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European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions

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Task 9 - Forest fires

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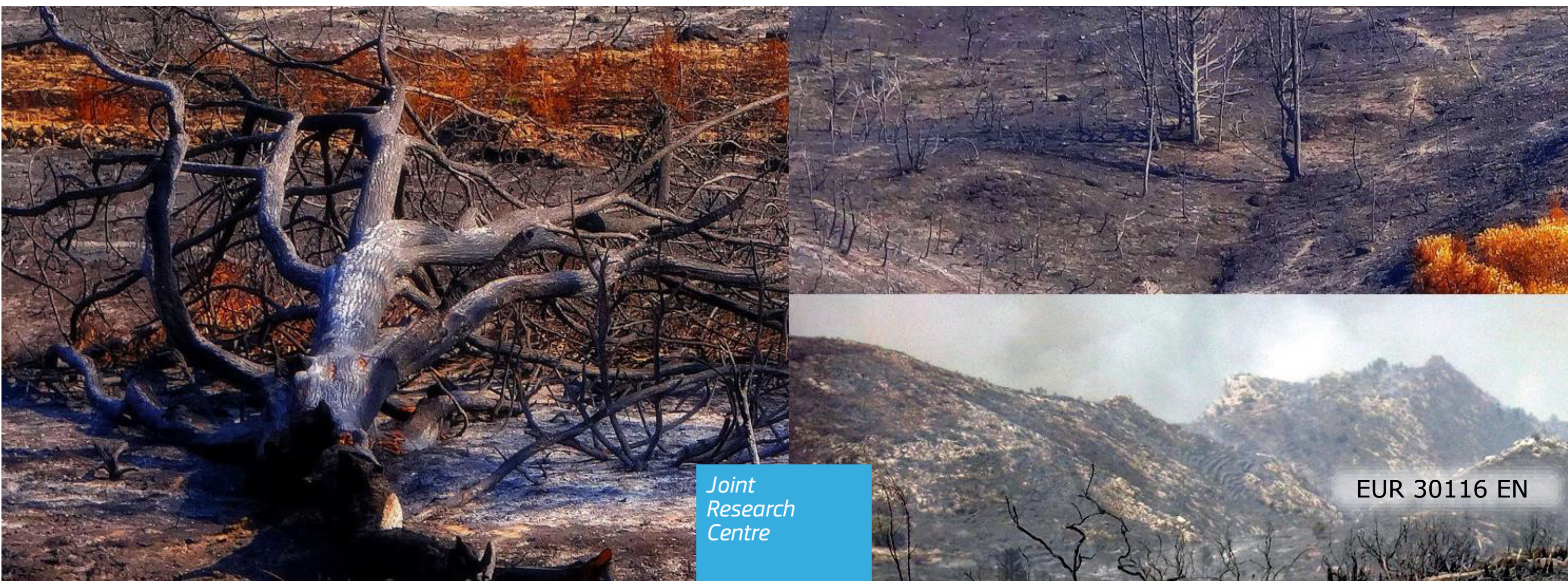

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Contents

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Images in the front cover: left and top right, wildfire in Rhodes, Greece – adapted from an image authored by Alan Eng (CC-BY) http://preview.tinyurl.com/flickr-alaneng-14151661831. Bottom right, wildfire in Alicante, Spain – adapted from an image authored by Sergio Jordá Gregori (CC-BY) http://preview.tinyurl.com/flickr-sergiojorda-17666900792.

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Executive summary

In Europe, forests cover over one third of the land area, but the continent is characterised by high fragmentation of land cover, with complex patterns of human settlements and land uses, where populated areas are frequently found close to wildland. This human-nature interface may be due to either expansion of wildland (for example on abandoned agricultural areas) or to the extension of settlements in areas previously characterised by a high proportion of wildland. Consequently, wildfires have a great impact on agricultural resources and urban settlements, with critical consequences for the safety and health of citizens, the safeguard of economic assets and the provision of essential services from fire-damaged ecosystems. Furthermore, climate change may directly change fire regimes in Europe and globally and affect the biophysical conditions of ecosystems so that, in some areas of Europe, the current vegetation structure might become irrecoverable after fire damage.

Wildfires: interactions among changing weather, vegetation and human factors

Several factors are important to understand the variable distribution and damage of wildfires and prepare for practicable adaptation options. **Weather and climate, vegetation condition and composition, and human factors play an essential role in fire regimes**. Weather and climate define the composition and structure of vegetation fuels. Although human activities and vegetation management shape the actual state of vegetation fuels, their typology is subject to the general ecological domains in which they exist. Additionally, weather effects can strongly influence the susceptibility to fire of vegetation fuel. Weather can control the moisture content of the vegetation, allowing a rapid wetting or drying of fine fuel (litter, needles, mosses, twigs), while having a slower response on coarser wooden fuels. The moisture level in these different fuels, along with weather factors such as wind speed, affect the ease of ignition, potential propagation and severity of a fire.

Extremes of fire danger and damage **In Europe, the number of days with high-to-extreme wildfire danger is expected to increase with the changing climate**. Wildfire risk can be identified as the joint effect of the level of wildfire danger in a given area, and its potential impact for citizens. Under climate change, specific components of wildfire risk may be expected to increase in various European areas [35, 75, 93], raising the impact for the people and ecosystems exposed in vulnerable areas. As a main component of risk, wildfire danger is linked with the factors, including weather and climate, which can worsen either the likelihood of ignition, or the behaviour of the fire once ignited. Nevertheless, weather conditions alone cannot precisely predict where wildfires will be ignited. In Europe, the vast majority of fires are caused by human actions [35]. These actions are related to socio-economic aspects which are difficult, if not impossible, to be quantitatively modelled especially under climate-change scenarios. However, **not all the ignited fires have the same impacts**. What weather and climate may help to predict is the behaviour component of the fire danger, that is, the potential spread and intensity of fires once they are ignited; particular weather conditions of high temperature, low relative humidity and fast wind speed facilitate the spread of uncontrollable fires. In addition to weather conditions, other factors such as fuel types and topography determine the conditions of fire spread. Two wildfires ignited in the same place, but under different weather conditions, may result in very different levels of damage. **The distribution of wildfires in Europe and the damage they may generate is remarkably**

variable, with 65 % of the overall area burnt caused by only 1.2 % of the European fires, and a very small share of the total number of fires (less than 0.3 % of wildfires) causing more than 40 % of the annual burnt area. These **extreme fire events show a strong connection with co-occurring extreme conditions of fire danger, as a fire ignited when fire danger conditions are particularly unfavourable may become uncontrollable and cause major damage. In Europe, these extremes of fire danger may be expected to increase significantly with the changing climate** (see Figure 1).

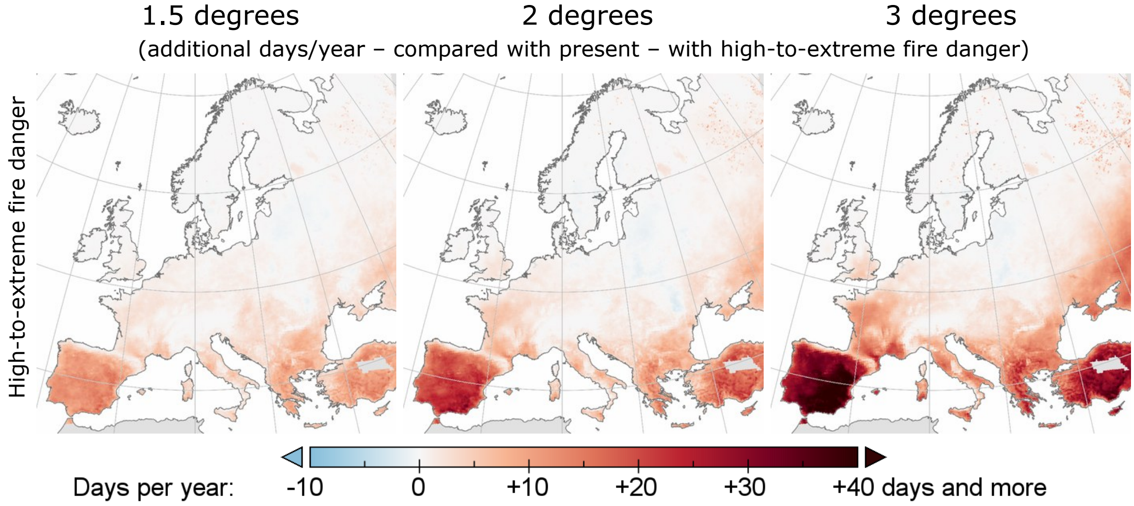


Figure 1: **Number of days per year with high-to-extreme fire danger** (daily FWI ≥ 30). Additional days per year with high-to-extreme fire danger, with reference to the situation in the control period 1981-2010, for different levels of global warming. Red shades denote an increment of days, blue shades a decrement. See Figure 10 and Figure 11 for more details.

The intensity of wildfire danger is summarised by assessing the changes in the frequency of different classes of danger (from relatively low values of danger up to higher values linked with extreme fire danger)[2]. Fire danger is determined by the overall combination of precipitation, temperature, wind, and humidity patterns, and their climatic changes. The effect of weather on fuel and vegetation complexes are discussed in the next section. In Mediterranean Europe, an increasing number of days per year is predicted in the higher danger classes (from high to extreme fire danger) under future climate scenarios. A marked increase is predicted of days with high-to-extreme fire danger in the Iberian Peninsula, Turkey, along with part of Greece and the Balkans, part of central and southern Italy, and of France. Although the projected worsening of fire danger is smaller with 1.5 °C global warming, relative to 2 °C or 3 °C warming, fire danger is still predicted to be consistently worse than at present, as fuels will transition to drier fuel complexes under future climate scenarios, more prone to forest fires. The areas with increased high-to-extreme fire danger are notably expanded (see Figure 1) at 1.5 °C. This expansion is further increased at 2 °C and even more at 3 °C.

Other European regions show consistent worsening patterns. Southern UK, Belgium, part of the Netherlands and Germany, and the Pannonian Basin enclosed by the Carpathians and the Transylvanian Plateau display an increasing number of days with high-to-extreme fire danger. This is more evident in the 2 °C than in the 1.5 °C warming scenario, and is projected to worsen in the 3 °C warming scenario.

[2] Six equi-spaced classes of increasing fire danger by weather, monitoring the expected evolution under climate change of the annual number of days falling within each class of danger. This ranges from the number of low-danger days (lowest class of danger) up to the number of extreme-danger days (highest class of danger). See Figure 10 and Figure 11 for more details.

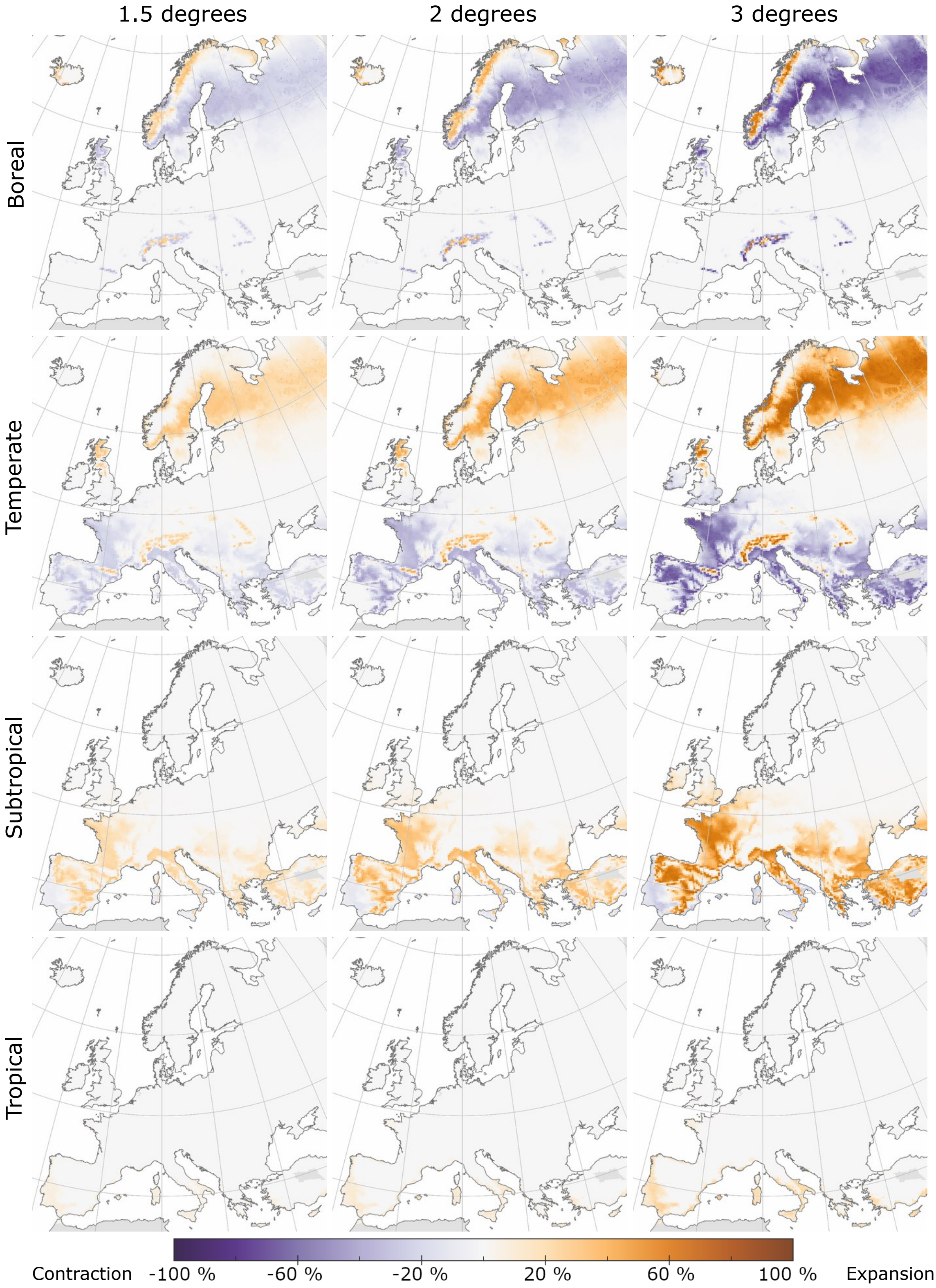


Figure 2: **Areas bioclimatically more vulnerable for the exposed vegetation**. Shifting components of the vegetation ecology (ecological domains: Tropical, Subtropical, Temperate, and Boreal) in relation to vegetation fuel complexes in Europe. The figure shows the expected change in the future scenarios, compared to 1981-2010. Darker colours (either brown or violet) indicate a higher stress to the vegetation currently established in a given area, due to a stronger change of the prevalent ecological domain. A substantial shifting of all the domains towards North is expected. This results in a substantial contraction of the Boreal domain, as the Temperate domain shifts North. The Subtropical domain is expected to expand around the Mediterranean region, and to contract in extreme Southern areas of the Mediterranean region, where the Tropical domain, currently absent in Europe, is expected to appear and possibly become a significant ecological component. From [27]: see Figures 9, 12, and 13 for more details.

Changing ecosystem vegetation, fuel and resilience Climate change is expected to exert a direct influence on the structure and composition of terrestrial ecosystems. This may affect wildland vegetation (forests, shrub and grassland) with changes in the spatial distribution of the future ecological zones, their typical plant associations, and corresponding fuel characteristics. This may include **negative effects not only on the vegetation before a fire occurs; but also after the fire, diminishing its resilience and thus limiting the vegetation recovery** (post-fire recovery).

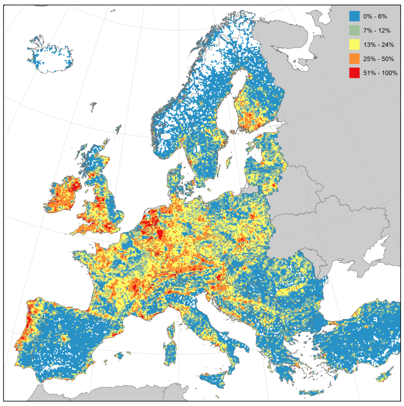
In particular, the risk posed by wildfires in a specific area may rise with increasing levels of fire danger and vulnerability. This may happen due to the effect on vegetation of the changing climate, which may introduce an important stress factor. Areas with higher climate-driven stress are susceptible to higher degradation of the local vegetation. In these areas, the accumulation of dead woody debris on the ground may directly affect the spread and intensity of fires, and raise the overall fire risk. In addition, **vulnerability to fires may worsen further because of declining ecosystem resilience, which may hamper the regrowth of existing species and lead to unwanted ecosystem transitions**. This might trigger a chain of disruptions in the services provided by the affected ecosystems.

Figure 2 summarises the expected changes of the prevalent ecological domains (European ecological domains: Tropical, Subtropical, Temperate, and Boreal, following the global FAO definition [49]) in relation to vegetation fuel complexes. Elements of a fuel complex include the tree canopy, the understorey vegetation, along with ground material from the decomposition and regeneration processes. Pronounced variations of the ecological domains due to the changing climate may help identify, with a uniform criterion at the continental scale, areas in which the current vegetation is highly vulnerable. However, even a relatively small change in the ecological domain pattern may still be associated with a high local change of vegetation vulnerability. Major changes of the ecological domains will surely induce a major stress on the structure and composition of vegetation fuels, leading to changes in the vegetation vulnerability to fire, which may worsen under changing climate.

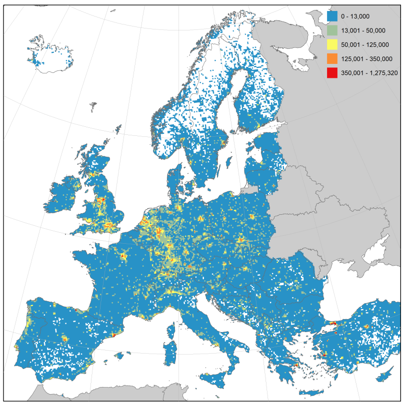
A substantial shift of all the domains towards North is expected, along with the appearance in Europe of climatic features specific to the Tropical domain, namely in extreme Southern areas of the Mediterranean region. Most intense changes in the ecological domains appear to concentrate in the Mediterranean region and in the southern part of both the current temperate and boreal domains. The intensity of change appears to increase when comparing the 1.5 °C global warming scenario with the 2 °C and 3 °C scenarios, with a remarkable stability of the patterns between different scenarios.

Vulnerable interfaces between human settlements and wildland The climatic effects on the vegetation and the potential decrease of the ecological resilience, describe an important dimension of the vulnerability to wildfires. Another key component is directly linked to identifying in which areas the exposed population is most vulnerable to forest fires. **Climate-driven changes of fire regimes will potentially affect European citizens, in particular where human settlements are close to wildland areas**. In this vulnerable interface between wildland and urban presence (the so-called Wildland-Urban Interface, WUI), the risk of fire may be especially high for the population [100, 108, 54].

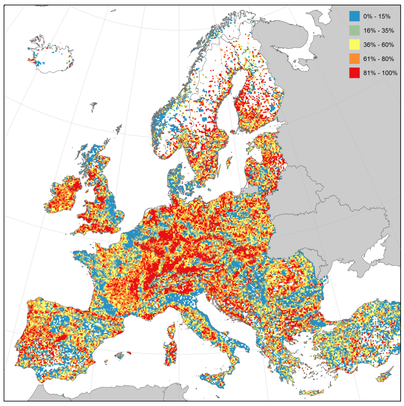
A key vulnerability nexus between human presence and wildfire risk. Two main components link the human presence in the vulnerable interface with the resulting overall risk. Most of the fire ignitions are linked to human actions, which are frequent in the WUI. Furthermore, most of the



Wildland-urban interface (WUI): Percentage of land area which lies in the WUI (ensemble median, by spatial cell).



Vulnerable population: Number of people living in the WUI (ensemble median, by spatial cell).



Vulnerable population: Percentage of population living in the WUI (ensemble median, by spatial cell), compared with the total people (also outside the WUI).

Figure 3: **Vulnerable population by proximity to wildland fuels**. Vulnerable interface between wildland and urban presence (Wildland-Urban Interface, WUI), where the risk of fire may be especially high for the local population. The spatial extension of the interface is illustrated (map at left), along with the amount of population more vulnerable to wildfires because of living in the interface (maps at the centre and right).

burned areas in the Mediterranean region occur within or next to WUI areas. This may be defined as an *active* role of the WUI in increasing the fire risk. The second component of WUI population vulnerability is a *passive* consequence of the increased risk. Once a given fire is ignited close to the WUI, neighbouring locations are also threatened. This means that the **population living in the WUI are more vulnerable to wildfires** (see Figure 3).

1 Introduction

An overview of wildfire damage in Europe 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 [30, 1]. To this area, shrubland and grassland may be added to encompass the extent of European areas with an important component of wild land.

In recent years, large forest fires have repeatedly affected Europe, in particular the five Mediterranean countries Portugal, Spain, Italy, Greece and France (part of the Mediterranean region of the European Union, EU-Med), which on average account for around 85 % of the total burnt area in Europe per year ([35] see Figure 4). In these five countries, the average damage between 1999 and 2016 was more than 400 thousand ha, and higher than 700 thousand ha one year in five. In 2017, the worst year for the last two decades, the total annual burnt area of Portugal, Spain, and Italy alone exceeded 0.8 million ha. Other countries of the region (for which less data are available and with higher uncertainty) also suffer from a substantial annual damage by wildfires.

In Figure 5 and Figure 6, an overview is offered of burnt area in hectares across Europe and the Middle East. Figure 5 shows the statistics in the European Union for the years 2007-2017 (estimates from satellite images of fires of over 30 ha, as mapped by the European Forest Fire Information System, EFFIS). Figure 6 shows the corresponding statistics for the available countries outside the European Union, for the years 2009-2017.

The inadequacy of average trends to fully capture the dynamics of extremes In the previously mentioned five EU-Med countries, there has been overall a slight downward trend since the 1980s in terms of reported burnt area in forests and other wooded land. The number of fires

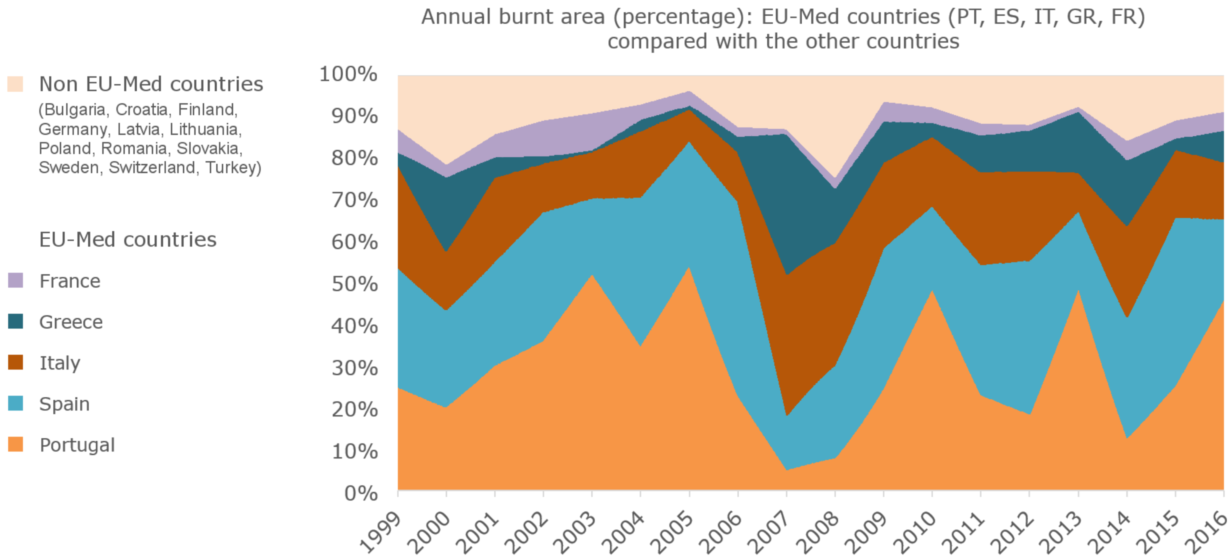


Figure 4: An official source of fire damage in Europe: country-reported data from the Fire Database of the European Forest Fire Information System (EFFIS) [9, 94]. Annual burnt area (relative proportion) of five EU-Med countries (France, Greece, Italy, Portugal, Spain) and of 12 other countries (Bulgaria, Croatia, Finland, Germany, Latvia, Lithuania, Poland, Romania, Slovakia, Sweden, Switzerland, Turkey). Percentage of burnt area per year, where 100 % represents the total annual burnt area of all the 17 countries. Derived after de Rigo *et al.* ([35] see in particular fig. 4 and 5).

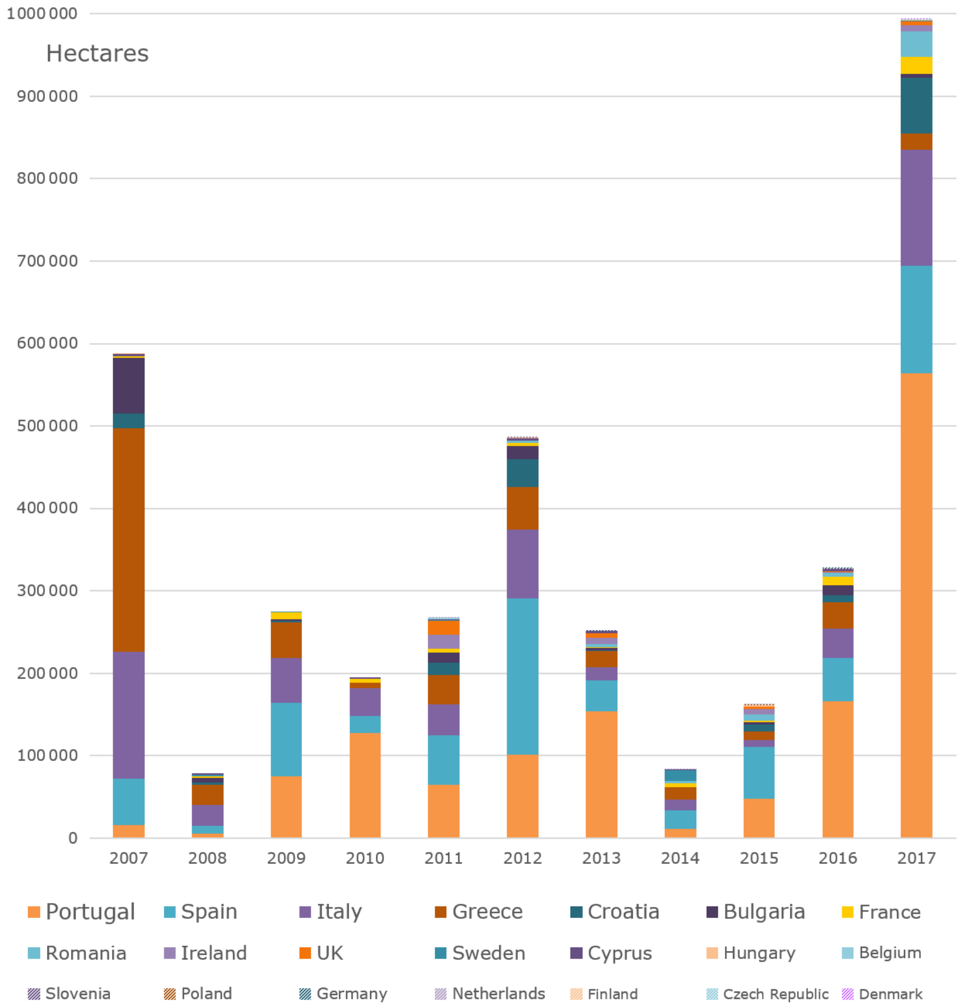


Figure 5: Another harmonised and independent source of fire damage in the European Union, from the European Forest Fire Information System (EFFIS). Overview of total burnt area for the years 2007-2017 from satellite images of fires of over 30 ha mapped by EFFIS. Countries are ordered by total size of burnt area over this period. Note that the burnt area mapped for Portugal in 2017 exceeds the combined total for all countries in all except one of the previous 10 years. Country names with size proportional to the order of magnitude of the total burnt area. Image adapted from San-Miguel-Ayanz *et al.* [95].

reported over the same interval show a slightly more complex rise and fall pattern that may also be linked to an improvement in reporting the smaller fires during the 1990s [94]. This promising decreasing trend of burnt area in the Mediterranean Europe has been linked with the progress in fire management and prevention [104].

However, "extreme" years where the total burnt exceeds the average by a significant margin happen every 2-5 years. In Figure 5, it may be noted that the burnt area mapped for Portugal along in 2017 exceeds the combined total for all countries in all except one of the previous 10 years. Perhaps counterintuitively, a run of years with fewer or smaller fires may result in a build-up of fuel leading to more extreme fires in bad years, if aggressive fuel management is not undertaken [4], meaning that looking only at multi-year averages may mask the underlying patterns.

As Figures 4, 5, and 6 highlight, these patterns are specific to the local characteristics of each

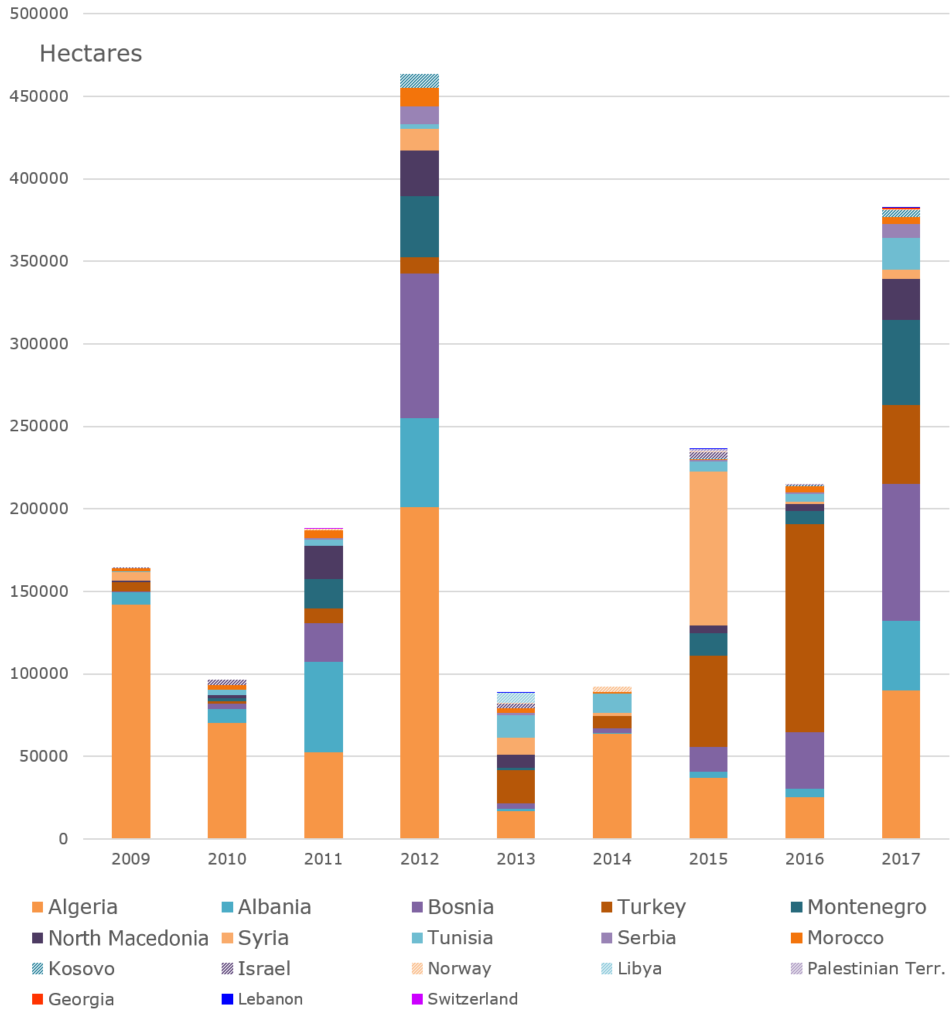


Figure 6: Fire damage across Europe and the Middle East (available countries outside the European Union, see also Figure 5), from the European Forest Fire Information System (EFFIS). Overview of total burnt area for the years 2009-2017 from satellite images of fires of over 30 ha mapped by EFFIS. Countries are ordered by total size of burnt area over this period. Country names with size proportional to the order of magnitude of the total burnt area. Image adapted from San-Miguel-Ayanz *et al.* [95].

European region. At the country (and sub-country) level, human aspects may be uneven. Differences in the availability and allocation of fire-fighting resources, in the local strategies for fire prevention and management of fuel, and also in the population behaviour, may mark comparably different responses to fire danger and ignition, which may reverberate into variable patterns of fire damage. All these human-related elements are very challenging to model, given the systematic lack of harmonised information on them. In addition, at the local scale differences in the typology and fragmentation of land cover, and in the local vegetation distribution and structure, may further exacerbate the variability of fire damage patterns.

A fragmented European wildland and its interface with urban areas Europe is densely populated, with about 3 % of world land hosting almost 7 % of the world population [31, 43]. The continent is characterised by high fragmentation of its land cover and uses, with intricate patterns related to the density and distribution of human settlements and activities, and populated areas are frequently found close to wildland. It comes as no surprise that the important role of human activity (whether accidental, negligent or deliberate) is one of the most common causes of fire

[55, 35]. Changing socio-economic conditions in several regions may result in a change in the local land use, with agriculture abandonment and unmanaged re-vegetation of areas that are close to human settlements and which were previously characterised by more favourable fuel conditions [78, 76]. On the other hand, the fragmented borders of some large urban settlements are expanding over areas previously occupied by important share of wild land. Both phenomena lead to a relevant interface between wildland and urban areas (the so called Wildland-Urban Interface, WUI : see the corresponding part in the methodology section) which is especially vulnerable to fire hazard [98]. As a consequence, fires in European forests and wildland also have a great impact on agricultural resources and urban settlements, with critical consequences for the safety and health of citizens, the safeguard of economic assets and of the provision of essential services from fire-damaged ecosystems. At regional, national, and sub-national level, the spatial extent of this WUI interface was investigated in several studies with different methodologies, data and assumptions [59, 51, 40, 69, 70]. Here, a preliminary harmonised overview of the distribution in Europe of the wildland-urban interface is presented for the first time at a high spatial resolution [17]. This result is based on the combination of pan-European land cover [7, 8] and global high-resolution information on human settlements [80].

The key role of weather and climate on fire danger and large fires In addition to the direct human role in the changing patterns of wildfire, the indirect role of the climate and of its on-going change exerts a clear influence on the weather-driven danger of fire. The projected trends of burnt area under climate change scenarios have been estimated as largely increasing [97], although "complex relationships between climate, vegetation and fires hamper the applicability of fire impact models to conditions that are very different from the current ones" [103]. Extreme weather events, such as prolonged dry spells and droughts, or intense dry wind, are expected to increase in frequency with the changing climate (for a literature overview, see [35]). In 2017 [75], there were unusually high fire levels during the fire season in many parts of the world, with extensive and severe fires occurring in Chile, the Mediterranean, Russia, the US, Canada and even Greenland. In Europe, the mapped burnt areas of fires over 30 ha in 2017 was almost 1 million hectares (993600 ha) compared with a 2008–2016 average of around 213,000 ha [95]. Climate is just one of many factors influencing wildfire risk, but negative climatic conditions enable fires to take hold and spread quickly. In a high fire year the number of fires do not necessarily increase by much but the difference is in the severity and size of the burn area resulting from fires once started.

The specificity of wildfires as a natural hazard It is here important to understand why wildfires as a natural hazard do not necessarily show the typical saturation which may be observed in other hazards. For example, floods or windstorms may inflict severe damage in areas directly hit by an extreme event. However, although precipitation and wind energy are key driving factors of the disturbance (flood or windstorm), which may be subject to cumulative effects and delayed impacts (e.g. from water runoff), these effects are fortunately not self-sustaining. Analogously, dry or windy weather conditions may be key factors for the spread of a fire once ignited.

However, a key fact to understand about wildfires is that they can be a self-sustaining phenomenon which is linked with the amount of fuel available to burn, and which may spread far from the initial ignition point under favourable weather conditions. The energy and spread of a wildfire is connected with both the biomass it can enter in contact with and effectively burn, and the weather or climatic conditions. The distribution of wildfire events in Europe is uneven and confirms the key role of the most extreme events in the overall damage by fire. Only 3.6 % of the wildfires recorded by the Fire Database of EFFIS have an area burnt greater than 30 hectares.

However, they contribute to more than 79 % of the total burnt area. Larger fires are even less frequent, but their damage is outstanding. 1.2 % of the fires exceed 100 ha, and less than 0.3 % is greater than 500 ha, respectively contributing to 65 % and 40 % of the overall burnt area. Only less than 0.1 % of the wildfires spread for over 1000 ha: this very small percentage alone is responsible for 30 % of the damaged area in Europe. This prompts us to investigate the factors behind these extreme events [35].

Weather conditions and European large fires A number of factors contribute to forest fire ignition, including vegetation conditions and composition, as well as human behaviour. However, weather and climate are considered to be among the main factors influencing wildfire potential, and they also influence some of the other factors. For example, rainfall amounts and patterns affect 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. Climate variables such as wind speed are also important because they can affect the rate at which a fire might spread following ignition.

In the Mediterranean areas of Europe, precipitation and soil moisture appear among the most important factors associated with spatial patterns of fire occurrence. Fernandes *et al.* [45] 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.* [88] found two categories of weather-driven large wildfires: those driven by strong winds and dry air conditions (i.e. the wind-forced mode of Hernandez et al., 2015a, 2015b) and the others occurring with comparatively weak winds but hotter weather. In Greece, Karali *et al.* [60] underlined the impact of high temperature and wind speed on critical fire danger, while Founda and Giannakopoulos [50] linked the extensive and destructive forest fires that occurred in Greece during 2007 with the extreme hot summer and a co-occurring prolonged drought. In Italy, Cardil *et al.* [10] found a clear relationship between high-temperature days and burnt area due to large wildfires. In Spain, De Luís *et al.* [19] 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. If several of these factors coincide the effects are likely to be magnified. It is worth noting that on the "worst day of the year" in Portugal, 15 October 2017 [4], weather and climate hazards came together with a prolonged drought coinciding with the very strong winds associated with Hurricane Ophelia. The result was fire activity not seen before in Europe: a greater area burnt in one day than had occurred during the rest of the year, the largest pyro-convective phenomenon[3] recorded in Europe so far and the largest in the world in 2017 [57].

Effects of climate change on vegetation, and implications for fire vulnerability In addition to the direct fire danger driven by weather conditions, the potential impact of a fire ignition may be magnified by the conditions of the threatened vegetation. Vegetation fuel may be characterised by variable moisture, with different behaviour of fine materials and coarse wooden fuels (on this, see in the following methodology section the part describing a standardised index of fire danger by weather). Under climate change, the hazard will become higher than at present, which means adaptation strategies are needed to avoid an increase in the devastating effects of forest fires on ecosystem functioning and biodiversity. Unfortunately, the functions and services provided by an ecosystem might not be so easily recovered after major fire damage. Even for

[3] Pyro-convection can be generally defined as the transfer of heat by the circulation or movement of the local heated air (along with other fire emissions and smoke); in particular, it is the vertical transport of atmospheric properties driven by or enhanced by fire. For an introduction, see Charney and Potter [13].

supposedly less complex ecosystems, such as a grassland, the speed of the post-fire recovery may be largely overestimated. Just one year after a fire, a grassland may appear to be green again. However, the new vegetation may be quite different from the original. Several stages of ecological succession may follow the first vegetation regrowth, with variable temporarily dominant species (and potentially worse temporary fuel characteristics) until the original ecosystem is recovered. Therefore, even a grassland may require several years to re-establish the balanced ecosystem functions and services provided before the fire. The example applies even more demandingly to forest ecosystems.

Human intervention may assist the post-fire restoration of valuable ecosystems and of their impaired services. For example, young exemplars of the main tree species may be planted to accelerate the vegetation regrowth in a burnt forest area. However, this assisted restoration is only a first step for the original ecosystem services to be recovered – even assuming that climate change is not affecting the process. The frequency of fires is also an important parameter to understand whether a certain ecosystem may be able to recover. Multiple wildfires may occur in the same area, every time breaking the natural process of the ecological succession towards the pre-existing ecosystem. Sometimes, this may eventually lead to an entirely new ecosystem being established instead of the original one. Climate change may aggravate this phenomenon, making originally typical plant species no more suited to live in the changed bio-climatic conditions. This would impede the re-establishment of the original ecosystem even if the fire damage were not recurrent in the area. Since the resistance to bio-climatic fluctuations of a mature healthy ecosystem is usually greater than the resilience of a damaged ecosystem (e.g. due to fire damage), wildfires might be triggering broader transitions in ecosystems already declining due to climate change [36, 87, 85, 41, 102].

The vulnerability of a specific plant species to the changing climate might not be easily related with the overall stress to which the whole vegetation assemblage is subject. Several vegetation species contribute to the composition of those ecosystems suitable to thrive in a given ecological zone, and the dominant weather and climatic conditions exert a strong effect not only on the composition, but even on the structure of vegetation (i.e. the layers of trees, shrubs and understorey plants) [30, 34, 82]. As a consequence, aggregated comprehensive indices are essential (rather than focusing on species-specific details) to support the detection of where the changing bio-climatic conditions are expected to increase the cumulative stress in several species belonging to a certain vegetation assemblage. In the following methodology section, an aggregated index is discussed to summarise the climatic shift of the main ecological domains as defined by FAO [49, 29, 34] and delineate the emerging areas of potential combined vulnerability of several vegetation components.

2 Methodology

In the research performed within the third instance of the PESETA research [35], robust statistics were introduced to estimate the potential evolution under climate change of the the fire danger extremes. These statistics were designed to analyse the higher quantiles of danger, also providing an assessment of the robustness of estimated climate-driven change, by assessing the agreement among models on whether the predicted difference between future and control period (anomaly) was positive. In this work, a similar modelling methodology is extended to complement the previous results [35] with new data-transformation statistics computed based on the percentage of days above a given threshold of fire danger (classes of weather-driven danger).

The vegetation potentially exposed to wildfires in Europe spans over three main ecological domains of the five classified by FAO [49]. The local ecological patterns of European vegetation can show dominant characteristics belonging to the boreal, temperate, or subtropical domain. In addition to the dominant ecological domain, each area may show ancillary components from other domains (for example, a temperate area with a secondary subtropical component). When – due to climate change – a secondary/absent component becomes dominant, or vice-versa, then the local vegetation fuels, their structure and composition, are stressed to shift not simply to adjust their *within*-domain ecology, but instead to move into a completely new ecological domain – an indication of major climate-driven vulnerability.

Finally, the European population potentially exposed to wildfires includes densely populated areas where smoke and air-pollution by fires may affect citizens (with respiratory and other health impacts [16, 84, 110, 6, 48]) even quite far from where the fire emissions were originated. However, some settlements have a direct interface with potentially burnable wildland, and the population in these areas is more vulnerable to increased ignition and subsequent local spread of wildfires. Here, an outline is presented on how to detect these more vulnerable areas for the exposed population.

Climate change models

The European climate analysis is based on the outcomes of the JRC PESETA III project [35], where a high-emission scenario was considered following the corresponding concentration trajectory adopted in the Fifth Assessment Report by the IPCC [64, 71, 105, 99]. This scenario focuses on a Representative Concentration Pathways (RCP) for which radiative forcing increases 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. In addition, a scenario with mitigated emission pathway (RCP 4.5 scenario) is also considered. Results focus on different global warming levels, compared with pre-industrial conditions. In particular, 1.5 °C, 2 °C, and 3 °C of global warming are assessed. Due to technical incompatibilities and consequent unacceptably high computational uncertainty, some runs are excluded from specific parts of the current analysis (See Tables 1, 2, 3).

Table 1 shows the institutions and acronyms associated with the global circulation models and the regional climate models which define the EURO-CORDEX climate-projection realisations considered in this study. Table 2 provides an overview of codes associated with each EURO-CORDEX model run, along with the corresponding institutions, Regional Climate Models (RCMs) and driving Global Circulation Models (GCMs) . Finally, Table 3 summarises the time intervals associated with each period (hereinafter abbreviated as *per*) considered in the cluster of sectoral analyses

Table 1: 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 [35, 39].

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
DMI	Danish Meteorological Institute
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
KNMI	Royal Netherlands Meteorological Institute
MOHC	Met Office Hadley Centre
MPI-M	Max Planck Institute for Meteorology
SMHI	Swedish Meteorological and Hydrological Institute, Rossby Centre

Table 2: 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 (RCMs), driving Global Circulation Models (GCMs), and acronyms (RCM-GCM). The first five models (A-E) were used as core models in the third instance of the PESETA series [35].

Code (model run *mod*)	Institution(s)	Regional Climate Model	Driving Global Circulation Model	Acronym
A	CLMcom	CCLM4.8-17 (R1)	CNRM-CERFACS-CNRM-CM5 (G1)	R1-G1
B	CLMcom	CCLM4.8-17 (R1)	ICHEC-EC-EARTH (G2)	R1-G2
C	IPSL-INERIS	WRF331F (R3)	IPSL-IPSL-CM5A-MR (G4)	R3-G4
D	SMHI	RCA4 (R5)	MOHC-HadGEM2-ES (G5)	R5-G5
E	SMHI	RCA4 (R5)	MPI-M-MPI-ESM-LR (G3)	R5-G3
F	CLMcom	CCLM4.8-17 (R1)	MPI-M-MPI-ESM-LR (G3)	R1-G3
G	DMI	HIRHAM5 (R2)	ICHEC-EC-EARTH (G2)	R2-G2
H	KNMI	RACMO22E (R4)	ICHEC-EC-EARTH (G2)	R4-G2
I	SMHI	RCA4 (R5)	CNRM-CERFACS-CNRM-CM5 (G1)	R5-G1
J	SMHI	RCA4 (R5)	ICHEC-EC-EARTH (G2)	R5-G2
K	SMHI	RCA4 (R5)	IPSL-IPSL-CM5A-MR (G4)	R5-G4

within the PESETA IV project – to which this study belongs. The array of time intervals associated with the future periods with nominal global warming 1.5 °C, 2 °C, and 3 °C is heterogeneous even within each period. In particular, not all the corresponding model time-intervals begin after the conclusion of the Control period.

Table 3: Time intervals associated to each climatic period considered in the cluster of sectoral analyses within the PESETA IV project – to which this study belongs. The array of time intervals associated with the future periods with nominal global warming 1.5 °C, 2 °C, and 3 °C is heterogeneous even within each period (see supporting information of [39]). In particular, not all the corresponding model time-intervals begin after the conclusion of the Control period (in red, periods beginning within the Control period). For each model and scenario (RCP 4.5 or RCP 8.5), the year is shown when the GCM associated to the model projects the nominal global warming to exceed a threshold (1.5 °C, 3 °C, or 3 °C), compared to pre-industrial levels. The first five models (A-E) for the high-emission scenario were used as core models in the third instance of the PESETA series, as they encompass a high share of the overall modelling variability [35] (in bold). Due to technical incompatibilities and consequent unacceptably high computational uncertainty, some runs are excluded from specific parts of the current analysis. For those parts, the core set of models (referred as *core models*) was used instead of the complete set.

	1.5 °C global warming		2 °C global warming		3 °C global warming
	RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5	RCP 8.5
Model code	CGM (years in the +1.5 °C clim. period)	CGM (years in the +1.5 °C clim. period)	CGM (years in the +2 °C clim. period)	CGM (years in the +2 °C clim. period)	CGM (years in the +3 °C clim. period)
A	2035 (2021-2050)	**2029 (2015-2044)**	2057 (2043-2072)	**2044 (2030-2059)**	**2067 (2053-2082)**
B	2033 (2019-2048)	**2026 (2012-2041)**	2056 (2042-2071)	**2041 (2027-2056)**	**2066 (2052-2081)**
C	2023 (2009-2038)	**2021 (2007-2036)**	2042 (2028-2057)	**2035 (2021-2050)**	**2054 (2040-2069)**
D	2021 (2007-2036)	**2018 (2004-2033)**	2037 (2023-2052)	**2030 (2016-2045)**	**2051 (2037-2066)**
E	2034 (2020-2049)	**2028 (2014-2043)**	2064 (2050-2079)	**2044 (2030-2059)**	**2067 (2053-2082)**
F	2034 (2020-2049)	2028 (2014-2043)	2064 (2050-2079)	2044 (2030-2059)	2067 (2053-2082)
G	2032 (2018-2047)	2028 (2014-2043)	2054 (2040-2069)	2043 (2029-2058)	2065 (2051-2080)
H	2032 (2018-2047)	2026 (2012-2041)	2056 (2042-2071)	2042 (2028-2057)	2065 (2051-2080)
I	2035 (2021-2050)	2029 (2015-2044)	2057 (2043-2072)	2044 (2030-2059)	2067 (2053-2082)
J	2033 (2019-2048)	2026 (2012-2041)	2056 (2042-2071)	2041 (2027-2056)	2066 (2052-2081)
K	2023 (2009-2038)	2021 (2007-2036)	2042 (2028-2057)	2035 (2021-2050)	2054 (2040-2069)

Fire danger by weather: frequency of days with higher danger

Weather influences the fire hazard by affecting the ease of ignition, rate of spread, fire intensity and overall impact of wildfires. This may be represented quantitatively by exploiting a rating index, known as *fire danger* by weather.

In this study, Canadian Fire Weather Index (FWI) system [106, 18, 67] is used to estimate numerically the weather-driven fire danger. This is done on a daily basis, combining temperature, wind speed, relative humidity, and precipitation to rate the fire danger for a certain day, also taking into account the history, i.e. the cumulative dynamic effect of the weather in the previous days (see also the appendix for more details). The literature widely supports the relationship between large wildfires and this rating index [11, 53, 38, 37].

Different ranges of danger rates (from relatively safer ranges of values, to high and extreme ranges) are expected to become less or more frequent in future, outlining a sort of unique 'fingerprint' of the changing fire danger by weather in a certain area. To ease the understanding of this 'fingerprint', the daily multi-model projections are summarised by considering six daily classes of fire danger (from days with low danger up to days with extreme danger), and the percentage of days within a corresponding range of fire-danger values (see Figure 10 and Figure 11 in the Results section).

Areas bioclimatically more vulnerable for the exposed vegetation

Two wildfires with a comparable burnt area, but affecting different vegetation, may result in very different levels of damage, and recovery paths of the damaged vegetation. Rather than modelling the tree species for which detailed data are available – and ignoring the cumulative role and interactions of all the other plant species – the approach here proposed focuses on a holistic, integrated analysis of the main ecological components (ecological domains [49, 29, 34, 27]) which support the existence and specific structure of the current vegetation assemblages.

For example, in a forest this comprises the various tree species composing the canopy, the trees and shrubs in the understorey, the herb and ground layers, including both living and dead biomass. All these elements define the local typology of fuel. Pronounced variations of the ecological-domain components due to the changing climate may help to identify, with uniform criteria at the continental scale, areas subject to a high potential vulnerability of the current vegetation [96, 49, 72, 44].

FAO classifies five main ecological domains for vegetation: Polar, Boreal, Temperate, Subtropical, and Tropical [49]. The European vegetation potentially exposed to wildfires comprises biomes in the boreal, temperate, and subtropical domain [49, 29, 34, 27].

Boreal, Temperate, and Subtropical vegetation domains each encompass multiple sub-domain zones (see Figure 7), and may be defined with a focus on the regional broad patterns (e.g. including as subtropical even high mountain peaks in the Mediterranean region, see Figure 8), or the local patterns (e.g. considering the vegetation succession in Mediterranean mountains in its local specificity, varying from subtropical at low-elevation slopes, to predominantly temperate at intermediate elevation, up to showing marked boreal components at the higher peaks, see Figure 9).

A preliminary assessment of local ecological patterns is here presented, and for each area in Europe the corresponding contribution of each domain component is estimated [49, 29, 34, 27]. In addition to the Boreal, Temperate, and Subtropical components, the appearance is estimated in Europe of climatic features specific of the Tropical domain, namely in extreme Southern areas of the Mediterranean region (See Figures 12, 13, and 14).

However, within-domain bioclimatic shifts are here not considered (e.g. sub-domain partitions such as ecological zones). Therefore, even in areas not highlighted in this analysis local factors (not considered in a general ecological-domain overview) may induce a high vulnerability of vegetation to changing bioclimatic conditions. Part of these factors may be the object of future analysis at the sub-domain level[4].

[4]Other factors are more difficult to assess: for example, the impact of increasing vapor pressure deficit (VPD) is reported to reduce global vegetation growth, offsetting the positive CO_2 fertilisation effect [109]. Therefore, CO_2 fertilisation and VPD appear to act on opposite directions, widening the uncertainty of models. Overall, increasing VPD may be "part of the drivers of the widespread drought-related forest mortality over the past decades, which has been observed in multiple biomes and on all vegetated continents" [109]. As such, this may contribute to worsening the estimates on vegetation vulnerability summarised in this work.

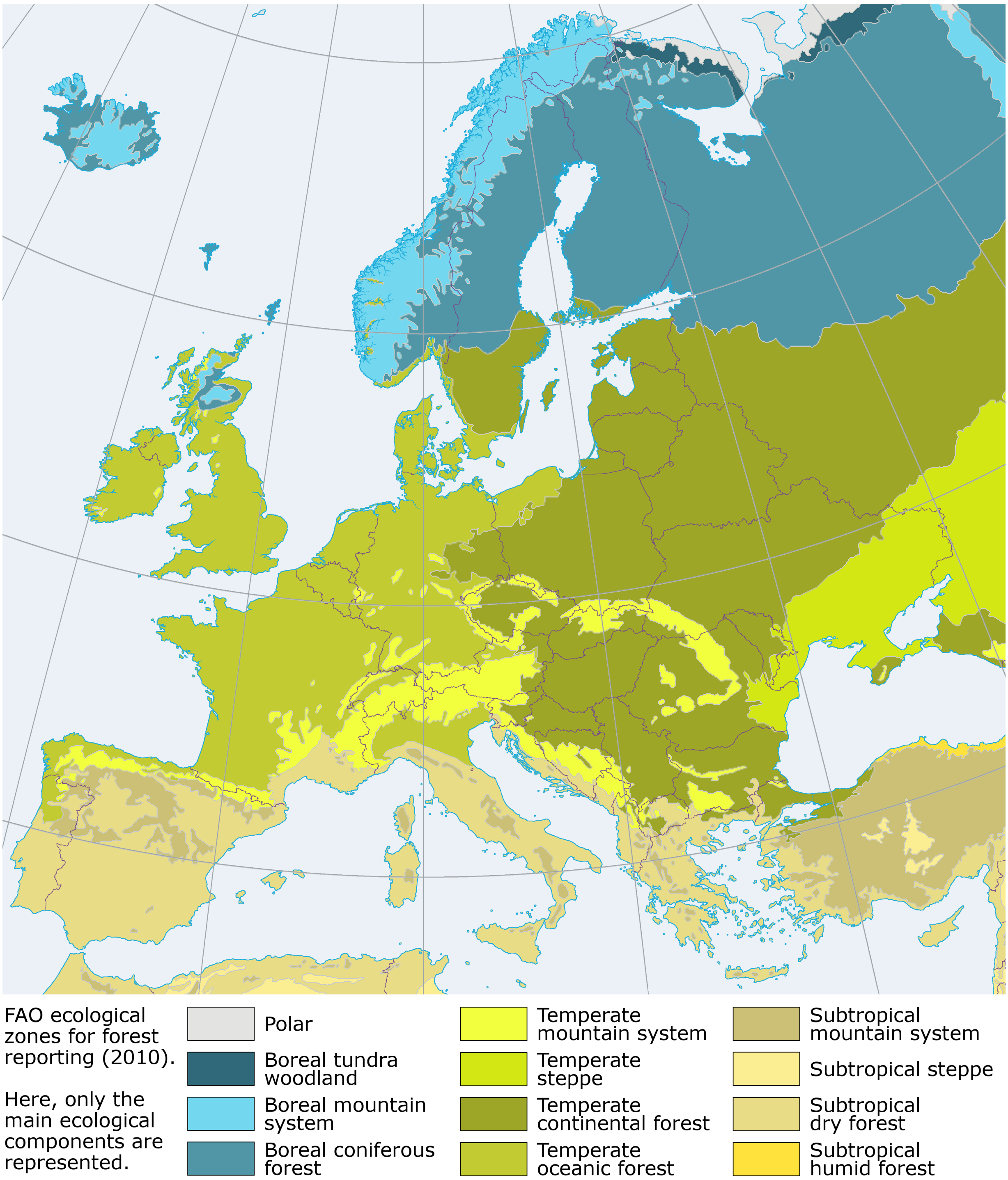


Figure 7: FAO ecological zones. At the first level five domains are distinguished based on temperature: Tropical, Subtropical, Temperate, Boreal and Polar. In Europe, these domains are distributed from South to North and Tropical is absent. At the second level, precipitation is used to subdivide the domains into a total of 20 subclasses, of which 12 can be found in Europe.

Figure 8: Domains (level 1) of the FAO ecological zones (see Figure 7). The domains are distinguished based on temperature and potential natural plant communities, and four domains can be found in Europe, namely Subtropical, Temperate, Boreal and Polar (Tropical is absent), distributed from South to North. The boundary of the detailed ecological zones shown in Figure 7 are represented in light grey.

Figure 9: Local ecological domains according to the criteria of temperature used in the FAO ecological zones when applied with the WorldClim data without considering the potential natural plant communities [29, 34, 27]. Compared with the FAO domains (see Figure 7), the extent of Polar and Boreal domains is larger due to the local effect of the altitude in mountainous regions, such as in Scandinavia, the Alps, the Iberian Peninsula, and Turkey.

Vulnerable population by proximity to wildland fuels

The vulnerable interface between wildland vegetation (including forests, shrubland and grassland) and human presence is where the risk of fire may be especially high for the local population. In this work, a high-resolution preliminary assessment is introduced to estimate the interface between urban areas and wildland (Wildland-Urban Interface, WUI [17]). This new continental-scale estimation of WUI follows a standardised definition, with an emphasis on the uncertainty. Following Stewart *et al.* [98], two components characterise the interface: the effect of settlements intermixed with wildland fuel, and directly vulnerable to local fires; and the effect of large core areas of vegetation fuels, which may generate violent wildfires able to produce embers or sparks carried by the wind, and creating new fires (spot fires) at a larger distance.

This detailed interface map may help to summarise two components of the vulnerability feedback between human presence and wildfire risk. A first component descends from the easier ignition of areas where people can have an easier access to wildland (see Figure 20 and Figure 21). Indeed, fire events with damage perimeters adjacent or intersecting the WUI appear to contribute the majority of the burnt area in several parts of the Mediterranean Europe. This was previously referred as an *active* role of the WUI in increasing the fire risk. The second component of WUI population vulnerability was noted as a *passive* consequence of the increased local risk. As ignition frequency is higher close to the WUI, under negative weather conditions some ignited point may occasionally become a large fire, able to threaten areas quite far from the original ignition. By definition of the WUI, part of these areas will be in the WUI, becoming passively vulnerable just because of their proximity to the WUI. Discriminating between these roles at the continental scale, and reconstructing the cause of each fire, may easily prove impracticable. However, a basic identification of the areas whose population is more vulnerable to fire risk does not require a detailed modelling of the fire causes. For this purpose, the spatial distribution of the WUI may be exploited as a simple proxy for the population vulnerability.

The percentage of wildland was estimated from the CORINE Land Cover (CLC) map of 2012 [7, 8], and varied between a minimum and maximum value depending on the inherent uncertain land cover class definition of CLC and other auxiliary data such as the JRC's global surface water [7, 79]. The Global Human Settlement Layer (GHSL) was used for housing unit counting [80, 81].

In addition, a harmonised preliminary pan-European map was derived estimating the population exposed to wildfires in the intermixed Wildland-Urban Interface (WUI) (see Figure 3) ranging between a minimum and maximum as a function of the uncertainty of the percentage of wildland estimated from the CORINE Land Cover map of 2012 [7, 8]. Population count was based on the Global Human Settlement Layer (GHSL) [52].

The WUI and the population within it provide a preliminary harmonised index of population vulnerability. However, this delineation cannot encompass the (even densely populated) areas which are far from the WUI, but potentially subject to the impact of smoke and air pollution generated by wildfires [16, 84, 110, 6, 48]. On this topic, still affected by wide uncertainty and missing knowledge [73, 84], recommendations are summarised in the conclusions of this work.

3 Results

As underlined in de Rigo *et al.* [35], the climate-driven changes in the damage produced by wildfires may be only estimated as a chain of impacts which link a changing fire danger with a landscape subject to partially independent changes. These changes are reflected in the varying uses of territory and in the vegetation conditions – including macroscopic modifications in the ecological regimes underpinning the fundamental structure of vegetation, and the corresponding typology of fuel available during fire events.

3.1 Changing frequency of fire danger classes due to climate change

de Rigo *et al.* [35] offered a European-wide outline of the potential climatic effects on fire danger extremes, remarking how – besides indirect factors – fire danger is directly and "clearly influenced by weather in the short term, and by climate and its changes when considering longer time intervals".

This influence is suitable for a more detailed analysis, considering the frequency of different fire danger classes (from relatively safer values of danger up to values correlated with extreme fire danger by weather), and their predicted changes under different scenarios. Figure 10 provides an overview of the expected climatic trend in the weather-driven component of fire danger. It summarises the changing patterns of fire danger in six equi-spaced classes of the aggregated Fire Weather Index. Values of FWI above 20 are associated[5] with high fire danger, while values exceeding 50 typically characterise extreme danger conditions [91]. An assessment of the uncertainty due to the variability of the estimates in different models is summarised in Figure 11, where the percentage of models is shown which agree in the *positive sign* of future change compared with the Control period. For a certain class of danger, a 100 % agreement means that all the models robustly indicate an increasing number of days. Conversely, a 0 % agreement means that all the models indicate a decreasing (or stable) number of days in the danger class. An agreement close to 50 % denotes the highest uncertainty.

Observing Figure 10, it may be noticed how the frequency of days in the lowest class of fire danger $\textit{FWI-class}^1 \equiv [0 - 10)$ is projected to decrease in the Mediterranean region (implying an increasing frequency of higher-danger days), with an intensity of change predicted to be strongest in the 3 °C global-warming scenario, and milder in the 1.5 °C scenario. Even in this mitigation scenario, however, for several areas in the Mediterranean region of Europe all the models agree in the sign of change (a decreasing frequency of the safest class of fire danger), with an agreement of at least 80 % of the models in the more uncertain areas of the Mediterranean. In the Mediterranean mountain systems, and in the Alps, the shift from the current distribution of fire danger classes to the future expected one appears to be limited, while in several other areas of Southern Europe even the higher danger classes display a marked predicted increase. This is particularly evident in the Iberian peninsula and Turkey, along with part of Greece and the Balkans, part of central and southern Italy, and of France. It is worth noting that even with mitigation that limits global warming to 1.5 °C, the predicted sign of change in fire danger is consistent among several models. Although the projected worsening of the climatic distribution of fire danger classes is smaller with

[5] For example, a comparable classification is described at http://effis.jrc.ec.europa.eu/about-effis/technical-background/fire-danger-forecast/, and implemented in the *Current Situation Viewer* of the European Forest Fire Information System, EFFIS.

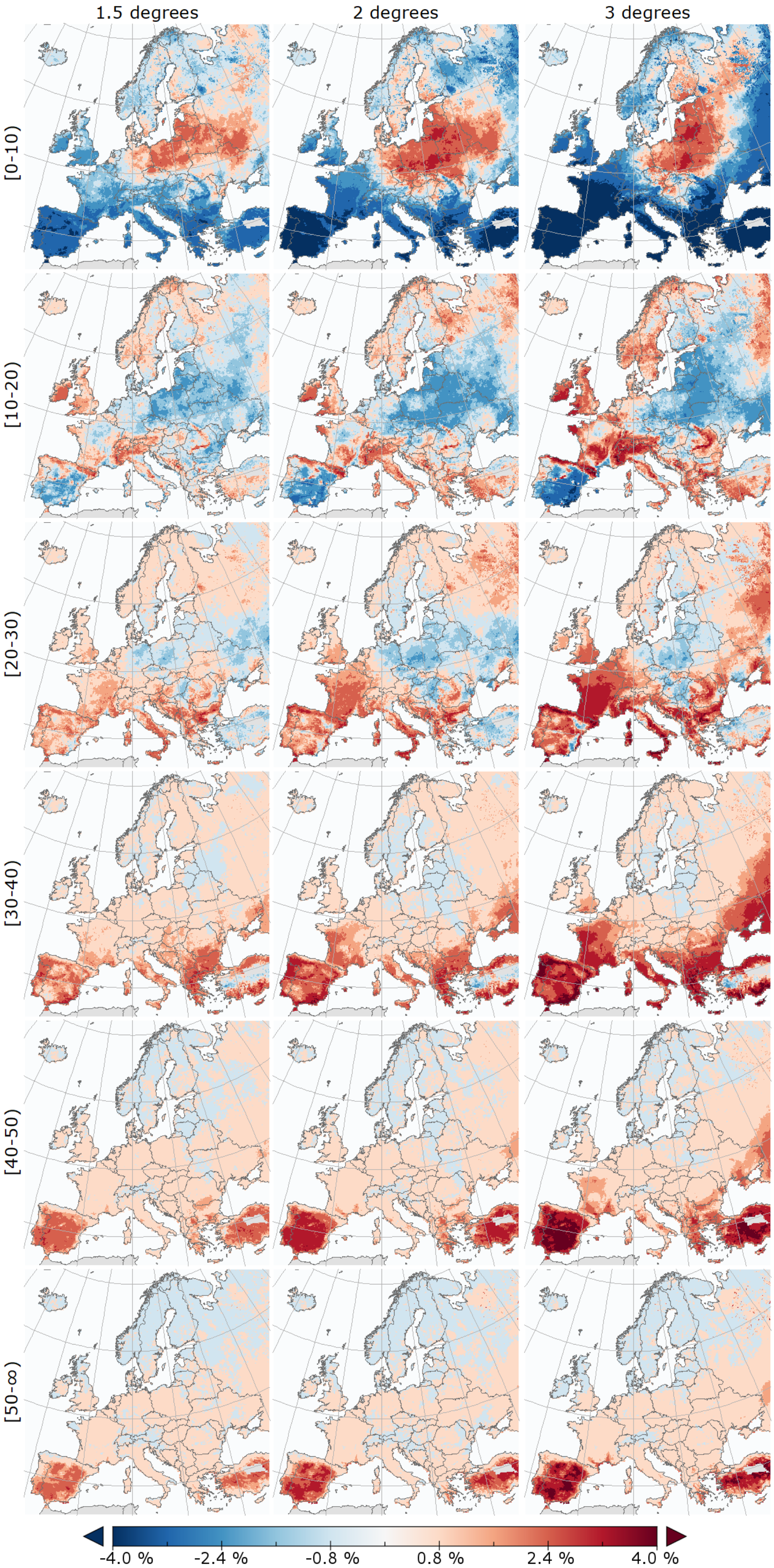


Figure 10: Change (anomaly) of the average annual proportion of days in each fire-danger class, as estimated from the aggregated Fire Weather Index (FWI), in the future scenario-realisations as compared to the control period. The results show an ensemble (median) of the *core models* (see Table 3). In the Mediterranean region, the frequency of higher-danger days is expected to increase (**bottom**). In Central-Eastern Europe, the frequency of moderate/mid-danger days is projected to decrease as the frequency of days of the least dangerous class of the FWI [0 − 10) increases by around up to 4 % (**top**). However, this trend does not affect the frequency of higher-danger days. Figure 1 shows a summary aggregation of the three higher classes of danger (daily $FWI \geq 30$).

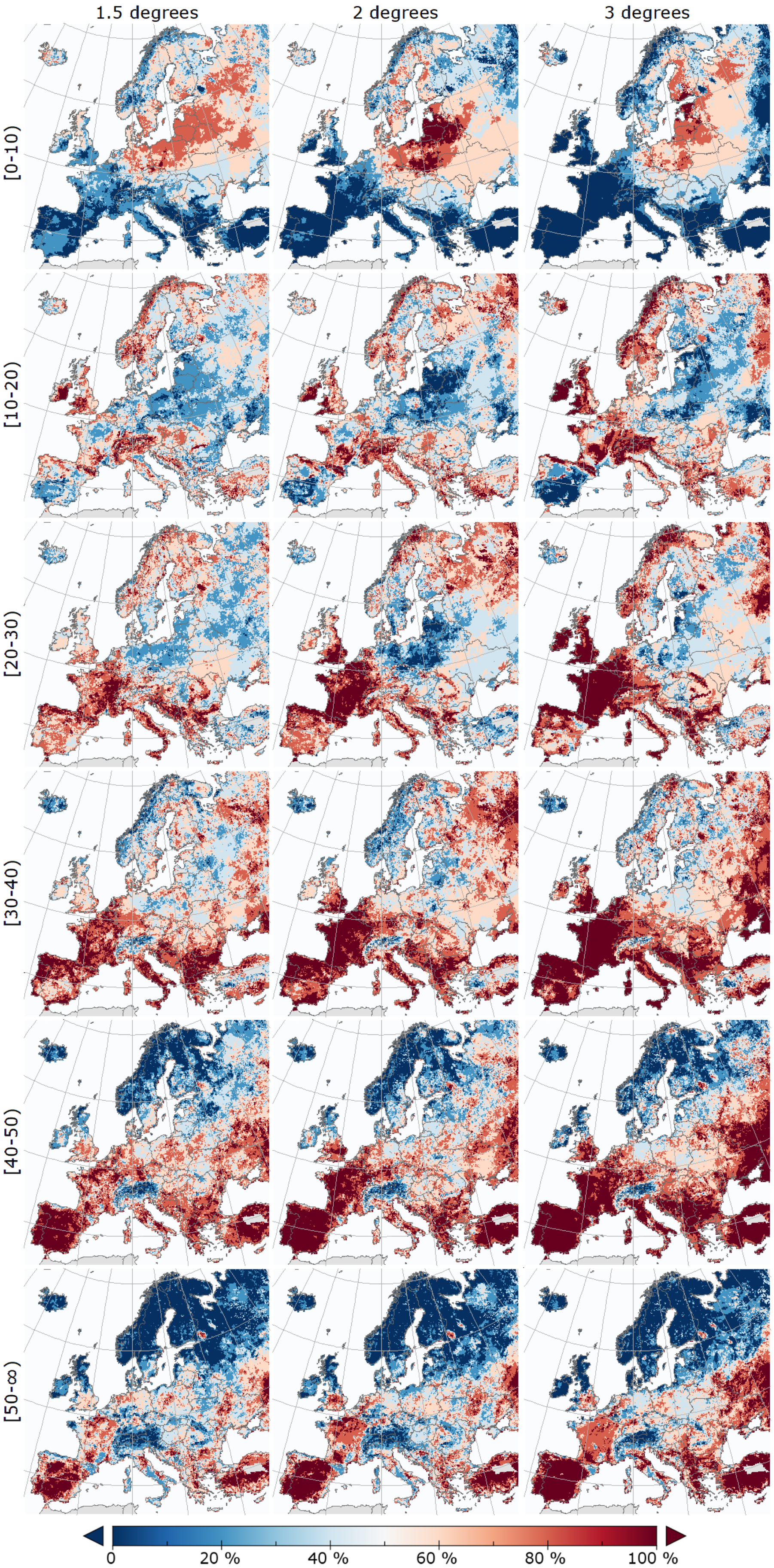


Figure 11: Assessment of the uncertainty of Figure 10 due to the variability of the estimates in different models: percentage of *core models* (see Table 3) for which the proportion of days in each fire-danger class of the aggregated Fire Weather Index (FWI) is expected to increase in the future scenarios realisations as compared to the control period. There is a very strong agreement among the models (often 100 %) that the frequency of days of the most dangerous classes of the FWI will increase in Southern Europe (**bottom**). In Central-Eastern Europe, there is an agreement that the frequency of moderate/mid-danger days (but not of the higher-danger days) will decrease as the number of days of the least dangerous class of the FWI will increase (**top**).

1.5 °C global warming, relative to 2 °C, and even more compared to the 3 °C warming, fire danger is still predicted to be consistently worse than at present.

A contrasting climate signal is instead predicted for the area southern to the Baltic sea (centred around Poland, Lithuania, Latvia, Belarus) with border effects partially covering the Czech Republic, the eastern part of Germany, and the Pannonian region. In these areas, the frequency of days in the lowest class of fire danger appears as increasing. This frequency increase of safer fire danger conditions implies a decreased frequency of more dangerous conditions. However, in the Pannonian region this decrease only appears to refer to intermediate danger classes.

The territories exposed to the oceanic influence of the Celtic sea (in particular, Britanny in France, Wales and South West England in the United Kingdom, and the southern part of Ireland) display a decreasing number of days in the safer fire danger class, and a corresponding increased frequency of the intermediate danger classes. This is more evident in the 2 °C than in the 1.5 °C warming scenario, and the predicted change in the 3 °C warming scenario also appears to include the whole southern UK, Belgium, part of the Netherlands, and an extensive part of France. In the Fennoscandian Peninsula [6], the pattern of change is more various and uncertain, with the boreal mountain systems more affected by a frequency shift from low to intermediate danger. Higher classes appear to decrease slightly in frequency.

3.2 Vulnerable vegetation due to climate change

Concerning the vulnerability of vegetation to wildfire damage, a set of fuzzy components of the local ecological domains was estimated following the criteria of temperature used in the FAO ecological zones [49, 29, 34].

In particular, Figure 12 and 13 show the fuzzy local ecological domains in the control period and future scenario realisations. An ensemble is shown (median) of all the models (see Table 3), expressing the average percentage of years expected to fit in the defining criteria of the domains. For each domain and model run, this data-transformation aggregates the annual estimates in a given spatial cell into a fuzzy index ranging from 0 (ecological domain with negligible influence on the cell) to 100 % (ecological domain with an exclusive local influence) [27].

The criteria are those of FAO ecological zones (see Figure 7) for temperature only (i.e. ignoring a further subdivision of ecological domains in sub-domain zones with specific natural plant communities). A substantial shifting of all the domains towards North is expected (See Figure 13), along with the appearance in Europe of climatic features specific of the Tropical domain, namely in extreme Southern areas of the Mediterranean region (See Figure 14). The most intense changes in the ecological domains appear to concentrate in the Mediterranean region and in the southern part of both the current temperate and boreal domains. The intensity of change appears to increase when comparing the 1.5 °C global warming scenario with the 2 °C and 3 °C scenarios, with a remarkable stability of the patterns between different scenarios. These findings are in line with the predictions of Feng *et al.* [44], who focused on the end-of-century reporting a comparable spatial pattern of changes in major climate types. Alkemade *et al.* [2] also report a comparable pattern of projected changes combining the areas where species turnover is expected to increase, and the areas where species are projected to be displaced.

[6] Fennoscandia comprises Sweden, Norway, Finland, Karelia, and the Kola Peninsula, currently ranging from a boreal to a polar climate [34].

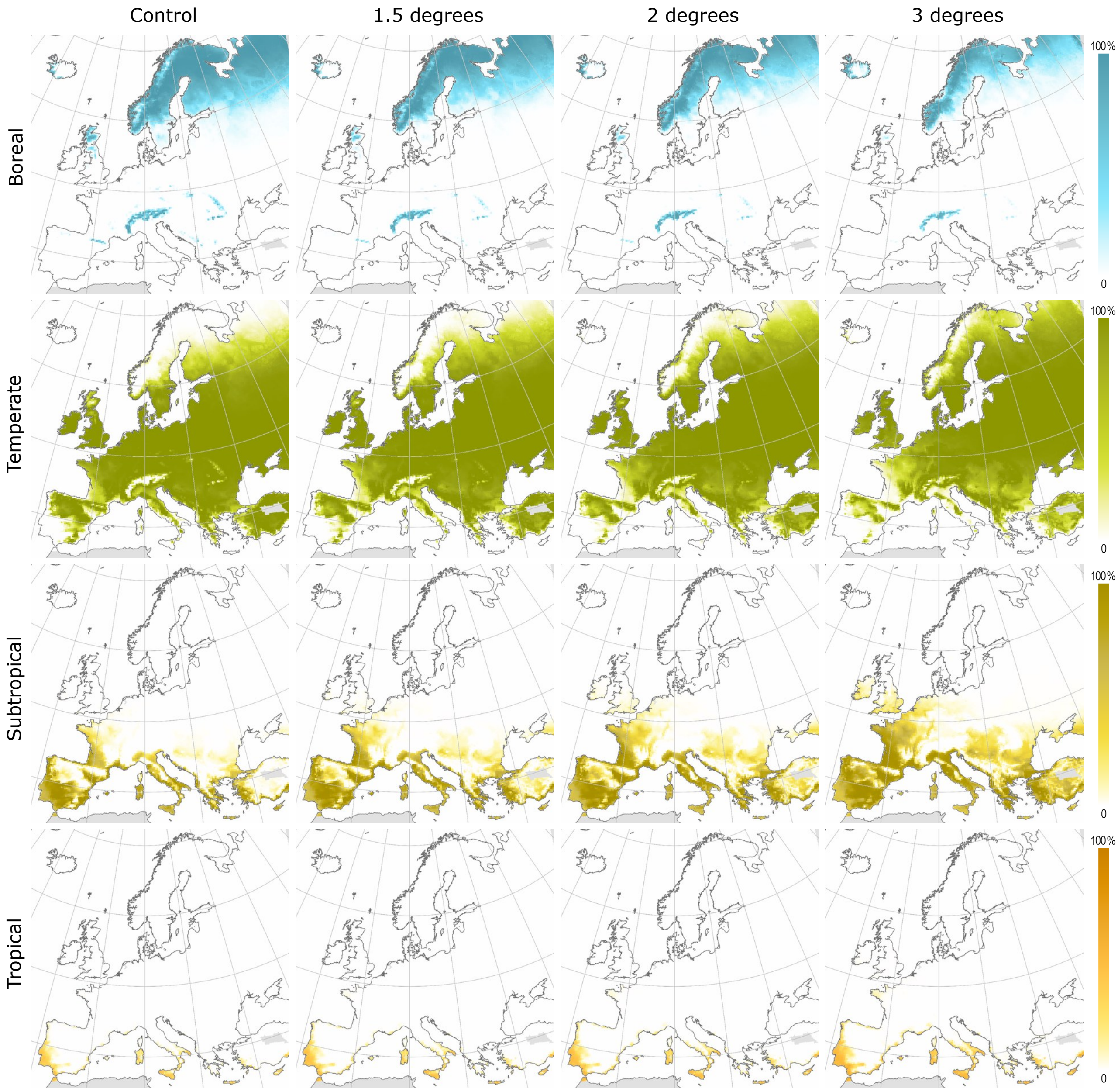


Figure 12: Fuzzy local ecological domains in the control period and future scenario realizations (from [27]). The figure shows an ensemble (median) of all the models (see Table 3), and expresses the average percentage of years expected to fit in the defining criterion of the domains. The criteria are those of FAO ecological zones (see Figure 7) for temperature only (i.e. ignoring potential subdivision of ecological domains in sub-domain zones with specific natural plant communities). A substantial shifting of all the domains towards North is expected (See Figure 13), along with the appearance in Europe of climatic features specific of the Tropical domain, namely in extreme Southern areas of the Mediterranean region (See Figure 14).

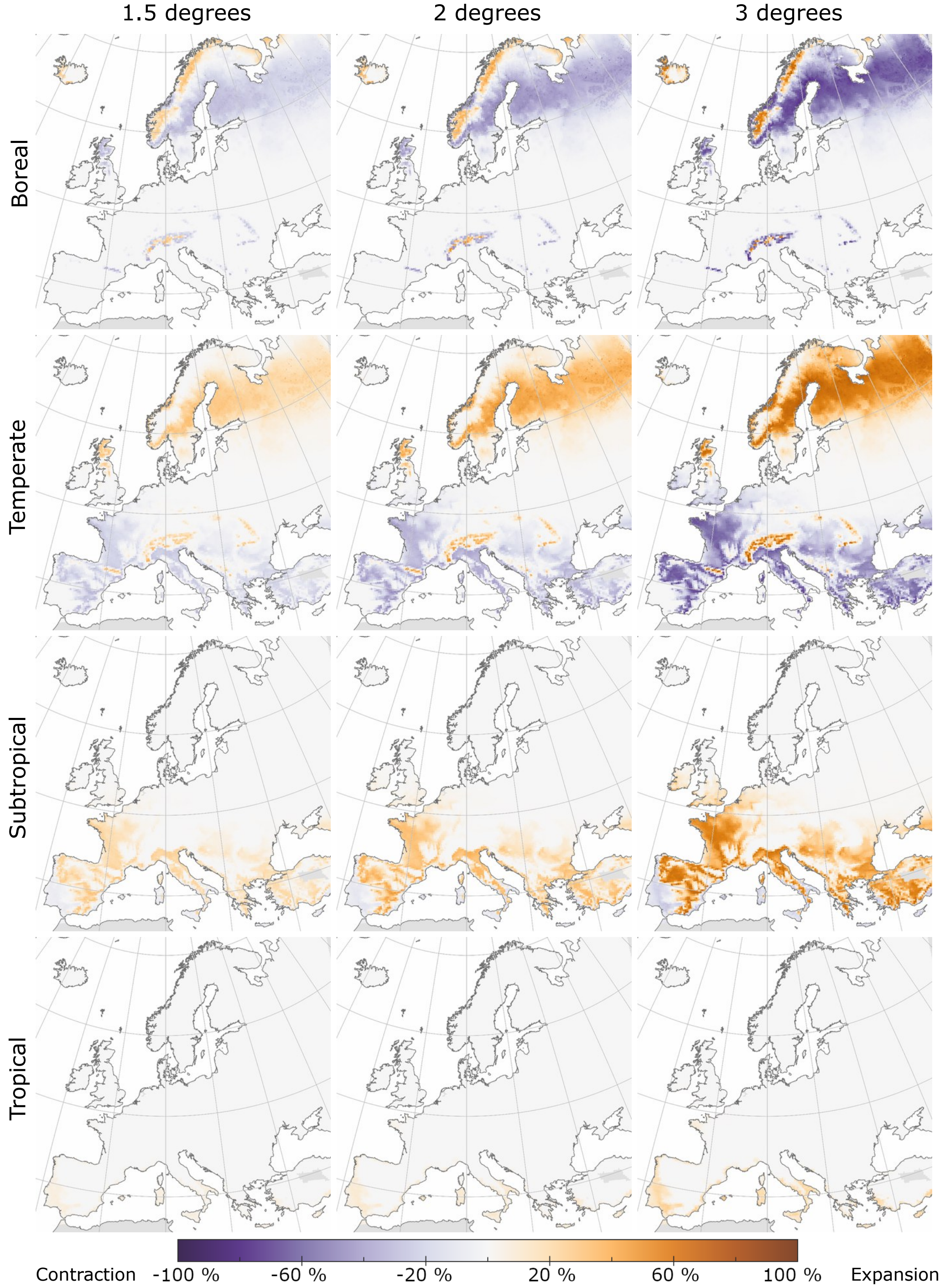


Figure 13: Change of the fuzzy components of the local ecological domains of Figure 12 in the future scenarios realisations as compared to the control period (from [27]). Ensemble median of all the models (see Table 3). A substantial shifting of all the domains towards North is expected. This results in a substantial contraction of the Boreal domain, as the Temperate domain shifts North. The Subtropical domain is expected to expand around the Mediterranean region, and to contract in extreme Southern areas of the Mediterranean region, where the Tropical domain, currently absent in Europe, is expected to appear and possibly become dominant (See Figure 14).

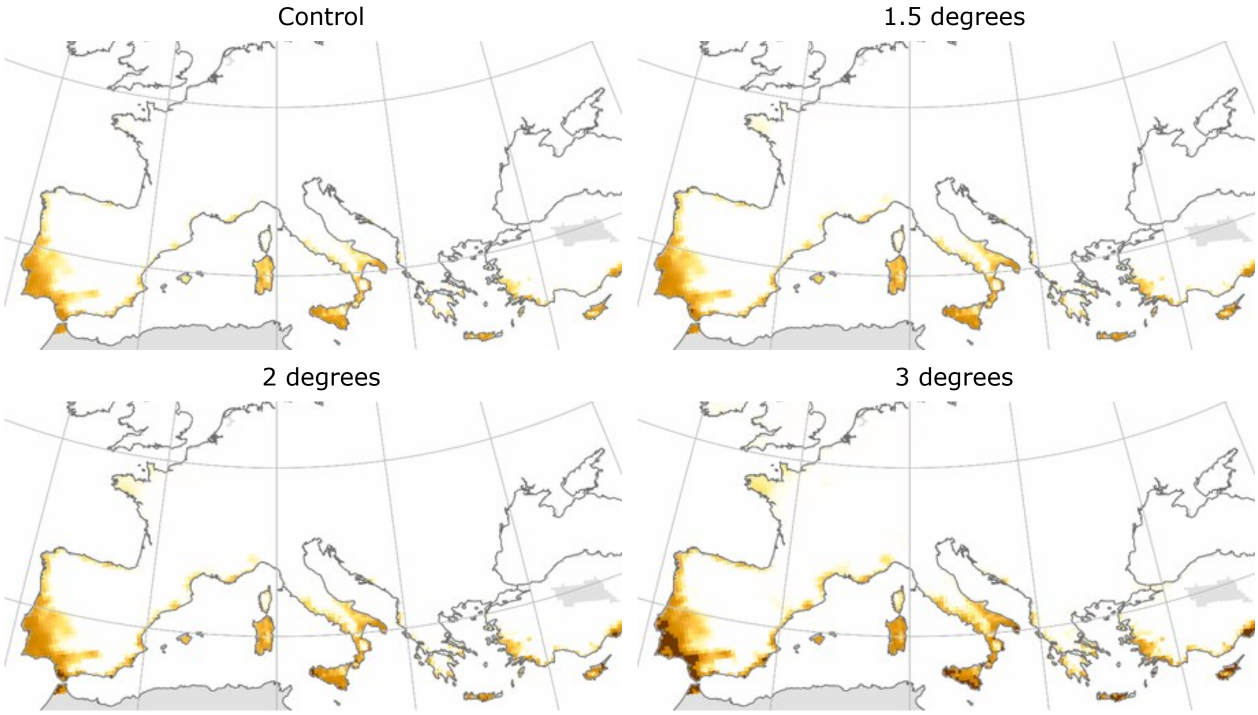


Figure 14: Fuzzy local Tropical domain in the control period and future scenario realizations (from [27]). The figure shows the fuzzy Tropical component of Figure 12, but highlights (in dark brown) the areas where the Tropical domain is expected to become a co-dominant component for the majority of the time (i.e. where the average percentage of days expected to fit in the definition of Tropical domain is greater than 50 %). A substantial increase of the Tropical domain is expected in extreme Southern areas of the Mediterranean region, especially in South-West of the Iberian Peninsula and Southern Italy.

3.3 Vulnerable population by proximity to wildland fuels

The executive summary already provides a European-wide summary (see Figure 3) of the vulnerable interface between wildland and human presence within settlements (wildland-urban interface, WUI), where the risk of fire may be especially high for the local population. The spatial extension of the interface is illustrated (Figure 3, map at left), along with the number of people more vulnerable to wildfires because of living in the interface (Figure 3, maps at the centre and right). The appendix shows additional high-resolution details, specifically on the relationship (easier to visualise) between the intermixed component of the Wildland-Urban Interface (WUI) and the fire damage (see Figure 20 and Figure 21).

4 Conclusions

Links with previous PESETA research The final report of the PESETA III project (Task 11, forest fires [35]) concluded highlighting – as key strategies to consider – the need for better vegetation management to reduce the likelihood of severe fires, and for specific fuel treatments to mitigate fire hazard in dry forests.

In the PESETA III research, limited, partial evidence from selected literature was noted as worth further investigation. In particular, indications were reported on how vegetation structure and composition, resistance and resilience to fire may be mutually connected in non-obvious ways. Some biodiversity-conservation protected areas may be affected less by wildfires than unprotected areas, despite having more fuel. Specific 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. Furthermore, evidence suggests that diversity of fire resistance and resilience traits might be more effective than simple functional richness (which highlights how focusing on generic biodiversity richness alone may not be enough to improve the vegetation resilience to wildfires). Overall, these highlights suggest to consider with great care simplistic solutions to cope with the changing fire risk, as wildfires "are a complex socio-spatial issue" and the "interactions between environment factors, the social context and the fire regime over the long term, as well as changing fire behaviour spatial patterns, resulting in the creation of new territories at risk, are still largely unknown" [93].

Shedding light on the nexus between human presence, vegetation and wildfire risk In this PESETA IV research, summary indices of potential vegetation vulnerability are introduced to account not only for single species vulnerability, but rather for the combined multifaceted impacts on vegetation structure and composition following the definition of ecological domains by FAO [49] and estimating their potential shift under different climate-change scenarios. Among the wild land exposed to the potential impact of wildfires, vegetation in the European areas more subject to intense changes of their ecological domains may become especially vulnerable to fire damage. This may happen due to two distinct but potentially co-occurring negative phenomena. First, a general decline of the local habitat suitability for the currently established vegetation associations – and a corresponding increase of dead biomass available as fuel. Second, the potential inability of the more vulnerable vegetation to re-establish, after a fire, its original set of ecosystem functions and services – because of the changed local ecological domain, no more suitable for the original vegetation.

In parallel with this analysis, a detailed assessment is proposed on the varying frequency of fire danger classes (from the relatively safer to the extreme danger conditions) under changing climate. **In a given area, the co-occurrence of an increasing number of high-danger days, and the presence of people potentially exposed to wildfires, *and* living within the more vulnerable interface between settlements and wildland, indicates an increasing fire risk.** Focusing on the population potentially exposed to wildfires in Europe, the interface between urban areas and wildland (WUI) is here identified as an indicator of where the people are more vulnerable, both due to the easier ignition of areas where people can have an easier access to wildland, and due to a *passive* consequence of the increased risk. Once a given fire is ignited close to the WUI, neighbour locations are also threatened.

An integrated assessment of the findings supports a recommendation to focus on the Mediterranean areas of Europe characterised by higher potential vegetation and population vulnerability, and higher potential fire danger. In addition, it may be necessary to focus attention on specific mountain areas (even outside the Mediterranean) especially on lower elevation areas where forests are dominant and more vulnerable to a rapidly changing ecology, and land abandonment may worsen the vegetation fuel and the WUI interface for the remaining population. On a different level, areas currently in the boreal ecological domain (now and in the future relatively less exposed to the worst fire danger conditions) might experience important bio-climatic changes which – with occasional more severe fire events – may worsen the conditions of fuel and the post-fire recovery.

4.1 Adaptation options

Climate change will increase wildfire risk, as fire danger and fire vulnerability will increase. **Potential adaptation options leading to decreasing fire risk may include actions to lower the values of the wildfire risk components** [25, 26]:

- **Reduction of human vulnerability by increasing preparedness and reducing fuel proximity to human settlements and infrastructures** : through clearing of vegetation around buildings and human infrastructures.
- **Reduction of human vulnerability by increasing awareness and preparedness on health hazards** : population at a large distance from fires may be affected by fire pollutants, due to the temporal persistence and huge volume of gasses released in extreme events. Education on safety and health impacts due to smoke and emissions from fires (short-term and longer term). Preparedness campaigns for citizens with pre-existing health conditions, those operating in wildfire emergency response, and firefighters.
- **Reduction of fire danger by reducing fire propagation** : reduction of fuel load by prescribed burning or use/removal of biomass, reduction of the combustibility of fuels by replacing forest species when feasible (towards less fire-prone species).
- **Reduction of fire danger by a reduction of fire ignitions** : awareness campaigns, education campaigns, training and rural campaigns for prescribed burning.
- **Reduction of fire danger by reducing fuel continuity** : inclusion of fire management planning in landscape planning, including fire breaks, discontinuity of fuels, mosaics of diverse land uses (managing the current landscape).
- **Reduction of ecosystem vulnerability by reducing fuel flammability** : through the use of less flammable species (e.g. deciduous species) and mix of tree species (managing and planning at the local scale).
- **Reduction of ecosystem vulnerability by improving vegetation resilience** : through regional planning of better landscape vegetation pattern (forestry, agriculture), adapting to changing bioclimatic conditions and regime of the potential fire frequency and severity (planning for the future landscape).

Post-fire adaptation options. The applicability of these adaptation options includes both pre-fire preparedness and post-fire recovery. Specifically, post-fire adaptation for the mentioned categories may be summarised as follows:

- **Reduction of human vulnerability by increasing preparedness and reducing fuel proximity to human settlements and infrastructures; reduction of human vulnerability by increasing awareness and preparedness on health hazards** : reconstruction after a fire event should minimise the risk of re-establishing an interface between buildings and human infrastructures and flammable vegetation fuels. Psychological support and training may focus on improving awareness and preparedness of more vulnerable citizens (e.g. those with pre-existing health conditions and those previously exposed to smoke pollution from fires). Lessons learned from the past fire event should inform training programs to improve community preparedness (social learning).
- **Reduction of fire danger by reducing fire propagation; reduction of ecosystem vulnerability by reducing fuel flammability** : the activities to support post-fire recovery of vegetation may consider, as an alternative to restoring pre-fire vegetation, the opportunity for a change in species. This option may complement the species traditionally found in an area with other species better adapted to climate change conditions (managing and planning at the local scale).
- **Reduction of fire danger by reducing fuel continuity; reduction of ecosystem vulnerability by improving vegetation resilience** : after a fire has occurred, there may be opportunities to plan for a future landscape, less fire-prone. This option can exploit the possibility to establish a more resilient distribution of vegetation types, better adapted to changing fire regimes (managing and planning at the landscape scale).

Annexes

Annex 1: on computational modelling, methods and data

A1.1 A standardized index of fire danger by weather

The hazard by wildfires may be represented in a quantitative way by defining a rating index, frequently called *fire danger*, to better support the integrated analysis of the factors determining the ease of ignition, rate of spread, difficulty of control and fire impact [14, 18]. The literature on how to implement effective fire danger rating systems encompasses several decades of research [12, 63, 15, 90, 37]. Among these long-lasting research programs, the Canadian one began in 1925 and led to the development of several fire danger systems [106] with successive improvements to account for the effects of weather on forest fuel and fire [18].

The Canadian Fire Weather Index (FWI) system [106, 18] is designed to provide a uniform numerical rating of the relative fire danger, 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. A number of studies have concluded that there is a significant relationship between FWI and forest fires [11, 53, 38, 37].

Table 4: Main characteristics nominally associated with the Fire Weather Index (FWI) system fuel moisture codes [106, 18]. 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 [35].

Fuel moisture code	Fine Fuel Moisture Code	Duff Moisture Code	Drought Code
Typology of moisture content (following the original definition [106, 18])	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

The system relies on a set of six components which transform the input data into intermediate quantities that are then used to estimate the final aggregated index (see Figure 15). Three of the components describe the state of the fuel (litter and organic layers, from the surface to the deeper levels of the soil, representing a schematic subdivision from fine biomass to coarse wooden fuels, see Table 4).

- The Fine Fuel Moisture Code (FFMC) 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.

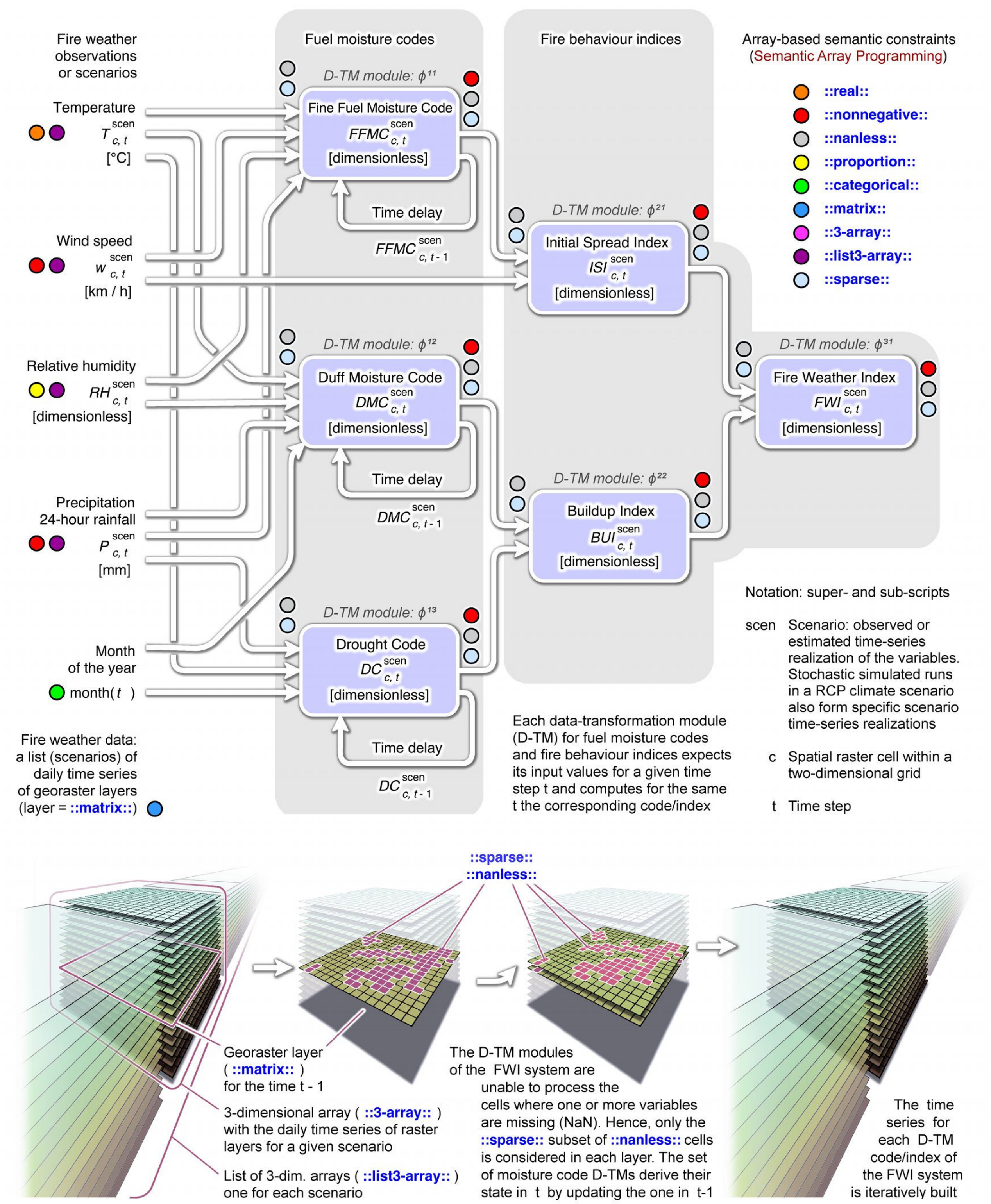


Figure 15: Modelling fire danger by weather under climate-change scenarios: summary of the modelling architecture for applying Canadian Forest Fire Weather Index system (FWI) to estimate the climatic fire danger potential in Europe. From: de Rigo [28]. The compact notation is exploited from the Semantic Array Programming (SemAP) approach [20, 22, 24] and its geospatial application [33, 24].

- The Duff Moisture Code (DMC) models a standard moisture content of loosely-compacted organic layers of moderate depth (duff layers and medium-sized woody material). More generally, this component represents wooden fuels of intermediate thickness.
- The Drought Code (DC) models a standard moisture content of deeper, compact, organic layers. More generally, this component is able to track seasonal drought effects on coarse wooden fuels.

The other components are related to fire behaviour (rate of spread, intensity).

- The Initial Spread Index (ISI) 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.
- The Buildup Index (BUI) combines DMC and DC to model the total amount of fuel available for combustion to the spreading fire.
- The final index FWI is a standard aggregated numerical rating of fire intensity which takes into account all the other components.

The FWI-system was 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. It is 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 effects on fire danger.

A1.2 Vulnerable vegetation: some details on the local patterns

Boreal, Temperate, and Subtropical vegetation domains each encompass multiple sub-domain zones (see Figure 7), and may be defined with a focus on the regional broad patterns (e.g. including as subtropical even high mountain peaks in the Mediterranean region, see Figure 8), or the local patterns (e.g. considering the vegetation succession in Mediterranean mountains in its local specificity, varying from subtropical at low-elevation slopes, to predominantly temperate at intermediate elevation, up to showing marked boreal components at the higher peaks, see Figure 9). Two high-resolution areas are here shown for the current situation estimated with the WorldClim data [29, 34, 27], to illustrate the different level of local details in the mountainous areas obtained with the regional broad patterns (Figure 16 and 17) compared with the local-pattern analysis proposed in this work (Figure 18 and 19).

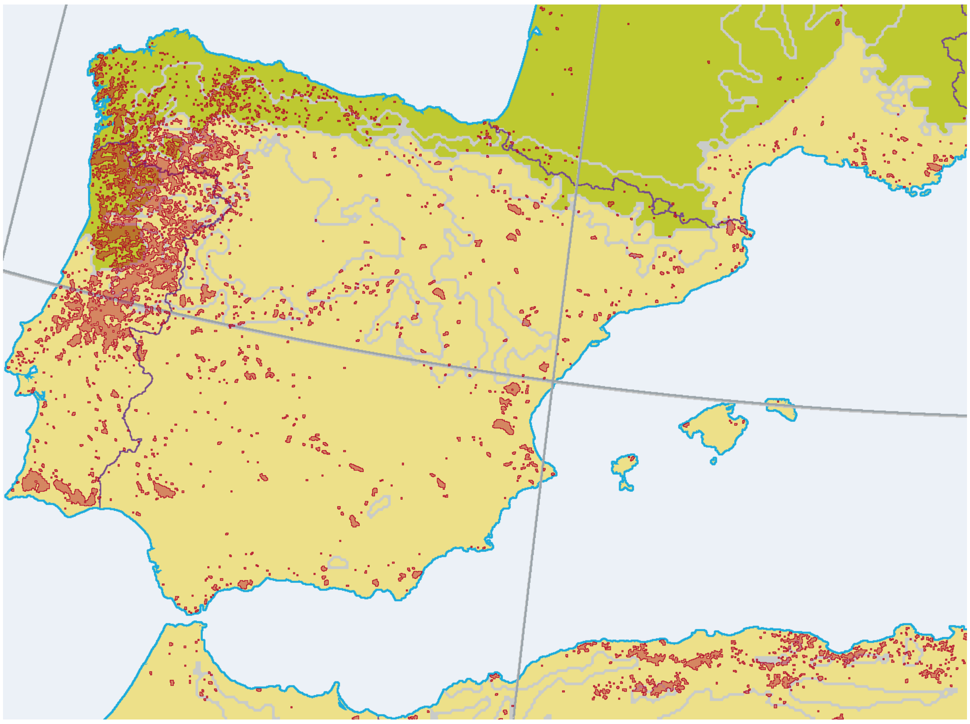


Figure 16: Domains (level 1) of the FAO ecological zones (see Figure 7) in the Iberian peninsula, namely Subtropical and Temperate. The fires of over 40 ha mapped by EFFIS from satellite images in 2000-2015 are associated mainly to the Subtropical domain and depicted in red. The boundary of the detailed ecological zones shown in Figure 7 are represented in light grey.

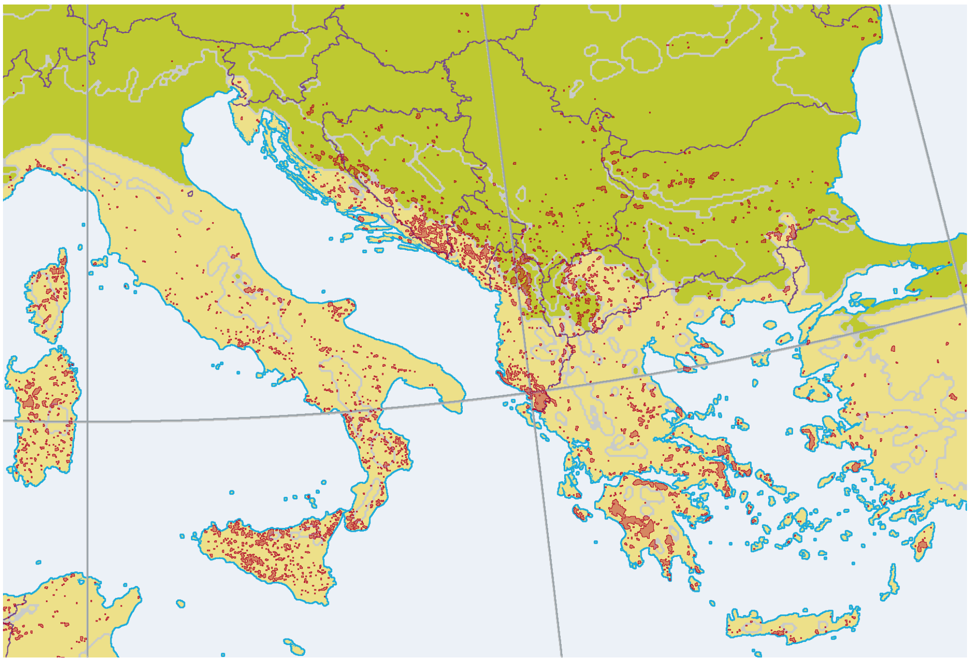


Figure 17: Domains (level 1) of the FAO ecological zones (see Figure 7) in Italy and the Balkans, namely Subtropical and Temperate. The fires of over 40 ha mapped by EFFIS from satellite images in 2000-2015 are associated mainly to the Subtropical domain and depicted in red. The boundary of the detailed ecological zones shown in Figure 7 are represented in light grey.

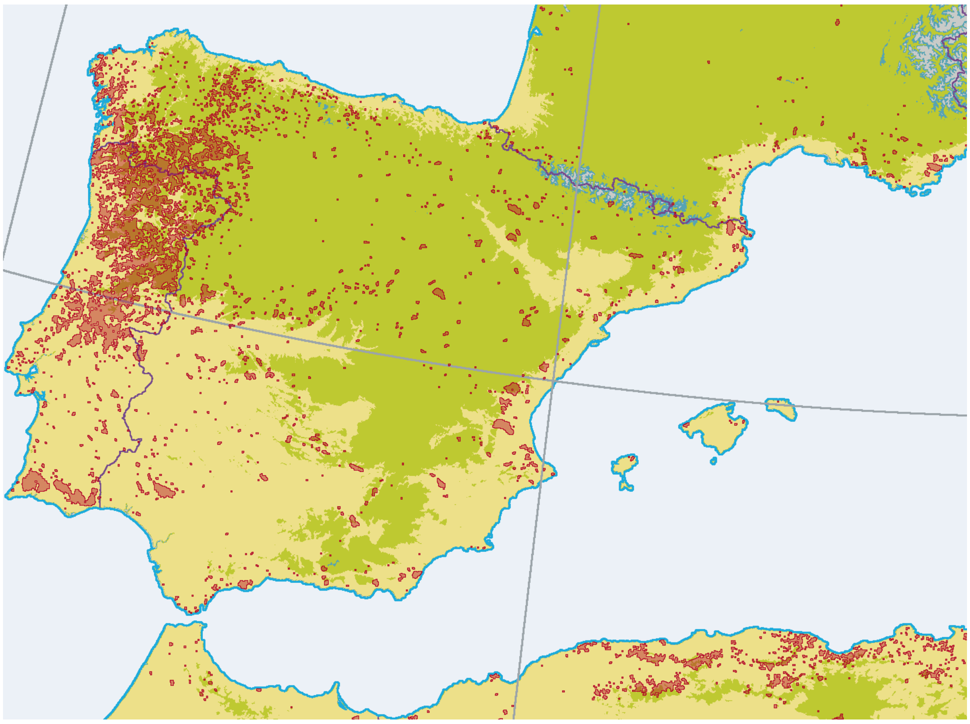


Figure 18: Local ecological domains in the Iberian Peninsula according to the criteria of temperature used in the FAO ecological zones when applied with the WorldClim data without considering the potential natural plant communities. The fires of over 40 ha mapped by EFFIS from satellite images in 2000-2015 are associated mainly to the local Subtropical domain and depicted in red. Compared with the FAO domains in this region (see Figure 16), the extent of the local Subtropical domain is much restricted due to the effect of elevation in mountainous regions.

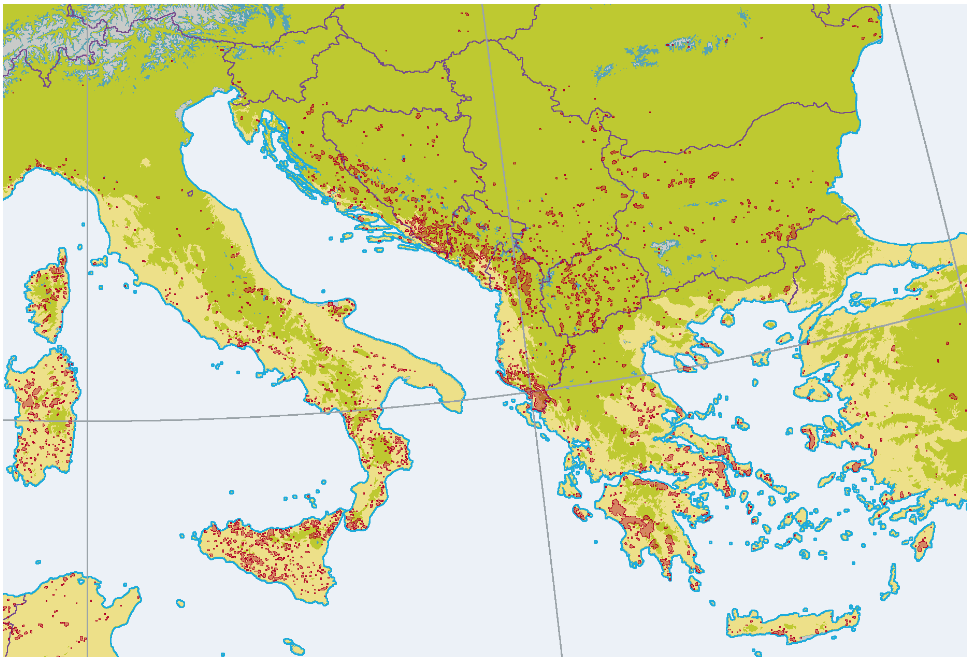


Figure 19: Local ecological domains in Italy and the Balkans according to the criteria of temperature used in the FAO ecological zones when applied with the WorldClim data without considering the potential natural plant communities. The fires of over 40 ha mapped by EFFIS from satellite images in 2000-2015 are associated mainly in the transition between local Subtropical and Temperate domains and depicted in red. Compared with the FAO domains in this region (see Figure 17), the extent of the local Subtropical domain is much restricted due to the effect of elevation in mountainous regions.

A1.3 Vulnerable population: some details in the intermix WUI

Two high-resolution areas are here shown, to illustrate the spatial relationship (easier to visualise) between the intermixed component of the Wildland-Urban Interface (WUI) and the fire damage.

As human factors are associated with the vast majority of European fires [35, 55], the distribution of settlements surrounded by a large percentage of wildland may be expected to be connected with the distribution of wildfires. Figure 20 and Figure 21 respectively show Portugal and Sicily (Italy). In the figure, the distribution of WUI is shown along with the fires contiguous to or intersecting part of the WUI compared with those disconnected from the WUI .

Figure 22 and Figure 23 show the corresponding population exposed to wildfires in the intermixed component of the Wildland-Urban Interface.

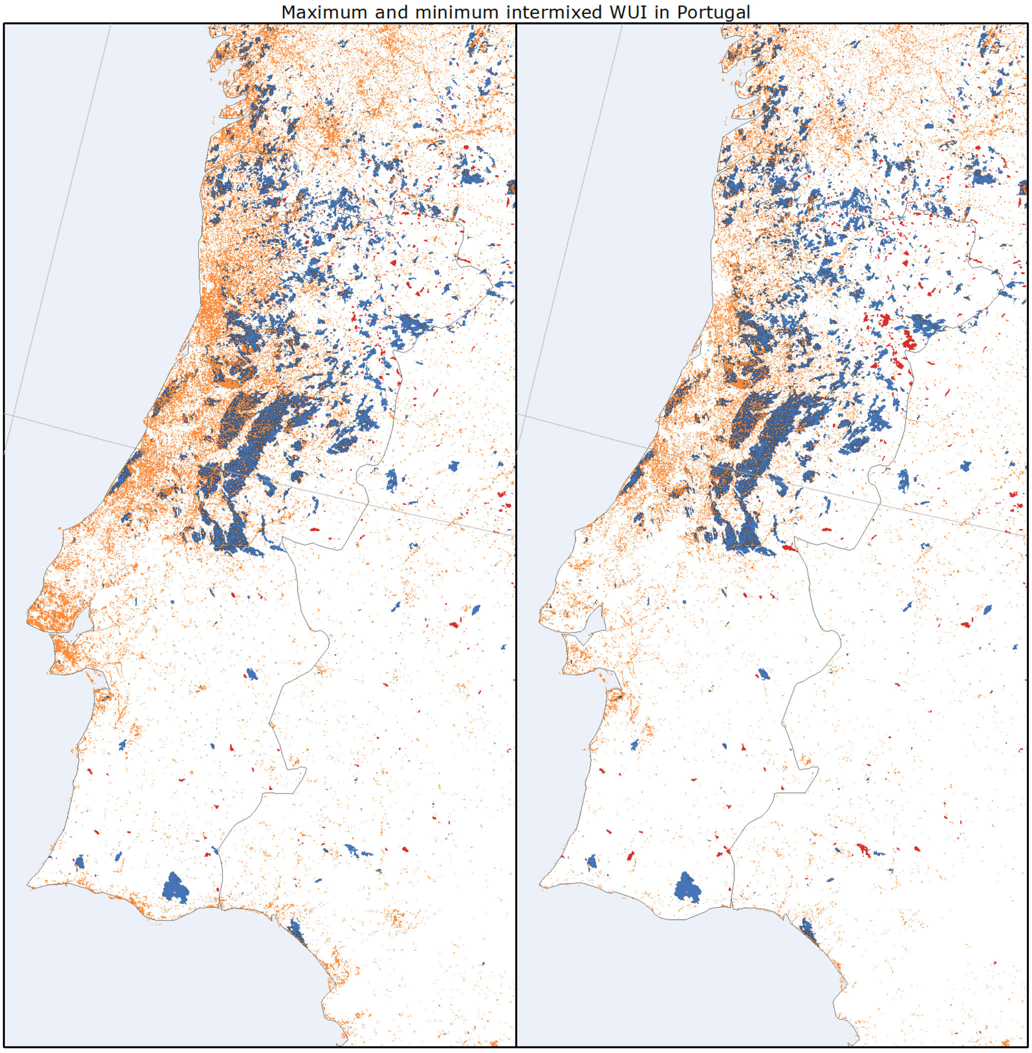


Figure 20: The relationship between the intermixed component of the Wildland-Urban Interface (WUI) and the fire damage is easier to visualise. Portugal, intermixed WUI and burnt-area by fires larger than 30 ha, as estimated by the European Forest Fire Information System (EFFIS) for the years 2000-2017. As human factors are associated with the vast majority of European fires [35, 55], the distribution of settlements surrounded by a large percentage of wildland (which is modelled by the interface component of the WUI) may be expected to be connected with the distribution of wildfires. In the figure, the distribution of WUI (**orange**) is shown for Portugal along with the fires contiguous to or intersecting part of the WUI (**blue fires**) compared with the ones disconnected from the WUI (**red fires**).

Maximum and minimum WUI in Sicily

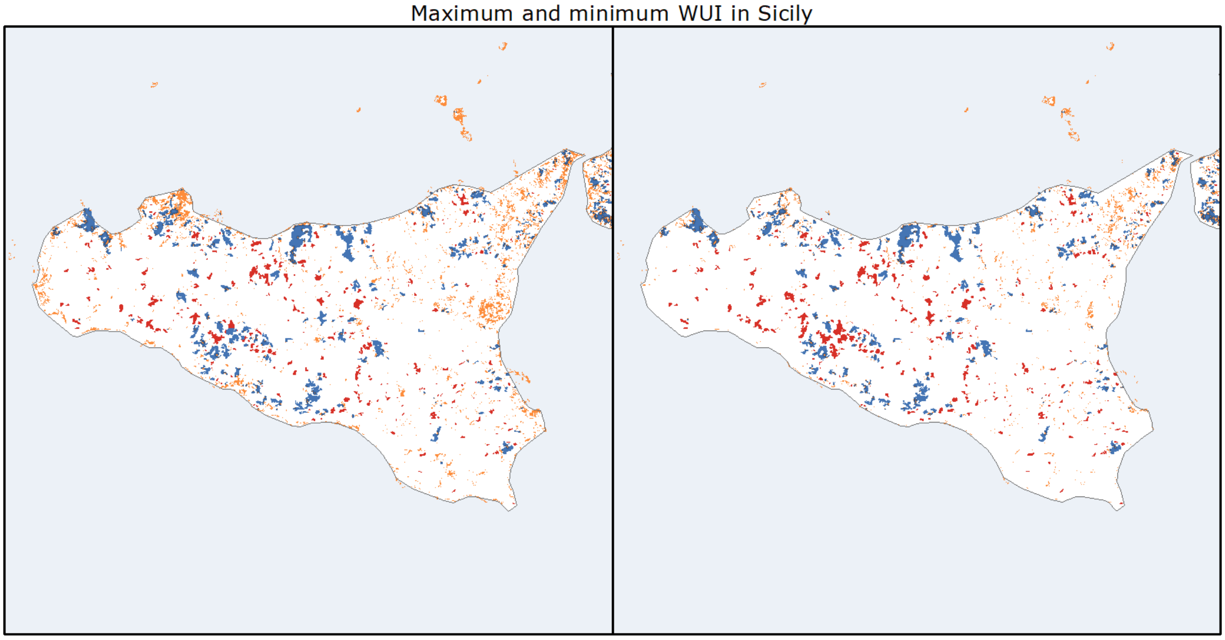


Figure 21: The relationship between the intermixed component of the Wildland-Urban Interface (WUI) and the fire damage is easier to visualise. Sicily (Italy), intermixed WUI and burnt-area by fires larger than 30 ha in Sicily (Italy), as estimated by the European Forest Fire Information System (EFFIS) for the years 2000-2017. As human factors are associated with the vast majority of European fires [35, 55], the distribution of settlements surrounded by a large percentage of wildland (which is modelled by the interface component of the WUI) may be expected to be connected with the distribution of wildfires. In the figure, the distribution of WUI (**orange**) is shown for Sicily (Italy) along with the fires contiguous to or intersecting part of the WUI (**blue fires**) compared with the ones disconnected from the WUI (**red fires**).

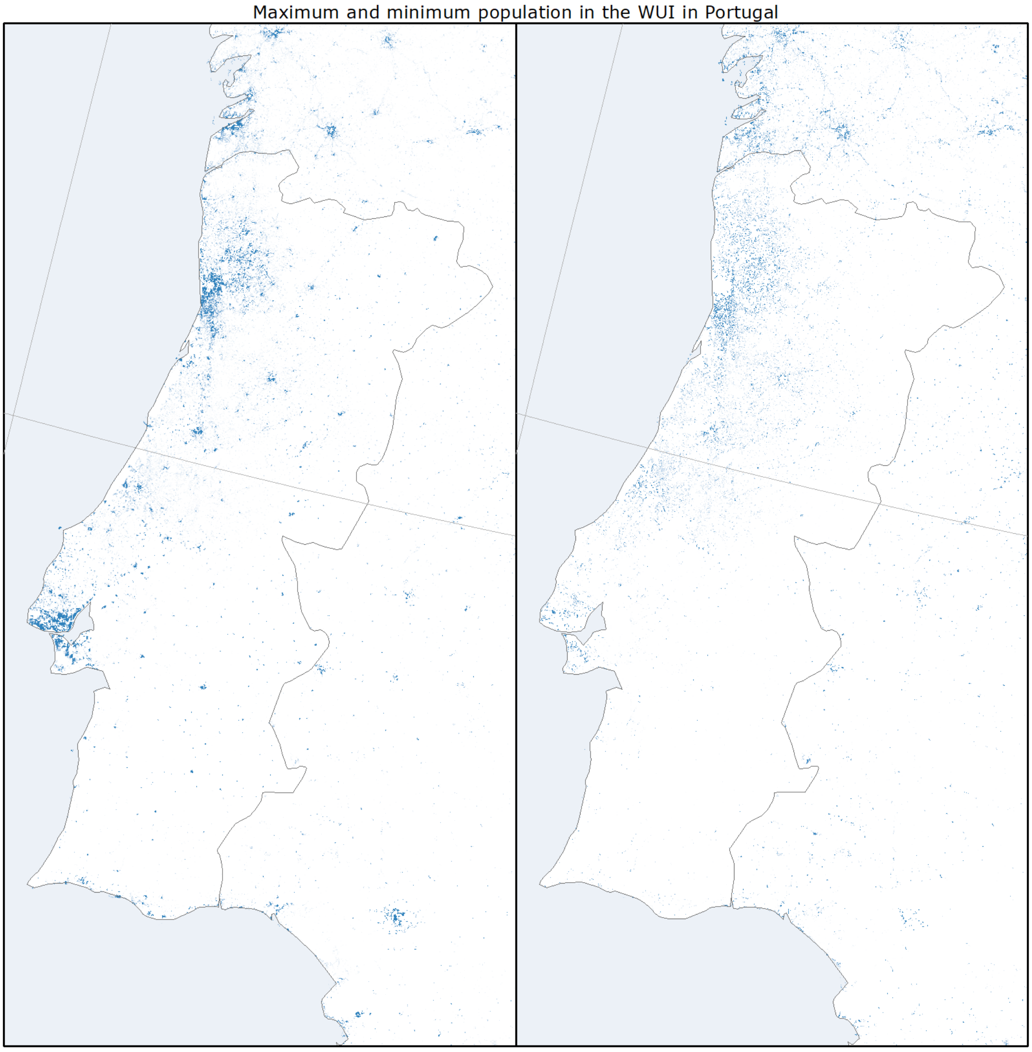


Figure 22: Population exposed to wildfires in the intermixed Wildland-Urban Interface (WUI) in Portugal (see Figure 20), ranging between a minimum (**right-hand**) and maximum (**left-hand**) as a function of the uncertainty of the percentage of wildland estimated from the CORINE Land Cover map of 2012 [7, 8]. Population counting was based on the Global Human Settlement Layer (GHSL) [52].

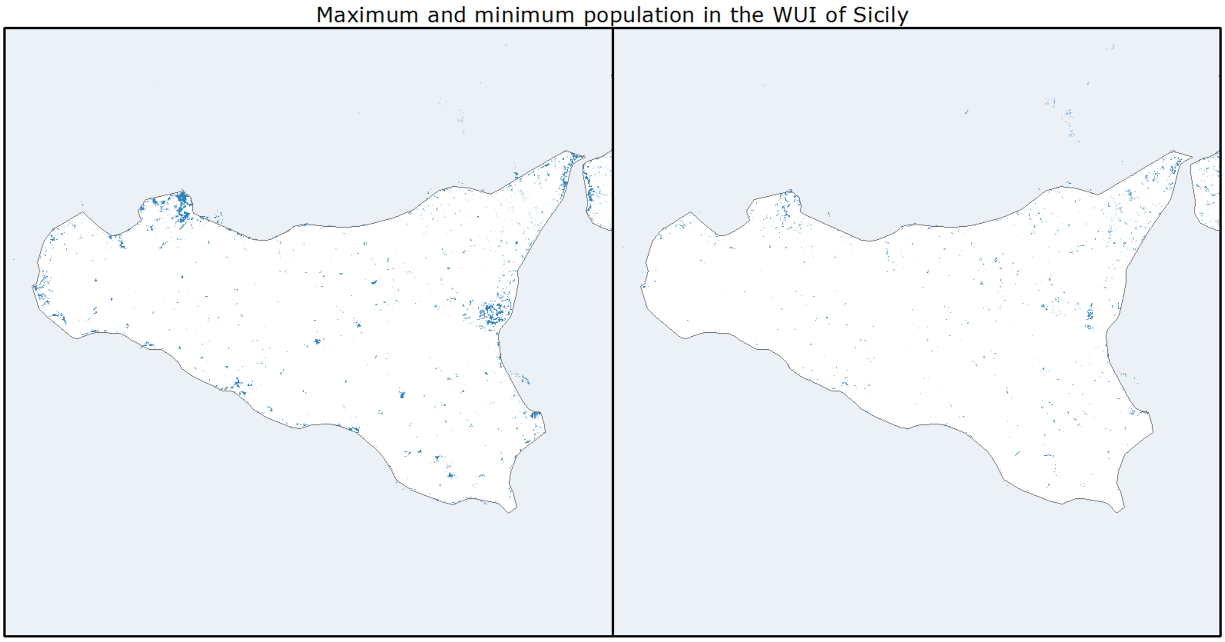


Figure 23: Population exposed to wildfires in the intermixed Wildland-Urban Interface (WUI) in Sicily (see Figure 21), ranging between a minimum (**right-hand**) and maximum (**left-hand**) as a function of the uncertainty of the percentage of wildland estimated from the CORINE Land Cover map of 2012 [7, 8]. Population counting was based on the Global Human Settlement Layer (GHSL) [52].

Box 1. Authors' contributions

Here, the authors' contributions are summarised following the taxonomy of roles described in Allen *et al.* [3], and further recommended by a joint initiative of several main publishers worldwide [68, 5]. To each contribution role, an active link points to the corresponding taxonomy dictionary item. Authors' initials are used to identify each co-author. See Section Authors. This work is based on the conceptualisation, investigation, data and methods (both formal analysis and computational aspects) of [17, 27, 25, 26, 35, 67].

Abbreviations: ^{M} research management/strategy; ^{T} technical aspects.

Conceptualization	DdR^{T}, HC^{T}, JSMA^{M}	Methodology	DdR, HC, THD
Software	DdR, HC	Formal analysis	DdR, HC
Investigation	DdR, HC, THD	Resources	JSMA^{M}, GL^{T}, THD^{T}
Validation	HC, DdR, GL	Data curation	GL, DdR, THD, HC
Writing (original draft)	DdR, HC, THD	Writing (review and editing)	DdR, HC, THD, JSMA, GL
Visualization	HC, DdR	Supervision	JSMA
Project administration	JSMA	Funding acquisition	JSMA

Competing interests The authors declare no competing interests.

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List of abbreviations and definitions

The following list is mainly derived from de Rigo *et al.* [35], de Rigo *et al.* [32], San-Miguel-Ayanz *et al.* [92], and de Rigo [24]. Other sources are indicated in the single definitions.

Agroforestry	A land-use system with two or more interacting plant species, where at least one of them is a tree or shrub. In agroforestry, typically woody species are intermixed with crops or pastures. Definition from San-Miguel-Ayanz *et al.* [92].
Anomaly	In the analysis of climate change, 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 15.
CLC	*CORINE Land Cover*, possibly the most well-known CORINE program. It it an inventory of land cover in 44 classes, and presented for most of Europe as a cartographic product at a scale of 1:100000 with a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena. CLC is part of the Copernicus Land Monitoring Service, from which can be downloaded the entire time series available (1990, 2000, 2006, and 2012). See https://land.copernicus.eu/pan-european/corine-land-cover.
CMIP5	*Coupled Model Intercomparison Project phase 5*, a set of coordinated climate model experiments, dealing with global coupled ocean-atmosphere general circulation models (GCMs) [101]. 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.* [92].
CORDEX	*Coordinated Regional Climate Downscaling Experiment* initiative, a coordinate effort to advance and the science and application of regional climate downscaling [56]. See http://www.cordex.org.
CORINE	*Coordination of Information on the Environment*. A programme initiated in the European Union in 1985 as a prototype project working on many different environmental issues. The CORINE databases and several of its programmes have been taken over by the European Environment Agency. CORINE Land Cover is part of this program. See https://www.eea.europa.eu.
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 15 and Table 4.
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 15 and Table 4.
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 [23, 33, 24]. 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.

EU-Med	Mediterranean region of the European Union [42]. Countries in the EU-Med region are severely affected by forest fires. For five of them (Portugal, Spain, Greece, Italy, and the Mediterranean part of France) a longer time series of country-provided data is currently available in the Fire Database of EFFIS [94].
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, RCM) to improve global circulation models (GCM) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) [61, 58, 65, 107]. See http://www.euro-cordex.net.
European atlas of forest tree species	Comprehensive research initiative focused on the trees living in the European forests, based on an intensive harmonisation endeavour to integrate the multiplicity of specialised sources available at different scales. A multi-institution voluntary effort by a group of international authors, advisors and reviewers produced the printed version of the Atlas (edited by the JRC), and supports periodic updates in the online full version integrating recent or extended literature, improved data and modelling, extended statistics and iconography. As a central system for integrating information specific to each tree species in Europe, and to the overall European forests and wildland, the Atlas modelling and information system is based on a dynamic database on the bioclimatic ecology of forests, distribution of trees, their use, threats, and eventually the vulnerability that climate may trigger [30, 34, 31, 92]. See https://w3id.org/mtv/FISE-Comm/v01.
ESM	*European Settlement Map*: a spatial raster dataset that is mapping human settlements in Europe, produced with GHSL technology by the JRC. See https://land.copernicus.eu/pan-european/GHSL/european-settlement-map.
FAO	*Food and Agriculture Organization* of the United Nations. See http://www.fao.org.
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 15 and Table 4.
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 15.
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 [18, 106]. 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 15.
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.* [92].
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 [33, 24].
GHG	Atmospheric *greenhouse gas*.

GHSL	*Global Human Settlement Layer*. Global spatial information about the human presence on the planet in the form of built up maps, population density maps and settlement maps. It is supported by the Joint Research Centre (JRC) and the Directorate-General for Regional Development (DG REGIO) of the European Commission, together with the international partnership GEO Human Planet Initiative. Among the products, the [ESM]European Settlement Maps are pan-European built-up layers derived from higher resolution imagery. See https://ghsl.jrc.ec.europa.eu.
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" [62]. 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.* [32].
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 15.
JRC	*Joint Research Centre*: as the European Commission's science and knowledge service, the Joint Research Centre supports European Union policies with independent scientific evidence throughout the whole policy cycle. See https://ec.europa.eu/jrc/en/about/jrc-in-brief.
P	*Precipitation*. One of the input variables required by the FWI system.
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.
PESETA IV	The fourth instance of PESETA (PESETA IV) focuses on assisting the work on the review of the EU Adaptation Strategy. The proposed work also aims to support the implementation of Action 4 of the EU Adaptation Strategy by deepening and further refining existing JRC bottom-up analyses of climate change impacts and adaptation. It expands on the climate runs used in the JRC PESETA III project. Compared to JRC PESETA III, the new project improves, extends and further integrates the JRC sectoral impact models. It considers 30-year time windows centred on specific warming levels, specifically 1.5 °C, 2 °C and 3 °C average global warming compared to pre-industrial levels.
Pyro-convection	It can be generally defined as the transfer of heat by the circulation or movement of the local heated air (along with other fire emissions and smoke); in particular, it is the vertical transport of atmospheric properties driven by or enhanced by fire [13]. While every fire, even small, is associated to some degree of pyro-convection, some fires may generate cumulus clouds (pyrocumulus, or their extreme manifestation pyrocumulonimbus) when moist air, vertically moving by pyro-convection, condensates [13]. These phenomena may also be followed by smoke-induced density currents able to contribute to rapid wind shifts and drastic reductions in visibility [66].
Prescribed burning	Also known as *controlled burning*, it refers to the removal of existing flammable biomass (vegetation fuel) by using fire under controlled conditions, typically with the approval of and appropriate operational plan and the expert verification of which vegetation, topography, weather, and moisture conditions are compatible with the operation safety [46, 89, 47].
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 [71, 83].

RCP4.5	Mitigated-emission RCP scenario of climate change (*stabilization pathway*). It assumes an increase of the radiative forcing throughout the 21st century up to reach an approximate level of 4.5 W per m^2 by the end of the century [71, 83].
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 [86, 74] 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.
Resprouting	The resilience ability of some plant species to survive fire damage and regrow by activating dormant vegetative buds. Contrary to resprouters, several plant species are killed by fire and their regeneration relies on seeds which survived the fire event, or which colonise from outside the damaged area.
RH	*Relative humidity*. One of the input variables required by the FWI system.
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 [74, 83].
Semantic constraint	In computational modelling, it formally expresses a logical or mathematical property characterising the quantitative meaning (semantics) of a certain quantity [21, 20, 22, 24, 92]. For example, considering the annual time series of the weather-driven fire danger rating in a given area, the multi-model median of the days in which the rating is above a medium-danger threshold cannot be less than the median of days above a high-danger threshold, while between different models this constraint does not hold.
SemAP	*Semantic Array Programming*. In computational science, a computational modelling approach to compactly process arrays of data preserving the consistency of their underpinning semantics [20, 22, 33, 24]. 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.
Silvopastoralism	The agroforestry practice of livestock grazing in a area with a forest component [77].
SRES	IPCC *Special Report on Emissions Scenarios* [74].
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" [74].
T	*Temperature*. One of the input variables required by the FWI system.
w	*Wind* speed. One of the input variables required by the FWI system.
WorldClim	*WorldClim* is a set of global gridded climatic data with a spatial resolution of about 1 km^2. See http://www.worldclim.org.
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.

List of Figures

List of Tables

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