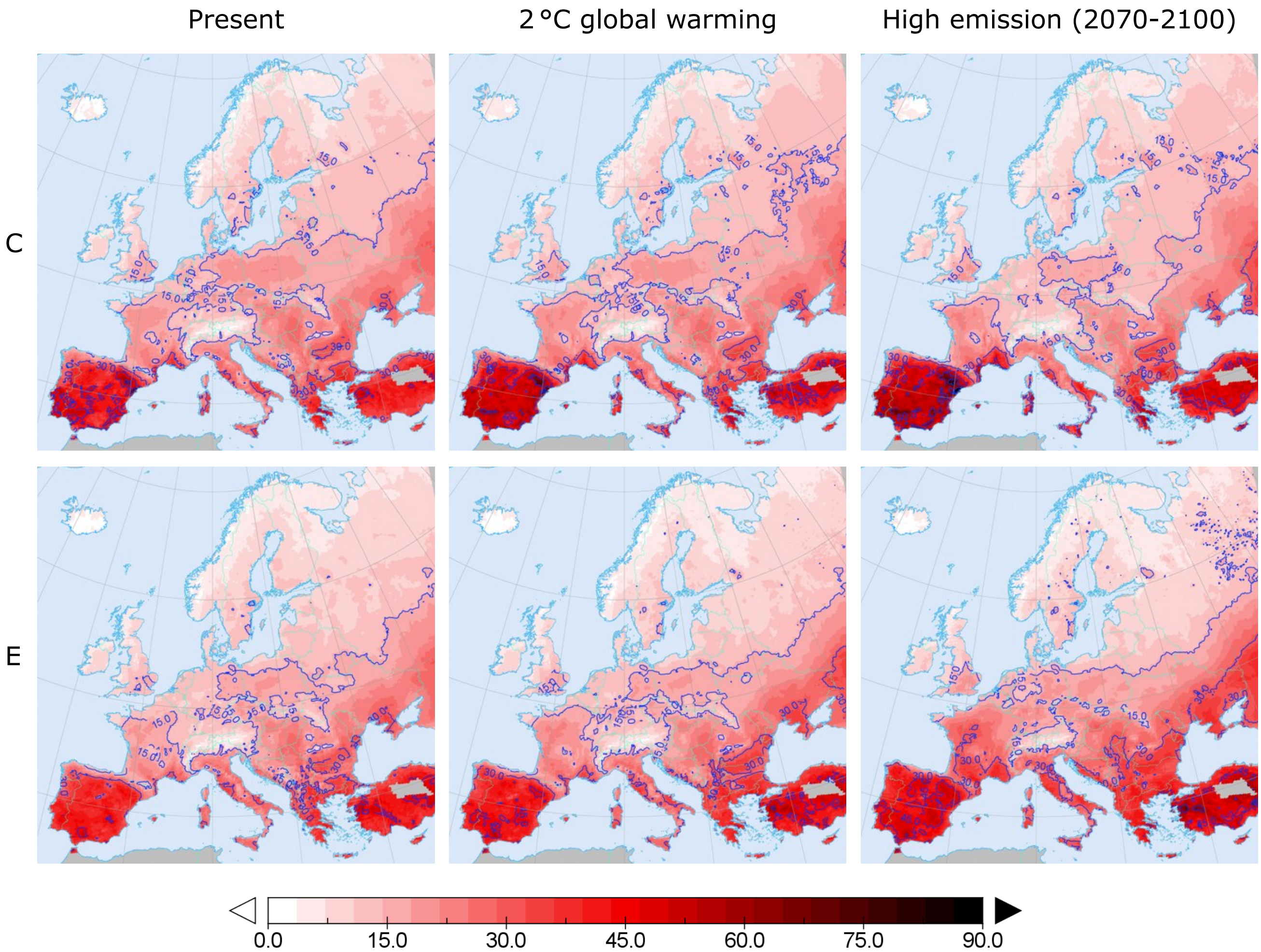


Figure 3: Overall weather-driven forest fire danger in present, and under two climate change scenarios, according to two different climate models (C,E, see Table 3), selected to demonstrate the effect of using different climate models. Contour lines denote increments by 15 units of the index. Figure used in [30]. More details may be found in Figure 8.

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This publication benefited from the peer-review of the PESETA III project[2] with the comments and suggestions of its advisory board and the other external referees.

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We also acknowledge the Earth System Grid Federation infrastructure, an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

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[2] https://ec.europa.eu/jrc/en/peseta .

Abstract

Forests cover over a third of the total land area of Europe. In recent years, large forest fires have repeatedly affected Europe, in particular the Mediterranean countries. Fire danger is influenced by weather in the short term, and by climate when considering longer time intervals. In this work, the emphasis is on the direct influence on fire danger of weather and climate.

For climate analysis at the continental scale, a daily high-emission scenario (RCP 8.5) was considered up to the end of the century, and a mitigation scenario that limits global warming to 2 °C was also assessed. To estimate fire danger, the Canadian Fire Weather Index (FWI) system was used. FWI provides a uniform numerical rating of relative fire potential, by combining the information from daily local temperature, wind speed, relative humidity, and precipitation values. The FWI is standardised to consider a reference fuel behaviour irrespective of other factors. It is thus well suited to support harmonised comparisons, to highlight the role of the varying climate in the component of fire danger that is driven by weather.

Results Around the Mediterranean region, climate change will reduce fuel moisture levels from present values, increasing the weather-driven danger of forest fires. Furthermore, areas exhibiting low moisture will extend further northwards from the Mediterranean, and the current area of high fuel moisture surrounding the Alps will decrease in size. Projected declines in moisture for Mediterranean countries are smaller with mitigation that limits global warming to 2 °C, but a worsening is still predicted compared with present.

There is a clear north-south pattern of deep fuel moisture variability across Europe in both climate change scenarios. Areas at moderate danger from forest fires are pushed north to central Europe by climate change. Relatively little change is expected in weather-driven fire danger across northern Europe. However, mountain systems show a fast pace of change.

Adaptation options Key strategies to be considered may include vegetation management to reduce the likelihood of severe fires, as well as fuel treatments to mitigate fire hazard in dry forests. These measures should be adapted to the different forest ecosystems and conditions.

Limited, preliminary knowledge covers specific but essential aspects. Evidence suggests that some areas protected for biodiversity conservation may be affected less by forest fires than unprotected areas, despite containing more combustible material. Specific typologies of old-growth forests may be associated with lower fire severity than densely stocked even-aged young stands, and some tree plantations might be more subject to severe fire compared with multi-aged forests. Particular ecosystems and vegetation associations may be better adapted for post-fire recovery, as long as the interval between fires is not too short. Therefore, deepening the understanding of resistance, resilience and habitat suitability of mixtures of forest tree species is recommended.

Human activity (accidental, negligent or deliberate) is one of the most common causes of fire. For this reason, the main causes of fire should be minimized, which includes analysing the social and economic factors that lead people to start fires, increasing awareness of the danger, encouraging good behaviour and sanctioning offenders.

Limitations Bias correction of climate projections is known to be a potential noticeable source of uncertainty in the predicted bioclimatic anomalies to which vegetation is sensitive. In particular, the analysis of fire danger under climate change scenarios may be critically affected by climatic modelling uncertainty. This work did not explicitly model adaptation scenarios for forest fire danger because ecosystem resilience to fire is uneven and its assessment relies on factors that are difficult to model numerically. Furthermore, a component of the proposed climate-based characterization of future wildfire potential impacts may be linked to the current distribution of population, land cover and use in Europe. The future distribution of these factors is likely to be different from now.

1 Introduction

Forests cover about 215 million ha in Europe (approximately 33 % of total land area), and an additional 36 million ha are covered by other wooded lands ([1]; statistics from the Ministerial Conference on the Protection of Forests in Europe, [2]). In 2010 alone, wildfires were responsible for the damage of 0.5 million ha in European forests [1, 2]. In the current year 2017, in November the cumulated annual burnt area of Portugal, Spain and Italy was higher than 0.8 million ha[3].

Variability of fire damage in Europe In recent years, large forest fires have repeatedly affected the continent, in particular the Mediterranean countries [17, 18, 19, 20, 21, 22, 31]. Figure 4 shows a comparison between the annual burnt area in five EU-Med countries (Portugal, Spain, Italy, Greece and the Mediterranean region of France) and in another 12 countries – based on data from the Fire Database of EFFIS ([32, 17], country-provided information here updated to 2016, the most recent consolidated revision). In the five EU-Med countries alone, the average damage between 1999 and 2016 was more than 400 thousand ha, and above 700 thousand ha one year in five. The variability of the fire damage is evident with years in which the weather conditions contributed to amplify the impact. However, some years show higher than average damage – with different absolute scales of intensity – in both the EU-Med region and in several other countries. Other years highlight regional patterns (e.g. medium or high damage in the EU-Med region with minor impacts elsewhere).

Figure 5 shows instead the relative proportion of the burnt area for the same five EU-Med countries and the 12 other countries. Patterns are evident where disproportional damage affects specific group of countries. This may be appreciated both in the EU-Med region and in the other countries. For example, within EU-Med countries the years 2003, 2005, and 2010 show comparable proportions even if with a variable absolute (hectares, see Figure 4) intensity of damage. The years 2000, 2007-8, and 2014 show another pattern of damage proportions among EU-Med countries. Clusters of regional patterns are evident even in the other countries. These spatial (regional) and temporal (annual) patterns underline the extent of variability of the fire damage in Europe. A multiplicity of factors has been correlated with this variability.

European wildfires, weather and climate Weather and climate are among the main factors influencing wildfire potential [33, 34]. In the Mediterranean areas of Europe, precipitation and soil moisture appear among the most relevant factors associated with spatial patterns of fire occurrence [35, 36]. Fernandes *et al.* [37] correlated large wildfires in Portugal with forest areas subject to extreme weather conditions, combined with high fuel hazard and subsequent fast fire spread. Ruffault *et al.* [38] found the occurrence of large wildfires in the Mediterranean France primarily driven by a "wind-forced mode" [39, 40] during weather conditions which tend to increase dry surface winds. They also found another category of weather conditions leading to large fires, "occurring with comparatively weak winds but hotter weather". In Greece, Karali *et al.* [41] underlined the impact of high temperature and wind speed on critical fire danger, while Founda and Giannakopoulos [42] linked the extensive and destructive forest fires occurred in Greece during 2007 with the extreme hot summer and a co-occurring prolonged drought. In Italy, Cardil *et al.* [43] analysed heat waves in Sardinia, finding a clear relationship between high-

[3]Data from the European Forest Fire Information System (EFFIS), http://effis.jrc.ec.europa.eu. The underpinning methodology for the fire damage assessment is accessible at http://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-damage-assesment.

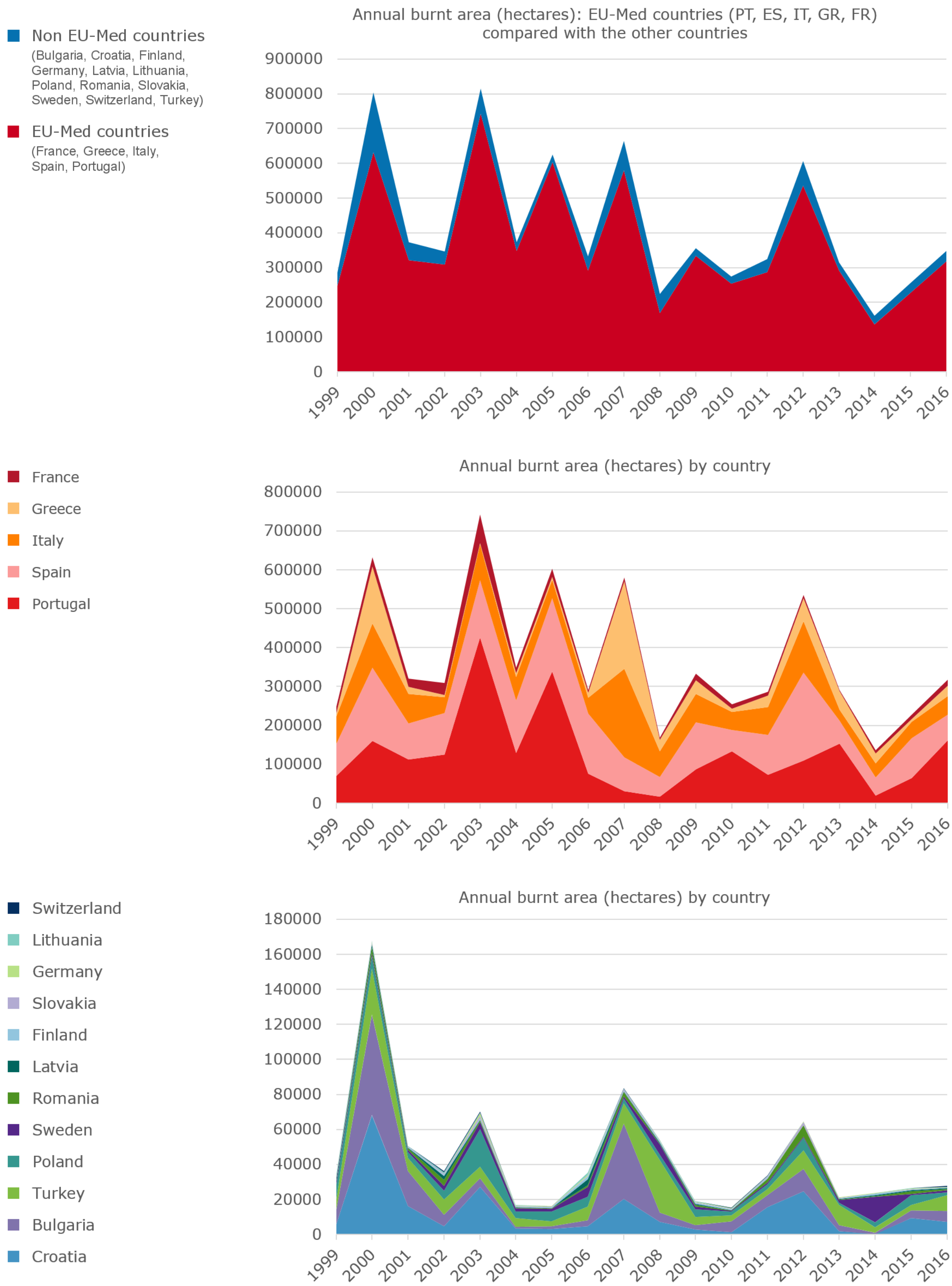

Figure 4: **Top**: annual burnt area (hectares) of five EU-Med countries (France, Greece, Italy, Portugal, Spain) and of 12 other countries (see legend). Country-reported data from the Fire Database of EFFIS [32, 17]. For comparison, in the current year 2017 – end of October – the provisional cumulated annual burnt area was about 900000 ha in the five EU-Med countries, and over one million ha considering even the 12 other countries (EFFIS fire damage assessment, see footnote 3). **Middle**: total annual hectares burnt for each of the EU-Med countries. **Bottom**: total annual hectares burnt for each of the other countries. The interannual variability is evident. However, some years (e.g. 2000, 2003, 2007, and 2012) show higher than average damage – with different absolute scales of intensity – in both the EU-Med region and in several other countries. Other years (e.g. 2005, 2009, and 2016 concerning the EU-Med region) highlight regional patterns (e.g. medium or high damage in the EU-Med region with minor impacts elsewhere). Countries sorted by total burnt-area.

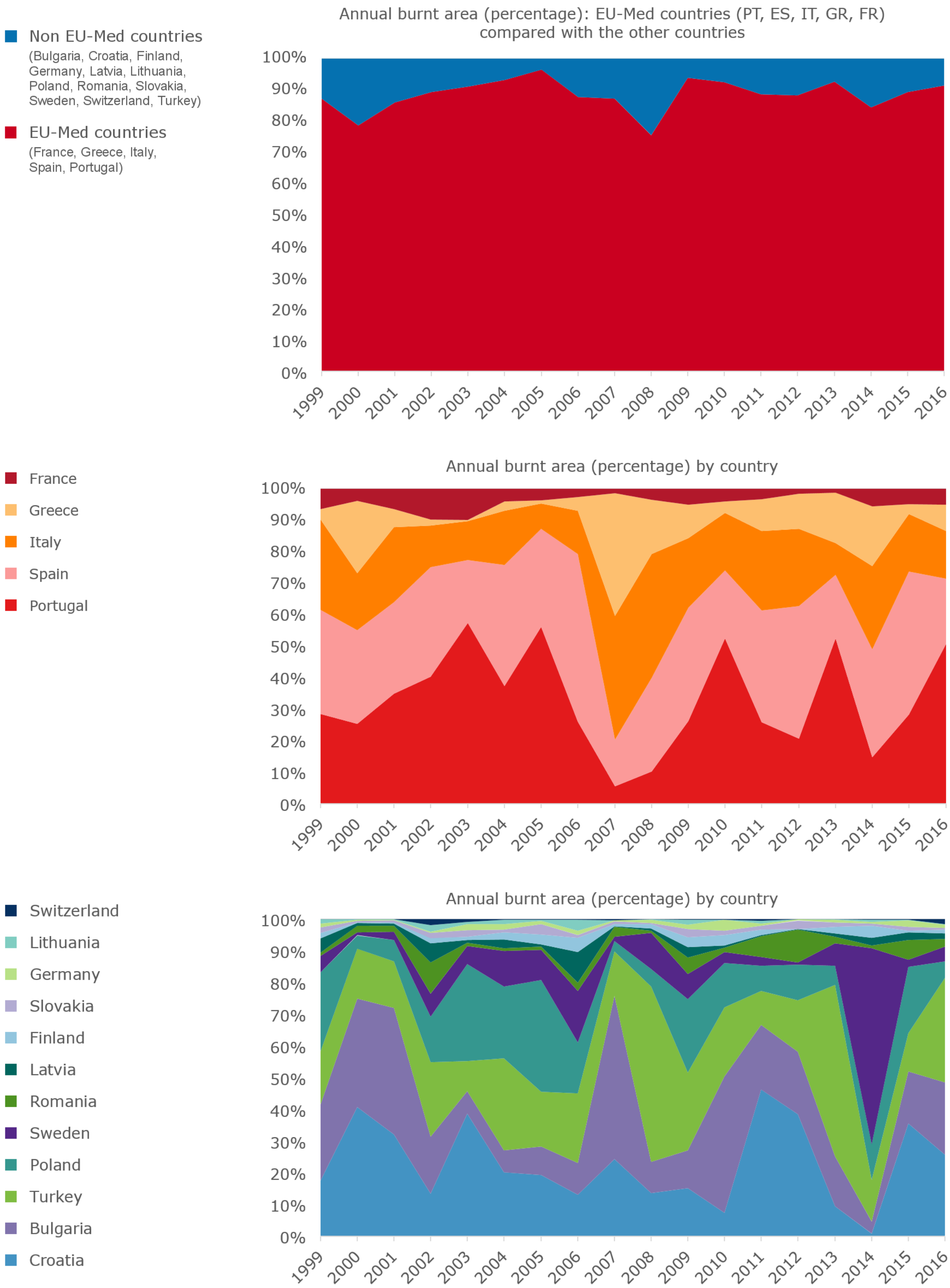

Figure 5: **Top**: annual burnt area (relative proportion) of five EU-Med countries and of 12 other countries (see legend). Country-reported data from the Fire Database of EFFIS [32, 17]. Percentage of burnt area per year, where 100 % represents the total annual burnt area of all the 17 countries. **Middle**: relative proportion with the aggregated total of the EU-Med countries of the annual burnt area of each EU-Med country. **Bottom**: as in the middle diagram, but for non EU-Med countries. Patterns are evident where disproportional damage affects specific group of countries. This may be appreciated both in the EU-Med region and in the other countries. For example, within EU-Med countries the years 2003, 2005, and 2010 show comparable proportions even if with a variable absolute (hectares, see Figure 4) intensity of damage. The years 2000, 2007, and 2014 show another pattern of damage proportions among EU-Med countries. Comparable clusters of regional patterns are evident even in the other countries. Countries sorted by total burnt-area.

temperature days and burnt area due to large wildfires. In Spain, De Luís *et al.* [44] suggest that a decrease in the average annual precipitation may have increased the fire frequency and the areas of higher fire danger, with potential repercussions on soil degradation and desertification patterns.

Wildfires in a broader context of ecosystem disturbances Wildfire disturbances to forest resources may interact with biological invasions such as emerging plant pests and diseases [4, 1, 3, 45, 46]. The changing pattern of bioclimatic conditions may unevenly alter the habitat suitability of different forest tree taxa with a potential further diversification of fire ecology and impacts among plant communities and forest types [47, 48, 49]. Seidl *et al.* [50] report that in the last decades, changes in the European forests co-occurred with the already changing climate and contributed to intensify the effect of forest disturbances. They review several components associated with climate change which may be expected to intensify the wildfire response as well as the occurrence of some biotic disturbances such as bark beetles.

Temperature and drought stress have been correlated at regional scale with both abiotic and biotic disturbances (damage by wildfire and bark-beetle attacks [5, 6, 7]). Even temperate forests appear as affected by a climate-driven exacerbation of these disturbances [51]. In Europe, Seidl *et al.* [52] assessed for the first decade of the twenty-first century forest-fire timber damage greater than $9 \cdot 10^6\,\mathrm{m}^3$ per year and noticed how intensifying forest disturbance regimes due to climate change may affect the function of forests as a carbon sink while also impacting on a broad variety of ecosystem services (see also Figure 16 and de Rigo *et al.* [1]).

2 Weather, climate and fire danger: the Canadian Forest Fire Weather Index system

Fire danger may be quantitatively defined as a rating index to support the assessment of the factors which determine the ease of ignition, rate of spread, difficulty of control and fire impact [53, 16]. The study of fire danger rating systems and their relationship with weather patterns has been active for several decades and is strategic in the many countries where forest resources, their management and sustainability play a vital role [54, 55, 56, 57, 58].

For example, in Canada the research on forest fire danger rating began in 1925, leading over the years to the development of multiple fire danger systems with increasing general applicability across the Canadian forests [59]. In particular, the effort to account for the effects of weather on forest fuel and fire [16] was at the basis for the definition of the Canadian Forest Fire Weather Index (FWI) system, which dates back to 1970 following several years of research in the Canadian Forestry Service, to also incorporate some of the best features from the previous Canadian fire danger indices [59].

The Canadian FWI system has been exploited by several authors to correlate climate change with expected changes in fire severity and damage [60, 61]. In Portugal, Carvalho *et al.* [62] found a highly significant relationship between FWI and forest fires, and large wildfires have recently been assessed in relation with the FWI-system components and their quantile distribution [37]. In south-eastern France, Fréjaville and Curt [63] demonstrated the predictive ability of the FWI system, while fire occurrence in Crete, Greece, was correlated with FWI by Dimitrakopoulos *et al.* [64]. The FWI contributed to highlight a "positive signal of fire danger potential over large areas

Table 1: Main characteristics nominally associated with the Fire Weather Index (FWI) system fuel moisture codes [59, 16]. Fuel moisture codes are the subset of dynamic D-TM components supporting the FWI ability to integrate multiple conceptual layers of fuel and their corresponding time scales spanning over orders of magnitude. Timelag is a qualitative measure of the nominal rate at which fuels lose moisture (see footnote 5). See Eqs. 1a-1c and the matrix 4 for an overview of the fire weather variables processed by each D-TM module. Each fuel moisture code is computed for a specific spatial cell c and time t, generating a different time series for each climate scenario realisation *scen* (see Section modelling structure and semantics).

Fuel moisture code	Fine Fuel Moisture Code $FFMC_{c,t}^{\mathrm{scen}}$ (Eq. 1a)	Duff Moisture Code $DMC_{c,t}^{\mathrm{scen}}$ (Eq. 1b)	Drought Code $DC_{c,t}^{\mathrm{scen}}$ (Eq. 1c)
Typology of moisture content	Top litter layer. Litter, other cured fine fuels (needles, mosses, twigs < 1 cm in diameter)	Duff layer. Moderate depth, loosely compacted layers with decomposing organic matter	Deeper layer of more compact organic matter
Timelag [days]	2/3 (16 hours)	12	52
Approx. water capacity [mm]	0.6	15	100
Approx. fuel load [kg/m^2]	0.25–0.5	5	25–44

of the Mediterranean" [65]. Di Giuseppe *et al.* [58] recently reported that in wide areas of the Earth the FWI appears suitable to identify dangerous conditions for potential fire events.

3 Modelling architecture: assessing the climatic signal of fire danger potential

The Canadian FWI system is designed to provide a uniform numerical rating of the relative fire potential, by dynamically combining the information from local temperature, wind speed, relative humidity, and precipitation (24-hour rainfall) values.

Provided a daily time series for each of these weather data variables is available, the system is capable to process either actual observations or future simulated estimates. The FWI system is standardised to consider the behaviour of a reference fuel type (mature pine stand), irrespective of other factors affecting fire danger such as the topography and the actual or future fuel details and other anthropogenic aspects [16].

3.1 Key concepts

The system relies on an array of six components which transform input data into intermediate quantities then exploited to estimate the final aggregated index. These conceptual modelling units are here referred as data-transformation modules (D-TM) [66, 67, 68] and belong to two groups: three fuel moisture codes and three fire behaviour indices [16, 59]. A detailed description of the D-TM components in the FWI-system and the logics behind their chain of data-transformations may be found in Van Wagner [59], De Groot [16], and the corresponding computational aspects in Van Wagner and Pickett [69], Wang *et al.* [70], de Rigo [71].

Here, a synopsis of the semantics associated with each D-TM is summarised to highlight the different role of the weather data and the propagation of the related information. This is essential to understand how the scenario analysis of changing climate reverberates in a complex network of FWI-system information flows. The fuel moisture codes model the daily changes in the moisture contents of three classes of forest fuel with different temporal inertia (see Table 1):

Fine Fuel Moisture Code (FFMC) It provides a numerical rating of the moisture content of the top litter and other cured fine fuels, indicating the relative ease of ignition and flammability of fine fuel.

Duff Moisture Code (DMC) It models a standard moisture content of loosely-compacted organic layers of moderate depth (duff layers and medium-sized woody material).

Drought Code (DC) It models a standard moisture content of deeper, compact, organic layers. This D-TM is able to track seasonal drought effects on forest fuels.

The fire behaviour indices mathematically are stateless D-TM components. This means that they are without an internal memory of the past conditions, while instead they rely on the combined information offered by the different temporal inertia of the fuel moisture codes, which they process as input information (see also the information workflow matrix 4):

Initial Spread Index (ISI) It represents the expected rate of fire spread. It considers the combined effects of wind and the FFMC on the rate of spread. However, it excludes the influence of variable quantities of fuel.

Buildup Index (BUI) It combines DMC and DC to model the total amount of fuel available for combustion to the spreading fire.

Fire weather Index (FWI) It offers a standard aggregated numerical rating of fire intensity which combines ISI and BUI.

3.2 Modelling structure and semantics

The FWI system requires, to be modelled under different scenario realisations, a multiplicity of modelling dimensions. First, the aforementioned array of weather data which varies in space and time for each scenario realisation – each driven by a corresponding combination of global and regional climate models. Second, the array of components of the FWI system, their interactions and the logical constraints among the array of variables to be respected within each D-TM. This set of quantities and relations may be formalised following the Semantic Array Programming (SemAP) paradigm [72, 73, 68] and its geospatial application [67, 68]. The array of weather data may be defined as:

$P_{c,t}^{\text{scen}}$	Precipitation [mm]
$RH_{c,t}^{\text{scen}}$	Relative humidity [dimensionless]
$T_{c,t}^{\text{scen}}$	Temperature [°C]
$w_{c,t}^{\text{scen}}$	Wind speed [km/h]
$\text{month}(t)$	Month of the year

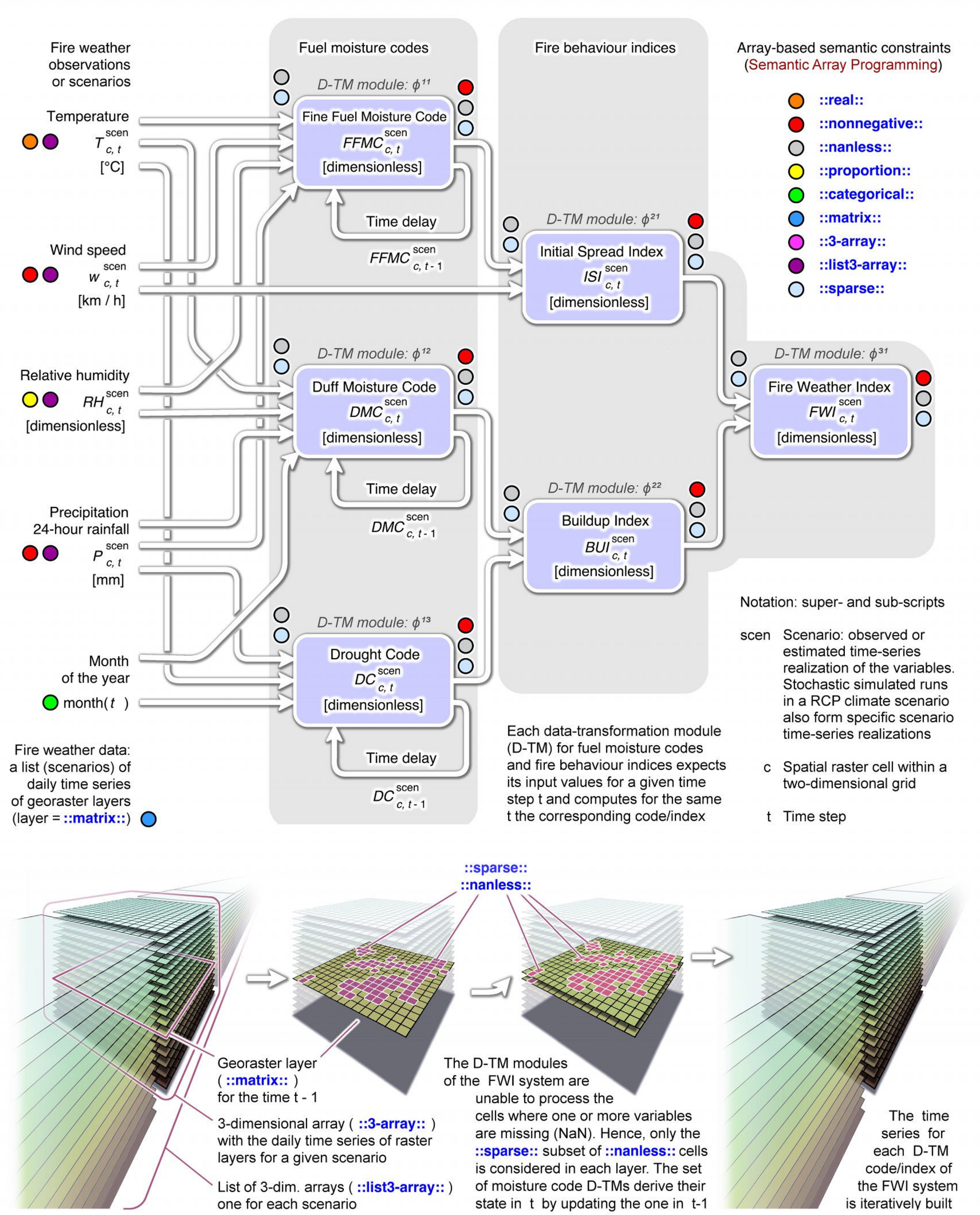

Figure 6: Modelling architecture for the application of the Canadian Forest Fire Weather Index system (FWI) to assess the climatic signal of fire danger potential in Europe. From: de Rigo [71]. The compact notation is exploited from the Semantic Array Programming (SemAP) approach [72, 73, 68] and its gnal of fire danger potential in Europe. From: de Rigo [71]. The compact notation is exploited from the geospatial application [67, 68] (see footnote 4).

where

- scen is a given scenario instance, defined as either an observed (i.e. historical data) or estimated time series which corresponds to a particular realisation of the variables. A scenario time-series realisation $\{P, RH, T, w\}_{\cdot,\cdot}^{\text{scen}}$ spans over the entire spatial extent and covers a certain temporal range (for example, the historical time interval is 1961-2005 while the future climate projections cover the years 2006-2100 [74]). It is for example the output of a particular stochastic simulated run generated by combining a specific general circulation model, regional climate model (and potentially a subsequent specific bias correction procedure, for the supported variables) for a given climate scenario (e.g. the more recent high-emission scenario from the Intergovernmental Panel on Climate Change [75, 76, 77]).
- c is a given spatial cell in the two-dimensional raster grid of the fire weather variables. The grid follows the one of the climate models.
- t is a given daily time step.
- month(t) is a stateless data-transformation which converts a given time t into a numeric integer ::index::[4] associated to its corresponding month of the year.

The FWI system is composed of the six components:

$FFMC_{c,t}^{\text{scen}}$	Fine Fuel Moisture Code [dimensionless]
$DMC_{c,t}^{\text{scen}}$	Duff Moisture Code [dimensionless]
$DC_{c,t}^{\text{scen}}$	Drought Code [dimensionless]
$ISI_{c,t}^{\text{scen}}$	Initial Spread Index [dimensionless]
$BUI_{c,t}^{\text{scen}}$	Buildup Index [dimensionless]
$FWI_{c,t}^{\text{scen}}$	Fire Weather Index [dimensionless]

Structure and semantics of the workflow Irrespective of the details on the actual data transformations operated within each module, the overall workflow of weather information required by the fuel moisture codes may be summarised in Figure 6 by three D-TM module interfaces described as ϕ functions in the following equations (variables aligned for better readability):

$$FFMC_{c,t}^{\text{scen}} = \phi^{1,1}(\ FFMC_{c,t-1}^{\text{scen}}, T_{c,t}^{\text{scen}}, w_{c,t}^{\text{scen}}, RH_{c,t}^{\text{scen}}, P_{c,t}^{\text{scen}}\ ) \tag{1a}$$

$$DMC_{c,t}^{\text{scen}} = \phi^{1,2}(\ DMC_{c,t-1}^{\text{scen}}, T_{c,t}^{\text{scen}}, RH_{c,t}^{\text{scen}}, P_{c,t}^{\text{scen}}, \text{month}(t)\ ) \tag{1b}$$

$$DC_{c,t}^{\text{scen}} = \phi^{1,3}(\ DC_{c,t-1}^{\text{scen}}, T_{c,t}^{\text{scen}}, P_{c,t}^{\text{scen}}, \text{month}(t)\ ) \tag{1c}$$

[4] Here the compact notation from the SemAP approach is exploited. A given semantic constraint *sem* is expressed with the notation ::<sem>:: and a corresponding formal description of the constraint may be accessed in the associated active link [78]. See Figure 6 for an overview.

The estimated fuel moisture codes are then processed by two intermediate fire behaviour indices (see Figure 6):

$$\begin{aligned} \mathit{ISI}^{\text{scen}}_{c,t} &= \phi^{2,1}(\ \mathit{FFMC}^{\text{scen}}_{c,t}, \quad w^{\text{scen}}_{c,t}\ ) \\ &= \phi^{2,1}(\ \phi^{1,1}, \quad w^{\text{scen}}_{c,t}\ ) \end{aligned} \tag{2a}$$

$$\begin{aligned} \mathit{BUI}^{\text{scen}}_{c,t} &= \phi^{2,2}(\ \mathit{DMC}^{\text{scen}}_{c,t}, \mathit{DC}^{\text{scen}}_{c,t}\ ) \\ &= \phi^{2,2}(\ \phi^{1,2}, \quad \phi^{1,3}\ ) \end{aligned} \tag{2b}$$

Finally, the estimates from $\mathit{ISI}^{\text{scen}}_{c,t}$ and $\mathit{BUI}^{\text{scen}}_{c,t}$ are aggregated in a single derived index:

$$\begin{aligned} \mathit{FWI}^{\text{scen}}_{c,t} &= \phi^{3,1}(\ \mathit{ISI}^{\text{scen}}_{c,t}, \mathit{BUI}^{\text{scen}}_{c,t}\ ) \\ &= \phi^{3,1}(\ \phi^{2,1}, \quad \phi^{2,2}\ ) \end{aligned} \tag{3}$$

The following workflow matrix summarizes the input information (weather data and intermediate derived quantities) which each D-TM module $\{\phi^{1,1}, \cdots, \phi^{3,1}\}$ processes. The time delay applied to some quantities is indicated:

	$T^{\text{scen}}_{c,\cdot}$	$w^{\text{scen}}_{c,\cdot}$	$RH^{\text{scen}}_{c,\cdot}$	$P^{\text{scen}}_{c,\cdot}$	month$(\cdot)$	$\phi^{1,1}$	$\phi^{1,2}$	$\phi^{1,3}$	$\phi^{2,1}$	$\phi^{2,2}$	$\phi^{3,1}$
$\phi^{1,1}$	t	t	t	t		$t-1$					
$\phi^{1,2}$	t		t	t	t		$t-1$				
$\phi^{1,3}$	t			t	t			$t-1$			
$\phi^{2,1}$		t				t					
$\phi^{2,2}$							t	t			
$\phi^{3,1}$									t	t	

(4)

Structure and semantics of the dynamic components The first layer of D-TM components within the FWI system ($\phi^{1,1}$, $\phi^{1,2}$, $\phi^{1,3}$) is of particular interest to understand the propagation and time latency of the climate signal within the remaining layers of FWI-system components. The first D-TM layer is composed of dynamic sub-systems which update their state from the value in the previous time step with the information available in the current time step (see first layer components in the matrix 4).

For each of these components, the dynamic behaviour is characterised by the changes to the moisture state associated with the corresponding fuel (litter and other cured fine fuel for $\phi^{1,1}$;

loosely compacted, decomposing organic matter for $\phi^{1,2}$; and a deep layer of compact organic matter for $\phi^{1,3}$). The changes of the moisture state for all the first-layer FWI-system components follow the drying or wetting of the corresponding fuel. Despite this structural similarity, the three components are designed to account for quite different drying speeds. As a proper measure of the specific drying speed of each component, the *timelag*[5] has been proposed [59]. Table 1 summarises these core dynamic characteristics.

4 Climate analysis

The complex chain of feedbacks between climate and wildfires displays a large set of uncertainties with nonnegligible variability even among predictions based on the same climate change scenario but derived after different climate models [79].

Unfortunately, currently emissions appear to slightly exceed the highest emission scenario within the more recent set of scenarios considered by the Intergovernmental Panel on Climate Change (IPCC) [77, 76]. Actually, one of the more optimistic IPCC scenarios has been recently discarded by some studies given its questioned feasibility [80, 81, 77]. A recent study based on past emissions as proxy information to "implicitly account for accumulating legislation and regulation over the past 30 years since climate change became a global issue" highlighted the need for rapid reductions in emissions to limit below 2 °C the global temperature increase by the end of the century [82]. Despite the efforts, in 2017 the global-scale carbon emissions are expected to increase by 2 % [83, 84, 85, 86], with time "running out on our ability to keep global average temperature increases below 2 °C and, even more immediately, anything close to 1.5 °C" [86]. A recent work assessed the Intended Nationally Determined Contributions (INDCs) of 188 countries in the context of the Paris Agreement, concluding that from INDCs "in the best of cases, annual world emissions would increase by around 19.3 % in 2030" and that if "this level remain constant between 2030 and 2050, the world temperature would increase by at least 3 °C" [87]. In addition, a study by Brown and Caldeira [88] on global warming inferred from recent global energy budget suggests that the IPCC scenarios may underestimate the future average pattern of warming.

Within this context, understanding the broad spectrum of potential consequences of a sustained trend of high carbon emissions on wildfire danger (and their linkage with vegetation and anthropic factors) is pertinent [89]. Therefore, for the proposed climate analysis at the continental scale a high-emission scenario has been considered following the corresponding concentration trajectory adopted in the Fifth Assessment Report by the IPCC [9, 10, 11, 90].

The current understanding of the climate system components derives from combining observations, studies of feedback processes, and model simulations. As a background reference, some general consequences of the current and imminent state of the Earth system are supported by a broad agreement of the scientific community. Irrespective of the considered scenario, the IPCC underlined how it is "virtually certain that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean

[5] The *timelag* associated with a certain drying speed may be defined as the required time to lose a standard share of the free moisture content above equilibrium, where the default share is conventionally set to $(1 - 1/e)$, i.e. approximately two thirds of the free moisture [59]. The reference weather conditions here refer to a noon temperature of 21 °C, relative humidity of 45 %, and a wind speed of 13 km/h [16].

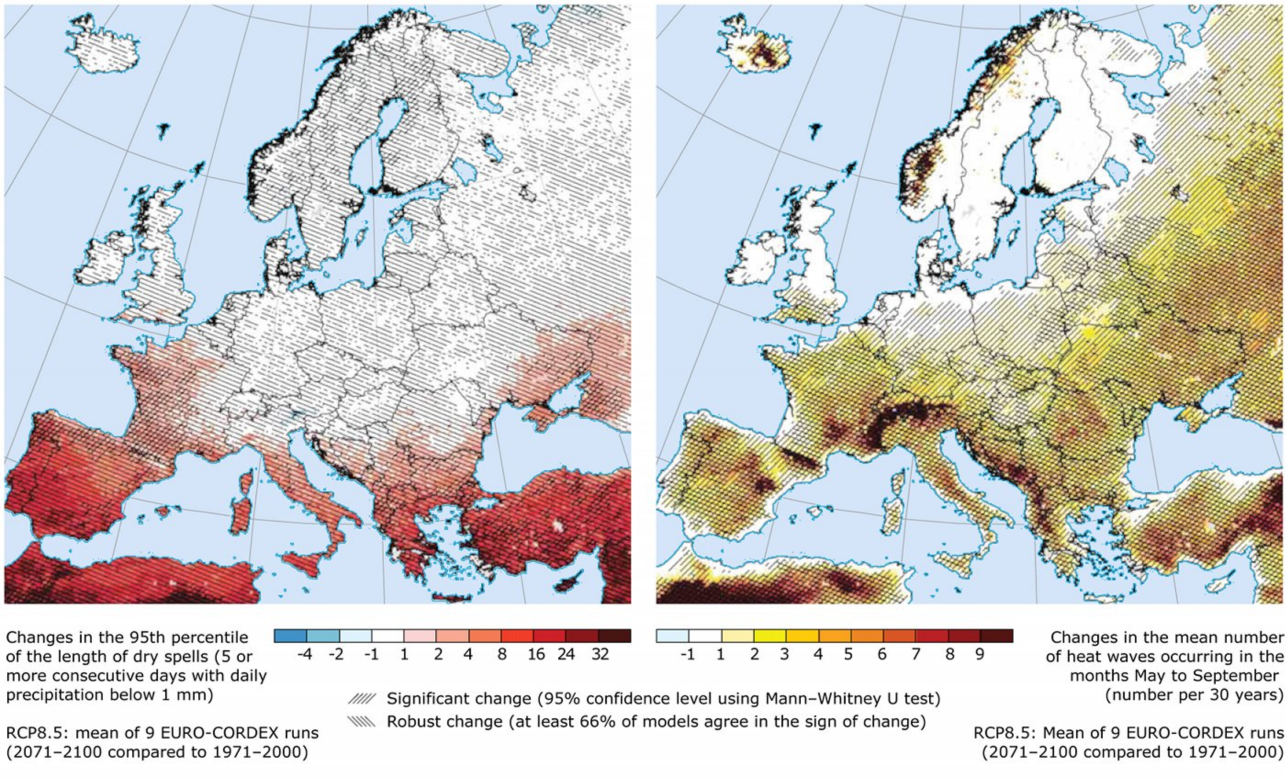

Figure 7: Average over 9 EURO-CORDEX regional model simulations for the RCP8.5 scenario. Adapted after Kovats *et al.* [91], Jacob *et al.* [92]. The period 2071–2100 is compared to 1971–2000 (instead of the interval 1981-2010 considered as Control period in this study, Table 4). *Left*: estimated behaviour of the longer dry spells (dry spells are here defined as time intervals of at least 5 consecutive days with daily precipitation below 1 mm). Long dry spells are associated with FWI-system dynamic components such as $DMC_{c,t}^{\mathrm{scen}}$ and $DC_{c,t}^{\mathrm{scen}}$ [93] and may be linked to increased fire hazard [94, 95, 96, 97]. In particular, the map illustrates the projected changes (in number of days) for the dry spells in the 95th percentile of length. *Right*: estimated increment in the number of heat waves during the months May to September (expressed in number of heat waves per 30 years). Heat waves are here defined as time intervals of more than 5 consecutive days where the daily average temperature is at least 5 °C above the mean maximum temperature of the May to September season in the control (here, the years 1971–2000). Heat waves are associated with a clear pattern of increased fire activity [98, 7, 99, 100]. These maps may be compared with the statistics in Figure 8 referring to the time period Long-term (see Table 4).

temperatures increase. It is very likely that heat waves will occur with a higher frequency and duration" [11]. Several studies estimated for Europe a faster warming of high-percentile summer temperatures compared with mean temperatures [11].

4.1 High-emission scenario analysis in Europe

High-emission scenarios are among the more worrying for the predicted increase of heat waves and long dry spells in the European continent. Kovats *et al.* [91] and Jacob *et al.* [92] estimated the long term effect of high emissions on these extreme weather events (see Figure 7, which may be compared with the results on fire danger for the Long-term time period in Figure 8 and Figure 12), highlighting a strongest expected impact in Southern Europe – even if the number of heat waves is predicted to increase all over Europe. A global analysis by Russo *et al.* [101] similarly concluded that heat waves, from exceptional events, may become much more frequent in the southern part of Europe [101]. This would be a worrying trend even considering only their association with a clear pattern of increased fire activity [98, 7, 99, 100]. Furthermore, some dynamic components of the FWI-system ($DMC_{c,t}^{\text{scen}}$ and $DC_{c,t}^{\text{scen}}$ [93]) are associated with long dry spells and may be linked to increased fire hazard [94, 95, 96, 97].

High-emission scenarios and fires: the state of art Seidl *et al.* [52] assessed under a high-emission scenario the increased effect of forest fires in Europe within a broader context of abiotic and biotic forest disturbances. Veira *et al.* [102] reported that midlatitude and boreal fire seasons may largely expand within high-emission climate change scenarios, with predicted fire activity significantly shifting north in the Northern Hemisphere. Their study suggests that the potential increase of black carbon emissions in midlatitude and boreal areas might compensate the possible decrease in the tropical emission fluxes, highlighting potential enhanced importance of extra-tropical wildfires compared to tropical ones [102]. Knorr *et al.* [8] corroborate the potential future increased role of extra-tropical fire emissions. Their work suggests how under a high-emission scenario we might currently experience a temporary minimum of wildfire emissions, which they report to be largely independent of demographic scenarios and the variability generated by different model runs within the same high-emission scenario.

Loehman *et al.* [3] recently assessed the potential interaction between wildfires, insects and diseases under a high-emission scenario. They highlight how the interaction between abiotic and biotic forest disturbances appear as not purely additive, with non-linear behaviours and feedbacks. Changing climate patterns may have a direct impact on the habitat suitability (HS) of forest tree species (for an overview on terminology, ambiguity, uncertainty and the multifaceted concepts related to HS, see e.g. [47, 103, 104]). The indirect climate impact on forest disturbances "may offset or exacerbate [direct] climate influences". If warmer maximum temperatures might increase annual burned area, and fire frequency, at the same time milder minimum temperatures might favour the winter survival of some forest pests [3], with disturbance interactions potentially able to act synergistically with the direct negative impacts of climate change on forests. Barbero *et al.* [79] also focused on a high-emission scenario for analysing very large fires – which strongly contribute to total burnt area – with an ensemble of statistically downscaled global climate models. Their results project an increased potential for very large fires[6] in the United States by means of increased frequency of the conditions which favour these fires, and a projected extension of the seasonal time window in which fuel and weather would support the spread of very large fires.

High-emission scenario analysis of fire danger in PESETA III The next section summarises the results of the expected evolution of fire danger in Europe under climate change – in particular, under a high-emission scenario analysis. The set of climate model-runs considered is the common core set exploited within the PESETA III project. It focuses on a Representative Concentration Pathways (RCP) for which radiative forcing reaches a high value by the end of the century. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time dependent projections of atmospheric greenhouse gas (GHG) concentrations. The downscaled RCP8.5 scenario [75] from EURO-CORDEX [105, 92, 106, 107] is exploited. Tables 2 and 3 summarise the provenance of the scenario realisations, highlighting the associated research institutes and both the global and regional models which underpin each realisation. For

[6] In their work, very large fires are defined as having a burnt area greater than 5000 ha. This criterion is variable in the literature.

Table 2: Institutions and acronyms associated to the global circulation models and the regional climate models which define the EURO-CORDEX climate-projection realisations (model runs) considered in this study.

Acronym	Institution name
CLMcom	Climate Limited-area Modelling Community
CNRM/CERFACS	Météo France, Centre National de Recherches Météorologiques - Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique
EC-EARTH	EC-Earth Consortium
ICHEC	Irish Centre for High-End Computing
INERIS	Institut National de l'Environnement Industriel et des Risques
IPSL	Institut Pierre-Simon Laplace
MOHC	Met Office Hadley Centre
MPI-M	Max Planck Institute for Meteorology
SMHI	Swedish Meteorological and Hydrological Institute, Rossby Centre

Table 3: Short codes associated to each EURO-CORDEX climate-projection realisation (model run, abbreviated as *mod*) considered in this study, and corresponding institutions, regional climate models (RCM) and driving Global Circulation Models (GCM).

Code (model run *mod*)	Institution(s)	Regional Climate Models	Driving Global Circulation Models
A	CLMcom	CCLM4-8-17	CNRM-CERFACS-CNRM-CM5
B	CLMcom	CCLM4-8-17	ICHEC-EC-EARTH
C	IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR
D	SMHI	RCA4	MOHC-HadGEM2-ES
E	SMHI	RCA4	MPI-M-MPI-ESM-LR

Table 4: Time intervals associated to each period (abbreviated as *per* in the equations) considered in the cluster of sectoral analyses within the PESETA III project – to which this study belongs. It should be noticed how the array of time intervals associated with the period "2 degrees global warming" is heterogeneous. In particular, not all the corresponding model time-intervals end after the Short-term time period. As a consequence, the statistics in Figure 8 and Figure 10 for these two time periods do not always follow a strictly monotonically increasing time arrow.

Scenario time period *per*	Time code	Time interval	Model code	Year when the model GCM projects a global 2 °C warming compared to pre-industrial level	
Control period	cp	1981-2010	A, B, C, D, E		
Short-term	st	2021-2050	A, B, C, D, E		
2 degrees global warming	2d	2016-2045	D	2030	(period not ending after Short-term)
		2021-2050	C	2035	(period not ending after Short-term)
		2027-2056	B	2041	
		2030-2059	A	2044	
		2030-2059	E	2044	
Long-term	lt	2071-2100	A, B, C, E		
		2071-2098	D		

better comparison with previous studies [108], it should be recalled that RCP8.5 is derived after the A2r scenario providing a revised quantification of the original IPCC A2 SRES [75, 109] and assumes an increase of the radiative forcing throughout the 21st century up to reach an approximate level of 8.5 W per m^2 by the end of the century. The values of precipitation and temperature were bias-adjusted following Dosio [74], Dosio *et al.* [110], Dosio and Paruolo [111].

5 Fire danger: results and discussion

Figure 8 summarises the results for the climate change assessment of the FWI aggregated component. All the FWI-system components have been estimated daily from 1980 to 2010 for the models A, B, C, D, E[7]. The results are summarised with a robust statistic estimating the 90 % quantile of the daily FWI computed over each time period, to highlight the upper tail of FWI values in each scenario realisation. To better understand the statistic, it is worth mentioning that its computing method processed – for each time period and each climate-projection realisation – more than 10000 daily maps for each of the FWI-system components, so as to derive the corresponding FWI aggregated component – one raster map per day. For a given spatial cell, only 10 % of the daily maps' values exceed the 90 %-quantile value.

More precisely, for each spatial cell c in a given scenario realisation $\text{scen} = \{\text{model}, \text{time-period}\}$:

$$\mathit{FWI}^{\text{scen}}_{c,q90\,\%} = \arg \min_{\mathit{FWI}_c \in \{\mathit{FWI}^{\text{scen}}_{c,t}\}} P[\mathit{FWI}^{\text{scen}}_{c,t} \leq \mathit{FWI}_c] \geq 90\,\% \qquad \forall t \in \text{scen} \tag{5}$$

where $P[\mathit{FWI}^{\text{scen}}_{c,t} \leq \mathit{FWI}_c]$ is the probability for $\mathit{FWI}^{\text{scen}}_{c,t}$ not to be greater than FWI_c.

These statistics may be compared for the Control period with the total cumulated burnt area as mapped by the European Forest Fires Information System (EFFIS) from 2000 to 2015 (Figure 9). The pattern of fire damage in Central and Southern Italy, Greece, Southern France, and Balkans near the sea is comparable. The higher concentration of burnt area in the Northern Portugal and Northwest Spain is also linked to the distribution and typology of vegetation and to the local interface between urban areas and wilder lands. Additionally, the Long-term statistics may be compared with the change patterns of the longer dry spells and heat wave frequency (Figure 7). The shift to north of the current levels of fire danger potential appears as uneven and sometime discontinuous, with multiple models predicting an expansion in the western France and a northern shift in the eastern part of the continent. In the Mediterranean Europe, the fire potential appears as increasing in several scenario realisations.

Among the FWI-system components, the drought code $DC^{\text{scen}}_{c,t}$ is characterised by the highest timelag (see Table 1), then propagated to the depending FWI-system components (Eqs. 1a-1c and matrix 4). As a consequence, and given the definition of this component, the extreme values of $DC^{\text{scen}}_{c,t}$ are well suited to analyse the effect of long periods of dry weather. A robust statistic was computed to estimate the 95 % quantile of the daily drought code computed over each time

[7] The first year of the simulation – 1980 – is the one before the beginning of the Control-period time interval, so as for the dynamic FWI-system components $\phi^{1,1}$, $\phi^{1,2}$, $\phi^{1,3}$ to complete a transitory trajectory from the initialization.

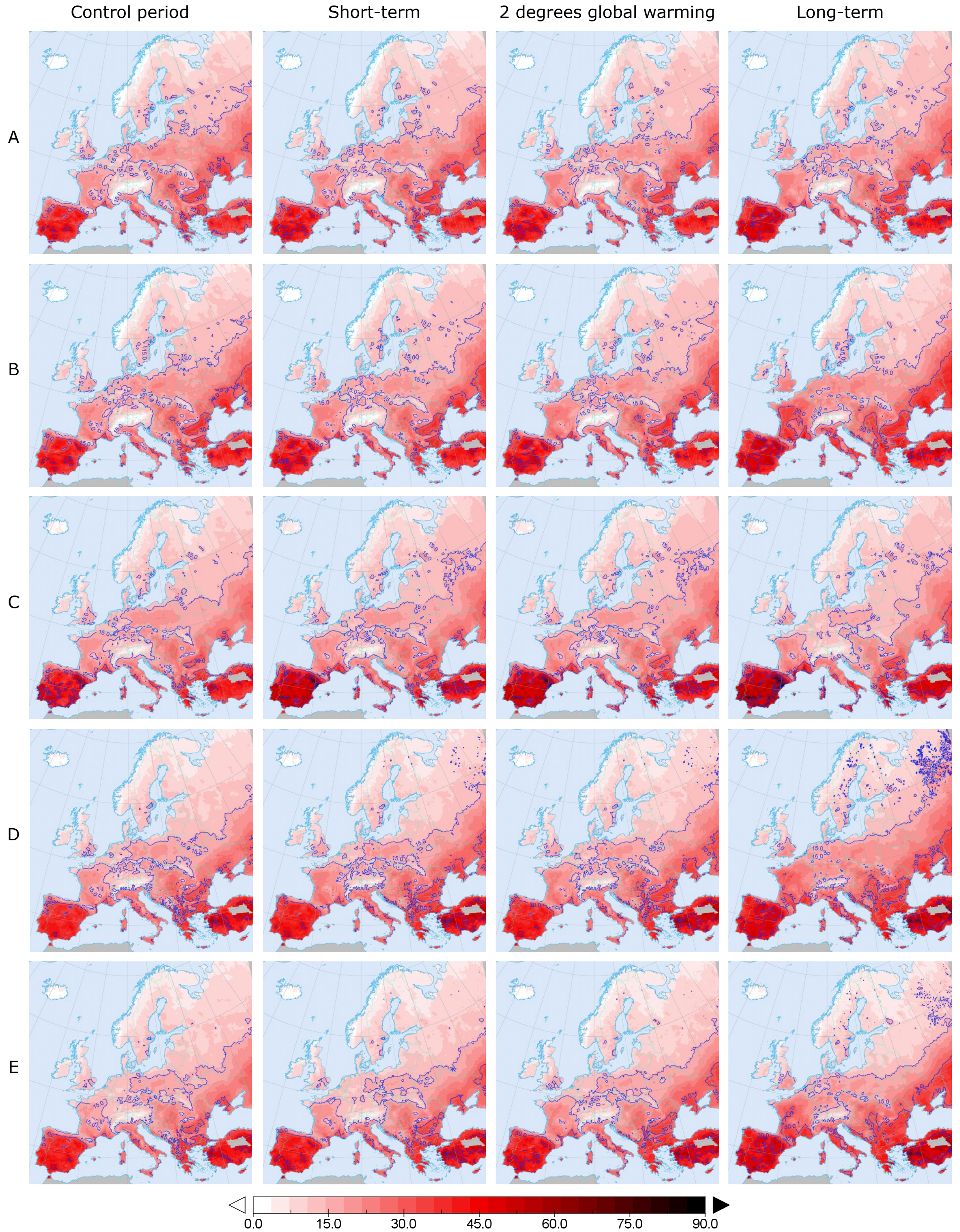

Figure 8: Results for the climate change assessment of the Fire Weather Index (FWI) aggregated component, computed daily from 1980 to 2100 for the models A, B, C, D, E (see Table 3; the outcomes for each model are summarised in the corresponding row of the figure). The daily $FWI_{c,t}^{\text{scen}}$ has been computed for each scenario realisation based on a corresponding model. The entire time series has been estimated (from the end of the control period, the scenario RCP8.5 has been used) and the 90 % quantile – $FWI_{c,q90\,\%}^{\text{scen}}$ – of each time period (columns) has been computed. A broad set of patterns is evident, from very stable areas to highly variable ones. To better detect the changes, contour lines are highlighted corresponding to increments by 15 units of the $FWI_{c,q90\,\%}^{\text{scen}}$ values. The scale of the quantile statistics based on the dimensionless FWI values is limited to 90 even if higher values are possible.

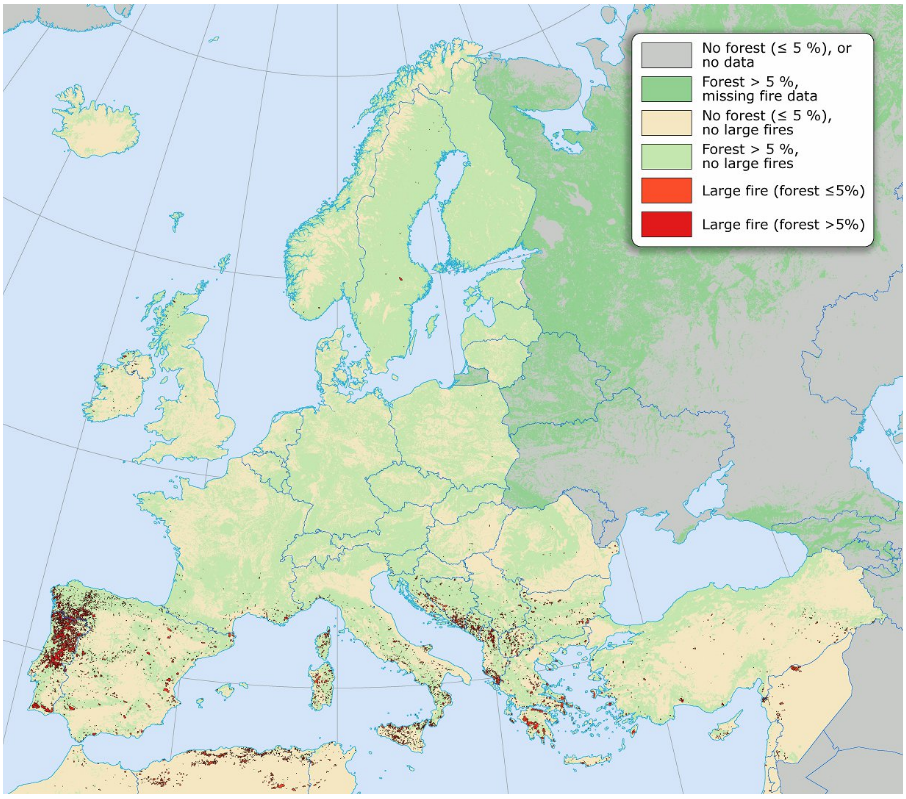

Figure 9: Total cumulate burnt area as mapped by the European Forest Fires Information System (EFFIS) from 2000 to 2015. Adapted after de Rigo *et al.* [1]. Although most wildfire impacts are concentrated in the Iberian peninsula and across Mediterranean Europe, almost all countries have been affected, at least in some years, by large fires (more than 40 ha). This map may be compared with the statistics on Fire Weather Index as summarised in Figure 8 for the Control-period time interval (see also Table 4).

period, emphasizing the very upper tail of DC values in each scenario realisation:

$$DC^{\mathsf{scen}}_{c,q95\,\%} = \mathsf{arg} \min_{DC_c \in \{DC^{\mathsf{scen}}_{c,t}\}} P[DC^{\mathsf{scen}}_{c,t} \leq DC_c] \geq 95\,\% \qquad \forall t \in \mathsf{scen} \tag{6}$$

To improve the understandability of the patterns of variability, Figure 10 shows the ensemble quartiles based on all the models. It should be noticed how the array of time intervals associated with the period "2 degrees global warming" is heterogeneous (see Table 4). In particular, not all the corresponding model time-intervals end after the Short-term time period. As a consequence, the statistics in Figure 8 and Figure 10 for these two time periods do not always follow a strictly monotonically increasing time arrow. Overall, the Short-term and "2 degrees global warming" periods do not show major dissimilarities.

Finally, Figure 11 offers a comparison between different period-based statistics of the same FWI-system component, completing the exemplification based on the drought code $DC^{\mathsf{scen}}_{c,t}$. The more diverse periods (control period and end of century) are assessed. Here, the 95 % quantile of the daily drought code $DC^{\mathsf{scen}}_{c,q95\,\%}$ computed over the Control and Long-term periods is compared with

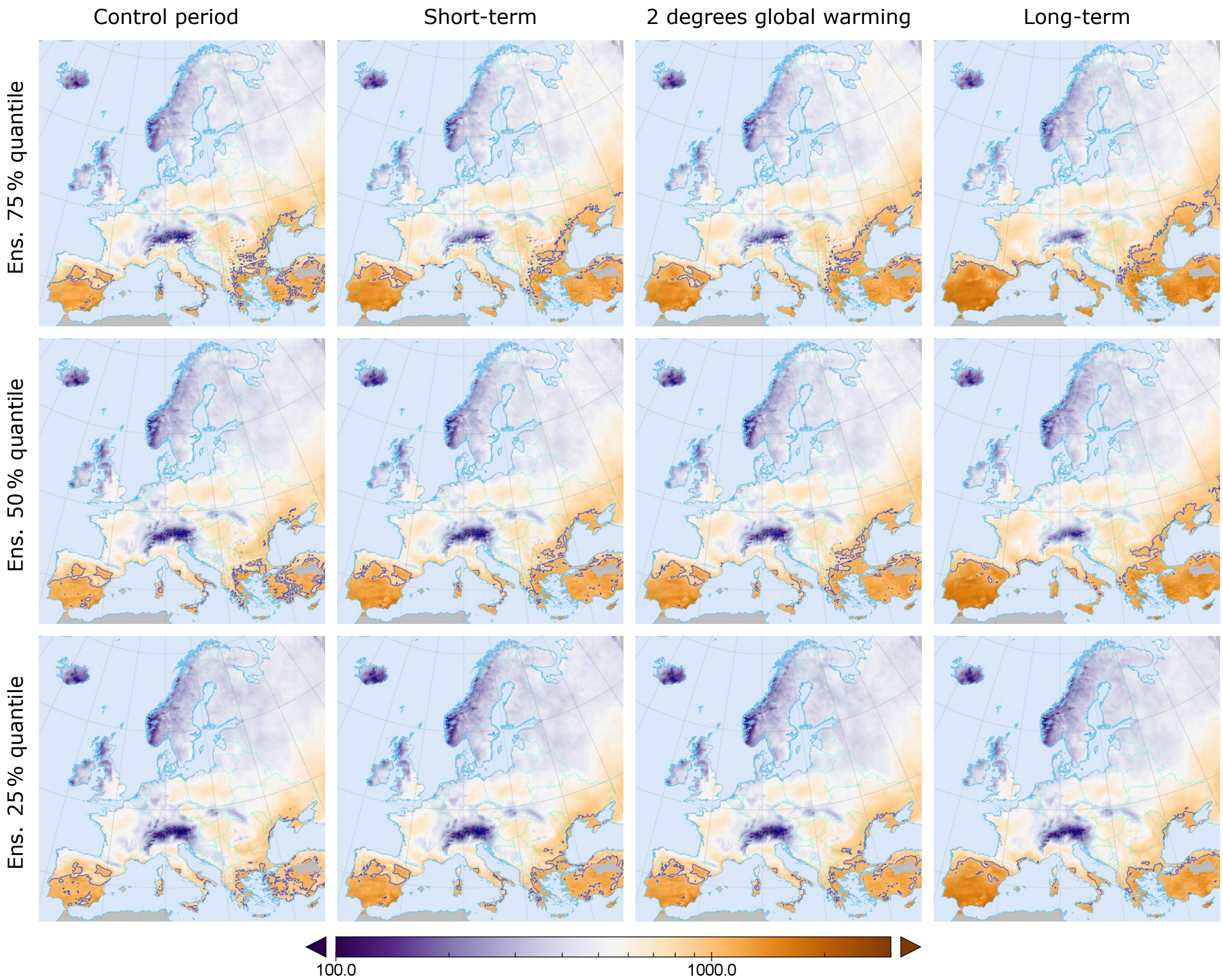

Figure 10: Results for the climate change assessment of the Drought Code (DC) component of the Canadian Fire Weather Index system (FWI), computed daily from 1980 to 2100 for the models A, B, C, D, E (see Table 3). Among the FWI-system components, DC is characterised by the highest timelag (see Table 1). As a consequence, the extreme values of DC are well suited to analyse the effect of long periods of dry weather. To offer a clearer summary of the variability, the ensemble quartiles based on all the models are shown in the corresponding row of the figure (see also Figure 11). The daily $DC_{c,t}^{\text{scen}}$ has been computed for each scenario realisation based on a corresponding model. The entire time series has been estimated (from the end of the control period, the scenario RCP8.5 has been used) and the 95 % quantile – $DC_{c,q95\,\%}^{\text{scen}}$ – of each time period (columns) has been computed. As underlined in Figure 8, a broad set of patterns is evident, from very stable areas to highly variable ones. To better detect the changes, a logarithmic scale is used and contour lines are highlighted corresponding to the orders of magnitude (powers of 10: 100, 1000) of the $DC_{c,q95\,\%}^{\text{scen}}$ values.

a simple statistic as the average $DC_{c,\text{avg}}^{\text{scen}}$ – computed over the same periods:

$$DC_{c,\text{avg}}^{\text{scen}} = \sum_{DC_c \in \{DC_{c,t}^{\text{scen}}\}} DC_c \cdot \frac{1}{\#\{DC_{c,t}^{\text{scen}}\}} \qquad \forall t \in \text{scen} \tag{7}$$

The ensemble quantiles are defined for a generic period-based statistic *period-stat* (such as the

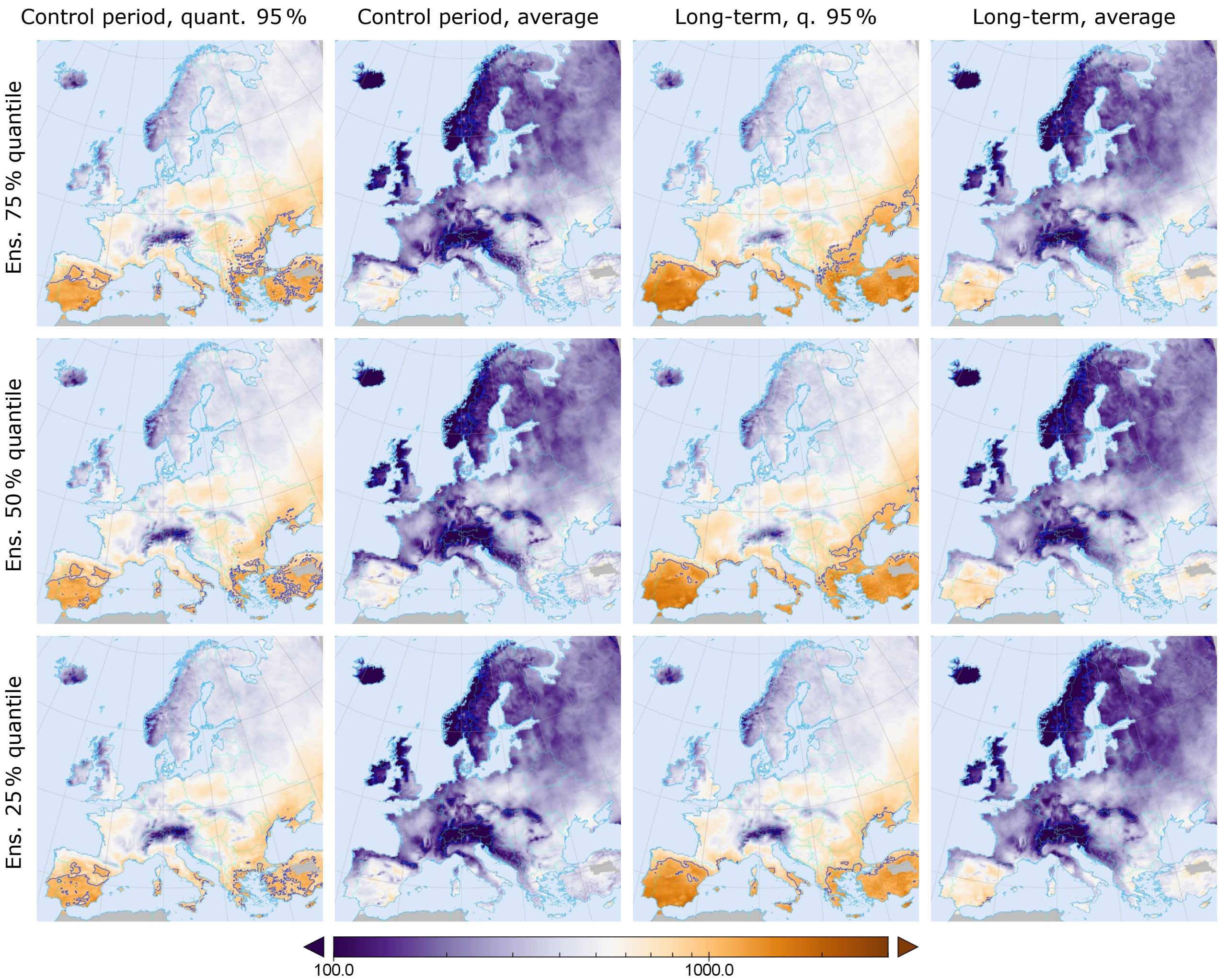

Figure 11: Results for the climate change assessment of the Drought Code (DC) component of the Canadian Fire Weather Index system (FWI), computed daily from 1980 to 2100 for the models A, B, C, D, E (see Table 3). As for other FWI-system components, the variability of DC is twofold. First, even within a local geographic area the time series of DC values may span over large intervals. In the figure, the entire time series has been estimated (from the end of the control period, the scenario RCP8.5 has been used) and the 95 % quantile – $DC^{\text{scen}}_{c,q95\,\%}$ – of two time periods (1st and 3rd columns) has been compared with the corresponding average values – $DC^{\text{scen}}_{c,\text{avg}}$ (2nd and 4th columns). Second, the uncertainty driven by the climate simulations adds additional variability to the estimates. This may be appreciated by comparing the ensemble quartiles based on all the models, which are shown in the corresponding row of the figure. For example, the extent of variability is evident in the Southern Balkans and northto the Black sea. Remarkably, the variability is non-negligible even in the Control period, where the fire damage models are typically trained against the real observed time series of FWI-system components (see the summary Section on the sources of uncertainty). This variability highlights how the regionally-downscaled bias-adjusted realisations of the climate scenario (model runs A-E) induce a dispersion uncertainty in the FWI-system components of the Control period, which is then propagated by the fire damage models in addition to the observed higher dispersion uncertainty of the projected FWI-system components (see also Figure 8). A logarithmic scale is used and contour lines are highlighted corresponding to the orders of magnitude (powers of 10: 100, 1000) of the $DC^{\text{scen}}_{c,\cdot}$ values.

aforementioned $q95\,\%$ and *avg*) as:

$$DC^{\text{Q\,\%, period}}_{c,\text{period-stat}} = \arg \min_{DC_c \in \{DC^{\text{scen}}_{c,\text{period-stat}}\}} P[DC^{\text{scen}}_{c,\text{period-stat}} \leq DC_c] \geq Q\,\% \qquad \forall\,\text{scen} : \{\cdot, \text{period}\} \tag{8}$$

where for the case of ensemble quartiles $Q \in \{\,25\,\%,\ 50\,\%,\ 75\,\%\,\}$, and all the models $\{\,mod_1\ \cdots\}$

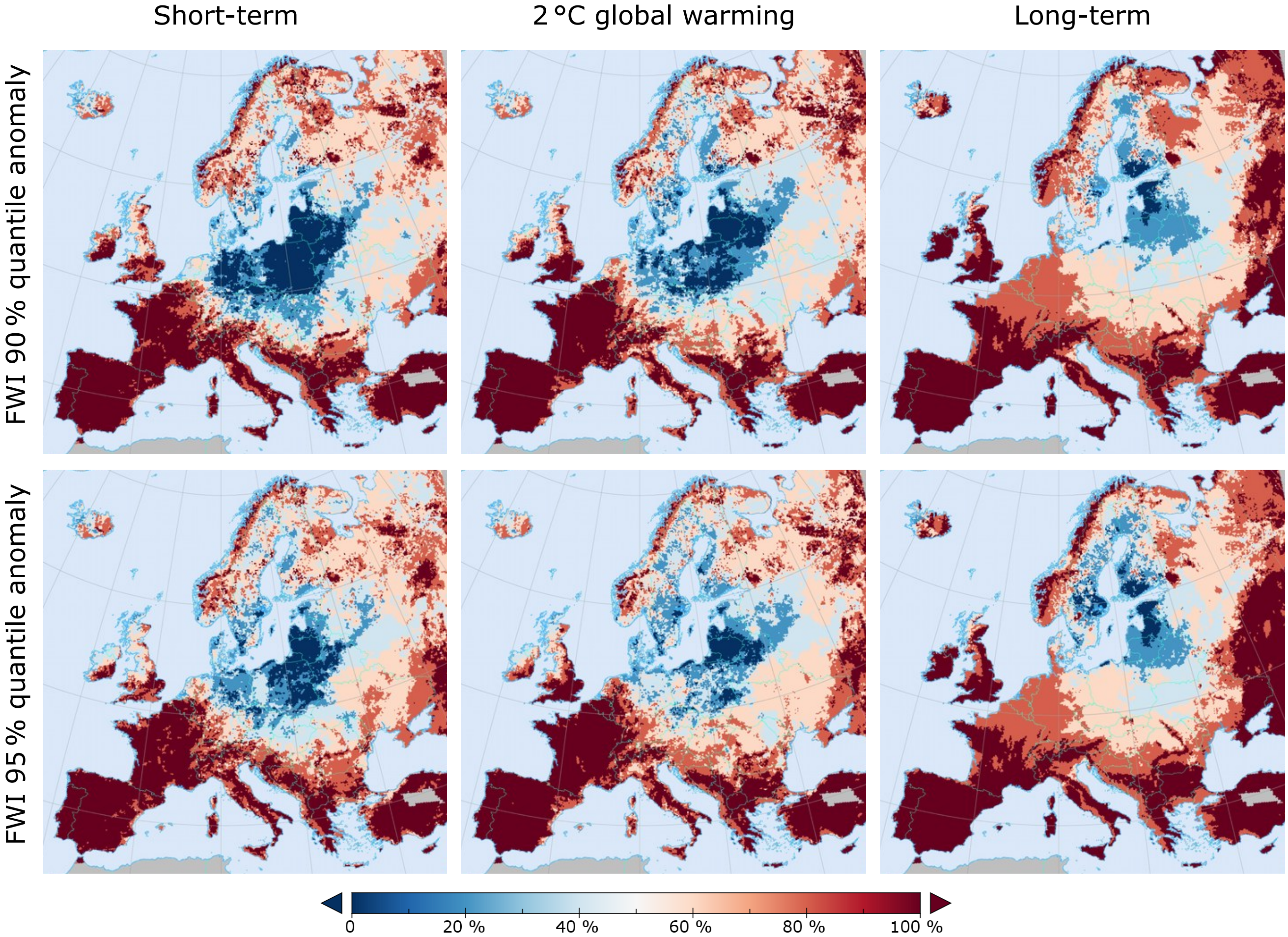

Figure 12: Robustness of the estimated climate-driven change in the overall fire danger extremes. Ensemble analysis for the anomaly of the Fire Weather Index (FWI) aggregated component, computed daily from 1980 to 2100 for the models A, B, C, D, E (see Table 3). The daily $FWI_{c,t}^{\text{scen}}$ has been computed for each climate-projection realisation based on a corresponding model. The entire time series has been estimated (from the end of the control period, the scenario RCP8.5 has been used) and the extreme events of fire danger have been assessed. In particular, for each time period (see Table 4) the 90 % quantile – $FWI_{c,q90\,\%}^{\text{scen}}$, first row – and the 95 % quantile – $FWI_{c,q95\,\%}^{\text{scen}}$, second row – have been computed and the difference between future and control period (anomaly) has been determined. The percentage of models for which the fire danger is expected to increase is shown.

are considered for a given time period *per* – so as for the corresponding scenario realisations $scen = \{mod, per\}$ to entirely cover the period. The ensemble quartiles describe in a simple summary half[8] of the overall uncertainty driven by the climate simulations. For example, the extent of variability – within the same time period – of both $DC_{c,q95\,\%}^{\text{scen}}$ and $DC_{c,\text{avg}}^{\text{scen}}$ is evident in the southern part of the Balkan peninsula and northto the Black sea. Remarkably, the variability is non-negligible even in the Control period, where the five time series of a given FWI-system component under the corresponding five scenario realisations *scen* would ideally be expected to collapse to a single time series, identical to the observed historical time series. In the summary Section on the sources of uncertainty this aspect is further discussed.

Robustness of the estimated climate-driven change in the fire danger Figure 12 offers an ensemble analysis for the anomaly of the Fire Weather Index (FWI) aggregated component. As explained in the previous section, from the daily $FWI_{c,t}^{\text{scen}}$ time series for each scenario reali-

[8]The central part of uncertainty between the quartiles $25\,\%$ and $75\,\%$.

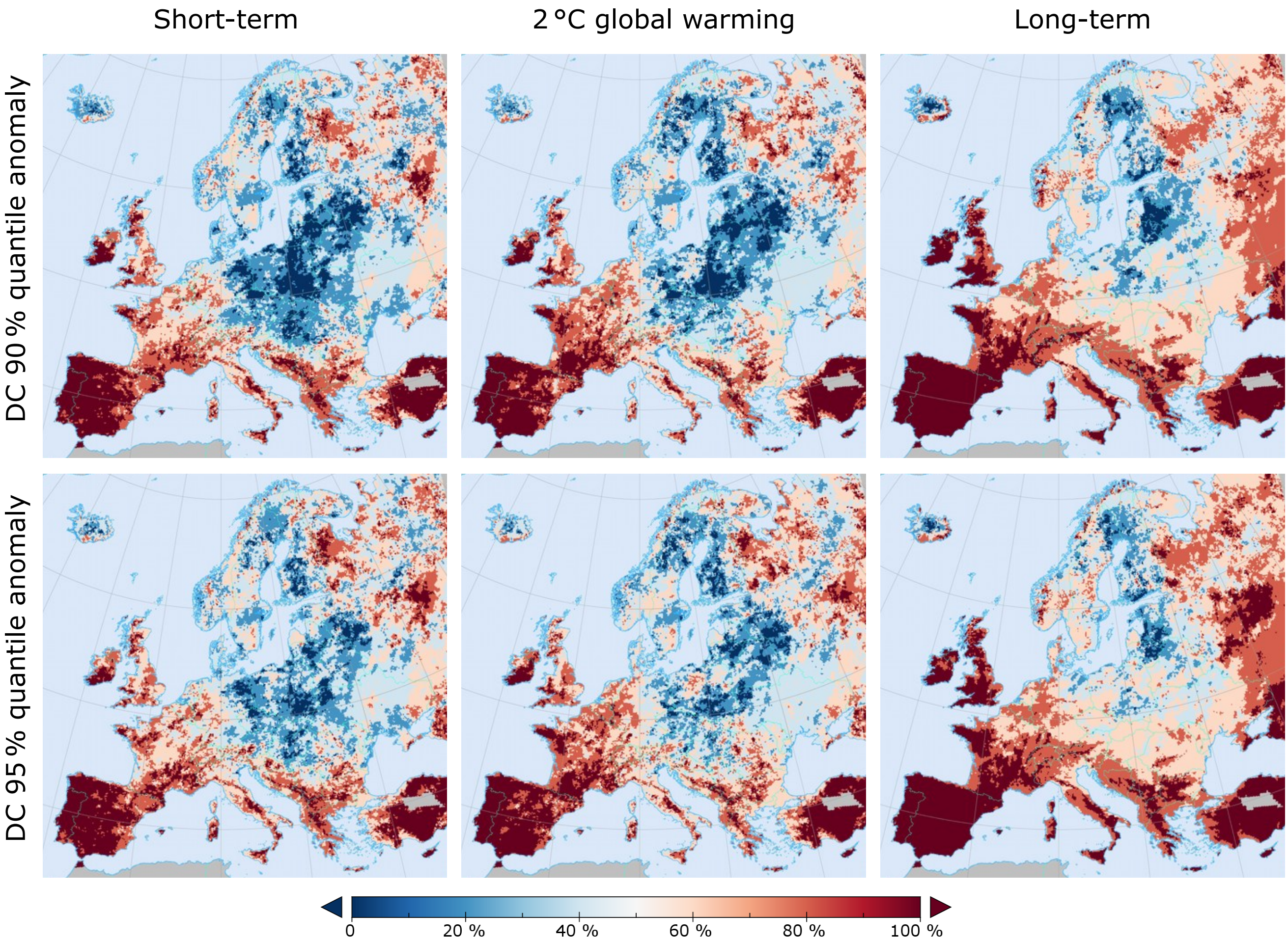

Figure 13: Robustness of the estimated climate-driven change in the fire danger extremes, focusing on the effects of long periods of dry weather. Ensemble analysis for the anomaly of the Drought Code (DC) component of the Canadian Fire Weather Index system, computed daily from 1980 to 2100 for the models A, B, C, D, E (see Table 3). DC models the fuel moisture of the deep layers of wood, leaves, soil and other organic matter on the ground. The daily $DC_{c,t}^{\text{scen}}$ has been computed for each climate-projection realisation based on a corresponding model. The entire time series has been estimated (from the end of the control period, the scenario RCP8.5 has been used) and the component of extreme dry-weather events in fire danger has been assessed. In particular, for each time period (see Table 4) the 90 % quantile – $DC_{c,q90\,\%}^{\text{scen}}$, first row – and the 95 % quantile – $DC_{c,q95\,\%}^{\text{scen}}$, second row – have been computed and the difference between future and control period (anomaly) has been determined. The percentage of models for which the deeper fuel moisture is expected to decrease is shown.

sation the extreme events of fire danger have been assessed. In particular, for each time period (Table 4) the 90 % quantile $FWI_{c,q90\,\%}^{\text{scen}}$ and the 95 % quantile $FWI_{c,q95\,\%}^{\text{scen}}$ have been computed and the difference between future and control period (anomaly) has been determined. The percentage of models for which the fire danger is expected to increase is shown in Figure 12. Even in the short-term, in most of the Mediterranean areas of Europe all the models agree (dark red) on an increased climate-driven danger. Conversely, over most of Latvia, Lithuania, Poland and Eastern Germany all the models agree (dark blue) on a decreased danger – compared with an already relatively low danger in the control period. Similar patterns may be observed in the scenario referring to a global warming of 2 °C, with an area of robust (dark red) danger increase showing broad overlaps compared with the short-term period; and a reduced area where a robust decrease of danger is expected. The long-term period shows a higher variability among models. However, a substantial area of Mediterranean Europe is robustly predicted to experience an increased climate-driven fire danger, including the entire Iberian peninsula, the totality of Mediterranean France, a large area north-east of the Black Sea, and (with some variability) central/southern Italy. The area with robust danger decrease is further reduced and shifted north compared with the other time periods.

It may be interesting to disentangle the effects of drier weather periods and how their predicted change (anomaly) under a high-emission scenario may affect the overall fire danger – again, taking into account the uncertainty of climate models. Figure 13 offers an ensemble analysis for the anomaly of the Drought Code (DC) component of the Canadian Fire Weather Index system. As discussed, DC models the fuel moisture of the deep layers of wood, leaves, soil and other organic matter on the ground, supporting the analysis of the effects which dry deep fuel may exert on fire danger. Similarly to the analysis summarised in Figure 12, the component of extreme dry-weather events in fire danger has been assessed from the daily $DC_{c,t}^{\text{scen}}$ time series for each scenario realisation. In particular, for for each time period the 90 % quantile $DC_{c,q90\,\%}^{\text{scen}}$ and the 95 % quantile $DC_{c,q95\,\%}^{\text{scen}}$ have been computed and the difference between future and control period (anomaly) has been determined. The percentage of models for which the deeper fuel moisture is expected to decrease is shown in Figure 13.

Compared with Figure 12, a higher variability may be observed. Even in the short-term, in most of the Iberian peninsula and Turkey all the models agree (dark red) on extreme events with a decreased deep fuel moisture, which contributes to worsen the corresponding fire danger. Despite having lower absolute patterns of fire danger and dryness of deep fuel (see Figure 8 and Figure 10), models also agree on extremes with decreased deep fuel moisture in Ireland. In France, Italy, Greece and the Balkans, local patterns of drier deep fuel are highlighted by most of the models, with uncertain dynamics over large areas. The areas where in Figure 12 models agree on a decreased fire danger also show a model agreement on drier extreme conditions of deep fuel – however, with larger uncertainty. Similar patterns may be observed in the scenario referring to a global warming of 2 °C. The long-term period shows a substantial area of Mediterranean Europe which is robustly predicted to experience drier extremes in the deep fuel, including the entire Iberian peninsula, and (with some variability) most of Mediterranean France, central/southern Italy, Greece and the Balkans. A large area at north-east of the Black Sea also shows a higher model agreement on worsened deep fuel moisture extremes.

This study on the potential climate effects on forest fires mainly focused on the climate-driven changes in the characteristics of fuel (varying moisture, drought effects, potential rate of fire spread) and on estimating their aggregated contribution to fire danger potential. Under the analysed climate change scenario RCP 8.5, other factors might modify the severity of effects. For example, Krause *et al.* [23] highlighted the changes in lightning ignitions and flash frequency which might significantly alter fire activity in many regions.

Some more general sources of uncertainty should be emphasised. Hantson *et al.* [26] reported a negative trend between observed mean fire size and population density. They also found a negative trend concerning cropland cover, with a possible connection with landscape fragmentation (see also [24]). Bistinas *et al.* [25], Aldersley *et al.* [112] found more complex patterns between burnt area and population density. Knorr *et al.* [8] correlate the potential future increased role of fire emissions from extra-tropical areas, compared with those in the tropics, also linking it to the differential patterns of population growth and associated decreased burnt areas.

A global analysis by Archibald *et al.* [113] underlined the complex interactions among fire, climate, vegetation, and anthropic activities, pointing out how "fire is unlikely to be unilaterally responsive to climate in a deterministic way". More specifically, in the Mediterranean areas of Europe land cover spatial patterns and interfaces have been correlated with fire occurrence [114, 35, 36].

6 Vegetation conditions and composition, human factors, and adaptation options: a literature overview

As discussed, fire danger is clearly influenced by weather in the short term, and by climate and its changes when considering longer time intervals. Vegetation conditions and composition, as well as human behaviour, are also important factors. In the previous sections of this work, the emphasis was on the direct influence on fire danger of weather and climate.

In this section, the role of vegetation and forests (whose types and species composition in Europe are quite variable) is briefly reviewed from literature, even if the state of art in quantitatively predicting the important nexus of fire with plant functional traits remains rudimentary [15]. The human component in the occurrence of wildfires is evident in Figure 15, where the reported human causes associated with fire occurrence in Europe (either deliberate or due to accident/negligence) are the majority, compared with natural causes. The quantitative relationship of human factors with fire danger and damage is still poorly understood in its multifaceted aspects [115, 116, 117, 118, 112]. Nevertheless, a reasoned literature overview on the human component of fires is here presented.

6.1 The complex response, resilience and adaptation potential of vegetation, plant communities and ecosystems to changing fire danger and fire regimes

Although many plants in the Mediterranean ecosystems may display favourable traits to mitigate the impact of fire disturbances, the resilience of a variety of ecosystems to frequent fires is poor, suffering strong alteration and potential post-fire disasters [119]. The adaptation of vegetation and ecosystems to fire is a complex topic, where the role of functional traits and the serious impact of changing fire regimes is frequently underlined [120, 121, 48, 122].

Forests and fire Forest trees play a key role under the changing patterns of fire danger and damage, due to their biomass and fuel[9], their longer life (and corresponding higher temporal inertia) compared with other plants, and their importance in shaping a variety of ecosystems. Several forest tree taxa present in the Mediterranean subtropical forests [124, 125] and in the subtropical mountain systems [126, 127] may be subject to degradation (including towards potentially fire-prone shrublands [128]) under an increasing frequency of fire disturbances even where the capability of re-sprouting, or the thick bark and high crown of some taxa [129, 130, 131] may imply a higher probability of surviving single fire events [132, 133, 134]. Despite often being susceptible to recurring fire damage [135, 128], other forest species show remarkable serotiny

[9]For example, compared to grasslands the fuel load in forest areas may be from three times up to more than 20 times bigger (tons dry mass ha^{-1} [123] Table 2-1).

[136, 137], re-sprouting or other fire adaptation mechanisms [1, 138, 139, 140, 141], or may behave as colonisers in fire-disturbed areas [142, 143, 144, 145].

Diversity and resilience The effect of wildfires in areas with different levels of species richness may be uneven (see Figure 14). Recently, Bradley *et al.* [146] reported how forests with higher levels of protection for biodiversity conservation may display lower fire severity values "even though they are generally identified as having the highest overall levels of biomass and fuel loading". Spasojevic *et al.* [147] focused on which particular aspect of diversity may better correlate with post-fire resilience and suggest that "high functional dispersion in traits associated with fire tolerance/resistance may contribute to the recovery of productivity after wildfire across a wide range of ecosystems from cold desert woodlands to forested mountains", where dispersion here may be conceptualised as the "degree of trait dissimilarity among species within a community".

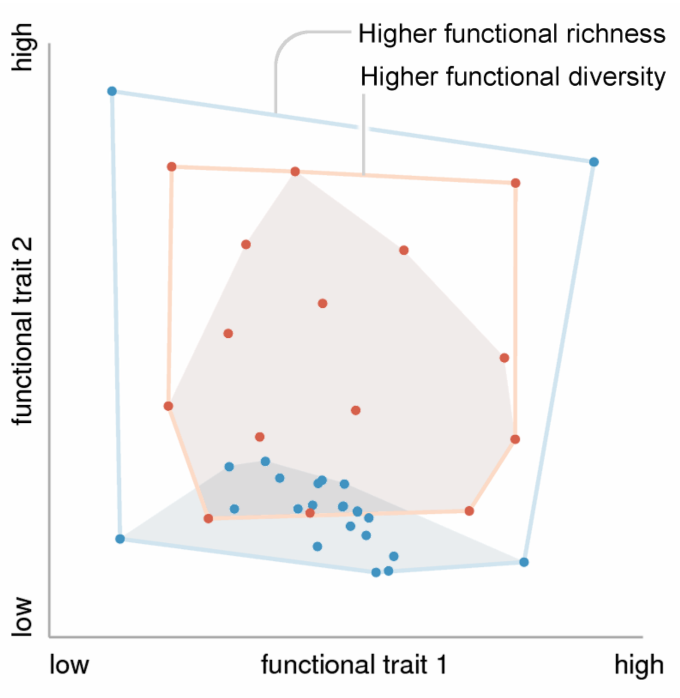

Figure 14: Species richness may not be directly associated with the overall fire resistance and resilience of vegetation. In this qualitative simplified representation, only two functional traits are exemplified, referring to corresponding fire resistance/resilience traits. In blue, a vegetation community with higher functional richness (i.e. higher convex-hull area, within the light blue polygon) is compared with a less rich community (red). However, the red community is characterised by a higher functional diversity, i.e. a higher dispersion/dissimilarity of the traits. Fire damage may affect the vegetation both *quantitatively* (decreased population density) and *qualitatively* (local extinction of the taxa associated with some traits). Post-fire dynamics may support a complete, partial or very limited population recovery (extent of *quantitative* recovery), depending even on the survived functional traits of the original community (extent of *qualitative* functional recovery). Qualitative impacts in the community composition – irrespective of the abundance or rarity of each trait – appear whenever the sub-population with a certain trait decreases up to become locally extinct. For example, a schematic comparison of this qualitative impact may be illustrated with the removal of the top-left and top-right components of each community. The residual functional richness in the blue community (light blue area) is smaller than the one surviving in the functionally more dispersed red community (light red area).

Another dimension of diversity is the age distribution of trees – a combined effect of fire regimes (among other potential disturbances) and forest management. Odion *et al.* [148] found that tree plantations may be more subject to severe fire compared with multi-aged forests. Lindenmayer *et al.* [149] review how industrial logging is likely to make some typologies of moist forests (where current fire regimes tend toward low frequency) "more, not less, prone to an increased probability of ignition [...] and increased fire severity and/or fire frequency". Lindenmayer *et al.* [150] underline how even in some moist temperate forests "logging-related alterations in stand structure increase the risk for both occurrence and severity of subsequent wildfires through changes in fuel types and conditions". They also illustrate a potential mechanism to explain why some specific young forests may burn at higher severity than some mature forests. In particular, densely spaced stands of regrowth sapling might be associated with more fine/medium fuels compared with old forests, and with shorter trees – so that "the flame height needed to scorch or consume the canopy in young stands is therefore significantly lower than in old-growth stands". In addition, densely stocked, even-aged young stands might be more susceptible to crown fire, compared with some typologies of old-growth stands "characterized by large relatively well-spaced trees with open crowns and small lateral subcrowns" [150]. In Spain, Puerta-Piñero *et al.* [151] report evidence supporting the higher post-fire recovery of stable forest areas compared with younger forests. They also investigate agriculture abandonment, suggesting that in their study area "the longer the time since crop abandonment, the more heterogeneity in species and diversity of functional responses to potential perturbations are present [...] which thus increases the probability of rapid post-fire forest regeneration" [151].

However, specific examples and mechanisms should not be generalised nor extrapolated from their context to cover the variety of forests found in Europe. It is crucial to underline how the typology and composition of forests plays an essential role in determining the overall forest resistance and resilience to fire disturbances. Higher biodiversity alone does not necessarily imply higher fire resistance and resilience. For example, the aforementioned work of Spasojevic *et al.* [147] highlights how some vegetation communities with low richness in functional traits associated with fire tolerance/resistance may still recover productivity more quickly from wildfire damage, provided they display a high dispersion (i.e. dissimilarity) in these functional traits, since in this case "the breadth of the overall trait space (high functional richness) is less important than having species with diverse, but not necessarily broadly different, strategies (high functional dispersion)". Figure 14 illustrates a qualitative overview of the difference between functional richness and dispersion.

Integrated strategies for combined vegetation pressures Some ecosystems and vegetation associations may be more adapted to fire disturbances with specific mechanisms to mitigate the post-fire recovery [152]. However, even among them, resilience to fire is uneven and its assessment relies on a complex array of factors [153]. Furthermore, future increased patterns of fire impact in areas currently not especially affected by this disturbance may act on much less resilient ecosystems where the potential damage to species richness and distribution, ecosystem functions and services may impact disproportionally. Concerning climate change mitigation and adaptation in forest resources and ecosystems, Seidl *et al.* [50] underline how understanding the interactions between abiotic and biotic disturbances is a key prerequisite. Past episodes of droughts and their association with wildfires were reported as a trigger of the structure and composition of forests in the mesic regions, while the potential co-occurrence of multiple factors might increase the risk of fires and biological invasions – e.g. climate-change driven droughts may affect wildfires both directly (combustion) and indirectly due to vegetation damage predisposing to biotic attacks [154, 155, 156, 157]. Millar *et al.* [158] review the principles for future climate adaptation considering "vegetation management to reduce the likelihood of severe wildfire or of beetle-mediated forest mortality", fuel treatments to mitigate fire hazard in dry forests and facilitate ecological restoration – to also improving resilience to the expected increased fire occurrence. These types of proactive methods might be expected to be part of a "move from compartmentalized to comprehensive strategies" [51].

On-site and off-site transdisciplinary feedbacks Even in the Mediterranean forests and woodlands more used to this recurring disturbance, large fires may increasingly affect areas with worrying current and potential erosion [159, 160]. This is due to the combined effect of extreme weather events and the typology of soil resources in the Mediterranean region. In particular, the current Mediterranean precipitation regimes are already characterised by intense rainstorm events during the cold season or between dry spells and droughts, which constitutes a typology of extreme weather events [161, 162, 163] predicted to intensify (see also Figure 7) with the warming climate and the stronger atmospheric moisture transport [164, 165, 166].

Turco *et al.* [167] suggest that in some Mediterranean regions, wet conditions antecedent to droughts may have an influence on fires, as they "may allow for the fine-fuel to grow" and "may also promote fuel gaps to be filled within the landscape, resulting in an increased abundance and continuity of fuel load". These alternate patterns of precipitation may exacerbate the potential impact of post-fire erosion due to the vulnerability of typical Mediterranean soils, frequently very thin [168, 169]. Local geography in hilly and mountainous areas has relevant impacts on the vegetation structure and composition [1]. In the Mediterranean, south-facing slopes may be associated with higher potential evapotranspiration and reduced density of vegetation cover, thinner soil and higher soil erosion [170, 171]. Puerta-Piñero *et al.* [151] found the "recovery of burnt sites to be significantly worse in the southern slopes compared to the northern ones". This may suggest a worse erosion-protection of the vegetation cover, within a potential feedback toward higher erosion rates in south-facing burnt areas. Slope instability, for example debris flows or landslide failures, are also a potential consequence of wildfires in susceptible areas, whose integrated impact with soil erosion may be noticeable [172, 173, 174, 175]. Beside erosion and slope instability [176, 177, 178], and perhaps more subtly, wildfires can result in a series of slow changes to the soil and vegetation affecting hydrological and geomorphological processes (e.g. preferential removal of organic matter and nutrients, or – at wider scale – soil redistribution rather than simple soil loss) [179, 170, 175]. As a consequence, the economic framework under which wildfire impacts are assessed needs to be cogent enough to cover the multiple dimensions of the problem and the array of uncertainties involved [68, 180]. The transdisciplinary nature of wildfire adaptation under changing climate suggests an integrated perspective over natural resources modelling and management [181, 182, 183]. A merely monetary assessment of the potential damage of wildfires under climate change is unable to encompass the intrinsically multidimensional array of on-site and off-site impacts, that are better assessed within a multi-criteria approach [1, 184, 176, 177, 185] – which, however, remains a challenging open problem at the scale considered in this study. In addition, the expected nonlinear interaction of tipping points further complicates a realistic analysis [186], which here is offered without considering these highly uncertain aspects – hence with a potentially serious source of underestimation of the overall damage feedbacks and repercussions.

Finally, as Keane *et al.* [187] highlight, although fire modelling is generally unable to "account for the large variability in fuel characteristics, yet predictions from these models are used extensively in fire management". If it is true that a "major factor influencing fire behavior and effects during large fire events is weather, not fuel, and weather might drive fire behavior predictions under severe drought, high temperatures, strong wind, and steep slope conditions", nevertheless the high uncertainty concerning vegetation fuel patterns and their sometime extreme variability could lead to high extrapolation errors which "may overwhelm the variability of fuel characteristics" [187]. Furthermore, model validation itself may be challenging, as "high uncertainty in fuel sampling and fire behavior measurements make it difficult to actually validate the fire behavior and effects predictions" [187]. Keane [188] concludes that a "first step in creating a common fuel description system is to fully understand the ecology of wildland fuels", suggesting that "[f]undamental ecological research must be done to determine the size and shape distributions of fuel particles on the plants and on the ground across all ecosystems and vegetation assemblages, and across landscapes".

6.2 Human factors and fire

Future patterns of European urban expansion, changes in forest areas due to varying timber demand and other indirect impacts such as modified profitability of agriculture may significantly alter the future distribution of forest cover, for example due to conversion of forests to agricultural land in some parts of northern Europe or conversely due to afforestation in areas with decreasing food production [189].

Given the challenging complexity of reliably projecting land use and cover – and their associated uncertainty – under climate change scenarios, the aforementioned relationships are difficult to assess. Furthermore, a component of the proposed climate-based characterization of future wildfire potential impacts may be linked to the current distribution of population, land cover and use in Europe. These spatial patterns may be anisotropically distributed with regard to the corresponding current climate components in the fire weather index. Therefore, part of the proposed analysis may be implicitly linked also to these complex – and still poorly understood – patterns.

The human influence on European fires Human activity (whether accidental, negligent or deliberate) is one of the most common causes of fire [190, 191, 192]. In Figure 15, we analysed the causes of fire as reported by 19 European countries in the Fire Database of EFFIS ([190], information here updated to 2016). Considering fires where information on their causes is available, only 4 % of the fires are not linked with human causes. It should be noticed how at the European scale, the information on fire causes is still affected by noticeable uncertainty with almost half of the records on fire events lacking a known cause. Despite the data uncertainty, the variability by country of the importance of human-caused fires, analysed against the share of uncertainty in the reported fire causes, is surprisingly low – and the overall percentage of human-caused fires is mostly above 90 % and always above 80 %. These findings are in line with the recent work of Balch *et al.* [193], whose analysis for the United States emphasise that human-started wildfires "accounted for 84 % of all wildfires". They further underline how in their study area human-started fires "tripled the length of the fire season, dominated an area seven times greater than that affected by lightning fires, and were responsible for nearly half of all area burned" [193].

Wildland–urban interfaces and land abandonment Syphard *et al.* [194] highlight the importance of the impact of population and wildland–urban interface (WUI) on forest fire spread, which is confirmed by e.g. Vilar del Hoyo *et al.* [195] and Gallardo *et al.* [196]. McCaffrey [197] emphasises the importance of genuinely understanding wildfires as a natural hazard and discusses the role of social learning for raising awareness on the concept of defensible space in WUI areas and capitalising collective experience. Shafran [198] focuses on the risk externalities faced by citizens in WUI areas when dealing with the effectiveness of defensible-space strategies, and highlights the role of collective behaviour – recommending policies supporting community

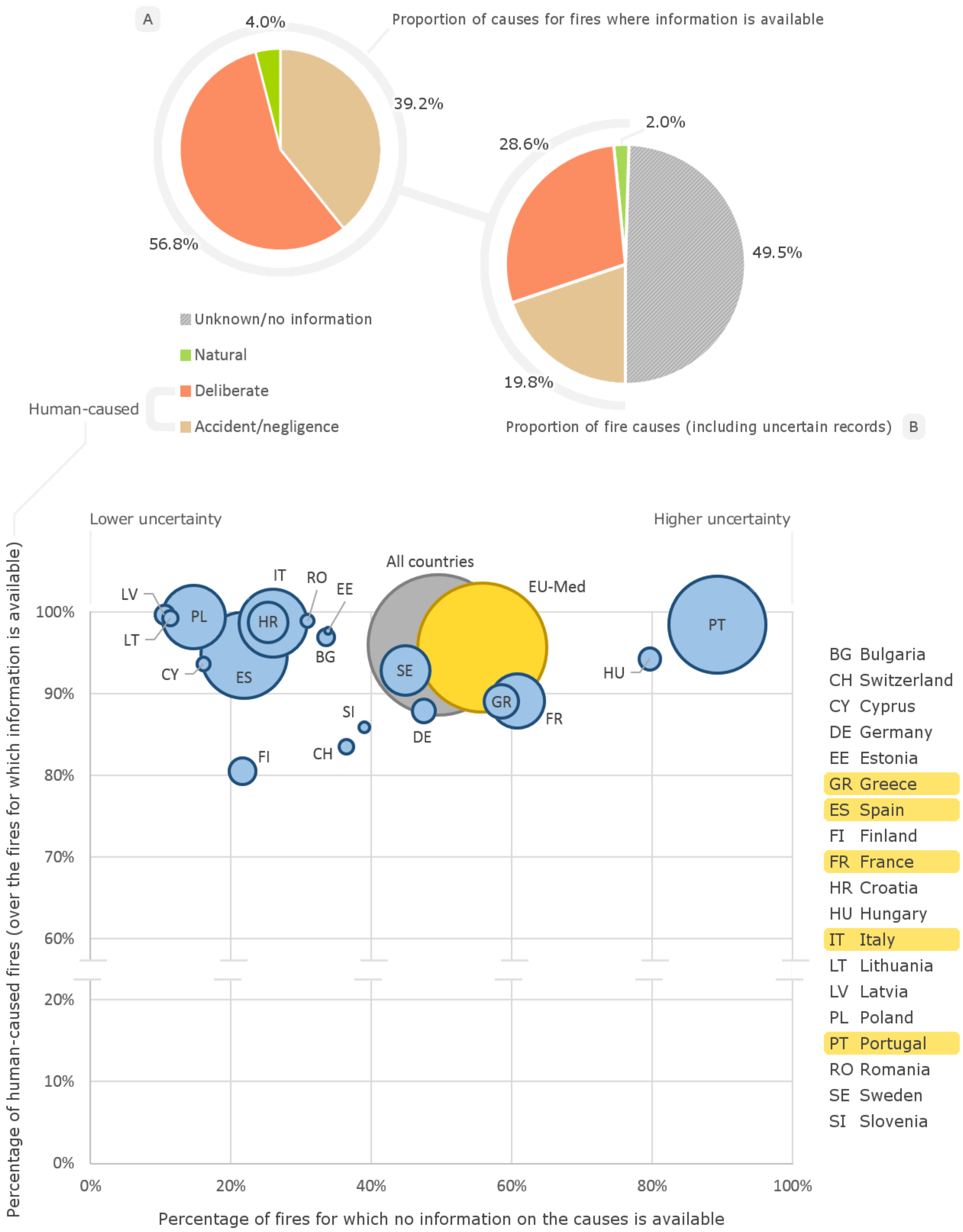

Figure 15: Causes of fire as reported by 19 European countries (Bulgaria, Croatia, Cyprus, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Latvia, Lithuania, Poland, Portugal, Romania, Slovenia, Spain, Sweden, Switzerland). **Top left (A)**: Considering fires where information on their causes is available in the Fire Database of EFFIS ([190], information updated to 2016), only 4 % of the fires are not linked with human causes – either deliberate or due to accident or negligence. **Top right (B)**: at the European scale, the information on fire causes is still affected by noticeable uncertainty with almost half of the records on fire events lacking a known cause. **Bottom**: despite the data uncertainty, the variability by country of the importance of human-caused fires, analysed against the share of uncertainty in the reported fire causes, is surprisingly low. Although the share of uncertain records varies from ≈ 10 % to ≈ 90 % depending on the country, nevertheless the overall percentage of human-caused fires is mostly above 90 % and always above 80 %. The bubble volumes are proportional to the number of fire records available for each country.

coalitions rather than individual initiatives. The importance of a social and policy perspective in this respects is also discussed by Winter *et al.* [199]. Tedim *et al.* [200] discuss the potential role in the European Union of an integrated strategy to complement current wildfire suppression practices with coordinated fuel management and social measures to reduce the probability of negligent and deliberate ignitions. They propose this adaptive management "not at the landscape [...] or community [...], or wildland-urban interface (WUI) [...] levels but at the territory scale" [199]. Pausas and Fernández-Muñoz [201] exemplified how depopulation of rural areas – leading to forest abandonment or lack of vegetation management – may cause an increase of the available fuel, favouring large forest fires with fast spread in connection with droughts. Nunes *et al.* [202] emphasise the role in Portugal of population density as a major factor to explain ignition. They also suggest that economic factors such as the varying unemployment rate may be significant to understand the spatial variability in density of ignitions. Socioecological causes are also highlighted. In particular, they underline – in line with Pausas and Fernández-Muñoz [201] – the importance of agricultural abandonment. They suggest agricultural abandonment to be linked with greater incidence of burnt areas, since this "has led to a marked increase in uncultivated land, which is covered mainly by shrubs, grass and other light vegetation that is very prone to fire" [202]. Nowadays, it is easy to start a fire even in current Mediterranean conditions: climate change will facilitate the ease of ignition even more compared to now. For this reason, the main causes of fire should be minimized, which includes looking at the social and economic factors that lead people to start fires, increasing awareness of the danger, encouraging good behaviour and sanctioning offenders [203].

In this perspective, forest monitoring and management may become a tool for adaptation. A good forest management would avoid fuel accumulation [204, 205] reducing the risk of extreme forest fires and increasing the tree resistance to the fire [206]. On the other hand, vegetation management taking into account high fire occurrence zones could help to decrease the ease of ignition or stop high-speed fire spread. An example could be the use of high water content species, as cypress, strategically placed to avoid new fires or decrease the spread rate [207, 141].

To conclude this overview of human factors affecting fire in Europe, it might be worthy recalling the comment by Hernandez *et al.* [39] – in line with the overall aim of our study: "despite the accidental and criminal nature of the wildfires in the Mediterranean, there is an extremely strong control of the concomitant weather on the wildfire, whether it be on its extension or intensity". Therefore, efforts towards addressing the complexity of human factors in European wildfire preparedness, mitigation and adaptation should not be decoupled from the due awareness on the state and potential evolution of weather and climate driven factors.

7 Towards a more reliable fire damage assessment under climate change: obstacles, opportunities, and next steps

In the previous sections, it emerged several times the extent of limitations inherited by the currently highly uncertain or missing components of data and knowledge (both qualitative and quantitative, i.e. suited or adaptable for computational modelling applications). In addition to the fire danger assessment under climate change, and the literature overview on the role of vegetation and human factors on fire danger, we focused also on mitigating the gaps on data and knowledge which hamper a reliable extreme scenario assessment of fire damage. In this final section, we highlight some key points – both conceptual and on the actual methodological aspects of the implementation we contributed – towards a more reliable fire damage assessment under climate change.

7.1 Burnt area data

The changing fire danger patterns (see the ones estimated in this study: Figures 8, 10, 11) are a key component to understand the observed burnt area statistics over the Mediterranean European regions [208, 209]. To assess the stochastic relationship between weather and climate driven indices of fire danger, and the corresponding expected patterns of burnt area, we exploited the data from the Fire Database of EFFIS [32]. The Fire Database is a repository of over 2 million individual fire records from 24 countries in Europe and North Africa. In the Mediterranean region of the continent, consistent data availability begins from the mid 1980s.

Total burnt areas (excluding purely agricultural fires) were extracted for Portugal, Spain, Italy, Greece and the Mediterranean region of France. As part of the data validation process, the data were compared with the official figures reported annually by the countries to the "Forest fires in Europe, Middle East and North Africa" series [17, 18, 19, 20, 21, 22]. In general the numbers of fires and burnt areas were broadly similar, with minor exceptions in individual years, probably as a result of country validation of provisional figures after the publication of the reports. Gaps in the data were identified for two countries. Data from Greece from 1998 and later give a sum of the burnt areas from the fire database consistently around 75 % of the official annual total. In 1998, the national management of Greek data changed [98]. It is also stated in the recent reports that Greece now estimates some of the total annual burnt area from satellite imagery, meaning that not every individual fire is logged in the database. To compensate, each monthly total from 1998 is weighted by a variable factor whose multi-annual average is around 1.33, bringing it in line with the official annual totals. In Italy, data from Sardinia are missing from the fire database in the years 1985-1988 and 1990-1996. Data from Sicily are missing in 1985. Annual totals from these areas were found in the literature [210, 211, 212] and disaggregated monthly burnt area totals were estimated in proportion with the monthly pattern observed in the years when data were available.

As a consequence of this analysis, the updated dataset of monthly statistics on burnt area by country now available in the Fire Database offers an improved harmonisation. This is an opportunity for a future revision of the existing literature on empirical estimates (see next section) of burn area from weather/climate driven fire danger predictors. Since the currently available empirical equations are based on less accurate data, a systematic source of uncertainty in the computational workflow to assess future fire damage has now a potential for being mitigated.

7.2 Towards robust estimations of burnt area under climate change

Although the progress in fire management and prevention has been linked with the current decreasing trend of burnt area in the Mediterranean Europe [213], the projected trends of burnt area under climate change scenarios have been estimated as largely increasing [214].

The literature offers a variety of empirical equations to model the fire damage starting from available weather-based information [208, 209]. Conceptually, this substitutes the direct assessment of fire damage (e.g. burnt area as detected by direct observation and remote sensing) with a computational procedure based on two steps. First, fire danger by weather (e.g. the Canadian FWI system components) is estimated starting from weather information (e.g. temperature, precipitation, wind and humidity). Second, the fire danger components are exploited as indirect predictors to estimate the fire damage by means of empirical equations (e.g. country specific equations [208, 209]). Traditionally, these empirical relationships have been successfully applied to estimate the central values of the fire damage (see in Table 5 the empirical equations used in [208]). However, the PESETA series of projects is now focusing on extreme values to better assess the nonlinear variability of the potential damage, and to delineate worst-case scenarios. Given their nonlinear behaviour, extreme values of fire danger and damage are both subject to a noticeably higher uncertainty compared to their corresponding central values. This new challenging focus on higher quantiles requires some structural changes in the way the current empirical models are applied to estimate future fire danger. The Section on the sources of uncertainty summarises the current cumulated set of data and model uncertainties which prevents some existing empirical models to be reliably exploited for extreme scenario assessment.

In the following, we offer a proposal for a future modelling architecture to mitigate part of the cumulated uncertainty in the estimation of fire damage extremes.

As highlighted in Figures 8, 10, 11, the variability of fire danger estimates between different scenario realisations is non-negligible even in the Control period, where the weather time series should be ideally identical to the one historically observed. However, the small differences induced by the combination of different global circulation models, regional climate models (Tables 2, 3), and corresponding bias correction of part of the climate variables [74, 110, 111], propagate in measurable differences in the fire danger estimates.

Our proposal to mitigate this component of data uncertainty is to apply a bias correction on the empirical fire damage models, separately exploiting the time series of fire danger generated under each scenario realisation, and the newly available updated dataset of monthly burnt area statistics by country. This way, the existing models might be reused preserving the relationship they captured between the historical observed fire danger time series, and the less accurate statistics on fire damage which were available before our update. This relationship would be subject to a partial bias correction, to account for the differences in both the simulated fire danger series in the Control period, and the improved statistics on fire damage.

The second step of our proposal is to exploit a computationally intensive statistical resampling, in order to be able to estimate fire damage extremes instead of the traditional central values. The statistical resampling would be based on bootstrap ensembling of the bias-corrected empirical equations, where each bootstrap run would generate a corresponding aggregation of estimates

Table 5: Empirical equations used in the second instance of the PESETA project series to estimate the expected central (average) values of burnt area by country [208]. The logarithm of the burnt area is estimated.

Region	Equation	R^2	Cross validation R^2
Portugal	$7.206315 + 0.2875863 \cdot \max(0, \mathrm{FWI} - 12.95)$ $-0.5236354 \cdot \max(0, 12.95 - \mathrm{FWI})$ $-0.5736034 \cdot \max(0, \mathrm{ISI} - 3.76)$	0.80	0.74
Spain	$7.669756 + 0.1504978 \cdot \max(0, \mathrm{FWI} - 14.59)$ $-0.4332947 \cdot \max(0, 14.59 - \mathrm{FWI})$ $+0.6127046 \cdot \max(0, 5.78 - \mathrm{ISI})$	0.68	0.61
France Med	$6.283384 - 0.4090681 \cdot \max(0, 12.91 - \mathrm{FWI})$ $+0.3973366 \cdot \max(0, \mathrm{FWI} - 15.43)$ $-1.10153 \cdot \max(0, \mathrm{ISI} - 5.62)$	0.69	0.62
Italy	$6.886724 + 0.2024325 \cdot \max(0, \mathrm{FWI} - 6.04)$ $-0.761246 \cdot \max(0, 6.04 - \mathrm{FWI})$	0.80	0.75
Greece	$8.237785 - 0.2898507 \cdot \max(0, 18.27 - \mathrm{FWI})$ $+0.2992717 \cdot \max(0, \mathrm{FWI} - 24.75)$ $-0.4916414 \cdot \max(0, \mathrm{ISI} - 6.02)$	0.79	0.72

based on a training set with an average share of $1 - \frac{1}{e} \approx 63.2\,\%$ of the available burnt-area data and the remaining data exploited as run-specific validation set (*out-of-bag* or *out-of-sample* set, on average $\approx 36.8\,\%$ of the available data [215, 216, 217, 218, 219]). Given the stochastic bootstrap selection per each run, the procedure is a cross-validation. The statistical resampling would consider as minimal unit of data a single fire season (i.e. the sequence of monthly statistics within a given year), to preserve the cumulated effect of intra-annual patterns [220].

Following this novel proposal for estimating a more reliable projected distribution of burnt-area per each EU-Med country – and a corresponding extreme scenario analysis based not only on estimated central values of fire damage but instead on a more plausible stochastic simulation of their uncertainty – a simplified estimation of wildfire damage value in Euro/ha might become feasible. To transform the estimates of burnt-area damage into their associated damage value, the map by Oehler *et al.* [221] (Figure 16) may be exploited following Camia *et al.* [208]. This proposed quantification may ideally complement a more complete – but challengingly far more complex – future biophysical analysis on the response, resilience and adaptation potential of vegetation, plant communities and ecosystems to changing fire danger and fire regimes.

7.3 Sources of uncertainty: a summary

Bias correction of climate projections is known to be a potential noticeable source of uncertainty in the predicted bioclimatic anomalies to which vegetation is sensitive [223]. In particular, the analysis of fire danger under climate change scenarios may be critically affected by climatic modelling uncertainty [224, 65]. Within PESETA III, the bias correction was applied only to temperature and precipitation components [74, 110, 111]. The relative humidity was estimated from the other bias-corrected variables as a proxy for the real bias-corrected relative humidity

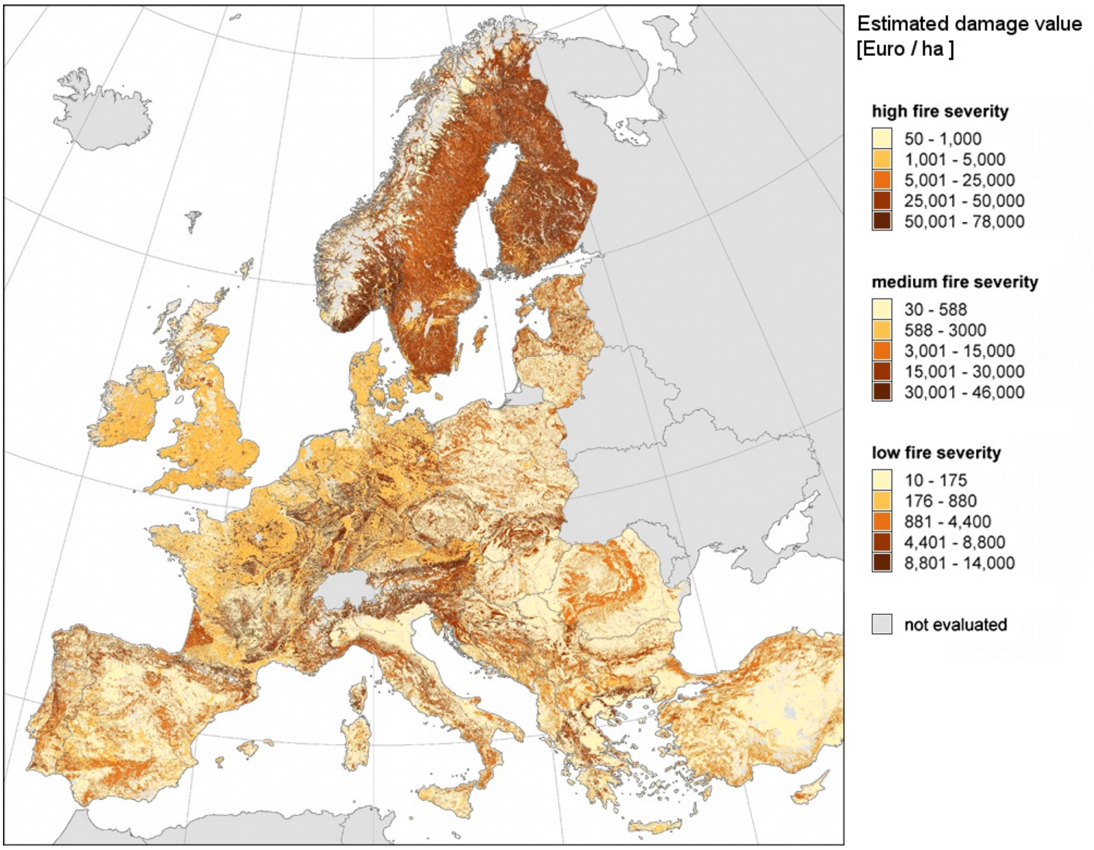

Figure 16: Map of estimated wildfire damage value in Europe under three different scenarios of fire severity (low, medium and high fire severity). Adapted from Camia *et al.* [208], Oehler *et al.* [221]. Colour scheme derived from Harrower and Brewer [222] (see http://colorbrewer2.org/?type=sequential&scheme=YlOrBr).

(unknown). Instead of the FWI-system required temperature at noon, the computing of the relative humidity exploited the maximum temperature, as the closest available proxy. The wind speed, instead, was not bias corrected for the PESETA III cluster of sectoral applications – since the data required for the correction were not available. As a consequence, the FWI-system components based on humidity and wind speed (see Eqs. 1a-1c and the matrix 4) are affected by this combined inconsistency, and the combination is cumulated over the time (given that the Canadian FWI system is a dynamic system). Noticeably, the drought code component is the only one not affected by this problem.

It should be noticed that even for the Control period the climate signal used in the second instance of the PESETA series differs from the agreed set of climate signals in PESETA III. This is because the different climate scenario realisations (Tables 2, 3) are applied even to the Control period.

The data uncertainty related to the official burnt area statistics were already discussed in the Section on burnt area data. The consequences of the combined effect of data uncertainty in the burnt area statistics and the fire danger uncertainty in the Control period were discussed in the previous section along with a proposed future mitigation strategy.

To the comments in Figure 11, a consideration may be added concerning the impact of the mathematical structure of different families of fire damage empirical equations. As discussed in Camia *et al.* [208], Amatulli *et al.* [209], the variable formulation of empirical equations to model directly the burnt area or instead its logarithm, their deterministic or stochastic parameterisation and the interplay of these elements with the modelled non-linearities may structurally bias some family of equations to over- or under-estimate the higher values of the burnt area signal (extrapolation bias). This may be especially problematic under Long-term climate change scenarios where the cumulated impact of the systematic extrapolation bias is stressed by patterns of predicted fire danger components which may be quite dissimilar from any pattern experienced within the Control period – which is also the period within which the empirical equations were trained. To mitigate this potential systematic bias, particular care would be required in selecting a set of empirical equation families so as to ensure that both over- or under-estimations would be expected under severe extrapolation.

Conclusions

Around the Mediterranean region, climate change will reduce fuel moisture levels from present values. The region will become drier, increasing the weather-driven danger of forest fires. Furthermore, areas exhibiting low moisture will extend further northwards from the Mediterranean than present, and the area of high fuel moisture surrounding the Alps in the present climate is predicted to decrease in size.

The danger of forest fires will increase relative to the present, in particular around the Mediterranean. This suggests that effective adaptation strategies will be crucial to lessening the detrimental impacts of climate change on forest fires, the direct damage to European citizens, and the reductions in biomass, biodiversity, and provision of ecosystem services that they can cause.

▸ Implications at the science-policy interface: adaptation options

The state of art covers a limited amount of case studies, with important missing knowledge. Nevertheless, literature review highlights a number of actions which can be taken that might mitigate the effects of increased forest fire occurrence in the future.

Key strategies Key strategies to be considered may include vegetation management to reduce the likelihood of severe fires, as well as fuel treatments to mitigate fire hazard in dry forests. These measures should be adapted to the different forest ecosystems and conditions.

Limited, preliminary evidences worth further investigation Observed evidence suggests that specific areas protected for biodiversity conservation may be affected less by forest fires than unprotected areas, despite containing more combustible material. Some typologies of old-growth forests may be associated with lower fire severity than densely stocked even-aged young stands. Some tree plantations might be more subject to severe fire compared with multi-aged forests. For specific typologies of forests, increasing the area of protected areas, such as Natura 2000 sites, might be even considered as a potential option for adaptation – if other strategies are considered in parallel. In this respect, the response of forest communities to fire is highly variable depending on their species composition and on the emergent properties associated with diverse mixtures.

Policy-relevant variability and uncertainty Different species have different levels of resilience to fires, as well as different levels of flammability. Some ecosystems and vegetation associations may be more adapted to fire disturbances with specific mechanisms to mitigate the post-fire recovery (e.g. ability to re-sprout, thick bark, high crown), as long as the interval between fires is not too short. In wrongly selected mixtures, the impact of forest fires might even be aggravated. Fire danger is also connected with the dynamics of droughts and other bioclimatic changes. A generic counting of species richness may not be directly associated with the overall response to fire of vegetation mixtures. Diversity in the functional traits related to fire resistance and resilience – along with the ability to cope with future bioclimatic habitat patterns, sometime quite different from current ones – might be more effective than simple functional richness. Therefore, deepening the understanding of resistance, resilience and habitat suitability of mixtures of forest tree species is recommended.

Human factors Human activity (whether accidental, negligent or deliberate) is one of the most common causes of fire. It is easy to start a fire even in current Mediterranean conditions: climate change will facilitate fire damage even more compared to now. For this reason, the main causes of fire should be minimized, which includes looking at the social and economic factors that lead people to start fires, increasing awareness of the danger, encouraging good behaviour and sanctioning offenders. In particular, the importance of the wildland-urban interface in potentially catalysing fire impacts should be focused in a context where wildfires are genuinely understood as a natural hazard and defensible space is considered even from a social and policy perspective.

▸ Limitations and next steps

PESETA III did not explicitly model adaptation scenarios for forest fire danger because ecosystem resilience to fire is uneven and its assessment relies on a complex array of factors that are very difficult to model numerically. Furthermore, a component of the proposed climate-based characterization of future wildfire potential impacts may be linked to the current distribution of population, land cover and use in Europe. The future distribution of these factors is likely to be different from now.

The analysis on forest fires within PESETA III focused on the foreseen wildfire danger scenarios based on the evolution of climatic variables that affect wildfire danger indices (Canadian Fire Weather Index system). PESETA IV will evolve from the work on wildfire danger to a very preliminary assessment of the wildfire risk components. As a general recommendation at the science-policy interface, given the current knowledge gaps future research should be supported on a deeper analysis of the ecological and human factors that affect fire occurrence.

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List of abbreviations and definitions

Anomaly	in climate-change analysis, it refers to the difference between the characteristics of a given quantity over two time periods. Given a statistic to aggregate the quantity time-series over a time period, the anomaly is the difference between the statistic over a period to investigate (e.g. future) and the same statistic in a control period.
BUI	*Buildup Index*, a component of the FWI system. It combines DMC and DC to model the total amount of fuel available for combustion to the spreading fire. See Figure 6.
CMIP5	*Coupled Model Intercomparison Project phase 5*, a set of coordinated climate model experiments, dealing with global coupled ocean-atmosphere general circulation models (GCMs) [225]. See http://cmip-pcmdi.llnl.gov/cmip5/ .
Computational model	mathematical model in computational science requiring computational resources to analyse or estimate specific statistics and information on the behaviour of a natural or artificial system. Definition from San-Miguel-Ayanz *et al.* [226].
CORDEX	*Coordinated Regional Climate Downscaling Experiment* initiative, a coordinate effort to advance and the science and application of regional climate downscaling [227]. See http://www.cordex.org .
DC	*Drought Code*, a component of the FWI system. It models a standard moisture content of deeper, compact, organic layers. This D-TM is able to track seasonal drought effects on forest fuels. See Figure 6 and Table 1.
DMC	*Duff Moisture Code*, a component of the FWI system. It models a standard moisture content of loosely-compacted organic layers of moderate depth (duff layers and medium-sized woody material). See Figure 6 and Table 1.
D-TM	*Data-transformation models* or *modules*. In computational science, the architecture of models may be structured in a data-oriented modular way. A D-TM is a conceptual modelling-unit which transforms a set of input data and model parameters into a corresponding set of output data [66, 67, 68]. In this context, ”data” as a concept is extended to include not only physical measurements but also derivative data (typically, derived as output of one or more models) and, as a particular case, the value of model parameters. D-TMs may be composed of sub-units - which are D-TMs themselves. Therefore, a D-TM may be described as a chain of D-TM units which exchange a flow of data, from the initial inputs up to the final desired output values. Data can also be exchanged asynchronously between D-TMs which physically run in different computational facilities. This eases the integration of the various conceptual modelling-units even when they are implemented in different programming languages, and eases the interaction among multiple research teams.
EFFIS	*European Forest Fires Information System*. It consists of a modular web geographic information system that provides near real-time and historical information on forest fires and forest fire regimes in the European, Middle Eastern and North African regions. Fire monitoring in EFFIS comprises the full fire cycle, providing information on the pre-fire conditions and assessing post-fire damages. See http://effis.jrc.ec.europa.eu/ .
EURO-CORDEX	European branch of the CORDEX initiative. EURO-CORDEX is a multi-institution voluntary effort to produce ensemble climate simulations for the European continent, using multiple downscaling models (regional climate models, RCP) to improve global circulation models (GCM) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [105, 92, 106, 107]. See http://www.euro-cordex.net .
FFMC	*Fine Fuel Moisture Code*, a component of the FWI system. It provides a numerical rating of the moisture content of the top litter and other cured fine fuels, indicating the relative ease of ignition and flammability of fine fuel. See Figure 6 and Table 1.
FWI	*Fire Weather Index*, a component of the FWI system. As a numerical index (not to be confused with the FWI-system of indices), it offers a standard aggregated numerical rating of fire intensity which combines ISI and BUI. See Figure 6.

FWI-system	The Canadian Forest *Fire Weather Index* system, an index of fire danger to account for the effects of weather on forest fuel and fire. The FWI is designed to provide a uniform numerical rating of the relative fire potential, by dynamically combining the information from local temperature, wind speed, relative humidity, and precipitation (24-hour rainfall) values. Provided a daily time series for each of these weather data variables is available, the system is able to process either actual observations or future simulated estimates. The FWI system is standardised to consider the behaviour of a reference fuel type (mature pine stand), irrespective of other factors affecting fire danger such as the topography and the actual or future fuel details [16, 59]. Among the various indices composing the FWI-system, a specific component of special importance is the FWI numerical index, which aggregates the other indices. See Figure 6.
GCM	*Global circulation model*, or *global climate model*. It is a climate model able to approximate the general circulation of atmosphere (and/or of oceans) at the global scale, considering the main fluxes of mass and energy. As a trade-off for its ability to cover the global scale, its spatial resolution is typically lower compared with RCMs – which may be exploited to refine the details of GCM simulations for a particular region of interest.
Geospatial	in computational science, it refers to data or information which is geographically distributed and covers significantly broad spatial extents. Under these circumstances, for example the simple approximation of the portion of Earth's surface covered by the spatial extent as a geometrical plane is no more valid. Definition from San-Miguel-Ayanz *et al.* [226].
GeoSemAP	*Geospatial Semantic Array Programming*. Geospatial application of the SemAP paradigm, where the conceptual units (D-TMs) of the modelling workflow are a composition of geospatial transformations and array-based D-TMs [67, 68].
GHG	atmospheric *greenhouse gas*.
GO-ESSP	*Global Organization for Earth System Science Portals*. See http://go-essp.gfdl.noaa.gov/ .
HS	*Habitat suitability*: potential suitability for a certain organism (e.g. a tree species) to live in a given local habitat. Although there is no agreement in defining *habitat* within the ecological literature, a working definition for operational purposes has been proposed as "description of a physical place, at a particular scale of space and time, where an organism either actually or potentially lives" [103]. As a quantity, HS is generally varying from 0 (0 %, unsuitable habitat) to 1 (100 %, potentially highly suitable habitat). For an overview on terminology, ambiguity and the multifaceted concepts related to HS, see e.g. de Rigo *et al.* [47].
IPCC	*Intergovernmental Panel on Climate Change*. See http://www.ipcc.ch .
ISI	*Initial Spread Index*, a component of the FWI system. It represents the expected rate of fire spread. It considers the combined effects of wind and the FFMC on the rate of spread. However, it excludes the influence of variable quantities of fuel. See Figure 6.
JRC	*Joint Research Centre* of the European Commission. See https://ec.europa.eu/jrc/en/about/jrc-in-brief .
P	*Precipitation*. One of the input variables required by the FWI system . See the Section on modelling structure and semantics.
PESETA	The context behind this study is based on a series of projects mostly developed within the European Commission, Joint Research Centre (JRC) . Within this project series, PESETA (*Projection of Economic impacts of climate change in Sectors of the European Union based on bottom-up Analysis*, https://ec.europa.eu/jrc/en/peseta), cross-disciplinary aspects are essential.
PESETA III	The third instance of PESETA (PESETA III) focuses on supporting the implementation of Action 4 of the EU Adaptation Strategy by deepening and further refining existing JRC bottom-up analyses of climate change impacts. It contributes to report on the Strategy's implementation that the Commission will present to the European Council and Parliament. A common set of five climate scenario realisations (model runs) drive the assessment of sectoral biophysical impact models with a strategic focus on the biophysical dimension of impacts. The analysis includes the 2030s time horizon, and explores the challenging characterisation of extreme events with their peculiar uncertainty, and aims at fostering an updated review of potential adaptation options.

RCP	*Representative Concentration Pathways*. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time dependent projections of atmospheric greenhouse gas (GHG) concentrations [9, 228].
RCP8.5	High emission RCP scenario of climate change. It is derived after the A2r scenario providing a revised quantification of the original IPCC scenario family SRES A2 [75, 109] and assumes an increase of the radiative forcing throughout the 21st century up to reach an approximate level of 8.5 W per m^2 by the end of the century.
RCM	*Regional climate model*. It is a climate model typically having a higher spatial resolution compared with the one of GCMs. As a trade-off, its spatial extent is limited to a particular region of the globe. It is used to refine the details of GCM simulations for a particular region.
RH	*Relative humidity*. One of the input variables required by the FWI system. See the Section on modelling structure and semantics.
scen	Climate scenario instance. It is defined as either an observed (i.e. historical data) or estimated time series – e.g. under climate change – which corresponds to a particular realisation of the variables. See the Section on modelling structure and semantics.
Scenarios	The future evolution of greenhouse gas (GHG) emissions is highly uncertain. Scenarios are alternative plausible descriptions of how the future may unfold. Each scenario is based on a coherent set of assumptions concerning key driving forces (e.g. demographic and socio-economic development, rate of technological change, prices) and relationships. Neither predictions nor forecasts, scenarios are tools to support the analysis on how driving forces may influence the dynamics of future emissions. They are useful to assess the implications of development, potential impacts, adaptation and mitigation actions, and the associated uncertainties [109, 228].
Semantic constraint	in computational modelling, it formally expresses a logical or mathematical property which characterises the quantitative meaning (semantics) of a certain quantity [78, 72, 73, 68, 226]. For example, considering the annual time series of the weather-driven fire danger in a given area, its 90 % quantile logically must be greater than or equal to the median value in the same area, while this constraint does not hold for the anomaly of the 90 % quantile compared to the anomaly of median values.
SemAP	*Semantic Array Programming*. In computational science, a computational modelling approach to compactly process arrays of data preserving the consistency of their underpinning semantics [72, 73, 67, 68]. SemAP is based on the modularisation of the modelling workflow into conceptual units (modules) of data-transformation (see D-TM), and on the systematic use of array-based semantic constraints. In this work, SemAP is applied for the statistical analysis of the FWI system.
SRES	IPCC *Special Report on Emissions Scenarios* [109].
SRES A2	The SRES A2 storyline and scenario family "describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines" [109].
T	*Temperature*. One of the input variables required by the FWI system. See the Section on modelling structure and semantics.
w	*Wind* speed. One of the input variables required by the FWI system. See the Section on modelling structure and semantics.
WUI	*Wildland-Urban Interface*. Agriculture abandonment may increase the available fuel in areas that become wildland. Urban expansion may generate new settlements surrounded by wildland. In both cases, these transitional areas between unoccupied land and human settlements may be particularly exposed to wildfire impacts. See the Section on human factors and fire.

See also Table 2, Table 3, and Table 4.

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