FIREURISK - DEVELOPING A HOLISTIC, RISK-WISE STRATEGY FOR EUROPEAN WILDFIRE MANAGEMENT

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Executive Summary

This document provides the analyses performed by different partners of FirEUrisk regarding the future vulnerability and exposure to future fire, incl. changes along the Wildland Urban Interface (WUI). The activities we present here, include: i) modelling fire smoke emissions and evaluating future population exposure to smoke for selected climate and land-use scenarios; ii) analysis of projected changes in fire behaviour, and fuel moisture to quantify changes in wildfire risk along the WUI; iii) analysis of changes in vulnerability of ecosystem service provision to identify which scenario conditions lead to new vulnerabilities and which can minimise future impacts; iv) assessment of the impact of intensified fire regimes (i.e., the increase in frequency or severity of fires) on plant vulnerability, v) a proposed methodology to map ecological vulnerability to wildfires under future scenarios; and vi) a participatory review with stakeholders regarding the identified projected changes in vulnerability, focusing on fire weather danger.

The results of the analysis shown here, builds on scenarios described in Deliverable 3.1 that developed downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA; Deliverable 3.2 that developed continental land-use change scenarios and stylised fuel management scenarios for the 21st century; and on results from Deliverable 3.4 that simulate fire and vegetation dynamics at three spatial scales. Deliverable 3.6 complements the analysis performed in Deliverable 3.5 that focused on future climate conditions and how they will affect fire regimes and fire risk. On the other hand, results from this deliverable are valuable for the implementation of Deliverable 3.7 - Identification of effective adaptation measures and Deliverable 3.8 - Adaption options to future fire preparedness planning at three spatial scales.

Future fire smoke emissions based on climate forecasts of total carbon emissions from wildfires for Europe at 9 km resolution were estimated, as well as future population exposure to smoke across Europe under different socio-economic pathways that was assessed using advanced meteorological and air quality models. The increased emissions of CO in some regions in Central Europe are expected to lead to a situation similar to the one of the Mediterranean Regions where wildfire smoke is already a significant problem. Other pollutants that are particularly dangerous for health found within wildfire-smoke are NOx which are predicted to follow the same trend seen in CO. There is a clear upward trend in fire-induced PM2.5 levels over time and a correlation between higher anthropogenic emissions and increased smoke exposure. We found no significant decrease in exposure levels in any region. The changes in Northern Europe are relatively small compared to other areas. In contrast, Southern Europe is expected to see a substantial increase in smoke exposure across all three future SSP scenarios. Notably, in the Balkans, a significant increase in exposure levels is only predicted under the SSP370 scenario, while other scenarios indicate exposure levels will remain nearly unchanged.

Changes in the wildfire risk along the WUI were analysed at three different locations: Central Region of Portugal (FirEUrisk Pilot Site 3), Attica region of Greece (FirEUrisk Pilot Site 5) and in the whole island of Sardinia, Italy (FirEUrisk Demonstration Area 5). First, we implemented a modelling approach based on the land use change projections developed in WP3 to predict the spatial patterns of the WUI until 2050 in decadal intervals. This resulted in sets of 10 m resolution WUI maps from 2020 to 2050 in decadal steps, based on the land-use/climate scenarios SSP1 and SSP3.

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These maps, in turn, inform fire simulations and subsequent risk assessments on the exact locations of the WUI in the two Pilot Sites (PS) and one Demonstration Area for which these projections have been made. Fire behaviour projections were made based on the use of the fire mapping and analysis system FlamMap. The simulations were performed with settings similar to the ones used in Work Package (WP) 1, during the analysis of fire propagation in the present-day (Deliverable 1.1 - Report on methodological frameworks for each Danger modelling process). The primary focus was on understanding the potential impacts of wildfires within Wildland-Urban Interface (WUI) areas, where the risk to human life and property is significant. By assessing changes in fire behaviour descriptors, such as rate of spread, fire intensity, and burn probability, this study provides critical insights into how wildfire risks may evolve and what strategies may be necessary to manage these risks effectively. The findings across all study areas indicate that wildfire danger and behaviour are expected to increase under future climate scenarios, with significant variability based on region and specific climate pathways. The study underscores the necessity of developing region-specific strategies that incorporate both climatic and land use factors to effectively manage and mitigate wildfire risks.

Changes in ecosystem service provision result from the combined effects of several drivers such as climate and land-use change that impact vegetation composition, fuel production as well as changes in fire regimes. We provide information on carbon sequestration as an example for ecosystem service provision. The complex interactions of those drivers reveal regionally different patterns, where one or a combination of the drivers affects the ability of the ecosystem to sequester more carbon than is released via decomposition, harvest or fire. Climate and land-use change as well as changes in future burned area affect carbon sequestration differently at the European scale (ET scale) with increases in carbon sequestration projected for Scandinavia, many mountain regions, but also some lowland regions, e.g. in central Europe. Carbon sequestration is projected to decrease further in highly managed regions that are dominated by agriculture already today and in the future, especially in western Europe and on the British Isles. The future socio-economic and climate pathway determines how strong carbon sequestration could increase in the Balkans by the end of the century, and how much the provision of this ecosystem service might get reduced on the Iberian Peninsula.

Regarding ecological vulnerability, we assessed plant vulnerability to intensified fire regimes, across different climates, habitats, and fire regimes globally and focusing specifically on the European Territory (ET). We show that, at global scale, increasing fire severity and/or frequency reduces plant abundance, diversity, and fitness, although the magnitude of the effect is limited and context dependent. Results also show that woody plants are more sensitive to intensified fire regimes than non-woody plants, suggesting that ecosystems dominated by woody plants may be particularly vulnerable. For the ET, the limited and highly variable data precluded a confident assessment of the effects of intensified fire regimes. The uneven distribution of fire effect studies, with a high concentration in Mediterranean regions, also highlights underrepresented environments (particularly non-fire prone ecosystems). Despite efforts to compile as many studies as possible, our results are limited by the available research. Nevertheless, results show that intensified fire regimes significantly reduce plant fitness particularly in conifer and mixed forests and in the short term (i.e., ≤2 years post-fire). Overall, these results emphasize the importance of considering different fire regime components (frequency, severity, type) for understanding fire effects in ecosystems. While spatial variations in fire activity can enhance biodiversity, temporal variations may reduce it, suggesting that some ecosystems may become

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less diverse if fire regimes continue to intensify. We show that intensified fire regimes can alter plant responses in many ecosystems, with the magnitude and key drivers of those effects being context dependent. These results can be a helpful instrument to understand future impacts of intensified fire regimes in the ET and predict future impacts.

We also developed a systematic methodology to map ecological vulnerability to wildfires under future scenarios in Europe. This is an essential step towards mitigating the impact of these increasingly frequent and severe events (intensified fire regimes). By integrating data, modelling risks, and engaging stakeholders, this approach provides a valuable tool for policymakers and land managers. The ultimate goal is to ensure that Europe's diverse ecosystems are protected and resilient in the face of a changing climate and evolving landscape.

Finally, we present the work on the participatory review process aimed at engaging local experts and stakeholders in discussions about projected changes in fire regimes and vegetation identified by the project. A participatory workshop was held in Greece, within the wider scope of the Demonstration Event in PS5 - Attica region, where the Fire Weather Index (FWI) and overall fire weather danger variables were reviewed by local stakeholders and experts. The participatory review workshop provided valuable insights into the participants' views on the impact of climate change on fire readiness and management. The feedback highlighted the importance of factors such as community preparedness, adaptation to climate change, and the need for high resolution maps. Participants also expressed the need for updating fire management tools to include future changes in fire regimes and vegetation and improve data resolution. Integrating detailed presentations on climate models and fire weather forecasting enhanced the participants' understanding and engagement during the workshop.

Key Take Aways



SMOKEY FUTURE: CO and NOx emissions from wildfires in Central Europe are expected to reach similar levels to those currently observed for the Mediterranean Region where wildfire smoke is already a significant problem. Regions that are already being impacted by smoke will also experience higher levels in the future.



INCREASED EXPOSURE: Southern Europe is anticipated to face heightened fire-induced smoke exposure across all the future SSP scenarios studied. In contrast, although Northern Europe experiences changes, they are not as pronounced compared as in other regions. Harmful health impacts are expected due to increased smoke exposure.



WILDLAND URBAN INTERFACE: Wildfire danger in the WUI is expected to increase under future climate scenarios, with significant variability based on region and specific climate pathways. To what extent it is difficult to predict, but this analysis shows the need of developing region-specific strategies that incorporate both climatic and land use factors to effectively manage and mitigate wildfire risk.

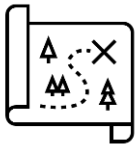
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CARBON SEQUESTRATION: Carbon sequestration is expected to increase in regions like Scandinavia, many mountain areas, and some lowlands, but decrease in highly managed agricultural areas, especially in western Europe and the British Isles. The extent of future changes in carbon sequestration, particularly in the Balkans and the Iberian Peninsula, will depend on socio-economic and climate conditions.



INTENSIFIED FIRE REGIMES: While spatial variations in fire activity can enhance biodiversity, temporal variations may reduce it, suggesting that some ecosystems may become less diverse if fire regimes continue to intensify. It is important to consider different fire regime components (frequency, severity, type) for understanding fire effects in ecosystems.



MAPPING ECOLOGICAL VULNERABILITY TO WILDFIRES UNDER FUTURE SCENARIOS: Developing a systematic methodology to map ecological vulnerability to wildfires under future scenarios in Europe is an essential step towards mitigating the impact of these increasingly frequent and severe events.



PARTICIPATORY APPROACH: Participants' views on the impact of climate change on fire readiness and management highlighted the importance of factors such as community preparedness, adaptation to climate change, and the need for high resolution maps.

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List of Acronyms

Table 1.1: List of Acronyms

List of Acronyms	
aBP	annual Burn Probability
BASE	Burnt Area Simulator for Europe
BMAX	maximum biomass
CC	Coping Capacity
CMIP6	Coupled Model Intercomparison Project Phase 6 (https://cds.climate.copernicus.eu/cdsapp#!/dataset/projections-cmip6)
DGVM	Dynamic Global Vegetation Model
MODIS	Moderate Resolution Imaging Spectroradiometer (https://www.earthdata.nasa.gov/learn/find-data/near-real-time/firms)
EC	Environmental constraints
EPL	Ecological Potential Losses
ERA5	European Reanalysis v.5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5)
ET	European Territory
EVA	Ecological Value Assessment
EVW	Ecological vulnerability to wildfires
FFM	Fire Forecasting Model (Sofiev et al, in prep.)
FFMC	Fine Fuel Moisture Content
FII	Fire Impact Index
FIL	Fire Intensity Level
FMC	Fuel Moisture Content
FWI	Fire Weather Index
GIS	Geographic Information Systems
GR	Growth Rate
LPJmLv5.6-SPITFIRE	Lund-Potsdam-Jena DGVM for managed Land with SPread and InTensity of FIRE process-based fire model embedded. Model version 5.6
NEP	Net Ecosystem Production, measure for carbon sequestration as the net balance between carbon uptake (photosynthesis) and carbon loss (decomposition, harvest, fire)
PS	Pilot Site
RCP	Representative Concentration Pathway
RST	Recovery Starting Time
RT	Recovery Time
RTi	Species-specific recovery timE
RVW	Vegetation Resistance to Wildfires
SILAM	System for Integrated modeLling of Atmospheric coMposition, v.5.8, http://silam.fmi.fi (Sofiev *et al.* 2015)
SSP	Shared Socio-economic Pathways
TPHM	Tree Potential Habitat Maps

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WRF	Weather Research and Forecasting, v.4.1 (Skamarock *et al.* 2019)
WUI	Wildland Urban Interface

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1 Introduction

Many ecosystems in the European Territory (ET) but also worldwide are experiencing a perturbation of their fire regimes (Keeley and Pausas 2019) because of factors such as land-use changes (Bowman *et al.* 2011; Moreira *et al.* 2011), climate change (Berg *et al.* 2017; Abatzoglou *et al.* 2019; Jones *et al.* 2022) and the expansion WUI (Radeloff *et al.* 2018; Jones *et al.* 2022). This perturbation, referred to as the intensification of the fire regime (Grau-Andrés *et al.* 2024), involves a change in the frequency, severity, and size of fires, moving beyond the upper values of their historical range of variability (Canadell *et al.* 2021; Pausas and Keeley 2021; Senande-Rivera *et al.* 2022; Whitman *et al.* 2022).

Fire is a natural process that has shaped many ecosystems over geological time scales and humans, together with climate, have affected fire regimes (Pausas and Keeley 2009). Although humans have taken advantage of fire for their own use, currently wildfires have become a critical problem in the European Territory, affecting human lives and infrastructure with significant socio-economic impacts, particularly evident in the WUI. The need for a smart strategy for fire management, founded on the understanding of both the negative and positive effects of fire, has been advocated for Europe for a long time (Rego *et al.* 2010).

1.1. Purpose of the document

The purpose of this document is to present the analyses performed by different partners of FirEURisk regarding the future vulnerability and exposure to future fire, including changes along the WUI. Specifically:

- Model fire smoke emissions and evaluate future population exposure to smoke for selected climate and land-use scenarios
- Analyse projected changes in fire behaviour, and fuel moisture to quantify changes in wildfire risk along the WUI.
- Analyse changes in vulnerability of ecosystem service provision to identify which scenario conditions lead to new or increased vulnerabilities enabling better planning to minimise future impacts.
- Assess the impact of intensified fire regimes (i.e., the increase in frequency or severity of fires) on plant vulnerability.
- Present results of the participatory review with stakeholders regarding the identified projected changes in vulnerability, focusing on the fire weather danger.

These analyses were performed at different scales. Future smoke emissions and population exposure to smoke, vulnerability of ecosystem service provision and the impacts of intensified fire regimes on vegetation were analysed at the European level. Changes in the wildfire risk along the WUI were analysed at Pilot Site level (Central region of Portugal and Attica region of Greece), and in Sardinia, Italy. Finally, the participatory review with stakeholders and experts, was also implemented at PS level (Attica region of Greece). Other analysis originally intended for this

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deliverable, regarding the evaluation of changes in future vulnerability for selected climate and land-use scenarios, were included in Deliverable 3.5, as they were considered to better relate to the topic of that deliverable.

The results of the analysis shown here, builds on scenarios described in Deliverable 3.1 that developed downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA; Deliverable 3.2 that developed continental land-use change scenarios and stylised fuel management scenarios for the 21st century; and on results from Deliverable 3.4 that simulate fire and vegetation dynamics at three spatial scales. Deliverable 3.6 complements the analysis performed in Deliverable 3.5 that focused on future climate conditions and how they will affect fire regimes and fire risk. On the other hand, results from this deliverable are valuable for the implementation of Deliverable 3.7 - Identification of effective adaptation measures and Deliverable 3.8 - Adaption options to future fire preparedness planning at three spatial scales.

1.1 Structure of the document

This document provides the analyses performed by different partners of FirEUrisk regarding the future vulnerability and exposure to future fire, incl. changes along the Wildland Urban Interface (WUI). The activities we present here, are structure in 6 chapters: i) chapter 2 focus on smoke emissions and exposure, and presents results on modelling fire smoke emissions and evaluating future population exposure to smoke for selected climate and land-use scenarios; ii) chapter 3 focus on changes in wildfire risk along the WUI and presents the analysis of projected changes in fire behaviour, and fuel moisture to quantify changes in wildfire risk along the WUI; iii) chapter 4 is devoted to the vulnerability of ecosystem services provision and describes the analysis of changes in the vulnerability of ecosystem service provision to identify which scenario conditions lead to new vulnerabilities and which can minimise future impacts; iv) chapter 5 is dedicated to ecological vulnerability, and presents an assessment of the impact of intensified fire regimes (i.e., the increase in frequency or severity of fires) on plant vulnerability and proposes a methodology to map ecological vulnerability to wildfires under future scenarios; and v) chapter 6 presents a participatory review with stakeholders regarding the identified projected changes in vulnerability, focusing on fire weather danger.

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2 Smoke emissions and exposure

Climate change is expected to significantly alter fire regimes, leading to changes in the frequency, intensity, and distribution of wildfires. These changes will have profound impacts on air quality and public health due to increased smoke exposure (Clarke *et al.* 2023; Romanello *et al.* 2023; van Daalen *et al.* 2024). This chapter includes the estimation of wildfire emissions for future climate scenarios and their impact on the air quality (Section 2.1). It also addresses the exposure of human population in the future with regards to poor air quality resulting from wildfires (Section 2.2).

2.1 Future smoke emissions

This section includes the activities performed within FirEURisk regarding the estimation of wildfire emissions for future climate scenarios and their impact on air quality. Here we present results on i) the relative change of monthly carbon emissions from wildfires when comparing the averages from the periods of 2000 to 2030 and 2070 to 2100 and ii) Total yearly CO and NOx emissions from wildfires averaged from the periods of 2000 to 2030 and 2070 to 2100.

The SPITFIRE model runs described in Deliverable 3.4 contains climatic forecasts of total carbon emissions from wildfires for Europe at 9 km resolution. Using the methodology described in the European Environmental Agencies' guidebook (San-Miguel-Ayanz *et al.* 2023) the total carbon emissions are converted to the emissions of different air pollutants such as nitrogen oxides (NOx) and carbon monoxide (CO).

The Tier 2 methodology described in (San-Miguel-Ayanz *et al.* 2023) starts with an estimate of emitted carbon considering the burned area, burnable biomass and burning efficiency. The latter two parameters, which are listed in the guidebook, are biome-specific. In the SPITFIRE fire regime model (Thonicke *et al.* 2010) input-data about the fuel conditions is provided by a Dynamic Vegetation Model (DGVM) thus allowing it to make use of more accurate fuel load and fuel moisture, which are provided to a Rothermel-based fire progression model (Thonicke *et al.* 2010). There, the total biomass burned and burning efficiency is estimated taking also into account the scorching of the canopy. The method employed in SPITFIRE is therefore more detailed than the one present in the Tier 2 methodology for the estimation of emitted carbon. The relative change of carbon emissions, based on SPITFIRE estimations, and comparing the 2000 to 2030 and 2070 to 2100 averages are represented in Figure 2.1. Two Shared Socio-economic Pathways (SSP) scenarios were considered: SSP1-2.6 and SSP3-7.0. The SSP1-2.6 combines SSP1, which is a storyline that envisions a sustainable, equitable world with strong environmental protection, with a Representative Concentration Pathway (RCP) that results in radiative forcing of 2.6 W/m² by the year 2100. On the other hand, the SSP3-7.0 describes a fragmented world with high levels of greenhouse gas emissions due to limited international cooperation and weak climate policies, leading to substantial global warming and severe environmental impacts by the end of the century (O'Neill *et al.* 2016).

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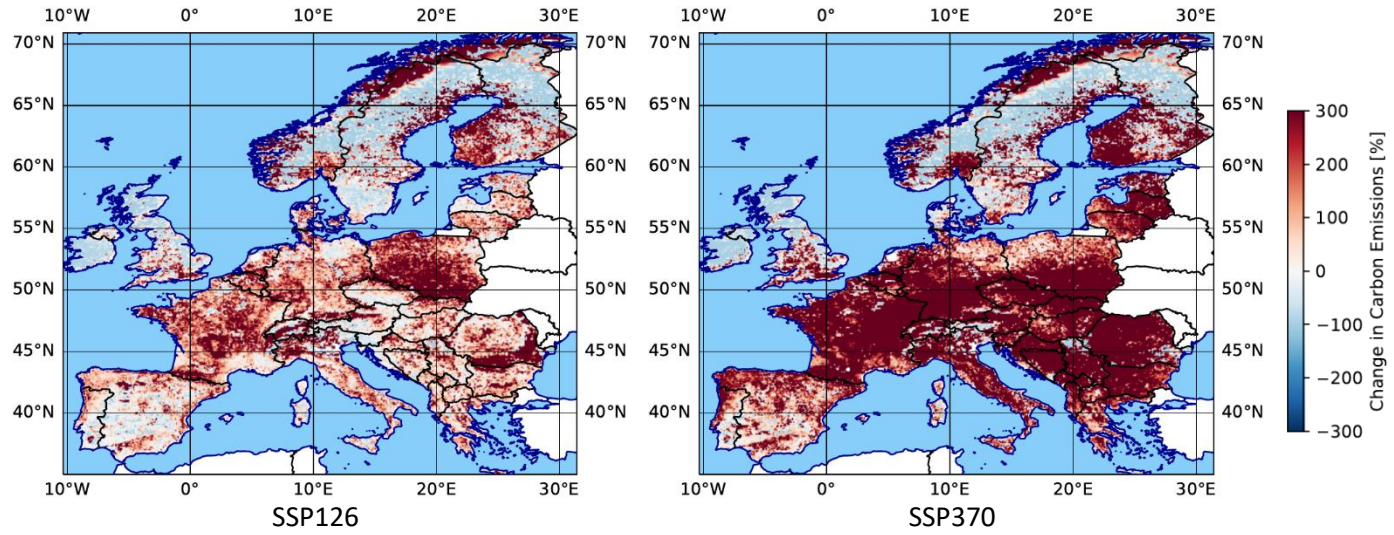


Figure 2.1. Relative change of annual carbon emissions from wildfires when comparing the averages from the periods of 2000 to 2030 and 2070 to 2100. Data derived from SPITFIRE simulations FireC_SSP1-2.6_ACCESS-CM2_SPITFIRE (left) and FireC_SSP3-7.0_ACCESS-CM2_SPITFIRE (right).

The predictions of changes in total vegetation carbon suggest significant changes in almost all regions of Europe, which are more pronounced for the scenario SSP3-7.0. The predicted changes follow roughly the same spatial distribution of the relative changes in burned area that can be seen in Billing *et al.* (2023). Since total carbon emissions are related to available carbon this effect could have had a significant impact on wildfire emissions. However, changes in burned area are considerably more relevant.

The emitted carbon from SPITFIRE (Billing *et al.* 2023) serves as input for the second step of the Tier 2 methodology that consists in the calculation of trace-gas emissions, which are modelled as being proportional to the carbon emissions. The emission ratios provided in San-Miguel-Ayanz *et al.* (2023) according to Andreae (1991) are provided in Table 2.1 and were used for the calculation of emissions by multiplying them with the mass of carbon formed.

Table 2.1 – Emission ratios of trace-gases as fraction of emitted carbon provided by San-Miguel-Ayanz and Steinbrecher (2023)

Species	gX/kgC emitted as CO_2 (best guess)
CO	230
CH_4	15
NMVOC	21
NOx	8
NH_3	1.8
N_2O	0.4
SOx	1.6

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Carbon monoxide is known to be particularly dangerous for the health of firefighters or other persons close to the fire (Reisen *et al.* 2015). In Figure 2.2, maps of the total yearly CO emissions from wildfires averaged from the periods of 2000 to 2030 and 2070 to 2100 are presented, for both climate scenarios.

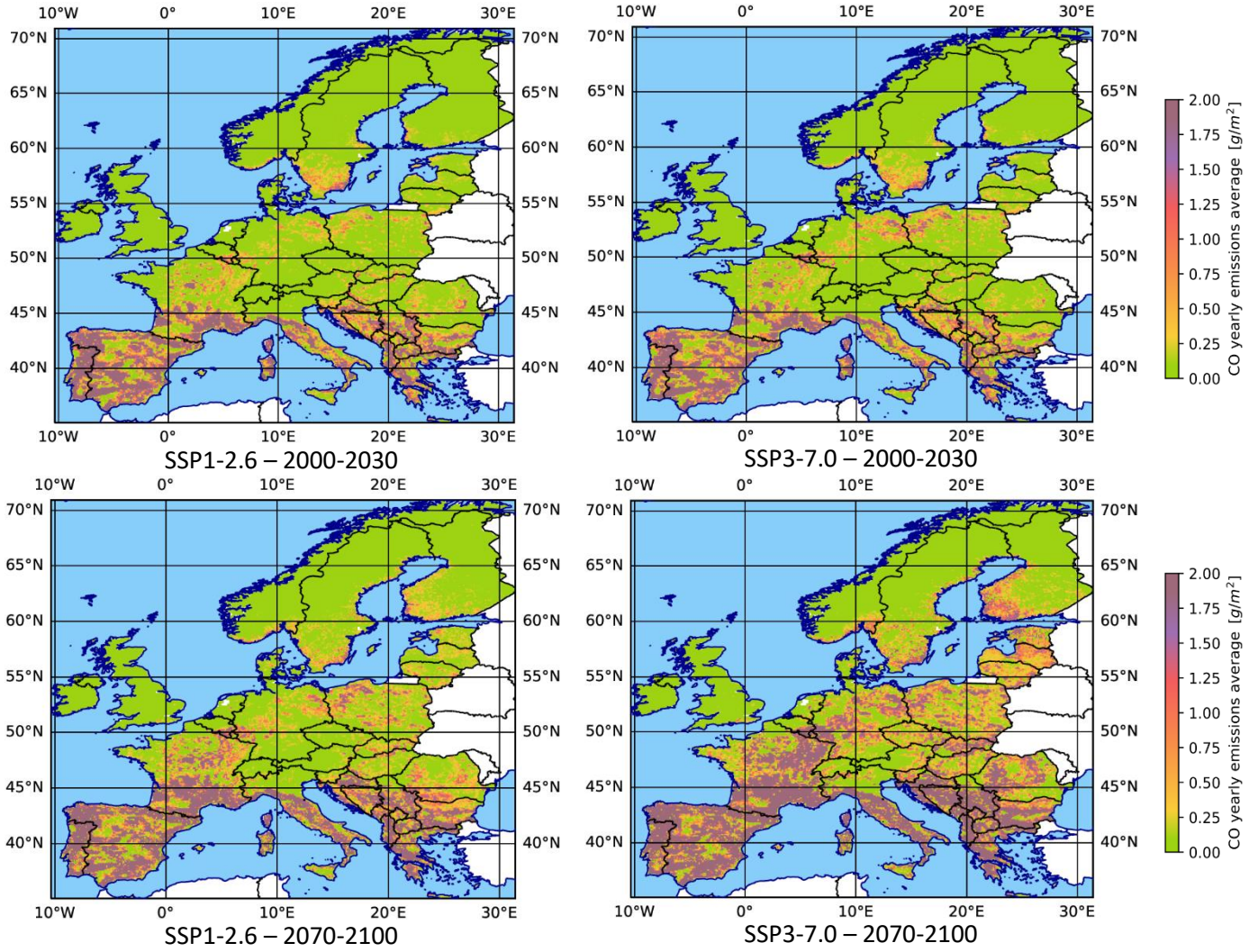


Figure 2.2. Total yearly CO emissions from wildfires averaged from the periods of 2000 to 2030 and 2070 to 2100. Data derived from SPITFIRE simulations FireC_SSP1-2.6_ACCESS-CM2_SPITFIRE (left) and FireC_SSP3-7.0_ACCESS-CM2_SPITFIRE (right).

The increased emissions of CO in some regions in Central Europe are expected to lead to a situation similar to the one of the Mediterranean Regions where wildfire smoke is already a significant problem. For example, on the eastern border with France the potential impacts of wildfire smoke on health are going to reach levels currently only seen on its southern coast. Regions that are already being impacted by smoke will also experience higher levels in the future.

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Other pollutants that are particularly dangerous for health found within wildfire-smoke are NOx which are predicted to follow the same trend seen in CO (see Figure 2.3). Nitrogen oxides, through reaction in the atmosphere with other species, will also lead to an increase of ozone in the atmosphere. Ozone concentrations typically reach dangerous values during wildfire events in cities that are within the path of the smoke cloud (Reisen *et al.* 2015).

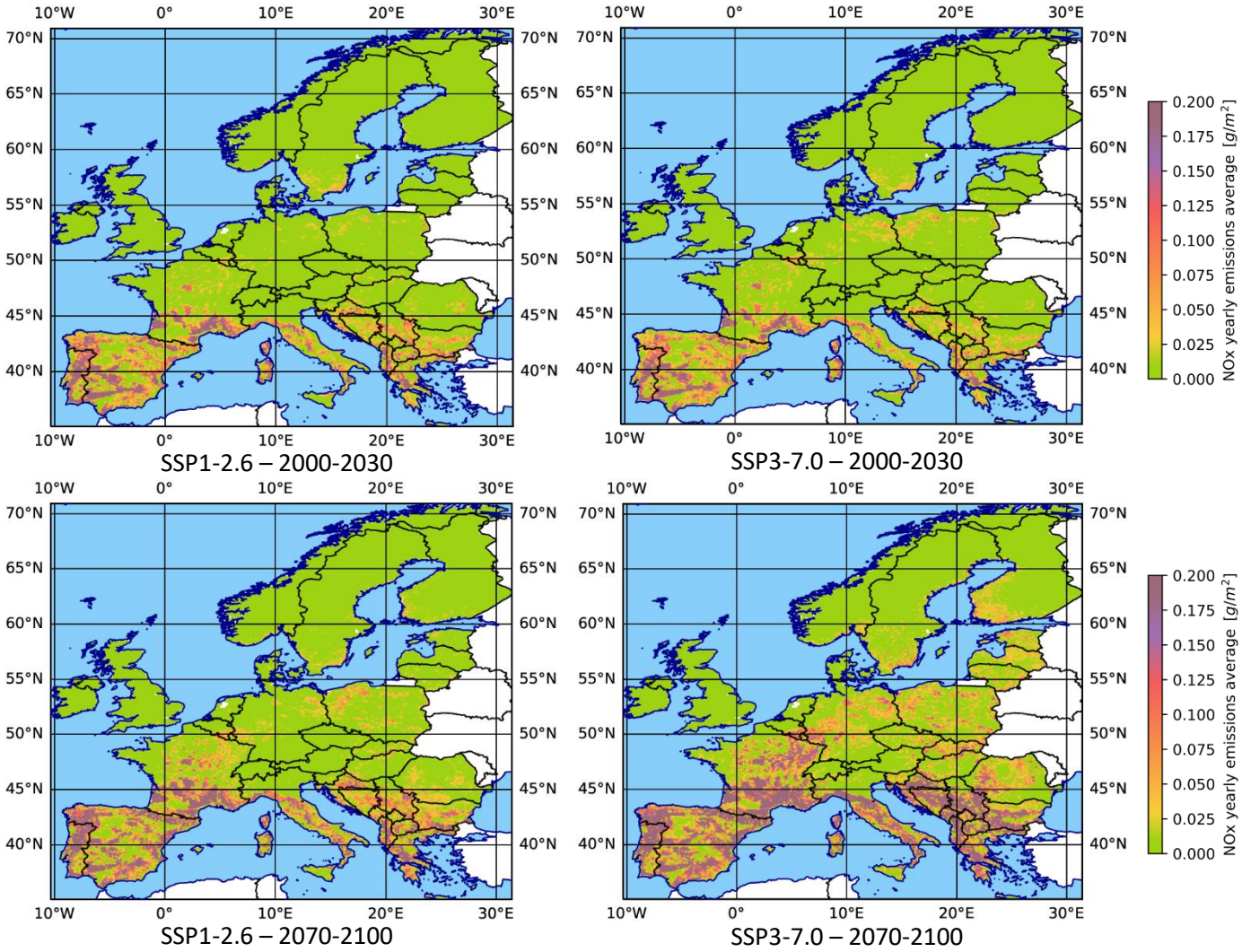


Figure 2.3. Total yearly NOx emissions from wildfires averaged from the periods of 2000 to 2030 and 2070 to 2100. Data derived from SPITFIRE simulations FireC_SSP1-2.6_ACCESS-CM2_SPITFIRE (left) and FireC_SSP3-7.0_ACCESS-CM2_SPITFIRE (right).

Particulate matter has negative effects on human health and the exposure of populations to it during wildfire events is widely studied (Reid *et al.* 2016). Since the trace gas emissions are proportional to the carbon emissions when using the described methodology, the relative changes from climate projections are similar for all species.

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2.2 Future population exposure to smoke

In this section we present the results of activities aiming to assess future population exposure to smoke across Europe under different socio-economic pathways, using advanced meteorological and air quality models. Initial and boundary meteorological conditions were sourced from the CESM2 global climate model (Danabasoglu *et al.* 2020). We used the numerical weather prediction model WRF (Weather Research and Forecasting, v.4.1, (Skamarock *et al.* 2019)) to dynamically downscale global data over Europe under different future scenarios from the CMIP6. The downscaled meteorological data were subsequently employed in the SILAM chemistry and transport model (Sofiev *et al.* 2015), to simulate future air quality levels across Europe.

Three Shared Socio-economic Pathways (SSP) scenarios were utilised: SSP1-2.6, SSP2-4.5 and SSP3-7.0, to address different levels of mitigation and adaptation (Rao *et al.* 2017). The SSP1-2.6 scenario aims to achieve a 2100 radiative forcing level of 2.6 W/m^2, keeping the temperature increase below 2°C compared to the preindustrial levels, which represent high socio-economic challenge to climate change adaptation and mitigation. The SSP2-4.5 describes a "middle of the road" socio-economic family with a 4.5 W/m^2 radiative forcing level by 2100. The SSP3-7.0 scenario is a medium-high reference scenario with the highest CO_2, methane and air pollution precursor emissions among the three scenarios considered here.

The SILAM model domain covers continental Europe within 30-72N, 25W-45E, with a resolution of 0.4 × 0.3 degrees (approximately 30 km). This setup extends up to 106 hPa with 19 vertical layers, using hourly meteorological data. The model accounts for both natural and prescribed anthropogenic emissions. The Fire Forecasting Model (FFM, Sofiev et al, in prep.) predicts wildfire-related emissions and corresponding exposure using a machine learning approach that correlates meteorological, land use, geophysical variables, and various fire danger indices with past fire energy releases. For FFM training and validation, global ERA5 reanalysis (European Reanalysis v.5) and satellite MODIS fire radiative power observations (MOD14/MYD14, collection 6) were utilised.

For all three future SSP scenarios, we focus on the surface-level fire-induced PM2.5 concentrations across Europe, serving as a metric for population exposure to smoke. Results show a clear upward trend in fire-induced PM2.5 levels over time (Figure 2.4). Notably, we observe a correlation between higher anthropogenic emissions and increased smoke exposure.

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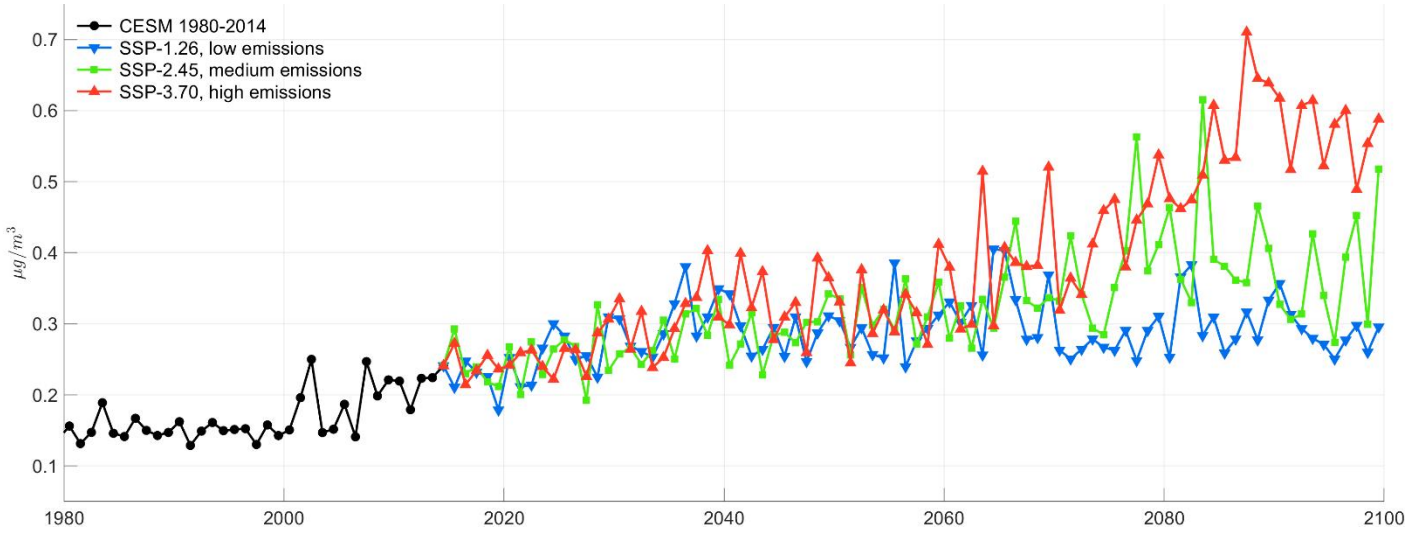


Figure 2.4. Individual fire-induced smoke exposure for historical period and future SSP scenarios.

In Figure 2.5 we present a detailed spatial distribution of these trends. There is no significant decrease in exposure levels observed across any region. While Northern Europe experiences changes, they are not as pronounced compared to other regions. In contrast, Southern Europe is expected to see a substantial increase in smoke exposure across all three future SSP scenarios. Notably, in the Balkans, a significant increase in exposure levels is only predicted under the SSP3-7.0 scenario, while other scenarios indicate exposure levels will remain nearly unchanged.

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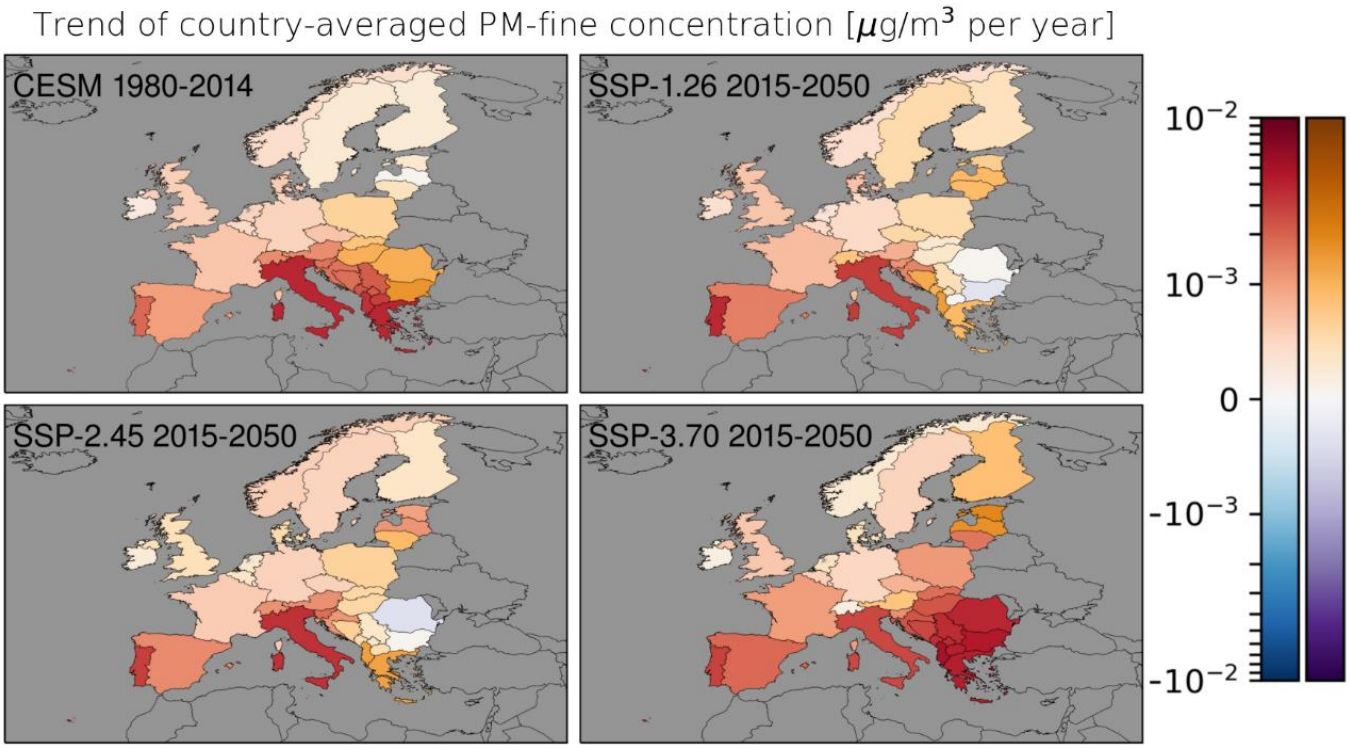


Figure 2.5. Trends of country-averaged individual smoke exposure for historical period and future SSP scenarios. Statistically significant trends (P<0.05) are shown in blue-red colours, while non-significant trends are represented in violet-brown colours.

These results underscore the importance of effective climate mitigation and adaptation strategies. Reducing emissions and enhancing fire management practices could mitigate the harmful health impacts associated with increased smoke exposure. By understanding these potential future scenarios, policy-makers and public health officials can better prepare for and mitigate the impacts of wildfire smoke on European populations. Future research should focus on refining these projections with higher-resolution models and incorporating additional socio-economic factors to better inform policy decisions.

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3 Changes in wildfire risk along the Wildland Urban Interface (WUI)

Analysing changes in fire behaviour between two different landscapes is nowadays relatively common, either to analyse the impact of fire on those same landscapes or on specific elements (Ager *et al.* 2010; Salis *et al.* 2013; Alcasena *et al.* 2015), or to evaluate different management alternatives (Stratton 2004; Arca *et al.* 2007; Finney 2007; Salis *et al.* 2016). For this purpose, spatial fire behaviour simulations are performed, which require a set of detailed data, describing the so-called fire environment (Countryman 1972), i.e., topography, fuels (vegetation) and meteorology.

The present fire behaviour analysis was performed at three different locations, with small variations in the methodology: Central Region of Portugal (PS3), Attica region of Greece (PS5) and in Sardinia, Italy (DA5). The analysis was focused on the changes in fire behaviour at the WUI, namely on its projections for the years to come. The work described in this section relates to the replication of this analysis for future scenarios, namely the Shared Socioeconomic Pathways (SSP) 1 (Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation)) and 3 (Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation))(Riahi *et al.* 2017).

The work presented in this chapter must be interpreted with caution, as it is based on several assumptions and uncertainties that are intrinsic to the used models and projections (see section 8.1 in Appendix).

3.1 Methods

3.1.1 WUI projections

To predict the spatial patterns of the WUI until 2050 in decadal intervals, we developed a modelling approach based on the land use change projections developed in WP3 (Figure 3.1). Our aim was to create binary WUI maps (WUI vs. non-WUI) with a spatial resolution of 10 m. Yet FirEUrisk landcover projections have a 1 km resolution, which required us to develop a two-step approach for WUI change mapping. First, using the official 2020 FirEUrisk WUI map (Bar-Massada *et al.* 2023), we built empirical models of WUI cover (%) at a coarse spatial resolution. We then developed a spatialisation approach, which allocates WUI changes (non-WUI to WUI, i.e., WUI gain; and vice versa for WUI loss) to different cells across the study areas according to the constraints (how much WUI is gained and lost) set by the first step.

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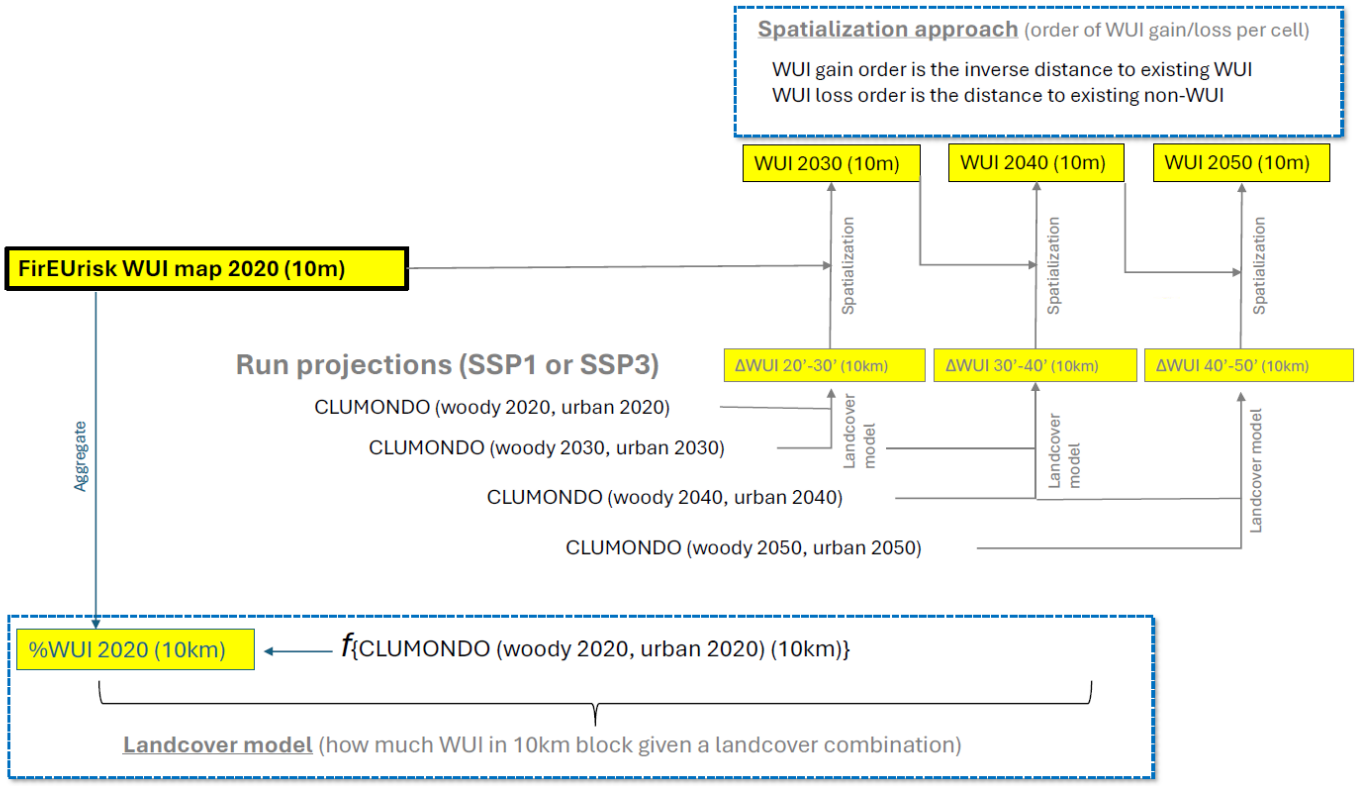


Figure 3.1. The WUI projection scheme. Yellow blocks represent maps, arrows are processes.

To build an empirical model of WUI change per time step (decade), we relied on our previous finding that at coarse scales, the amount of WUI per unit area can be reasonably well predicted by percentage of woody vegetation, the percentage of urban areas, and their statistical interaction (Bar-Massada *et al.* 2023).

We divided our study areas into blocks of 10 km to reduce edge effects, and calculated, in each block, the percentage of WUI in 2020 from the FirEURisk WUI map; and the percentages of woody vegetation and urban areas from the predictions of CLUMONDO, the landuse/landcover model which is used in FirEURisk to simulate landcover changes. Then, we fit Generalised Linear Models with a beta error distribution to predict WUI percentage per 10 km cell as a function of the interactive effect of woody percentage and urban percentage. We re-ran the predictive models for 2030, 2040, and 2050, each time using the corresponding land cover predictions for the independent variables, to generate predictions of WUI percentages per cells under future conditions. Finally, we calculated in each cell the amount of change in WUI percentages in each decadal time step, to yield estimates of the amount of WUI change as the number of 10 m cells that need to be added (in the case of WUI gain) or subtracted (for WUI loss) across time. In the second part of the analysis, we developed a spatialisation approach which allocates changes in 10 m WUI/non-WUI cells within 10 km blocks (as predicted in the previous step) according to a heuristic based on our understanding of historical WUI change processes.

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In general, under the simplifying assumption that no new settlements are built, WUI gains tend to occur at the outskirts of existing settlements when they encroach into surrounding wildland vegetation. A similar mechanism but with an opposite direction occurs when settlements surrounded by agricultural lands undergo land abandonment, which results in the replacement of fields by woody vegetation regrowth, also resulting in new WUI at the settlement's outskirts. The opposite process of WUI loss tends to happen when settlements expand into surrounding wildlands, their cores grow more distant from wildland fuels, resulting in loss of WUI. A different mechanism of WUI loss, based on the conversion of surrounding wildlands to agriculture, is not modelled here for the sake of simplicity.

To quantify the probability of WUI gain or loss, we used the following heuristic: the probability of conversion to WUI for a non-WUI cell is inversely related to its distance to the nearest WUI cell; and the probability of a WUI cell converting to non-WUI is linearly related to its distance to the nearest non-WUI cell. In each timestep starting from 2030, we calculated for all WUI cells the probability of them converting to non-WUI, and for all non-WUI cells the probability of them converting to WUI, and then either added (or removed) WUI cells according to the number of cells predicted to change per 10 km block according to the first step of the analysis. The new WUI map then serves as the basis for the subsequent allocation step under the constraints of the updated WUI change prediction.

The results of these analyses are sets of 10 m resolution WUI maps from 2020 to 2050 in decadal steps, the land-use/climate scenarios SSP1 and SSP3. These maps, in turn, inform the fire simulations (described below) and subsequent risk assessments on the exact locations of the WUI in the two pilot sites and one demonstration area for which these projections have been made.

3.1.2 Fire propagation modelling

Fire behaviour simulations for the future scenarios were made based on the use of the fire mapping and analysis system FlamMap (Finney, 2006). This system describes potential fire behaviour for constant environmental conditions (weather and fuel moisture). Fire behaviour is calculated for each pixel within the calculation domain (the "landscape") independently. This calculation includes different descriptor parameters, such as surface fire spread, flame length or crown fire characteristics. The moisture content of the fuels is adjusted in each pixel according to the terrain conditions (slope, altitude, orientation, shading, and weather). The analysis presented here for the three study cases follows the same methodological approach, but the input data is specific to each of the regions due to the representativeness that different climate models present in each of the regions. Similarly, for the central region of Portugal (PS3) and Attica region of Greece (PS5), fire behaviour simulations were carried out using two different FlamMap modules: FlamMap Basic (Finney 2006), and Minimum Time Travel (Finney 2002; Finney 2006). See Appendix 8.2 for full details on these modules.

For Sardinia (DA5), fire behaviour simulations were performed by using the Minimum Travel Time fire spread algorithm (Finney 2002; Finney 2006) as implemented in its command line version called "FConstMTT" and tested in previous works in Sardinia (Salis *et al.* 2021). A 150 m wildfire ignition probability grid derived from the historical 2003–2022 fire

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database was created, focusing on fires with size larger than or equal to 1 ha. This ignition map, which was held constant for all simulations, was generated with ArcGIS 10.8 (Esri Inc.) using the Point Density method with a 10 km bandwidth: this allowed to produce a continuous ignition probability map for burnable areas. For all simulations, a minimum set of 50,000 wildfire events, randomly sampled from the historical ignition probability map, was considered. We also adopted the annual Burn Probability (aBP) metric rather than BP. The aBP represents the annual likelihood of burning at each specific pixel given a specific modelling domain, landscape characteristics and weather conditions. aBP was expressed in hectares annually burned per km^2 of each given pixel: the higher aBP, the higher the likelihood of a pixel to burn annually. This output allows to quantify the likelihood of a pixel, and therefore of a given forest or land type, as well as WUIs, to burn.

The fire propagation potential for the present days has already been addressed in A1.1.5 of WP1 and reported on Deliverable 1.1, where all details pertaining data collection and processing were described. Overall, projections for the future are based on two Shared Socioeconomic Pathways: SSP1-2.6, which reflects low greenhouse gas emissions with climate adaptation by 2050 ("the green path"), and SSP3-7.0, which reflects a more fuel-based future with local rivalry ("the rocky road"). These are identified as SSP1 and SSP3. Details on orography, meteorological scenarios, fuels mapping scenarios, fuel moisture scenarios are described in appendix, section 8.3.

3.1.3 Scenarios and simulation settings

The combination of input data was specific for each of the regions under analysis. This was mainly due to the different availability of data, in particular to the different representativity of the climate change models for each of the regions.

- For the Central Region of Portugal (PS3), 16 scenarios were considered, resulting from the combination of SSP1 and SSP 3 Land use projections, “upper” climate projections for SSP1 and SSP3 (see section 8.3.2 in Annex), fuel moisture content (FMC) for high (percentile 90) and very high (percentile 95) wildfire danger, and 4 reference years (2020, 2030, 2040, 2050). The scenario naming used in the analysis combines all inputs as follows: SSP**X**_20**XX**_P9**X**. For instance, SSP1_2050_P95 refers to the simulations for SSP1, reference year 2050, and climate variables referring to percentile 95 (Wind and Fine Fuel Moisture Content (FFMC).
- For the Attica Region (PS5), 12 scenarios were considered resulting from the combination of two RCPs (RCP4.5 & RCP 8.5), two land-use/fuel model projections based on SSP1 and SSP3 pathways, FMC for high (percentile 90) and very high (percentile 95) wildfire danger, and 2 climatic periods: historical (1990–2004) and future (2035-2050).
- For Sardinia (DA5), 39 scenarios were considered, resulting from the combination of 4 climatic models (ERA5, ACCESS-CM2, EC-EARTH3, MPI-ESM1-2-HR), 3 SSPs (SSP1-2.6; SSP2-4.5; SSP5-8.5) for future conditions and 2 climatic periods: 1985-2014 for historical conditions and 2035-2064 for the future conditions.It does not seem entirely consistent to mix CMIP5 and CMIP6 data.

The simulations were performed with settings similar to the ones used in A1.1.5 of WP1 (Deliverable 1.1), during the analysis of fire propagation in the present-day. They were defined as follows:

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- Crown fire calculation model from Scott and Reinhardt (2001)
- Resolution: 150m in PS3; 100m in PS5; 150m in Sardinia (DA5)
- Maximum simulation time: 480 min in PS3; 60 and 360 min in PS5; in Sardinia, fire duration was randomly assigned to each simulated fire considering 3 durations (60 min, 180 min, 360 min), in order to partially capture the historical wildfire size duration variability of the study area
- Interval for minimum travel paths: 500m
- Spot probability: 0.02
- Spotting delay: 5 min
- Lateral search depth: 6
- Vertical search depth: 4

3.2 Results

Simulations of the behaviour of a potential fire come closer to reality the more homogeneous and simpler the surrounding conditions are. The variety of physical phenomena that affect fire behaviour makes it very difficult to quantify the individual contribution of each one. Even if the physical models were completely accurate, their application in real fire situations is largely conditioned by the reliability of the input data, namely fuels and meteorology. The first remark to be done in this section is to reinforce that the results are to be seen at the light of all the uncertainties inherent to the input data and the models behind fire propagation assessment (see Section 8.1). For the sake of simplification of the analysis, and ease of reading, not all the results are graphically presented, as the number of scenarios analysed was very large. We opted to present the most significant ones.

3.2.1 Central region of Portugal (PS3)

The scope of the analysis was to assess fire behaviour changes in the WUI, conditioned by the projections of land use and climate change. In that sense, the results are presented clipped to the projections of WUI focusing on the changes between consecutive reference years, i.e., the probable changes in fire behaviour descriptors between 2020 and 2030, 2030 and 2040, 2040 and 2050, and finally between the extremes 2020 and 2050. This was accomplished by calculating the difference between the referred years for each variable and standardizing its value (between -1 and 1) so that negative values represent decrease and positive values increase. For the statistical analysis, the original results were used. The WUI projections for the Central Region of Portugal (PS3) show light changes in the decades to come, including some decreasing in some scenarios. In average about 20% of the entire PS3 area was classified as WUI.
The total area for Pilot Site Central Region of Portugal (PS3) is of 6785 Km^2, and the WUI areas for each of the projected scenarios is shown in Table 3.1.

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Table 3.1. Projected WUI area and the respective percentage from the entire PS3

Socioeconomic Path	Year	Area (km^2)	Percentage from PS3
SSP1	2020	1364.1	20.1
	2030	1369.2	20.2
	2040	1367.7	20.2
	2050	1367.7	20.2
SSP3	2020	1364.1	20.1
	2030	1365.0	20.1
	2040	1370.9	20.2
	2050	1339.5	19.7

If we look at the changes between consecutive decades (Table 3.2) we notice that they are very small, and represent light variations in WUI, that sometimes appears in some parts of the region while disappearing from other parts. The most significant change appears to be on SSP3 between 2040 and 2050, with a 0.5% decrease.

Table 3.2. Projected WUI area changes between reference years and the respective percentage from the entire PS3

Socioeconomic Path	Decade	Change in area (Km^2)	Percentage change in area
SSP1	2020-2030	5.2	0.1
	2030-2040	-1.5	0.0
	2040-2050	-0.1	0.0
	2020-2050	**3.6**	**0.1**
SSP3	2020-2030	0.9	0.0
	2030-2040	6.0	0.1
	2040-2050	-31.5	-0.5
	2020-2050	**-24.6**	**-0.4**

With the Minimum Travel Time (MTT) algorithm we addressed i) the conditional probability of burning for each cell, in the case of a random fire starting in the simulation area and ii) the fire intensity level (FIL) as expressed by the conditional flame length, i.e., the expected length of the flames. For a clearer understanding of the results, and a visual reference, Figure 3.2 presents an example of some of the fire behaviour descriptors analysed.

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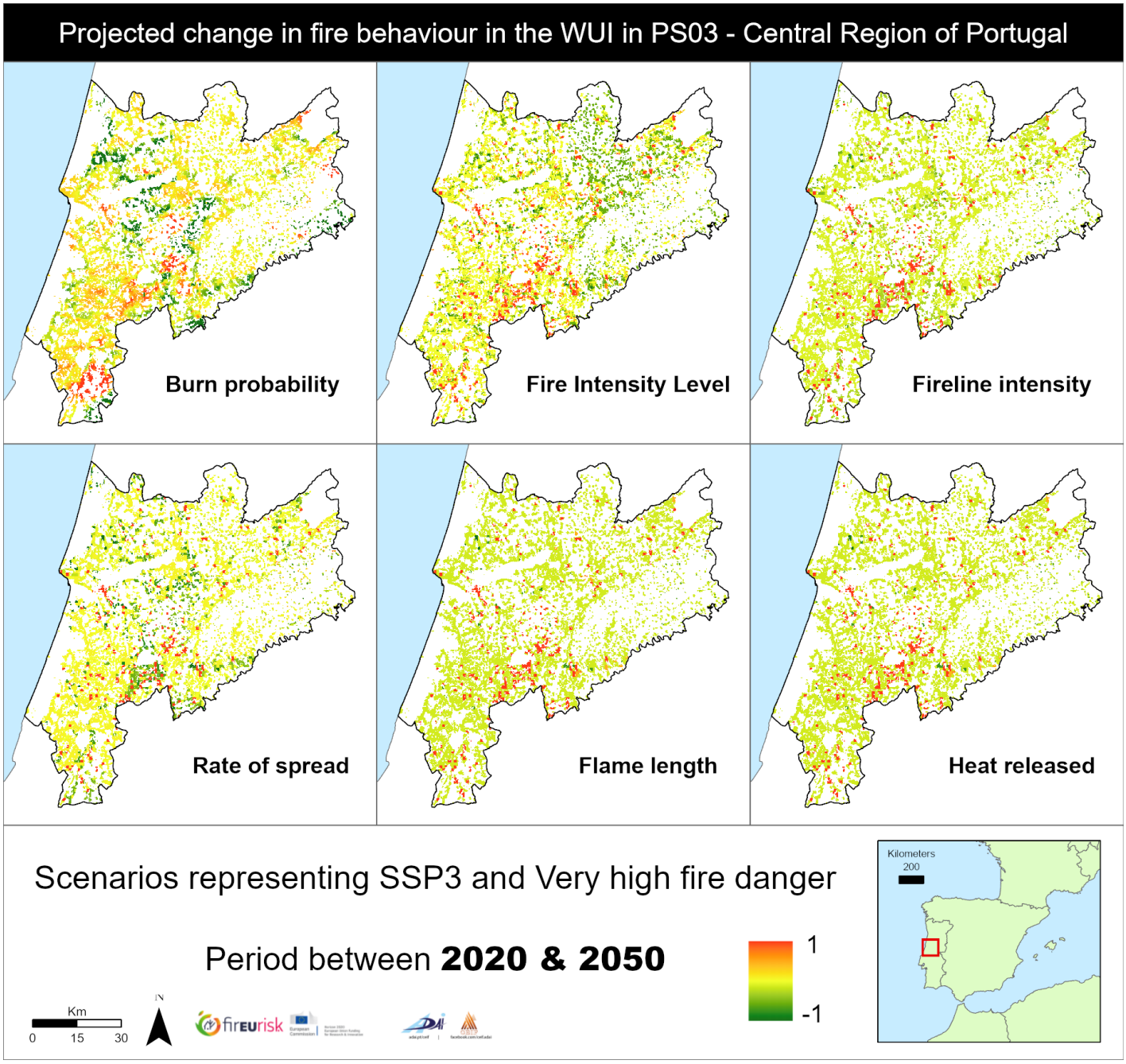


Figure 3.2. Fire behaviour changes between the 2020 and *2050, for SSP3 and very high fire danger, for PS3.*

The results of the burn probability assessment for all 16 scenarios are shown in Table 8.8. These results are unitless and should be seen comparatively with each other. In average, there are no clear tendencies between each consecutive reference year, but in terms of maximum values there is a marked increase in each combination of SSP and fire danger. For instance, for the combination of SSP1 and very high fire danger, burn probability doubles from 2020 to 2030, and

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then has smaller increases from 2030 to 2040 and to 2050. A tendency to increase in the maximum values can be observed in the other scenario combinations. In some cases, a slight decrease is observed, for instance, in the period from 2040 to 2050 for most scenarios. The results from Table 8.8 show values for all the WUI area in PS3, but the distribution of burn probability is not homogeneous throughout the Pilot Site. For example, in Figure 8.9 and Figure 8.10 we can observe how fire behaviour changes are spatially distributed, in very high fire danger SSP1 and SSP3 scenarios respectively. Strong red indicates high increase in burn probability and strong green high decrease, whereas yellows symbolize light to no changes. Focusing on the change between the first (2020) and last (2050) reference years (Table 8.9), we observe an increase in the maximum, mean and top percentiles for both SSP1 scenarios, but a decrease in all except the maximum value when considering SSP3 and very high danger scenarios.

Considering the conditional flame length parameter, the variations are much more subtle than in the burn probability. Table 8.10 (Appendix) presents the results for all scenarios, and Figure 8.11 and Figure 8.12 the respective spatial distribution for SSP1 and SSP3 with very high fire danger. Although the amplitude, or range, of the results is usually around 6 m, the average values when considering all the WUI are in the order of 1.5 m. We can observe a more homogeneous distribution of values but, similarly to the burn probability, the spatial distribution is unequal in the area. In SSP3 we can observe higher values at percentiles 95 and 99, than in SSP1. Looking at the change between the first (2020) and last (2050) reference years (Table 8.11), we observe an overall increase in all descriptive statistics, although with some exceptions, particularly win the SSP1 scenarios.

As described before, conditional flame length can be converted to FIL classes (see Table 8.2). All 6 FIL classes are identified in the WUI areas of the PS, being the average values roughly between 2 and 3 (Table 8.12). This is also emphasized by the majority values and their respective percentages. The upper percentiles correspond to the extreme cases in which, most times, wildfires are included in the more dangerous classes, where the suppression capability is diminished. It is possible to observe the percentage of each of the FIL classes in the respective scenario (Table 8.13). Clearly the prevailing classes are 2 and 3, which according to Table 8.2 correspond to surface fires with an easy to moderate suppression capacity from the firefighters. Nevertheless, there's still considerable percentages in the 4th and 5th classes, especially in SSP3, where values of 10 to 13% are common. These Fire Intensity Classes represent surface fires transitioning to crowns, rising the suppression capacity to "Extremely difficult". We also observe that the change tendency in the FIL is similar to the conditional flame length, which is somehow expected as it depends on this parameter. The FIL increase from 2020 to 2050 is more marked in the SSP1 and very high fire danger scenario (Table 8.14).

The results from the "Basic Fire Behaviour" module are different from the Minimum Travel Time in the sense that the outputs from MTT are produced only for the area within the spreading of each of the simulated fires (from the 100,000 ignitions used), and are affected by the direction of fire movement, accounting for heading, flanking, and backing spread (Finney 2006). Basic fire behaviour assumes independence of fire behaviour among neighbouring cells, producing estimates, at landscape level and for the main direction of spread, of the average values expected, according

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to the scenario established, for the linear intensity of the fire front, the flame length, the heat released, and the rate of fire spread.

The tendency to an average increase in rate of spread is higher in SSP1 scenarios, although not very marked. SSP3 scenarios present higher rates of spread, but with a slight decrease over the decades. Overall, the predicted rate of spread is within the suppression capacity (Table 8.15). The spatial distribution of the changes in rate of spread can be observed in Figure 8.13 and Figure 8.14. The average values shown in the tables can mask marked differences in some areas, as is clear, for instance, in the western half of the maps shown before (Figure 8.13 and Figure 8.14). Focusing on the change between 2020 and 2050 (Table 8.16), we continue to observe an increase in all statistics for both SSP1 scenarios, but a decrease is well noted when considering SSP3 scenarios.

Regarding fireline intensity, the values from percentile 95 in all scenarios except high fire danger for 2020 are above the firefighter's capability of extinction at present time. Considering percentile 99, only the results for 2020, in both fire danger conditions of SSP1, are marginally considered inside the capacity of extinction. In general, this fire descriptor increases over time in all scenarios (Table 8.17) The spatial distribution of the changes in fireline intensity can be observed in Figure 8.15 and Figure 8.16. The changes are not so clear as in the previous parameters. In average, fireline intensity shows a tendency to increase in all scenarios, going from 2020 to 2050 (Table 8.18), although the maximum predicted values show a decrease in the SSP3 scenarios, which is consistent with the previous parameters.

For flame length, all simulation results tend to average wildfires within the suppression capacity, although in the "Extremely difficult" class. Simulations for SSP3 give higher values than the ones for SSP1, but with no clear tendency to consistently increase or decrease between consecutive reference years (Table 8.19). The spatial distribution of the changes in flame length can be observed in Figure 8.17 and Figure 8.18. Changes are particularly visible when considering the period between 2020 and 2050, particularly in the western half of the Pilot Site (PS3). Considering the average values, predicted flame length shows a tendency to increase in all scenarios from 2020 to 2050 (Table 8.20), although, once again, the maximum predicted values show a decrease in the SSP3 scenarios.

The heat released or heat per unit area, expressed in KJ/m^2, is the amount of heat released per unit area during the period of continuous flaming. The simulation results for this parameter show similar results per combination of SSP and fire danger, in all simulations, with a slight tendency for increase with time (Table 8.21). Once again, and in accordance with all other results, the spatial distribution of the changes is not homogeneous across the Pilot Site. In this case, and as can be seen in Figure 8.19 and Figure 8.20, the differences are more marked in some cases than in other. For instance, the period from 2030 to 2040 seems to be where changes are less visible, but in all other cases they are very widespread across the region. The predicted heat release per unit area shows a slightly different tendency from the previous variables, as in many cases, statistics shows no change at all when considering the period between 2020 and 2050 (Table 8.22), particularly in the SSP3 scenarios. Nevertheless, in average and in maximum values, there seems to be a constant increase.

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It is important to note that the assessment made is not related to the entire study areas but rather focused on the WUI. The fact that some descriptors show decreasing values with the passage of time is not an indicator that wildfires will tend to become milder but may be an indicator that when they reach the WUI the impact may be lower, due to eventual changes that may be happening in the land cover of those areas. Nevertheless, the overall assessment shows a tendency to an increase in most scenarios. In the Central region of Portugal (PS3) there seems to be a difference in fire behaviour assessment from SSP1 to SSP3 scenarios, even if not in all descriptors. Some of the descriptive statistics presented show that there's a probability of not having significant changes in fire descriptors in the period from 2020 to 2050, even if they exist in the intermediate decades. In some cases, there is also a decrease, particularly in the maximum simulated values. In SSP1 the increase in the descriptors is generalized, for the same period. In each of the SSPs, the differences between fire danger scenarios (high and very high) show similar tendencies, with the fire behaviour descriptor values increasing as decades pass. In all scenarios' simulations, the general statistics tend to mask spatial changes, that are visible in the produced maps. Also, fire behaviour simulations in the projected scenarios seem to underpredict reality, as, in general, most fire descriptors suggest fires are within the suppression capabilities of firefighting resources, which is only true for a limited number of environmental conditions.

3.2.2 Attica Region (PS5)

The WUI in Attica region (PS5) is a dynamic and complex landscape where urban development meets natural vegetation. This region is characterized by a mix of dense residential areas, agricultural lands, and dense forests, particularly pine forests, which are highly flammable. The WUI areas in the whole of Attica region are constantly changing and are distributed around the densely populated area of the suburbs of Athens, at the foothills of the mountains surrounding the capital's basin and around the coastal settlements (Figure 3.3). The region's hot, dry summers and strong winds create ideal conditions for wildfires, as witnessed in the summer fires of 2024. These weather patterns can lead to rapid fire spread, increasing the vulnerability of WUI areas.

Future changes to the WUI in PS5, up to 2050, involve areas changing from WUI to urban or areas changing from rural or bushland to WUI with the building of new summer or permanent housing. The assessment of risk and future changes in the case of this PS is quite complex and depends on factors related on:

- The conditions within the WUI zone in any given time period (i.e. fire weather, fire behaviour);
- The WUI distribution in relation to the rest of the landscape and vegetation in the broader area of the Attica region which is also affected by significant fires every year. The type and distribution of vegetation in and around WUI zones play a crucial role. Dense, dry vegetation can act as fuel, making fires more intense and harder to control (Mahmoud and Chulahwat 2020);
- The direction of change to and from the WUI environment. The expansion of urban areas into previously rural or bushland regions increases the exposure of homes and infrastructure to wildfires. New developments often occur in areas that are naturally prone to fires, heightening the risk. A significant portion of building losses occurs within close proximity to wildland vegetation. Studies show that 95% of losses happen within 100 metres, and 100% within 850 metres of wildland vegetation (Caggiano *et al.* 2020).

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In order to study the changes in the fire along the WUI in PS5, we followed two steps of analyses:

a) The estimation and study of fire weather changes in the Attica region through the FWI system indices;
b) Fire simulations for the estimation of fire behaviour within and around the WUI areas.

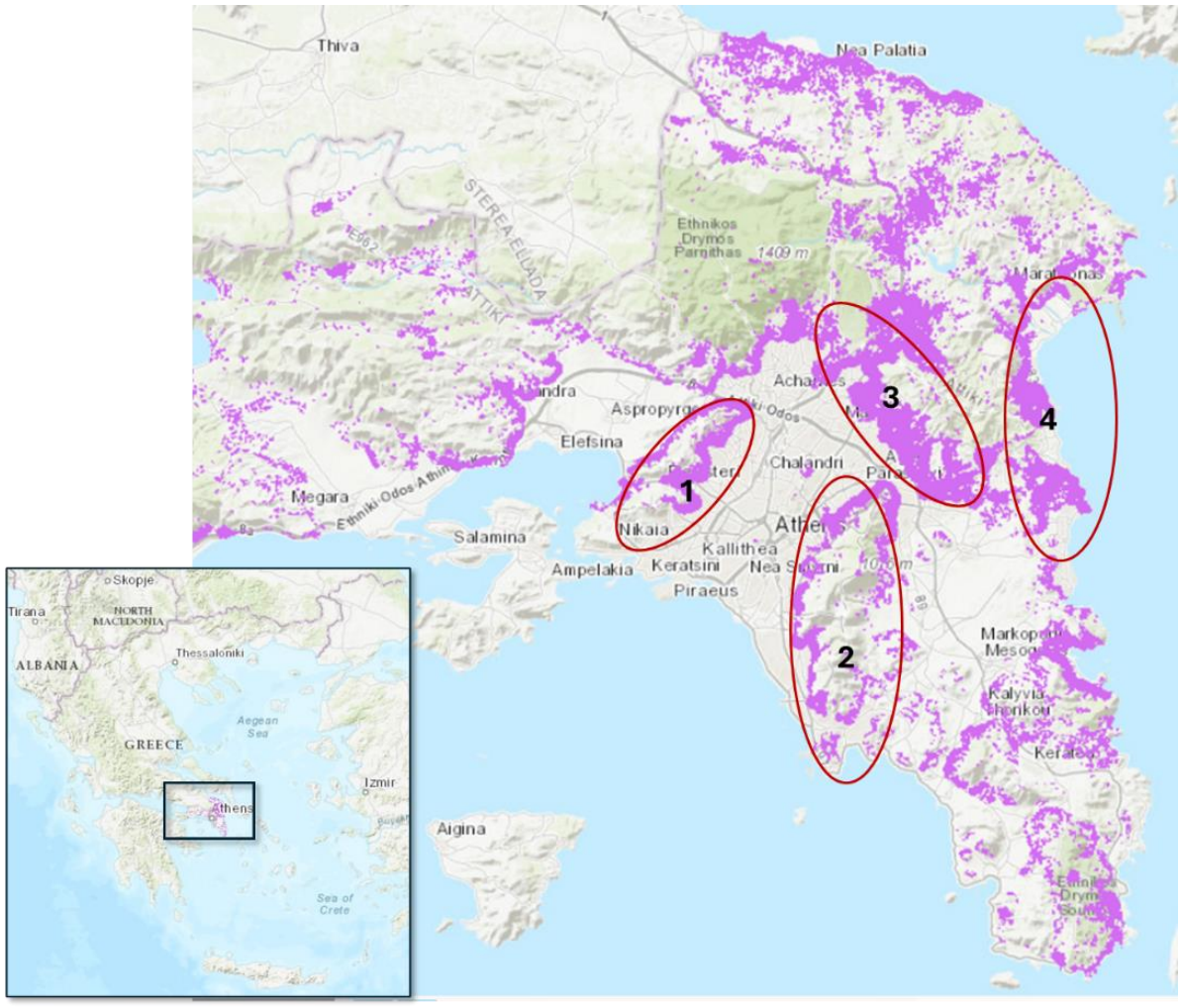


Figure 3.3: WUI areas in PS5 located at the foothills of the mountains surrounding Athens basin (examples 1& 2), around the densely populated area of the suburbs of Athens (example 3), and around the coastal settlements (example 4)

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Here we present the most important results and maps derived from the simulations of the 12 scenarios for the subareas defined as WUI in the historical (2020) and future period (2050) and for the whole area of the Attica region in which these WUI areas are included. For future fire simulations on the PS5, the 90th and 95th percentile values of climate data were generated for both the historical period (1990–2004) and the near future period (2035–2050) under RCP4.5 and RCP8.5 scenarios, specifically for the fire season from June to September. The input data was resampled at 100m, and the fire behaviour assessment was performed at a resolution of 100m as well, with all results being resampled to match the resolution of the more detailed WUI projections (10m), enhancing the analysis change in the propagation potential.

Figures 8.21, 8.22, 8.23, and 8.24 illustrate the Rate of Spread, Fireline Intensity, and Burn Probability for the simulation scenarios under SSP1 and SSP3 for the years 2020 and 2050, considering very high fire weather danger (95th percentile) and RCP8.5. These maps indicate that fire behaviour is quite severe in most WUI and wildland areas in the Attica region. The fire behaviour parameters are projected to increase across all future scenarios. Comparing future and historical values reveals changes ranging from mild to significant. While changes only within the WUI areas appear relatively mild (Figure 8.25-b, 8.26-b, 8.27-b and table 8.23, 8.24 and 8.25), there are adjacent areas where the changes are more pronounced (Figures 8.25-a, 8.26-a, 8.27-a). These significant changes are expected to substantially increase the vulnerability and exposure of the related WUI areas. Table 8.25 presents the maximum, and average burned area from the 60-minute fire simulations for each scenario, for the whole Attica region (PS5). This parameter is important for identifying changes in the size of fires during the first hour of their spread, where the response from firefighting forces is a critical factor in reducing the threat of developing into a significant fire spreading in WUI environments.

In summary, within the WUI areas, the changes appear relatively mild. This suggests that the fire behaviour parameters (such as rate of spread, fireline intensity, and burn probability) do not show drastic increases within these areas. In contrast, many areas adjacent to the WUI show more pronounced changes. This implies that even if the WUI areas themselves do not show dramatic changes, the increased fire behaviour in nearby forested areas could pose a greater threat to these areas as well. The heightened fire activity in adjacent regions lead to a higher risk of fires spreading into the WUI, thereby increasing the overall risk of WUI areas. Maximum and average burned area from the 60-minute fire simulations for each scenario in the Attica region (PS5) appear to be increased by 5-10% until 2050. This suggests a noticeable rise in the extent of areas affected by fire within the first hour of ignition. The increase in the burned area within the first hour implies that fires tent to be larger and they will spread more rapidly in the future, in Attika region affecting more often and more aggressively the WUI areas as well. This increased size and spread rate can overwhelm firefighting efforts, especially in WUI areas where the proximity to urban infrastructure and populations adds complexity to firefighting operations. Understanding this increase is vital for strategic initial attack planning and resource allocation. Prevention planners and firefighting forces need to be prepared for more aggressive initial fire behaviour, which may require enhanced training, better equipment, and more efficient deployment strategies to mitigate the increased risk.

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3.2.3 Sardinia (DA5)

Considering the 2020 data, WUI areas in Sardinia cover approximately 2,680 km^2, which correspond to about 11.2% of the regional territory. The main WUI areas are located in northern Sardinia and in the north-eastern coastal zone. A number of dispersed WUI areas are distributed all over the island, particularly in inner areas. The WUI projections for Sardinia show quite important changes for SSP1, which indicated increases in WUI areas (+155 km^2) from 2020 to 2040, and a significant reduction from 2040 to 2050 (-139 km2) (Table 3.3 and 3.4). On the contrary, projections based on SSP3 evidenced limited variations in WUI areas, with changes below 8 km^2 per decade in most cases. These differences in WUI projections between SSP1 and SSP3 are due to the respective land use input data. In fact, SSP1 scenario depicted a relevant increase in the anthropic areas for the coming decades, while SSP3 was more conservative and evidenced a much lower growth in anthropic areas for Sardinia. In more detail, anthropic areas for the baseline conditions covered about 5.4% of the Sardinia territory (3.2%, according to CLC2018 data). Considering the year 2030, this percentage reached 8.83% for SSP1 and 7.0% for SSP3. For the year 2050, anthropic areas reached 17.2% and 7.3% of the regional territory, for SSP1 and SSP3 respectively. Considering that, in our opinion, SSP1 scenarios were projecting a too strong increase in anthropic areas (close to 300% in 30 years, that means that in the period 2020-2050 about 280,000 ha of lands in Sardinia would be occupied by anthropic areas), we decided to discard this scenario for our spread simulations and WUI impact analysis.

Another interesting point regarding the WUI projections was the analysis of the fuel types at WUIs. The baseline conditions evidenced that about 30% of Sardinian WUI areas present forest fuel types, namely Mediterranean forests (22%) and shrublands (8%). Focusing on 2050, for SSP1 conditions this percentage did not present significant variations, while for SSP3 the incidence of forest fuels in WUI areas raised to about 50%: this increase was mostly due to the higher presence of shrublands (27%), which in broad terms occupied zones previously covered by agricultural mosaics and croplands.

Table 3.3. Projected WUI area in Sardinia, from 2020 to 2050, and respective percentage considering the entire DA5, for both SSP1 and SSP3 scenarios.

Socioeconomic Path	Year	Area (km^2)	Percentage from DA5
SSP1	2020	2680.6	11.2
	2030	2757.1	11.5
	2040	2835.9	11.9
	2050	2697.0	11.3
SSP3	2020	2680.6	11.2
	2030	2661.1	11.1
	2040	2668.4	11.2
	2050	2672.4	11.2

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Table 3.4. Projected WUI area changes in Sardinia, from 2020 to 2050, considering the entire DA5, for both SSP1 and SSP3 scenarios

Socioeconomic Path	Decade	Change in area (Km^2)	Percentage change in area
SSP1	2020-2030	76.5	0.3
	2030-2040	78.8	0.3
	2040-2050	-138.8	-0.6
	2020-2050	16.4	0.1
SSP3	2020-2030	-19.5	-0.1
	2030-2040	7.3	0.0
	2040-2050	4.0	0.0
	2020-2050	-8.2	0.0

The outputs of wildfire spread simulations for Sardinia as a whole are provided in Table 8.26 and Figures 8.28 to 8.32. As previously pointed out, 39 scenarios were simulated using as inputs a set of climate models (ERA5, ACC, ECH, MPI), land uses (CLC2018, BSL2015, LU2050-SSP3) and reference periods (1985-2014 and 2035-2064). The simulations were done at 150 m resolution, for a study area of about 24,000 km^2, and replicated hundred wildfire seasons focusing on wind conditions and fuel moisture related to high wildfire danger days, using as inputs the information coming from the climate data provided by METEOGRID in Deliverable D3.1 - Downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA. The main findings of our simulations can be summarised in the following points:

- Moving from historical climate conditions (1985-2014) to future years conditions (2035-2064), the likelihood of an increase in wildfire hazard and danger conditions is very high. This is observed for all climate models and landscape files. For instance, the average annual number of days with FWI ≥ 38 range from 33 in the historical climate conditions to 86 for future years, considering the SSP5-8.5 scenario. In terms of aBP, our wildfire spread simulations evidenced that the highest values were obtained with the 2035-2064 runs (e.g.: ECH585, with aBP values above 1.6 ha/km^2, which correspond to about 39,000 ha burned per year, that is approximately 2.5 times higher than the current values (15,000 ha burned per year)). The average simulated fire size did not present an increasing trend moving from historical conditions to future years. This could be related to the growth in the number of annual days with high fire danger associated with low wind speed conditions.

- Focusing on climate models, our simulations confirmed the general pattern of increasing wildfire danger and hazard conditions moving from historical to future conditions, and from SSP1-2.6 to SSP5-8.5. The most moderate climate model was MPI, which evidenced the lowest annual number of days with FWI ≥ 38 and the lowest aBP and annual AB for future conditions among the three climate models; moreover, if compared to ERA5 data, MPI was the closest climate model in terms of wildfire danger conditions for historical conditions. According to the most severe MPI scenarios, the annual area burned for future years could be around 21,000 ha, that is about 40% more

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than current annual area burned. The worst wildfire danger and hazard conditions were observed for the ECH climate model, particularly when considering SSP5-8.5 scenarios. In this case, the annual area burned could be very high and close to 39,000 ha. Finally, the ACC model presented intermediate conditions, even if the climate data were able to support the spread of large wildfires, as evidenced by the average fire size, which (with other inputs being equal) was often higher than the ECH outputs.

- The reference land use adopted for setting the landscape file was also associated with interesting variations in wildfire hazard. Generally, the differences between CLC2018 and BSL2015 were overall relatively limited and not significant, with differences in aBP in the most of cases below 0.04 ha/km^2, and with BSL2015 outputs in several cases lower than CLC2018 outputs. On the contrary, LU2050-SSP3 simulations presented much lower aBP and annual area burned values than the other two land uses; moreover, they evidenced slightly higher wildfire intensity metrics than BSL2015 and CLC2018. This could be related to the predicted future increase of forest land uses (about +15% combining the areas covered by shrubs and forests), which are on average characterised by low spread rates and high fire intensity, and the increase of managed permanent croplands (about +5-6%); in addition, the presence of herbaceous lands, which in the fire season are generally dry and can sustain the propagation of large fires, dropped by about 25% in future land uses

Focusing on Sardinia WUI areas, the outputs of wildfire spread simulations are provided in Table 8.27 and in Figure 8.33. Considering that the WUI projections were based on the BSL2015 data for both SSP1 and SSP3 scenarios, in this analysis we did not take into account the simulation outputs obtained with CLC2018 as landscape file. Moreover, as previously pointed out, we discarded the SSP1 land use and WUI projection scenarios as, in our opinion and as previously reported, were too pessimistic in terms of anthropic areas growth from 2020 to 2050. Therefore, we intersected wildfire spread simulation outputs for Sardinia with WUI areas, considering the following conditions: for 2020, we used the historical climate models and BSL2015 land uses (4 simulations); for 2050, we used the LU2050 landscape file and future climate models with 3 SSPS scenarios (9 simulations). The main results can be summarised in the following points:

A) Moving from baseline to future WUIs and climate scenarios, the likelihood of an increase in wildfire hazard and exposure at the Sardinian WUI level is high. This was observed for all climate models. For instance, the average aBP at WUIs increased from about 0.40 ha/km2 for ERA5 (0.38 for ACC; 0.39 for MPI) to values above 0.60 ha/km2 for the most severe scenarios of both ACC and ECH. A similar consideration is valid for the average annual area burned at WUIs, which ranged from a minimum value of 1035 ha for MPI for the historical conditions to 2027 ha for ECH585. Taking into account the average CFL, that is the average flame length for Sardinian WUI, in several cases we observed an increase in fire intensity levels moving from historical to future scenarios. A remarkable increase in the likelihood of crown fire occurrence at WUIs in future years was also observed: for instance, the annual hectares affected by crown fires would increase from about 20 ha (ECH, ACC, ERA5) to a peak of 90 ha (ECH585); values above 50 ha were presented for future years by both ECH and ACC. The only indicator that did not present any relevant variation or trend for future years was the ratio between the area burned at WUI and the total area burned, which ranged from 6.70% to 7.80%.

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B) Focusing on climate models, our simulations confirmed the main findings highlighted at the landscape scale level. The most moderate impacts at WUIs were observed with MPI, which showed the lowest aBP, annual AB, CFL and crown fire occurrence for future conditions; however, if compared to ERA5 data and historical conditions, MPI simulations were not so close as far as the fire intensity outputs are concerned (Avg CFL, annual crown fire occurrence). According to the most severe MPI scenario (SSP245), the annual area burned at WUIs for future years could be around 1200 ha, that is relatively close to the values observed with ERA5 (1061 ha) or MPI (1035 ha) for historical conditions. The worst wildfire hazard and exposure conditions at WUIs were observed for the ECH climate model, particularly when considering SSP5-8.5 scenarios. According to this specific condition, the annual area burned could be slightly higher than 2,000 ha, with an increase in the range 80-100% with respect to ERA5 and the ACC and MPI climate models for historical conditions. In this sense, the potential impacts for Sardinian villages and activities would be very significant, with an inherent increased risk of loss of human lives. This climate model also presented the highest annual crown fire occurrence likelihood at WUIs for future decades. The ACC model presented in broad terms intermediate results with respect to ECH and MPI, with the only exception for the average CFL outputs (which were generally higher than the other models, particularly for future conditions).

3.3 Concluding remarks

The purpose of the study for the 2 PS (central region of Portugal and Attica region) and Sardinia DA was to understand and predict the potential future behaviour of wildfires in WUI, where human development meets natural vegetation. These areas are particularly vulnerable to wildfires due to the proximity of homes and infrastructure to potential fire sources. Understanding fire behaviour in WUI areas helps in identifying potential risks and developing strategies to mitigate the impacts on human lives, properties, and natural resources which will be addressed in Deliverable 3.7 - Identification of effective adaptation measures and Deliverable 3.8 - Adaption options to future fire preparedness planning at three spatial scales.

The analysis for the central region of Portugal (PS3) focuses on the WUI areas within the study area and reveals a complex pattern of wildfire behaviour changes over time. While some descriptors show decreasing values, this does not necessarily indicate a reduction in wildfire severity. Instead, it suggests that changes in land cover might be influencing fire behaviour when wildfires reach the WUI. The study highlights a general trend toward increased fire behaviour in most scenarios, particularly under more aggressive climate pathways like SSP3 compared to SSP1. There is, however, a noted possibility of minimal changes in some fire descriptors between 2020 and 2050, with a tendency for spatial changes to be obscured by general statistics. Fire behaviour simulations also suggest that wildfires could be underestimated in projected scenarios, indicating that real-world fire conditions may exceed firefighting capabilities under certain environmental conditions. In the Attica region (PS5), the analysis indicates that within WUI areas, changes in fire behaviour are relatively mild. However, areas adjacent to the WUI show more pronounced increases in fire activity. This suggests that while the WUI itself may not experience drastic changes, the increased fire behaviour in

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nearby forested areas could pose a significant threat to regions and landscapes characterized by intense WUI environment. The simulations show a 5-10% increase in both the maximum and average burned areas from 60-minute fire scenarios up to 2050, indicating that fires are likely to be larger and spread more rapidly. This increased aggressiveness could overwhelm firefighting efforts, especially in WUI areas where the proximity to urban infrastructure adds complexity to fire suppression. This highlights the need for improved strategic planning and resource allocation to prepare for more intense initial fire behaviour. The Sardinia study area analysis shows a high likelihood of increased wildfire hazard and danger conditions moving from historical climate conditions (1985-2014) to future conditions (2035-2064). All climate models used in the study indicate a significant rise in fire weather index (FWI) days and annual burned area, particularly under the most severe SSP5-8.5 scenarios. The worst wildfire danger is observed with the ECH climate model, where the annual burned area could reach up to 39,000 hectares, a substantial increase from current levels. The study also highlights how different land use scenarios impact wildfire behaviour, with future projections showing an increase in forested areas that could reduce spread rates but increase fire intensity due to more fuel availability.

Overall, across all pilot sites, there is a clear indication that wildfire danger and behaviour are expected to increase under future climate scenarios, although the extent and nature of these changes vary by region and scenario. The findings emphasize the need for region-specific strategies that consider both climatic and land use factors to effectively manage and mitigate wildfire risks. Enhanced understanding and preparedness for more aggressive fire behaviour, particularly in WUI areas, are essential to protect both human lives and properties in the face of evolving wildfire threats. To address the increasing wildfire danger and more aggressive fire behaviour in and around WUI areas, under future climate scenarios, several fire management actions are recommended. These include developing region-specific strategies tailored to unique climatic conditions and vegetation types, and establishing adaptive management frameworks that are regularly updated based on the latest climate projections. Enhancing protection in WUI and adjacent areas through fuel management and building infrastructure hardening is also crucial. Improving fire detection and monitoring systems with advanced technologies and community-based efforts can enable faster response times. Strengthening firefighting capabilities with better training, equipment, and resource allocation is essential. Promoting integrated land management practices and increasing community engagement and education about wildfire risks and prevention measures are also key. Finally, investing in research and development to understand fire behaviour and develop innovative technologies will help improve fire management strategies. These proposals aim to enhance the ability to protect lives, property, and natural resources from wildfires. By addressing these recommendations, regions can better prepare for and mitigate the increasing wildfire risks posed by climate change and evolving land use patterns.

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4 Vulnerability of ecosystem service provision

Climate and land-use change affect ecosystem function and thus the provision of ecosystem services. Outputs from DGVMs can be used to assess the impact the combined effects of climate and land-use change have on the provision of carbon-, water- and habitat-related ecosystem services. Carbon-related ecosystem services include carbon storage and carbon sequestration. Carbon storage or Carbon sequestration refers to the balance between processes that lead to the uptake of carbon and processes that lead to the loss of carbon. The net balance quantifies if the ecosystem is losing or gaining carbon. Most existing estimations of carbon sequestration only consider carbon-uptake processes which is incomplete description of the carbon balance at the ecosystem-level. Carbon uptake processes refer to photosynthesis resulting in net primary productivity and carbon loss processes refer to heterotrophic decomposition of dead plant material, fire, crop harvest (on managed land only) and heterotrophic respiration.

Outputs from DGVMs integrate the reaction of the vegetation, the carbon and water cycles to changes in land cover, climate (e.g., to heat and drought stress, dry season length), meaning changes in tree cover can result from changes in land-use that reduces natural vegetation area, or climate-induced heat and/or drought stress which affect the productivity of the trees. Where land used for agriculture and/or managed pastures, or simply urban areas reduced natural vegetation areas, the storage of cycling of carbon and water also affected. Land cleared for agriculture, for example, also affects carbon sequestration due to increased carbon loss because of increased decomposition of soil carbon. Temperature increase additionally contributes to carbon release due to increase soil decomposition, which can also be a reason why carbon sequestration can change, changing an ecosystem from being a carbon sink (positive Net Ecosystem Production (NEP)) to a carbon source (negative NEP). Fire regimes affect the amount of dead and live fuel available, i.e. the amount of carbon that can be stored in vegetation (live fuel), litter (dead fuel) and thus soil, where litter is turned to humus via decomposition which then enters the long-term carbon storage in the top-soil layer. Changes in fire regimes alter carbon sequestration and storage as well as habitat, where the recovery from fire influences vegetation cover and composition. This bi-directional feedback impacts the interaction fire has with vegetation composition and productivity.

4.1 Methods

We analysed the simulation results of the LPJmLv5.6-SPITFIRE application to future climate and land-use changes which was used to quantify changes in future fire regimes (Deliverable 3.4) before to now analyse the impacts those changes in climate, land-use and fire might have on ecosystem service provision. We quantified carbon sequestration, expressed as net ecosystem production (NEP), under the low-warming scenario SSP1-2.6 (socio-economic changes follow the IPCC storyline SSP1 in combination with the low warming resulting from radiative concentration pathway RCP2.6, which would mean that the global climate target of the Paris Climate Accord is met) and SSP3-7.0 (combines IPCC SSP3 socio-economic pathway and climate trajectory RCP7.0, which means regional rivalry keep greenhouse gas emissions rising and thus climate warming to a 3 to 4°C warmer world).

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4.2 Results

Climate and land-use change as well as changes in future burned area affect carbon sequestration differently at the European scale (ET scale) with increases in carbon sequestration projected for Scandinavia, many mountain regions, but also some lowland regions, e.g. in central Europe (Figure 4.1, central and right figure). Carbon sequestration is projected to decrease further in highly managed regions that are dominated by agriculture already today (Figure 4.1, right figure) and in the future (Figure 4.1, central and right figure), especially in western Europe and on the British Isles. The future socio-economic and climate pathway determines how strong carbon sequestration could increase in the Balkans by the end of the century, and how much the provision of this ecosystem service might get reduced on the Iberian Peninsula.

Increases in carbon sequestration (positive NEP values, blue colour) can result from enhanced vegetation productivity as a result from increases in tree cover due to improved growing conditions or due to expansion of naturally vegetated area (resulting from land abandonment). Decreases in carbon sequestration (negative NEP, red colour) can result from climate-induced decreases in vegetation productivity, enhanced decomposition of dead organic material stored as litter and/or soil carbon or increased burned area and related fire-related carbon emissions.

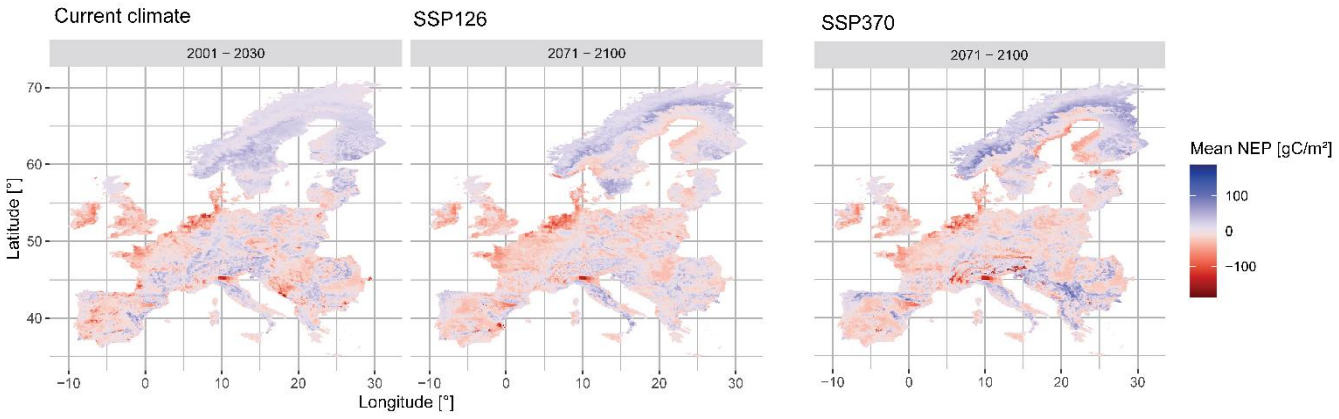


Figure 4.1 Carbon sequestration, expressed as mean net ecosystem production (NEP) in gram Carbon per m² (gC/m²), simulated by LPJmLv5.6-SPITFIRE under climate and land-use change scenarios following the modelling protocol described in D3.4. The left map shows current-climate carbon sequestration (averaged over 2001-2030), the central and right maps carbon sequestration under future conditions averaged over 2070-2100 under SSP1-2.6 (central) and under SSP3-7.0 (right) climate and land-use conditions.

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Climate change is projected to warm the high northern latitudes (Deliverable 3.1) with the effect that tree cover is projected to increase in Scandinavia under both climate change scenarios (Figure 3 in Deliverable 3.4). This can explain why carbon sequestration increases under both scenario groups, even though natural vegetated land is lost to other land uses in northern Scandinavia, and area burned increases throughout.

Climate warming increases the decomposition of carbon stored in litter and soil, and thus the carbon emissions to the atmosphere, with the effect that carbon sequestration decreases under both climate scenarios. Tree cover is projected to increase locally by up to 40% (Figure 3 in Deliverable 3.4) as well at the expense of grass cover, which results in higher amounts of carbon stored in aboveground vegetation (Figure 5 in Deliverable 3.4), but the area remains dominated by land used for intense agriculture and pastures, where biomass is harvested, i.e. carbon is removed from the system contributing to the continued decline in carbon sequestration. Burned area is expected to increase as well but remains at the current low level for the region, also in the future.

The combination of changes in land cover determining the area where natural vegetation can grow and where fire can burn, potentially changing tree vs. grass cover, vegetation productivity and biomass affects regions in Europe (ET simulation domain). The net effect on carbon sequestration might be regionally very different for a different combination of contributing factors. For example, land is projected to be abandoned in the Carpathian Mountain ranges or in the Balkans (Deliverable 3.2) and tree cover increases (Figure 3, Deliverable 3.4) accordingly, which means that the increase in area burnt under the SSP1-2.6 scenario (Figure 1, Deliverable 3.4) contributes to the decrease in carbon sequestration. Under the SSP3-7.0 scenario land cover change is only minor, but climate warming is increasing with the effect that burned area is increasing and therefore carbon sequestration is decreasing, affecting an even larger area (Figure 4.1, right map). A similar combination of contributing factors might explain the future loss of carbon sequestration on the Iberian Peninsula. Here, land abandonment is projected to occur in the southern part of the peninsula, allowing fire to increase because of more natural land being available again for burning, but because there is little change in vegetation biomass, changes in carbon sequestration are minor. In other parts of the peninsula, loss in vegetation biomass in combination with increasing area burnt, carbon sequestration changes. One exception is the Central region of Portugal, where slight increases in future carbon sequestration can be found which might be explained by only moderate increases in area burnt. The largest impact of fire is projected in the mountain areas of the Alps, where climate warming increases fire risk and increased vegetation, i.e. tree growth, at the same time. Here carbon sequestration is reduced under SSP370. More moderate climate warming would allow carbon sequestration to increase in this region.

4.3 Concluding remarks

Climate change is affecting the functioning of ecosystems in Europe, even under the low-intense SSP1-2.6 scenario burnt area will increase, vegetation composition will change and intensively used agricultural areas will continue to lose carbon via harvest and heterotrophic respiration. The increase in tree cover is often associated with a simultaneous reduction in herbaceous cover and an increase in carbon sequestration, as observed in Scandinavia. Where land is

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projected to be abandoned, e.g. in the whole Carpathian Mountains and southern Spain, natural vegetation regrows and with it burned area increases due to climate warming. Burned area is increasing in the Southern Europe, incl. in the Balkans, with large increases under the ”4°C warmer world” SSP370 scenario. We expect the vulnerability of the affected ecosystems to increase where carbon sequestration decreases during the 21st century. Fire-related carbon emissions are increasing in Southern Europe, here the vulnerability of the affected ecosystem is expected to increase due the projected changes in fire regimes. Even though the fire regimes are not affecting the functioning of temperate and boreal ecosystems to the point of endangering them, it is expected that the vulnerability might increase due to the projected increase in future area burnt.

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5 Ecological vulnerability

5.1 Impact of intensified fire regimes on plant abundance, diversity, and fitness

Plant species and communities are adapted to historical fire regimes (Keeley *et al.* 2011), and an intensification of these fire regimes (i.e., the increase in frequency or severity of fires) can substantially alter plant vulnerability (Karavani *et al.* 2018; Keeley and Pausas 2019; Whitman *et al.* 2019; Nolan *et al.* 2021). The frequency and severity of fires are two of the most important components of fire regimes affecting plant populations and communities. Surpassing optimal values of fire frequency may prevent plants from replenish their seed banks either in the canopy or in the soil (limiting post-fire recruitment) or their carbon and nutrient reserves (limiting post-fire resprouting), thereby increasing plant vulnerability (Hoffmann *et al.* 2012; Enright *et al.* 2015). Increased severity can also affect plant vulnerability by damaging plant organs important for persisting fire such as basal and epicormic buds, secondary meristems, seeds, and the hydraulic system (Schimmel and Granström 1996; Pausas and Paula 2020). Consequently, increased fire frequency and severity have been observed to alter vulnerability of species in several habitats, including grasslands (Collins and Calabrese 2012; Gomes *et al.* 2018), broadleaf forests (Fairman *et al.* 2016; Etchells *et al.* 2020), conifer forests (Schimmel and Granström 1996; Talluto and Suding 2008; DeSiervo *et al.* 2015; Turner *et al.* 2019), woodlands (Cavender-Bares and Reich 2012), and shrublands (Talluto and Suding 2008; Foster *et al.* 2018).

Here, we summarise plant responses to intensified fire regimes across different climates, habitats, and fire regimes globally and focusing specifically on the European Territory. For this, we conducted a systematic review and meta-analysis assessing the impact of intensified fire regimes on plant abundance, diversity, and fitness. Specifically, we analysed the following points:

1. **Effects of intensified fire regimes on overall plant abundance, diversity, or fitness.** Rationale: many plants may be unable to recover from fire regimes that fall outside their historical range (Enright *et al.* 2015; Johnstone *et al.* 2016; Keeley and Pausas 2019).
2. **Differential effects of increased fire severity and increased fire frequency in different habitats**. Rationale: potential step-changes in fire regime can be particularly important in forest ecosystems and overwhelm plant responses (Keeley and Pausas 2019; Fernández-García *et al.* 2020).
3. **Effects of fire severity at short- and long-term**. Rationale: impacts potentially diminishing over time may be especially evident for woody vegetation due to their slower growth rates (Keeley *et al.* 2005; Willms *et al.* 2017).
4. **Intensified wildfire regimes have greater effects on plants in wildfire studies compared to prescribed fire studies.** Rationale: fire severity and extent are expected to greater in wildfires (Alba *et al.* 2015; Allen *et al.* 2016).
5. **Differential effects of intensified fire regimes in Forests vs open-canopy ecosystems (e.g., grasslands, shrublands)**. Rationale: open-canopy ecosystems are historically more fire-prone (Dantas *et al.* 2016; Karavani *et al.* 2018; Pausas and Bond 2020) and are expected to be more resilient.
6. **Differential effects of intensified fire regimes in ecosystems from arid and cold climates vs temperate and tropical climates.** Rationale: plant recovery rates in arid and cold climates are more resource-limited (Fernández-García *et al.* 2020; Giorgis *et al.* 2021; Pellegrini *et al.* 2021).

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The full methodology and results are available in the 2024 publication by Grau-Andrés et al., "Global plant responses to intensified fire regimes" (Grau-Andrés *et al.* 2024).

5.1.1 Methods

This study was performed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (O'Dea *et al.* 2021; Page *et al.* 2021). We searched peer-reviewed articles and book chapters through the Scopus and Web of Science databases, utilising keyword combinations related to fire regimes and vegetation responses in the title, abstract, and keywords. Additionally, we also considered the articles listed in the references of the seven most cited publications among our selected studies, as well as in three recent relevant reviews (Foo *et al.* 2021). Titles and abstracts were screened using the revtools package (Westgate, 2019), using R software version 4.2.3 (R Core Team 2021). A total of 394 publications (46 within the European Territory) met the selection criteria for inclusion in the analysis:

- The study assessed vegetation responses to variations in fire severity and/or fire frequency (i.e., studies on fire extent, seasonality, or simple burnt vs. unburnt comparisons were not included).
- Vegetation responses could be classified as positive or negative (i.e., no-quantitative changes were not included).
- Fire regime effects were not confounded with other factors such as seasonality, ecosystem type, or management interventions.
- The study had an ecological relevance and close-to-real setting and was based on wildfires or prescribed fires in any season (i.e., small-scale experimental fires with artificial settings were not included).
- The study was based on original data (i.e., reviews and simulation studies were not included)
- The study was based on current fire regimes (i.e., paleo- and dendro-ecological studies were not included).
- The study provided information to calculate an effect size based on Hedges' d (i.e., mean, standard deviation, and number of observations of paired treatment groups) or to estimate d (using correlation coefficients or F-tests and number of observations) (Borenstein 2009; Lajeunesse 2013).

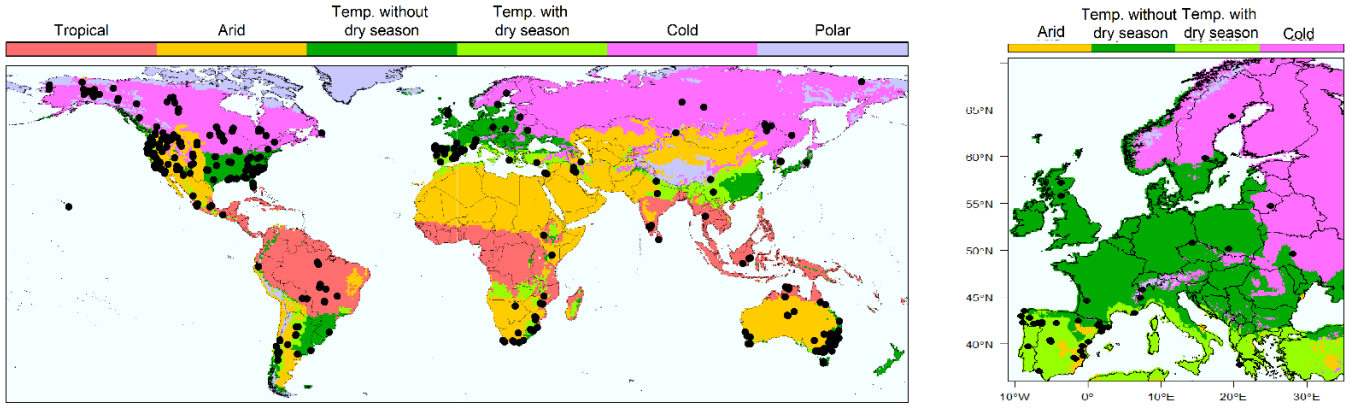


Figure 5.1. Locations of studies (circles) included in the meta-analyses at global scale (left) and for the ET (right). Climate zones follow the Köppen-Geiger classification system (Peel et al. 2007).

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Results across studies were standardised using Hedges' d, a bias-corrected effect size based on the standardised mean difference between "control" and "treatment" groups (Rosenberg *et al.* 2013). We extracted the mean, standard deviation, and number of observations of vegetation response metrics for lower ('control') and higher ('treatment') fire frequency or severity from figures, tables, and text. Effect size standardised responses of plants under intensified fire regimes relative to those under less intense fire regimes. Therefore, a positive effect size indicates a positive response to an intensified fire regime (i.e., increase abundance, diversity or fitness), while a negative effect size indicates a negative response. If for a same study more than two fire regime levels (e.g., low, moderate, and high) were available, we only considered the lowest and highest levels. It is possible that, for some studies, what was considered as an "intensified fire" regime, is within the historical variability. Nevertheless, by considering both frequency and severity, we explored the intensification of fire regimes in many environments, aligning with global change projections (Abatzoglou *et al.* 2019; Pausas and Keeley 2021; Jones *et al.* 2022; Senande-Rivera *et al.* 2022).

We categorised plant responses to intensified fire regimes into three main categories:

- **Abundance:** Includes metrics such as plant frequency, density, cover, size, biomass, and recovery.
- **Diversity:** Includes taxonomic and functional richness, Shannon-Wiener and inverse Simpson diversity indices, Pielou's evenness, and beta diversity.
- **Fitness:** Includes components such as survival, growth rate, photosynthetic and other fluxes, reproductive output, and nutrient content.

For each effect size, we compiled information on variables potentially affecting vegetation responses to altered fire regimes (i.e., moderator variables). The variables considered were:

- **Fire Type:** Wildfire and prescribed fires.
- **Time Since the Last Fire:** Short (24 months or less) and long (more than 24 months).
- **Fire Regime Component:** Fire severity and fire frequency.
- **Historical Fire Regime Type:** Surface fires, crown fires, and non-fire prone.
- **Plant Life Form:** Bryophytes, herbs, and woody vegetation.
- **Habitat Type:** Broadleaf forest, conifer forest, mixed forest, grassland, shrubland, and woodland.
- **Climate:** Arid, cold, temperate with a dry season, temperate without a dry season, and tropical.

The classification of the historical fire regime was based on the dominant fire regime type for each ecosystem, with mixed-severity fire regimes considered as crown fire regime. Climate types were defined according to the Köppen-Geiger classification system (Peel *et al.* 2007). A 24-month cut-off was defined for short versus long time since fire because the higher vegetation dynamics during the first two years after fire (Velle *et al.* 2014; Grau-Andrés *et al.* 2017; Giorgis *et al.* 2021). Time since fire was only considered for studying fire severity to avoid confounding effects with fire frequency.

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Statistical analyses were performed using multivariate mixed-effects linear models, implemented through the rma.mv function in the metafor package (Viechtbauer 2010). Separate models were fitted for each of the three response variables: abundance, diversity, and fitness. For each response variable, we first fitted a global model using Hedges' d and its variance without including moderator variables, to test the overall effect of intensified fire regimes on vegetation vulnerability. We then fitted models that included one moderator (i.e., fire regime component, fire type, time since the last fire, historical fire regime type, plant life form, habitat, or climate) to examine how different moderator variables affected plant responses.

5.1.2 Results

At a global scale, results show that intensified fire regimes significantly reduce plant abundance, diversity, and fitness (Figure 5.2). Most moderator variables had a significant effect on vegetation response. Particularly:

- **Fire regime component**: Both fire severity and frequency reduced plant abundance, while only fire severity reduced plant diversity and fitness.
- **Fire type:** Intensified fire regimes significantly decreased plant abundance, diversity, and fitness in wildfire studies but not in studies on prescribed fires.
- **Time Since Fire:** Increased fire severity reduced plant abundance in the short term (i.e., ≤2 years post-fire) and reduced plant diversity and fitness in both the long and short term.
- **Historical Fire Regime Type** In surface-fire regimes, intensified fire regimes reduced plant abundance and diversity, while in crown-fire regimes, they reduced plant abundance and fitness.
- **Plant Life Form:** Regarding plant life forms, intensified fire regimes significantly reduced the abundance and fitness of woody plants had no effect on herbs but had a positive effect on the abundance of bryophytes.
- **Habitat Type:** Significant negative effects of intensified fire regimes on plant abundance, diversity, and fitness were generally most evident in conifer and mixed forests.
- **Climate:** Intensified fire regimes impaired plants most strongly in cold climates, temperate climates with a dry season, and tropical climates, with diversity being less affected than abundance and fitness.

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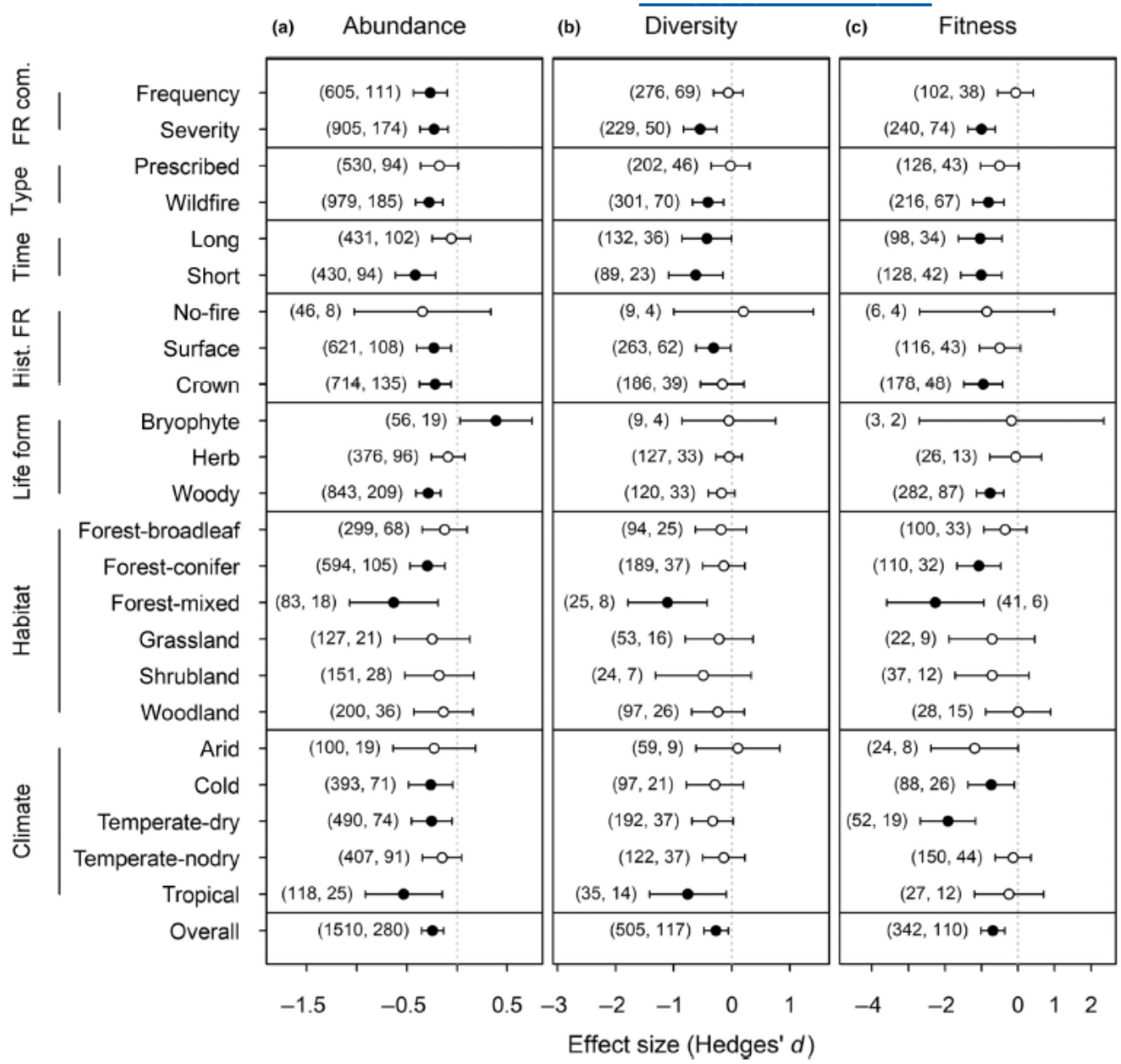


Figure 5.2. Response of plant abundance (a), diversity (b) and fitness (c) to intensified fire regimes across moderator categories and overall. Circles are effect size estimates and whiskers are 95% confidence intervals. Open circles indicate that estimates are not statistically significantly different from zero at α = 0.05, while filled symbols indicate significant differences. In parentheses, number of effects sizes, followed by number of studies. 'FR com.' refers to fire regime component; 'Type' refers to fire type; 'Time' refers to time since the last fire; and 'Hist. FR' refers to type of historical fire regime. Time since fire was only examined in fire severity studies (not for fire frequency). Analysis at Global scale (Grau-Andrés et al. 2024).

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For the analysis performed for the European Territory, intensified fire regimes significantly reduce plant fitness while results for abundance and diversity were not significant (Figure 5.3). Few moderator variables had a significant effect on vegetation response. Particularly:

- **Fire regime component**: When analyzing the two fire regime components separately (fire severity and frequency), neither of them was statistically significant for any of the vegetation responses considered (abundance, diversity and fitness).
- **Fire type:** The effect of fire type (wildfires vs prescribed fires) was also not statistically significant for any of the vegetation responses considered (abundance, diversity and fitness).
- **Time Since Fire:** Intensified fire regimes reduced plant fitness in the short term (i.e., ≤2 years post-fire), while there were no significant effects of time since fire for abundance and diversity.
- **Historical Fire Regime Type:** The effect of historical fire regime type (surface fires vs crown fires) was also not statistically significant for any of the vegetation responses considered (abundance, diversity and fitness). For the ET there was no study performed within the historical fire regime type "non-fire prone".
- **Plant Life Form:** Regarding plant life forms, intensified fire regimes significantly increased the abundance of bryophytes but had no effect on herbs or woody species.
- **Habitat Type:** Significant negative effects of intensified fire regimes on plant fitness were generally most evident in conifer and mixed forests. Plant abundance was reduced in grasslands and diversity was negatively affected in shrublands (note that the latest results are based on one single study each). For the ET there was no study performed in the habitat type "broadleaf forest".
- **Climate:** There was no significant effect of climate type ("Arid", "Cold", "Temperate dry", "Temperate no dry") on plant responses to intensified fire regimes. For the ET there was no study performed in the climate type "Tropical".

For the ET, the limited and highly variable data precluded a confident assessment of the effects of intensified fire regimes. The uneven distribution of fire effect studies, with a high concentration in Mediterranean regions, also highlights underrepresented environments (particularly non-fire prone ecosystems). Despite efforts to compile as many studies as possible, our results are limited by the available research. Nevertheless, results show that intensified fire regimes significantly reduce plant fitness particularly in conifer and mixed forests and in the short term (i.e., ≤2 years post-fire, Figure 5.3)). Additionally, data obtained at global scale (see below), where more studies have been performed, can be a helpful instrument to understand future impacts of intensified fire regimes in the European Territory.

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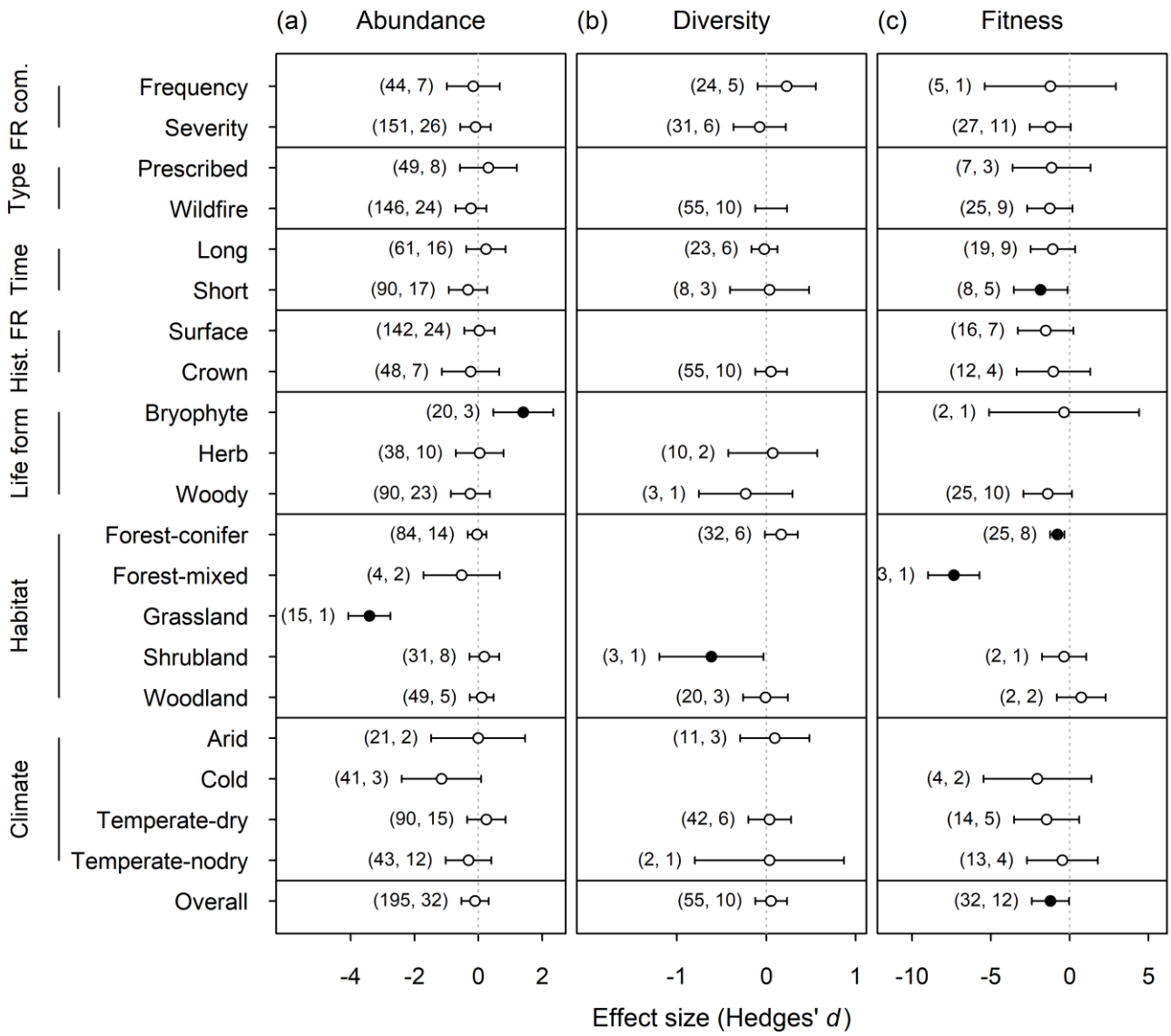


Figure 5.3. Response of plant abundance (a), diversity (b) and fitness (c) to intensified fire regimes across moderator categories and overall. Circles are effect size estimates and whiskers are 95% confidence intervals. Open circles indicate that estimates are not statistically significantly different from zero at α = 0.05, while filled symbols indicate significant differences. In parentheses, number of effects sizes, followed by number of studies. 'FR com.' refers to fire regime component; 'Type' refers to fire type; 'Time' refers to time since the last fire; and 'Hist. FR' refers to type of historical fire regime. Time since fire was only examined in fire severity studies (not for fire frequency). Analysis for the European Territory.

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At a global scale (Figure 5.2), there is evidence that increasing the frequency or severity of fires to historical extremes (intensified fire regimes) has an overall negative impact on plant abundance, diversity, and fitness. Plant abundance was reduced by both increased fire severity and frequency, while plant diversity and fitness were unaffected by increased fire frequency. Increased fire intensity negative effects may result from the heat surpassing the bark's capacity to protect the cambium and transport tissues, or when vegetative regenerative structures or seeds are damaged, affecting resprouting and recruitment abilities. Increased fire frequency can also hinder post-fire resprouting and recruitment by exhausting bud reserves and preventing the accumulation of soil or canopy seed banks, leading to abrupt post-fire vegetation changes.

Although fire is a natural process in many ecosystems, our findings indicate that the intensification of fire regimes has negative ecological consequences. The limited effect of increased fire frequency on diversity and fitness could result from negative responses being balanced by positive ones. For example, increased fire frequency often impairs dominant species' abundance, preventing competitive exclusion of other species, which could contribute to the observed neutral effect on diversity. Similarly, while increased fire frequency can negatively affect plant function, it can also enhance growth rates or reproductive output by rejuvenating plant communities or improving soil nutrient availability, leading to a neutral effect on fitness.

Intensified fire regimes reduced plant abundance at early post-fire stages, but the effect diminished over time (after two years post-fire). Our finding that plant abundance, diversity, and fitness were most strongly affected by intensified fire regimes in conifer and mixed forests suggests that forests are particularly sensitive to changes in fire regime. This is consistent with plants in less fire-prone ecosystems, such as forests, having fewer fire-adaptive traits and thus being more sensitive to fire than those in shrublands and grasslands.

Plant abundance and fitness were reduced by intensified fire regimes in cold climates and temperate climates with a dry season, partially supporting that ecosystems in drier and colder climates are particularly sensitive to fire effects. Moisture limitation, which can hinder post-fire plant recovery, may contribute to this pattern. Additionally, in drier climates, compound disturbances (i.e., fire followed by drought) further impair plant recovery, contributing to the observed greater fire effect compared to other climates. In cold climates, where fires are historically uncommon and plant recovery is limited by low temperatures, plants may be particularly sensitive to intensified fire regimes. Nutrient limitations prevalent across much of the boreal region could also hinder post-fire recovery.

Overall, our results highlight substantial negative effects of intensified fire regimes on plant abundance and fitness in ecosystems of dry and cold climates, and on plant diversity in tropical forests. Finally, this analysis has focused exclusively on vegetation vulnerability to intensified fire regimes. However, effects of intensified fire regimes can be extended to the fauna and soils for which the intensification of the different components of fire regimes (e.g., intensity, frequency, seasonality and extension) can have an important impact on the vulnerability.

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5.1.3 Concluding remarks

This study provides a solid scientific basis for decision-making in ecosystem conservation policies and fire management. The results of this study are important for predicting how the changes in fire regimes we are currently experiencing will affect plant communities. This can be crucial for developing management strategies and conservation policies that adapt to the more intense fire scenarios that are becoming common due to global change. Considering that it is impossible to manage the entire landscape all the time, a key point is to understand which ecosystems may be more susceptible and establish priorities for action. It's also important to recognise that some ecosystems may be quite resilient, where the best conservation strategy might be to not intervene. For instance, Mediterranean-type shrublands are largely dominated by crown fire regimes that have historically burned in high-intensity fires, and these ecosystems are notably resilient to such conditions. However, an increase in the frequency of disturbances can lead to a decrease in diversity. For instance, some communities (e.g. *Pinus sylvestris* forests) are resilient to low-intensity fires, being capable of surviving recurring surface fires but susceptible to high severity fires that can occur due to fuel accumulation as a result of fire exclusion and an appropriate management strategy in these cases may involve the use of prescribed burns to maintain the suitable regime of recurrent low-intensity fires.

5.2 Mapping ecological vulnerability to wildfires under future scenarios

Mapping ecological vulnerability to wildfires in future scenarios is becoming increasingly important, especially in Europe, where climate change, land-use changes, and socio-economic factors are contributing to the frequency and intensity of wildfires with important ecological consequences (see section 5.1 above). As these fires become more severe, understanding which areas are most at risk—and why—becomes critical for effective prevention, mitigation, and adaptation strategies.

Ecological vulnerability refers to the susceptibility of ecosystems to damage or degradation due to external stresses, such as wildfires. Mapping this vulnerability involves assessing various factors that influence an ecosystem's ability to withstand and recover from fire. This includes the type of vegetation, soil composition, topography, climate conditions, and human activities. Understanding these factors allows for the identification of areas that are particularly prone to severe impacts from wildfires. Europe's diverse ecosystems—from Mediterranean shrublands to boreal forests—face varying degrees of wildfire risk.

Climate projections indicate that many regions, especially southern Europe, are likely to experience hotter, drier conditions, which will exacerbate fire risks. At the same time, changing land-use patterns, such as urban expansion into forested areas and the abandonment of traditional agricultural practices, further alter the landscape's vulnerability to fire. Future scenarios for Europe can be modelled using climate projections, land-use change forecasts, and socio-economic developments. These scenarios provide a framework for predicting how the conditions that influence wildfire risk might change over time. To effectively map ecological vulnerability under these scenarios, the methodology must be both systematic and operational, meaning it can be applied consistently across different regions and timeframes. Key components of this methodology might include:

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- Data Integration: Combining data from multiple sources, such as satellite imagery, climate models, and land-use maps, to create a comprehensive view of current and future conditions.
- Risk Assessment Models: Using statistical and computational models to assess the probability and potential impact of wildfires under different scenarios. These models can incorporate variables such as vegetation type, fire history, and projected climate conditions.
- Scenario Analysis: Evaluating how different future scenarios affect ecological vulnerability. This might involve comparing a baseline scenario (current conditions) with various future projections (e.g., moderate versus extreme climate change scenarios).
- Spatial Analysis: Employing Geographic Information Systems (GIS) to visualize and analyse the spatial distribution of vulnerability. This allows for the identification of hotspots where intervention might be most needed.
- Stakeholder Involvement: Engaging with local communities, policymakers, and scientists to ensure that the methodology is grounded in practical realities and can be used to inform decision-making.

In summary, developing a systematic methodology to map ecological vulnerability to wildfires under future scenarios in Europe is an essential step towards mitigating the impact of these increasingly frequent and severe events. By integrating data, modelling risks, and engaging stakeholders, this approach provides a valuable tool for policymakers and land managers. The ultimate goal is to ensure that Europe's diverse ecosystems are protected and resilient in the face of a changing climate and evolving landscape.

5.2.1 Proposed methodology

The integration model for assessing ecological vulnerability to wildfires, developed in the FirEUrisk project under WP1, is outlined in Figure 5.4 (Arrogante-Funes *et al.* 2024). This model estimates potential ecological losses from wildfires by calculating Ecological Potential Losses (EPL), which reflect the loss of pre-fire ecological values. These losses are moderated by the system's Ecological Resilience (ER), defined by its ability to resist damage (Coping Capacity, CC) and recover (Recovery Time, RT) after a fire. Total EPL is calculated directly from the impact of the fire on the pre-fire ecological values (Ecological Value Assessment, EVA), reduced by the system's CC. When pre-fire values are diminished due to fire, EPL also considers the time required for recovery (RT). This methodology provides a dynamic and systematic approach to evaluating how fire affects ecological vulnerability. The process starts with an initial assessment of the baseline ecological value. When a wildfire occurs, this value decreases, representing the ecological losses in the affected area. However, the remaining viability of the ecosystem depends on its coping capacity, which determines how much of the ecological value is retained. Afterwards, the recovery phase begins, where factors such as climate, topography, and forest management influence the restoration of pre-fire values, aiming to reduce the long-term ecological impact. This model will be adapted for future use with available databases, focusing on integrating data sources that are less likely to change, such as topographic and geological information. The goal is to create a replicable framework that can be applied across different scenarios and regions to assess and mitigate ecological vulnerability to wildfires effectively.

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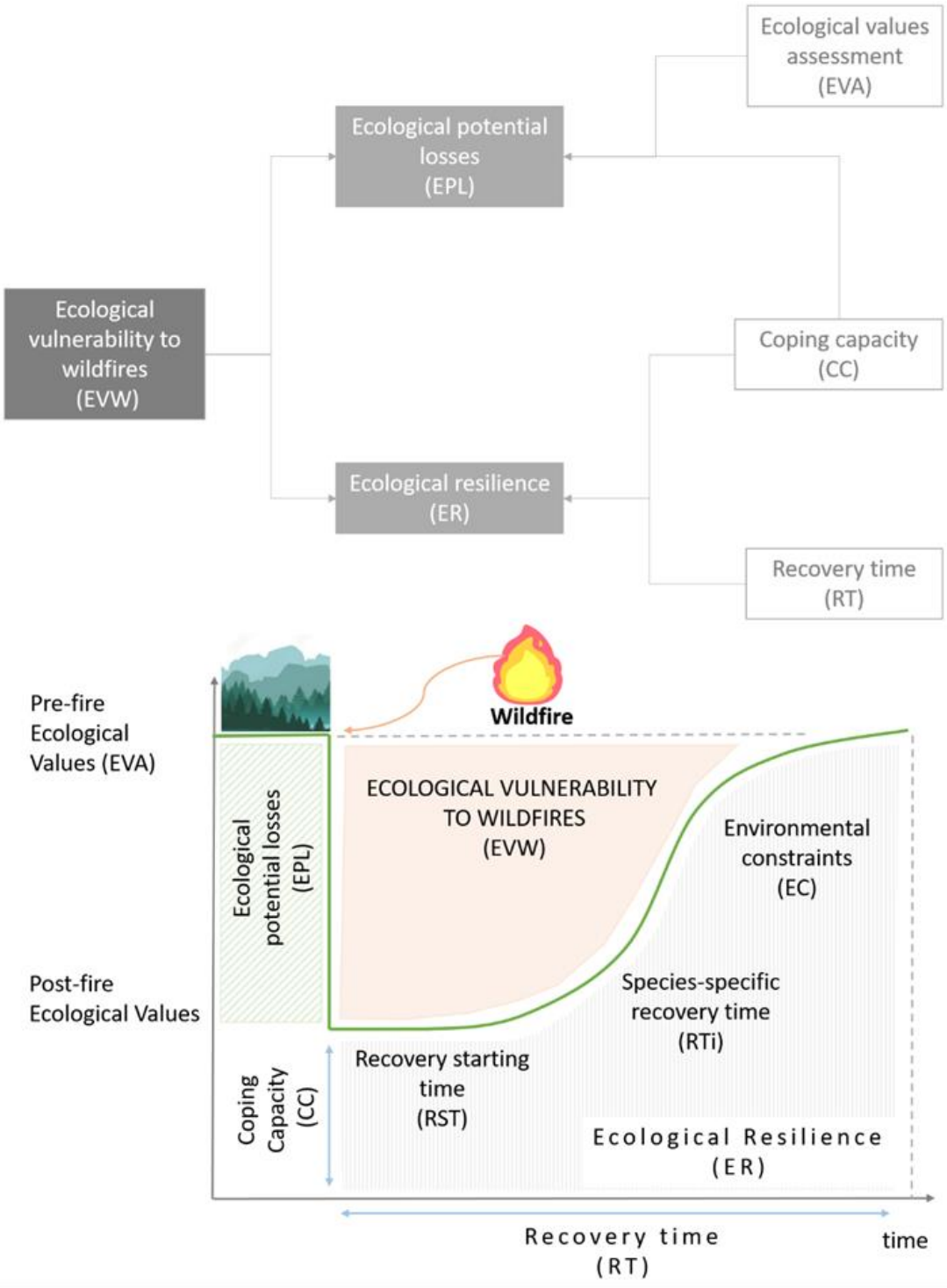


Figure 5.4. Components of the ecological vulnerability to wildfires and integration approach.

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5.2.2 Ecological values assessment

When assessing ecological vulnerability to wildfires, it's crucial to evaluate ecological values, such as biodiversity and ecosystem health, as these factors determine an ecosystem's ability to withstand and recover from fires. However, projecting these values into the future is challenging due to the lack of comprehensive databases, making detailed assessments difficult. A practical approach is to use the EU-Trees4F dataset, which provides current and future distribution data for 67 tree species across Europe (Mauri *et al.* 2022). Developed by the Joint Research Centre (JRC) and the University of Helsinki, this dataset maps areas where specific tree species can grow both now and under future climate scenarios. The projections cover different periods up to 2110 and are based on two scenarios: a moderate climate change scenario (RCP 4.5) and a more extreme scenario (RCP 8.5). By utilizing this data, researchers can estimate future ecological values based on tree species distributions under these two scenarios. To further refine this assessment, a pixel-level summation of tree species within each area can be performed. This involves counting the number of different species present in each pixel on the map. Regions with higher species counts would likely correspond to areas with greater biodiversity and ecological significance, indicating higher ecological values. In the absence of databases on the future distribution of other species, such as animals, this approach using EU-Trees4F simplifies the estimation of ecological values by focusing solely on tree species. While this method significantly simplifies the complexity of ecological assessments, it represents the best available option for now. Although it doesn't capture the full range of biodiversity, it provides a valuable starting point for identifying and prioritizing areas critical for conservation and wildfire management under the two climate scenarios provided by EU-Trees4F.

5.2.3 Estimating Ecological Resilience to Wildfires

Estimating an ecosystem's resilience to wildfires involves evaluating its coping capacity and recovery time. These metrics provide insight into how well an ecosystem can withstand fire impacts and how quickly it can return to its pre-fire state. The methodology for estimating these factors integrates fire scenario simulations to understand and mitigate ecological vulnerability better (Williams and Kapustka 2000; UNISDR 2009).

5.2.3.1 Fire Scenario Simulations

Fire scenario simulations are crucial for understanding how various conditions—such as vegetation type, fauna, and soil—respond to fires. These simulations help identify vulnerabilities and develop effective fire management strategies (Williams and Kapustka 2000; UNISDR 2009). They provide insights into ecosystem responses and adaptations, helping to pinpoint weaknesses in environmental resistance. In assessing ecological vulnerability to wildfires, incorporating fire scenario simulations is crucial for understanding and managing fire impacts on ecosystems. The Fire Impact Index (FII) developed in the FirEUrisk project plays a key role in this assessment (see Deliverable 3.5). It quantifies the relationship between fire-induced carbon emissions and both aboveground and belowground biomass, providing insights into how fire affects vegetation and soil.

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5.2.3.2 Fire Impact Index (FII)

The FII, calculated at a spatial resolution of 9 km, covers the period from 2000 to 2100. It uses carbon accumulation in vegetation (VegC) and carbon released by fire (FireC) to evaluate fire impacts on ecosystems (Billing *et al.* 2023). The FII integrates data from the LPJmLv5.6-SPITFIRE model, which incorporates variables such as tree cover and FWI and is combined with the Burnt Area Simulator for Europe (BASE) model, which uses ESA FireCCI51 burnt area data to estimate burnt areas (Billing *et al.* 2023). The FII is estimated under two climatic scenarios, SSP1-2.6 and SSP3-7.0, which align with the projections used in the EU-Trees4F database. These scenarios help assess the impact of fires under different future climate conditions, providing a comprehensive view of ecological vulnerability.

5.2.3.3 Coping Capacity (CC)

CC refers to an ecosystem's ability to resist the effects of a wildfire, minimizing damage and maintaining its structure and functionality. This depends on both physiological characteristics and fire conditions. In this study, CC was estimated under extreme fire conditions, using Vegetation Resistance to Wildfires (RVW) based on bark thickness. This trait, which protects trees from high temperatures, was rescaled between 0 (no resistance) and 1000 (high resistance) using data from the TRY and BROT 2 databases (Tavşanoğlu and Pausas 2018; Kattge *et al.* 2020). For forested areas, RVW was calculated at the pixel level using tree potential habitat maps (TPHM) and averaged over the species present (previous database, EU-Tree4F). For non-forested areas, CC was set to 0, as grasslands and shrublands do not possess fire-resistant traits. The pixel-level CC was then calculated as:

$$RVW = \frac{1}{\sum_{i=1}^{n} TPHMi} x \sum_{i=1}^{n} TPHMixFTrvwi$$

$$CC = RVW.(1 - FII)$$

where FII represents the fire impact index. This result was normalized between 0 (least resistant) and 1000 (most resistant) to map fire resistance levels.

5.2.3.4 Recovery Time (RT)

Recovery time refers to the period required for an ecosystem to return to its pre-fire conditions. This includes the restoration of vegetation, ecological processes, and biodiversity. The RT is influenced by species-specific growth rates, environmental constraints, and post-fire management practices. Species-specific recovery time (RTi) was calculated using yearly growth rate (GR) and maximum biomass (BMAX) for each species, based on data from forest growth models (Röder *et al.* 2008). Post-fire regeneration strategies, such as sprouting from trunk buds or belowground material, were also considered (Archibald *et al.* 2019). Recovery Starting Time (RST) was adjusted for various factors determined as Environmental constraints (EC): Climatic factors (e.g., precipitation, temperature), topo-edaphic factors (e.g., soil erosion, topography), and management practices were used to modify RST. For instance, soil erosion maps and forest management intensity data were employed to assess delays in regeneration (Seidl *et al.* 2011; Hengeveld *et*

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al. 2012). The final RT for each pixel was calculated by combining these factors, incorporating species-specific recovery times and adjustments for environmental constraints:

$$RT = 1 \Big/ \sum_{i=1}^{n} TPHMi. \sum_{i=1}^{n} TPHMix(RSTi + RTi)$$

$$RT = 1 \Big/ \sum_{i=1}^{n} TPHMi. \sum_{i=1}^{n} TPHMix(RSTi.ARSTm + (ARSTt + ARSTc) + RTi.ARTic)$$

where n is the number of species present in pixel p, and TPHMi represents the tree potential habitat map (database of EU-Tree4F).

5.2.4 Integration Method for Assessing Ecological Vulnerability to Wildfires

The methodology for integrating ecological vulnerability to wildfires, as detailed in the WP1 work of the FirEUrisk project and published by Arrogante-Funes *et al.* (2024), builds on previous frameworks for evaluating fire impacts and recovery. This approach involves a systematic assessment of potential ecological damages, considering both immediate and long-term effects of wildfires on ecosystems. The ecological vulnerability to wildfires (EVW) is calculated using the following equation:

$$EVW = \Big(EVA * \big(1 - (CC/1000)\big)\Big) \times \frac{1 - (1 + r)^{-lnRT}}{r}$$

where:

EVA: Ecological value assessment.

CC: Coping capacity, normalized from 0 to 1000, where 0 indicates low resistance and 1000 indicates high resistance.

RT: Recovery time, adjusted using a discount rate (r) of 2%, reflecting the diminishing significance of future values.

Discount Rate and Recovery Dynamics: A discount rate of 2% is applied to future ecological values to reflect their perceived uncertainty.

The formula includes a hyperbolic factor to ensure that long-term recovery effects do not become negligible. This approach models the fluctuation of recovery rates over time, using a logistic curve to represent the recovery dynamics (Röder *et al.* 2008; Chu *et al.* 2016; Viana-Soto *et al.* 2017).

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5.2.5 Benefits of Applying the Methodology for Estimating Future Ecological Vulnerability to Wildfires in Europe

Implementing the methodology for estimating future ecological vulnerability to wildfires, as developed in the FirEUrisk project, offers substantial benefits for Europe in various domains, including data management, cartography, conservation planning, and policy formulation.

5.2.5.1 Enhanced Data Management and Cartography

Comprehensive Data Integration: The methodology integrates diverse datasets, including ecological values, coping capacity, and recovery times. This comprehensive approach enhances the quality and reliability of ecological data, making it easier to monitor and analyse wildfire impacts across different regions.

Advanced Cartographic Tools: By producing detailed maps of ecological vulnerability, this methodology provides valuable visualizations of wildfire risks and impacts. These maps aid in spatial planning and resource allocation, offering a clear representation of areas most at risk and those requiring urgent attention.

5.2.5.2 Identification of Future Priority Areas

Targeted Risk Assessment: The methodology helps identify areas with high vulnerability to future wildfires. By highlighting these priority zones, stakeholders can focus their efforts on regions that are most at risk, ensuring that resources are allocated effectively to mitigate potential damage.

Predictive Analysis: Utilizing future climate scenarios and modelling the potential impacts of wildfires allows for predictive assessments of vulnerability. This forward-looking approach enables proactive planning and preparedness, rather than reactive responses to disasters.

5.2.5.3 Improved Management of Natural Spaces

Informed Conservation Strategies: Understanding the ecological vulnerability of different areas allows for the development of targeted conservation strategies. Managers can implement measures to enhance the resilience of ecosystems, such as selective vegetation management and habitat restoration, reducing the likelihood of severe damage from wildfires.

Optimized Resource Allocation: By identifying high-risk areas, the methodology supports the efficient allocation of resources for fire management and prevention. This includes directing funds and efforts towards areas where they will have the most significant impact on reducing vulnerability.

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5.2.5.4 Enhanced Policy Formulation and Implementation

Evidence-Based Policy Development: The detailed vulnerability assessments provide policymakers with robust data to inform decisions and develop effective fire management policies. This evidence-based approach ensures that policies are tailored to address specific vulnerabilities and mitigate potential risks.

Strengthened Prevention Measures: The methodology underscores the importance of prevention as a means to mitigate wildfire impacts. By identifying ecological weaknesses, it enables the implementation of preventive measures to avoid significant damage, ultimately enhancing overall ecosystem resilience.

5.2.6 Concluding remarks

The application of this vulnerability estimation methodology offers significant benefits for Europe by improving data management, advancing cartographic tools, and enabling targeted conservation and policy efforts. It provides a proactive framework for understanding and addressing the risks associated with wildfires, thereby enhancing the ability to prevent and mitigate their impacts. This approach ensures that resources are effectively used to protect vulnerable ecosystems, supporting sustainable management and policy development in the face of increasing wildfire threats.

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6 Changes in fire regimes and vegetation - participatory review with stakeholders and experts

Within the scope of A3.2.2 a participatory review process was envisaged, aimed at engaging local experts and stakeholders in discussions about projected changes in fire regimes and vegetation developed by the project. The objective was to validate and refine the identified vulnerability variables and assess changes in risk, incorporating local knowledge and expert insights into the project's framework. The participatory review process was based on the overall participatory approaches implemented within the project, namely around contextualization activities in WP1 (A1.2.2) and FirEUrisk Participatory Model developed within the framework of WP2 (A2.4.3).

6.1 Methods

6.1.1 Preparation phase - identifying variables and stakeholders

The preparation phase, spanning from March to May 2024, has been carried out by the assigned working group and aimed at the identification of:

- Vulnerability variables and drivers for change.
- Focus of the discussion to be carried out and outputs to be reviewed during the participatory process.
- Main stakeholders to be involved, in different Pilot Sites and Demonstration Areas.

The main activities carried out within this phase were:

- Data collection: a survey was coordinated by ISIG and SU and distributed internally among relevant project partners.
- Working group online meetings and discussions among project partners involved in the activities around the preparation of this deliverable (D3.6 - Future vulnerability and exposure to future fire, incl. changes along WUI).

Building on the work of WP1, the project team identified key vulnerability variables and potential drivers of change. These included climatic factors, vegetation patterns, community readiness, and historical fire regimes.
Specifically, the following have been highlighted by the internal survey as main relevant variables for potential local stakeholders:

- Climatic conditions.
- From a fire behaviour perspective: vegetation continuity (macro to mesoscale), structure and conditions (microscale), fuel moisture.
- Higher maximum temperature, drought.
- Land use change (land abandonment vs. urbanization and WUI expansion).
- Reduction in plant abundance, diversity and fitness.

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- Road accessibility.
- Vegetation types.

Among these, the following have been identified by the project team as relevant drivers for change:

- Future Fire Weather Index and its sub-components.
- Intensified fire regimes (increase in fire severity and/or fire frequency).
- Land use (namely fuel types).
- Step-changes in fire behaviour (i.e. surface-to-crown fires).
- Variables commonly used in containment modelling: viewshed from towns, road accessibility, cost distance to paths and tracks, distance to heliports, viewshed from roads, and vegetation height.
- Weather (wind influencing fire behaviour and the combination of all parameters influencing fuel moisture).
- Weather-related variables: dead FMC and wind speed.
- WUI declines due to land abandonment.
- WUI expansion following the construction of secondary homes in rural areas.
- WUI expansion following urbanization in vegetated areas.

For what concerns the focus of the participatory review and concrete outputs to be discussed the following have been identified:

- Adaptation and mitigation measures.
  - Potential outputs to be reviewed: data; combination of infographics and maps.
- Increased extreme fire weather danger days and increased fire weather danger.
  - Potential outputs to be reviewed: model simulations; outputs result in maps (e.g., future projections of FWI, or number of days with extreme FWI).
- Fuels and land management.
  - Potential outputs to be reviewed: maps of actual vs. future fire regimes under different land use scenarios focusing on WUI areas, current and future fuel maps, future climate scenarios.

With regards to the stakeholder identification, the working group has identified key experts and stakeholders, as follows:

- Governmental and Public Agencies:
  - Forest and fire managers
  - The Portuguese Forestry Institute
  - The Portuguese Agency for Integrated Fire Management
  - Local government

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- Provisional council of Barcelona (Diputacio de Barcelona)
- Land and Resource Management:
  - Land managers
- Community and Private Stakeholders:
  - Homeowners (both locals and secondary homeowners)
  - Firefighters
- Research and Academic Institutions:
  - Scientific community (fire ecology)

Following the results of the consultations with the project team, the working group identified the relevance and feasibility of performing a Participatory review workshop (in presence) in the PS5 - Attica, around the topic of Future Fire Weather Index (developed by NCSRD)

6.1.2 Implementation phase - conducting the participatory review exercise

The implementation phase was conducted from June to July 2024 and consisted of a series of coordination meetings and the organisation of an in-person workshop. The participatory review workshop was held in Rafina, Greece, on the 12th of June 2024, during the FirEUrisk demonstration event for the Attica region Pilot Site (PS5). This workshop, focused on the identified topic of increased fire weather danger, allowed for the validation of the findings and provided an opportunity for in-depth discussions and hands-on activities, furthering the understanding of fire risk and management strategies, within the context of the Attica region PS. The results of the workshop are reported in the following paragraphs.

6.1.3 Participatory review - The workshop

6.1.3.1 Participants

The workshop capitalised on the bigger Demonstration Event and brought together a diverse group of stakeholders, from local and regional levels involved in the Demonstration event activities:

- Total number of participants: 12
- Profiles: researcher/academic (6), community member (2), local authority/representatives of municipalities (2), forest management (1); fire-fighting volunteer (1).

6.1.3.2 Workshop script

The workshop was organised in a hybrid format, as were the sessions of the Demonstration event – so to allow for interaction with online participants.
The workshop was structured in the following sessions:

- Introduction to climate models and fire weather danger forecasting – by the project partner NCSRD:

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- The workshop began with an in-depth presentation on climate models and their applications in forecasting fire weather risk on two-time scales: long-term and seasonal. The presentation detailed the computation of fire weather danger using climate and seasonal estimation models, emphasising the benefits of high spatial resolution data for climate and topographic analysis.

- Climate change scenarios presentation – by the project partner NCSRD:
  - Participants were introduced to scenarios for the near future (2025-2049) and the far future (2075-2099) under different greenhouse gas emission pathways (RCP4.5 and RCP8.5). The FWI system and its components were explained, highlighting how fire weather danger is assessed and projected.
- Participatory review – facilitated by the project partner ISIG:
  - In the core session of the workshop, participants engaged in discussions on the identified vulnerability variables and potential drivers for change. They provided feedback on the relevance and impact of these variables in the context of fire readiness and management.
  - To allow for the participation and interaction with stakeholders online, the discussions were facilitated by a Mentimeter survey and were enriched by the participants' diverse backgrounds and expertise, leading to a deeper understanding of the issues at hand.

6.1.3.3 Key questions and summary of responses

The workshop included several key questions designed to stimulate detailed responses and insights from participants:

Understanding and application of climate models

- Participants discussed their understanding of climate models and their practical applications in forecasting fire weather risk.
- Although participants acknowledged that future climate change scenarios are not (or very little) currently considered within their planning work, they recognised their importance.
- The Fire Weather Index was, in fact, rated as highly relevant for fire management practices.
- The session underscored the importance of accurate climate modelling for effective fire management strategies.
- Participants emphasized the need for user-friendly tools and training sessions to enhance the practicality of these models.

Climate change impact on preparedness

- Participants observed significant impacts of climate change on fire readiness, prevention, and management.
- This highlighted the urgent need for adaptive strategies that can respond to the evolving challenges posed by climate change.

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Importance of different factors in Fire Management Strategies

Participants ranked the importance of various factors for their fire management strategies, including (following list reports on the order of ranking):

- Community readiness
- High-resolution maps
- Climate change adaptation
- Historical fire regimes
- Meteorological fire indices

Most helpful map type

Participants discussed the types of maps most helpful for fire preparedness activities.
Preferred map types included (in the order of ranking):

- Seasonal fire risk prediction maps
- High-resolution climate maps
- Historical fire occurrence maps
- Future fire risk projection maps

Future changes for climate adaptation

Participants ranked future changes for climate adaptation based on their importance for their work. The following indicates the ranking as decided upon by the participants:

- Updating policies and regulations
- Development of new fire management technologies
- Shifts in fire seasons
- Increased frequency of extreme weather events
- Changes in vegetation patterns

Evaluation of data resolution

Most participants found the temporal and spatial resolution of the provided data satisfactory. This feedback is crucial for improving the presentation and utility of data in future fire management tools.

Desired future changes for fire management tools

Participants suggested several enhancements for future fire management tools, including:

- Inclusion of seasonal indices.
- Increase citizens engagement in planning and throughout management cycle.

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- Enhanced preparedness knowledge modules.
- Integrate Artificial Intelligence components.
- Foster adaptive management by means of Digital twins.

6.1.3.4 Stakeholder feedback

Understanding and application of climate models

Stakeholders emphasised the importance of clear and practical applications of climate models. They noted that while theoretical models are valuable, practical tools that can be directly implemented in fire management practices are even more crucial. There was a call for user-friendly interfaces and training sessions to help stakeholders effectively access and leverage the available data.

Community preparedness

The need for community-based strategies was a recurring theme. Stakeholders stressed the importance of involving local population in fire preparedness and response activities. This includes public education campaigns, community drills, and the establishment of local fire brigades. Building community resilience was seen as essential for effective fire management.

Adaptation to climate change

Participants highlighted the necessity of adaptive strategies to cope with changing climate conditions. They recommended incorporating real-time data and forecasts into fire management plans, allowing for dynamic and flexible responses. Integrating climate change scenarios into long-term planning was also emphasized to ensure that fire management strategies remain relevant in the face of evolving risks.

High-resolution maps and data

The value of high-resolution maps and detailed data was widely recognised. Stakeholders expressed a need for maps that provide granular information on fire risk areas, weather patterns, and vegetation types. Regular updates to these maps were deemed essential to reflect current conditions and projected changes.

Historical fire regimes:

Understanding historical fire regimes was deemed crucial for predicting future fire behavior. Stakeholders called for comprehensive studies that document past fire events, their causes, and impacts. This historical data can inform present-day strategies and help anticipate potential future scenarios.

Meteorological Indices:

The use of meteorological indices, such as the FWI, was supported by stakeholders. Enhancing these indices with additional variables, such as soil moisture content and fuel load, was suggested to improve their predictive accuracy and utility in fire management.

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Future changes and adaptation strategies

There was a consensus on the need to prepare for future changes, including more frequent extreme weather events, shifts in vegetation patterns, and the development of new fire management technologies. Stakeholders recommended prioritizing research and development in these areas to stay ahead of emerging risks and to develop innovative solutions.

Policy updates and regulatory changes

Updating policies and regulations to reflect the latest scientific insights and technological advancements was emphasised. Stakeholders advocated for a proactive approach in policymaking, ensuring that regulations support adaptive and resilient fire management practices.

Integration of multidisciplinary approaches

The complexity of fire risk management requires a multidisciplinary approach. Stakeholders advocated for the integration of climate science with social, economic, and environmental considerations. This holistic perspective can lead to more effective and sustainable fire management strategies, addressing the multifaceted nature of fire risk.

6.2 Results

Based on the workshop findings and stakeholder feedback, several recommendations are made below to enhance the FirEUrisk project's use of climate data and the development of related products.

1. Enhance data resolution and accessibility:

- Improve the temporal and spatial resolution of climate data to meet the needs of stakeholders.
- Ensure that high-resolution maps are readily accessible and easy to interpret, providing granular details on fire risk areas, weather patterns, and vegetation types.

2. Develop adaptive management tools:

- Incorporate future changes in climate variables and fire risk projections into fire management tools.
- Develop tools that allow for dynamic updates based on real-time data and evolving climate scenarios, ensuring flexibility and responsiveness in fire management practices.

3. Increase stakeholder engagement:

- Foster continuous engagement with local experts and stakeholders to gather ongoing feedback and insights. This can be achieved through regular meetings, workshops, and online platforms.

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- Create platforms for citizen interaction to involve the community in fire preparedness and risk mitigation efforts. These platforms could facilitate sharing information, reporting fire incidents, and participating in preparedness drills.

4. Focus on practical applications:

- Develop practical applications of climate models that can be directly used by fire managers and decision-makers. These applications should be user-friendly and tailored to the needs of different stakeholders.
- Provide training and resources to stakeholders to enhance their understanding and use of these tools. Training sessions, webinars, and educational materials can help stakeholders effectively interpret and apply climate data in their work.

5. Incorporate seasonal and long-term projections:

- Include both seasonal forecasts and long-term projections in fire management strategies. This dual approach can help stakeholders prepare for immediate risks as well as future changes.
- Provide detailed scenarios for different time frames to help stakeholders plan and adapt accordingly. These scenarios should consider various factors such as climate change, vegetation shifts, and socio-economic developments.

6. Update policies and regulations:

- Use the insights gained from the review to inform policy updates and regulatory changes. Policy-makers should consider the latest scientific findings and technological advancements when developing fire management regulations.
- Ensure that regulations support adaptive and resilient fire management practices. Policies should encourage the use of innovative tools and strategies that can effectively address the challenges posed by climate change.

7. Integrate multidisciplinary approaches:

- Combine climate science with social, economic, and environmental perspectives to develop holistic fire management strategies. This multidisciplinary approach can address the complex nature of fire risk and enhance the sustainability of management practices.
- Foster collaboration between experts from different disciplines to leverage diverse knowledge and expertise. This can lead to more comprehensive and effective solutions for fire risk management.

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6.3 Concluding remarks

The participatory review workshop in Greece provided valuable insights into the participants' views on the impact of climate change on fire readiness and management. The feedback highlighted the importance of various factors such as community preparedness, adaptation to climate change, and the need for high resolution maps. Participants also expressed the need for updating fire management tools to include future changes and improve data resolution. Integrating detailed presentations on climate models and fire weather forecasting enhanced the participants' understanding and engagement during the workshop. The chosen methodology of combining webinars with an in-person workshop proved effective in gathering comprehensive feedback and validating the identified variables and drivers for change.

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8 Annex A: Detailed information regarding Chapter 3

8.1 Uncertainties and assumptions

The work presented in Chapter 3 must be seen with caution, as it is based on several assumptions and uncertainties that are intrinsic to the used models and projections. First, assessing any natural phenomena with mathematical models is a very complex task, and even if the models were perfectly accurate, which is practically impossible, the inputs rarely are. In fact, obtaining inputs to describe variables that change in space and/or time is usually difficult. In the case of fire behaviour assessment, three major sets of input data are required: orography, fuels and meteorology. The basic assumption behind wildfire modelling is that, in each area, the properties of all inputs required for the fire to progress are constant for a certain period of time, thus allowing fire propagation to be predicted. This is rarely true for any point in space and time. Fuel particles vary almost in each square centimetre, weather, particularly wind, varies every second and topography, although more constant, can have abrupt changes in a few meters distance. In the present work we are dealing with fire prediction for future projections of WUI areas, landscape and climate change, that originally have very coarse resolutions (ca. 8 to 9 km). In the case of WUI scenarios, and in the absence of specific models to project its development in time, a generic approach was developed, starting from the land use scenarios at 9 km resolution and constructing 10 m resolution projections for future WUI areas, based on GIS defined criteria. The inputs used were resampled to 100 m, to have a compromise between simulation time and accuracy of the results. The results were then resampled again to 10 m, to allow the analysis in the generated 10 m projections of WUI. All these assumptions and constrains were assumed by the authors as the best possible approach to fulfil this task, in the light of the available data for future scenarios.

8.2 Description of the fire propagation modules used

8.2.1 Basic fire behaviour (FlamMap Basic)

This module produces estimates of fire behaviour for the entire domain, cell by cell, assuming as constants the conditions described for each of them in the input data, and the fire, in the direction of the main spread (the "head of the fire"). The result is given in maps, or data layers, corresponding to the basic characteristics of fire propagation across the landscape - linear intensity, propagation speed and flame length - but without considering the spatial propagation characteristics of any particular fire occurrence. These variables can be analysed based on the information contained in Table 8.1, which classifies the type of fire through the descriptors of fire behaviour, associating them with difficulty in suppression.

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Table 8.1. Classification of forest fire type and respective suppression capability according to intensity (I), rate of spread (R) and flame length (L) (adapted from Viegas et al., 2020).

Type of fire		I	R				L	Spotting		Type of behaviour	Suppression capacity
		kW/m	m/min				m	Activity	Distance		
			a	b	c	d			m		
Normal	1	<500	<5	<15			<1,5	Null	0	Surface	Easy
	2	500-2.000	<15	<20			<2,5	Low	<100	Surface	Moderate
	3	2.000-4.000			<20	<50	2,5-3,5	High	≥100	Surface and transition to crowns	Very difficult
	4	4.000-10.000			<50	<100	2,5-10	Prolific	500-1.000	Surface and transition to crowns	Extremely difficult
Extreme	5	10.000-30.000			<150	<250	10-50	Prolific	>1.000	Crown fires and spotting	Virtually impossible
	6	30.000-100.000			<300		50-100	Massive	>2.000	Chaotic	Impossible
	7	>100.000			>300		>100	Massive	>5.000	Firestorm	Impossible

** Types of fuel: a) Shrubs and trees; b) Herbaceous; c) Trees and d) Shrubs and herbaceous.*

For the purposes of this work, we will group classes 5 to 7 in one, as the impact of a fire of this magnitude is such that the possibility of control is beyond the current extinguishing capacity. The type of fire is classified with an intensity class, for the sake of simplification, from "Low" (fire type 1) to "Extreme" (fire types 5 to 7). These simulations are not very demanding in terms of computational resources and the average simulation time is in the order of seconds or few minutes for each representative landscape scenario, across the entire territory considered.

8.2.2 Minimum Travel Time (MTT)

The MTT module produces landscape-scale simulations using multiple ignitions and a defined propagation time. The use of multiple ignitions in this module makes it possible to calculate two indicators, which were considered when comparing fire behaviour between scenarios: the burn probability (BP) and the conditional flame length probability (FLP). The burn probability refers to the number of times a given pixel "burns" as a function of the number of ignitions used in the simulation. In other words, the BP for a given pixel represents an estimate of the probability of it burning from a random ignition within the study region, for the simulation conditions used (Ager et alr. 2010). In a process similar to BP, FlamMap calculates the conditional probability of flame length (FLP). FLP represents the weighted probability of a certain flame length existing in a given pixel in the event of a fire occurring and can be considered an indicator of fire danger (Scott, 2006). In other words, the FLP is the result of the average of the flame lengths that occurred in a given pixel as a result of all the simulated fires. Unlike the basic fire behaviour module, which calculates the parameters in the main direction of spread ("head of the fire"), MTT calculates the expected flame length in each pixel taking into account the relative direction in which the fire encounters it and the main direction of spread (flank fire, head fire, back fire). To simplify analysing the FLP, FlamMap generates for each pixel a frequency distribution of flame length values in 20 intervals of 0.5 m in the metric system or six intervals in the imperial system. Roose et al. (2008) classified each of these six intervals (in feet, in the imperial system) as a FIL. Although these classes are based on the determination of flame length, the linear intensity of the fire front for each class break value can be easily

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determined. Table 8.2 (adapted from Scott, 2020), shows the values for flame length, surface fire linear intensity (from Byram, 1959) and crown fire linear intensity (from Thomas, 1963) corresponding to each of the six imperial fire intensity levels. As this is a smaller number and easier to interpret, we have chosen to use these classes for the conditional flame length and respective FIL results in the imperial system, even though all the simulations and results are presented in the metric system.

Table 8.2. Levels of fire intensity and the respective parameters that describe fire behaviour (adapted from Scott, 2020).

Fire Intensity Level (FIL)	Flame length class (ft)	Flame length class (m)	Linear surface fire intensity class (kW/m)	Linear crown fire intensity class (kW/m)
FIL1	< 2	< 0.6	< 88.6	< 108
FIL2	2–4	0.6–1.2	88.6–400	108–303
FIL3	4–6	1.2–1.8	400–965	303–554
FIL4	6–8	1.8–2.4	965–1803	554–851
FIL5	8–12	2.4–3.7	1803–4354	851–1559
FIL6	> 12	> 3.7	> 4354	> 1559

These classes are somewhat similar to those used to classify the difficulty of suppressing a fire, as mentioned in Table 8.1. In order to analyse the MTT module simulations in the light of these intensity levels, it is necessary to calculate the Conditional Flame Length (CFL) for each pixel in the analysis zone. The methodology used is an adaptation of the one proposed by Ager et al. 2010 and is based on calculating the weighted average of the size classes of the expected flame length in each pixel, taking into account the probability of it burning if there is any ignition in the study area. The CFL, considered a measure of fire danger (Ager et val. 2010), is calculated using the following equation:

$$CFL = \sum_{i=1}^{20} (FLP_i * F_i)$$

Where

FLP_i is the conditional probability in each flame length class

F_i is the flame length midpoint in each of these same classes.

Typically, the CFL values are lower than the flame length values calculated in the basic behaviour module because, as we've already mentioned, this module only considers the main direction of spread (head of the fire), whereas here the different types of fire fronts are taken into account (flank, head, rear). On the other hand, according to FlamMap's categorisation or indexing process, the maximum value assigned to the CFL is 10 m. In order to calculate the conditional probabilities (BP and FLP) more accurately, each pixel needs to "burn" as many times as possible, saturating the calculation area. For this reason, and for each of the analysed regions, we created a set of 100,000 random ignitions with ArcGIS Pro. The same set was used in all simulations, in each of the study areas.

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8.3 Input data

8.3.1 Orography

A Digital Elevation Model (DEM) was obtained from NASA's Land Processes Distributed Active Archive Center (LP DAAC). Version 3 of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) was downloaded, projected to ETRS89 and resampled to 100m. Slope and aspect were processed based on this dataset.

For Sardinia DA, topography layers were derived from 10m digital elevation data of the island (www.sardegnageoportale.it) and were resampled to 150m.

8.3.2 Meteorological scenarios

8.3.2.1 Central region of Portugal (PS3)

For PS3, climate data projections were obtained by Meteogrid in Deliverable 3.1 – Downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA, with 3 scenarios (lower, medium and upper): 7 models and their respective 4 SSPs have been used for evaluating climate change in each area of study. The index chosen to evaluate climate change was Drought Code (DC), a sub-index of the Canadian Fire Weather Index (FWI). DC was calculated for different periods for the 28 possible model-SSP combinations and the differences between the end of the century (2071-2100) and the beginning (1985-2014) have been sorted. Thus, the three scenarios were defined as follows:

1. Lower scenario: Model and scenario whose DC difference ranges in the lower band (percentile 10th).
2. Medium scenario: Model and scenario whose DC difference ranges in the median of all projections.
3. Upper scenario: Model and scenario whose DC difference ranges in the upper band (percentile 90th).

The "upper" datasets represent the projections for driest scenarios and were selected for the analysis.
Wind description for 2020, 2030, 2040 and 2050, from 1st of June to 30th of September (assuming this period as the "fire season"), was processed from the climate scenarios, using percentiles 90 and 95, and assuming it represents average daily conditions for very high and extreme fire danger. Wind speed was directly obtained, but wind direction was calculated in ArcGIS from the U and V components. The analysis resulted in 16 scenarios of wind speed and direction: percentiles 90 and 95 for the 4 reference years and the 2 SSPs.

8.3.2.2 Attica region of Greece (PS5)

For the Attica region of Greece (PS5) data were provided by NCSRD. Specifically, climate datasets were derived from 5km high resolution long-term climate simulations. Further information regarding model setup and validation results can be found in FirEURisk (Deliverable 3.1 - Downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA) and in the studies of Politi et al. 2021, 2022. A subset of the mentioned gridded datasets above, focus on the Attica

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region has been extracted for the need of the present analysis. Therefore, the Attica region consisted of 125 gridded points.

As input data for the future fire simulations, the 90th and the 95th percentiles values of the following selected climate data for the historical period (1990 – 2004) and the near future period (2035– 2049) under both RCPs (RCP4.5 and RCP8.5) during the fire season, considered from June to September, were produced:

- The sub-component that describes the moisture content of fine dead surface fuels, known as FFMC of the Canadian Forest Fire Weather Index (FWI) System (CFFWIS) was calculated using WRF model output time series of gridded precipitation, maximum temperature, wind speed, and relative humidity datasets.
- The mean wind speed (m/s)
- The max wind speed (m/s)
- In the context of future fire weather projections, the future changes of selected components of the FWI system as the Fire Weather Index (FWI), the FFMC, and the Daily Severity Rating (DSR), were estimated in mean monthly or annual timestep for the Greek Fire-season (May – October). For the comparison of the future changes, the absolute or the percentage differences of the near (2025-2049) and the far future periods (2075-2099) in regard to the historical period (1980-2004) were illustrated spatially in the following maps in Figures 8.1 to 8.6.

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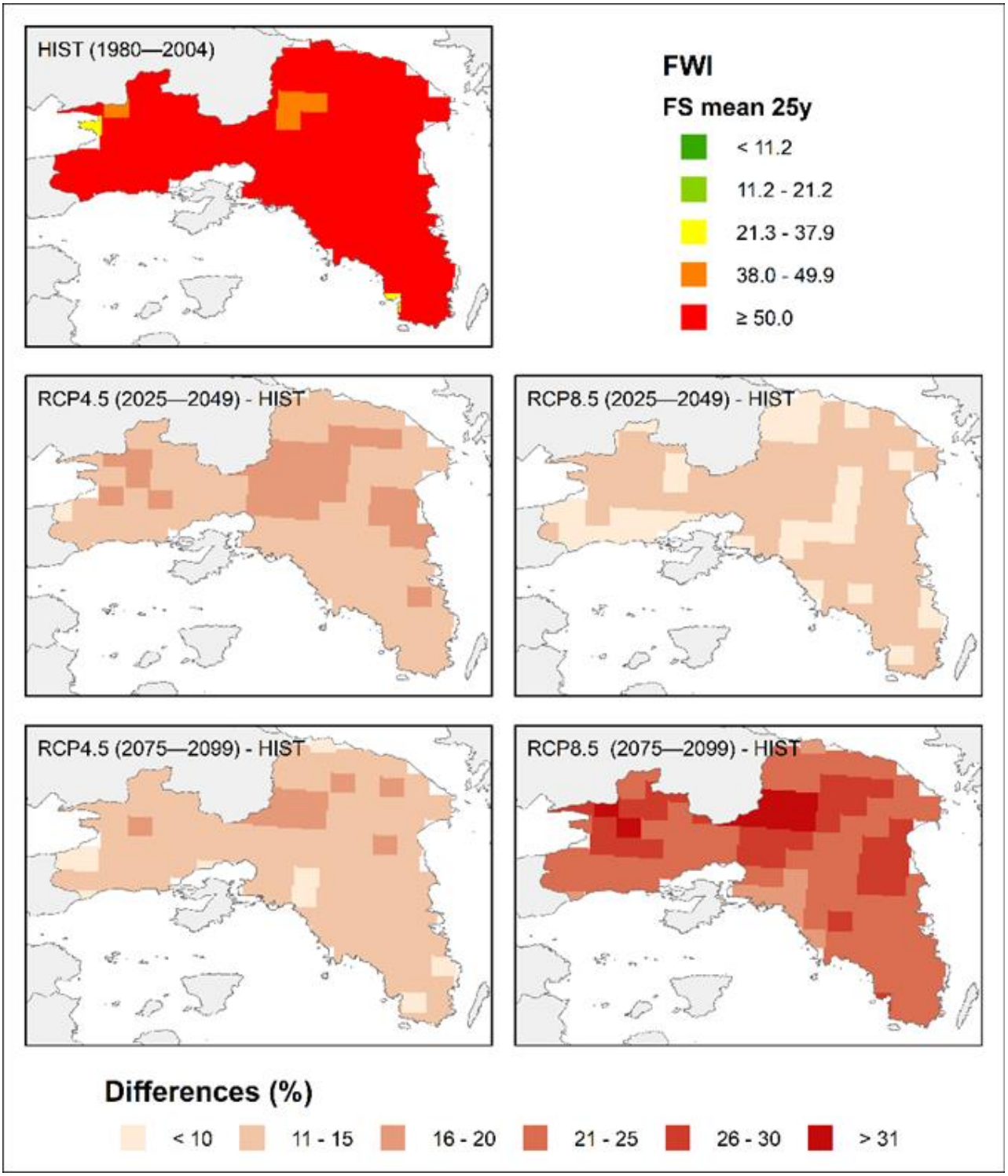


Figure 8.1. Estimation of mean FWI change for the entire Fire season in the near and far future for RCP4.5 and RCP8.5 for PS5 (Attica region)

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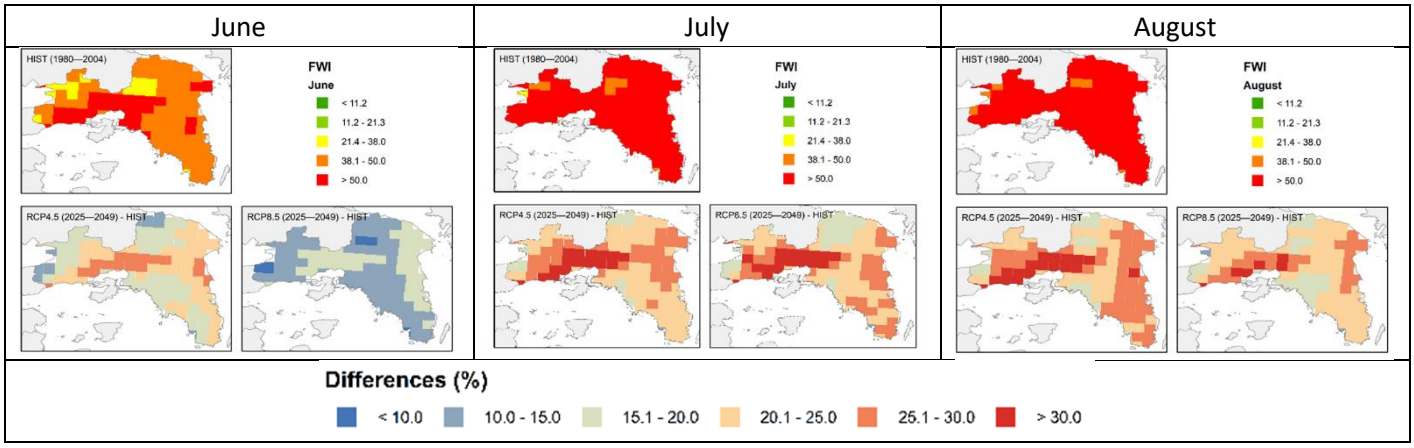


Figure 8.2. Estimation of mean monthly FWI change for summer period in the near future for RCP4.5 and RCP8.5 for PS5 (Attica region)

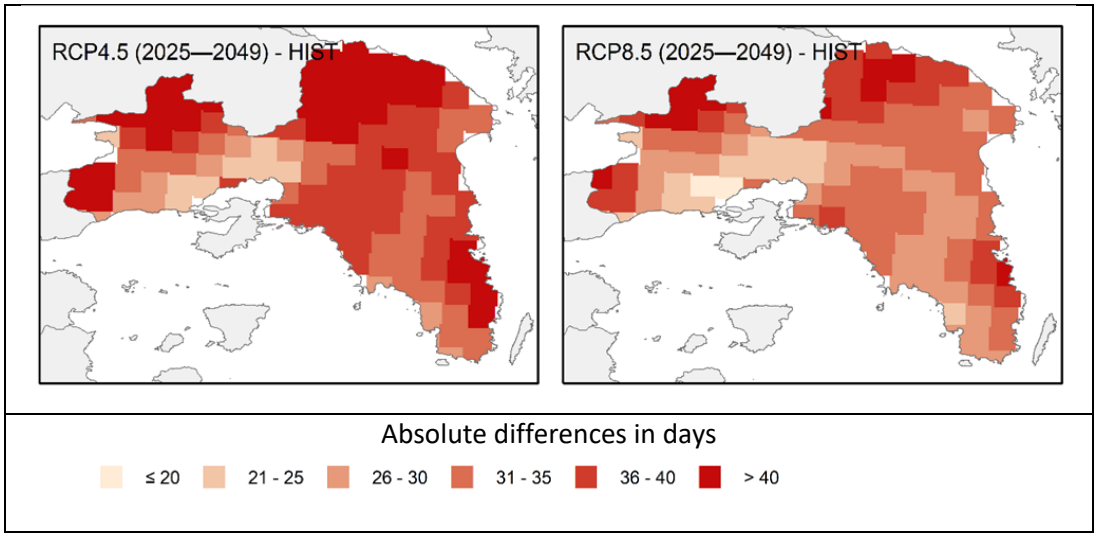


Figure 8.3. Absolute differences of the number of days with FWI > 50 in the near future under RCP4.5 και RCP8.5 for the entire fire season for PS5 (Attica region)

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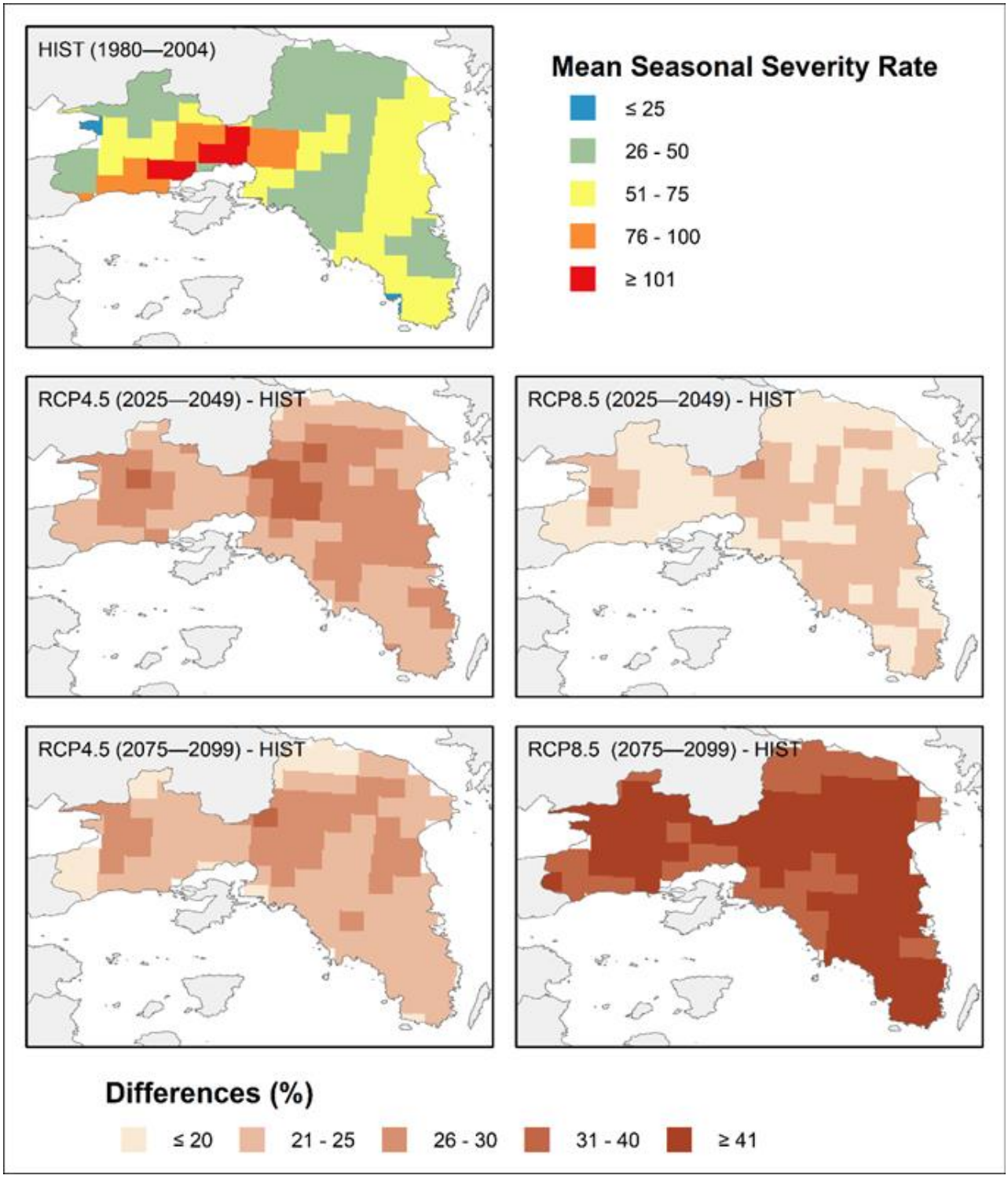


Figure 8.4. Estimation of mean Daily Severity Rate (DSR) change for the entire Fire season in the near and far future for RCP4.5 and RCP8.5 for PS5 (Attica region).

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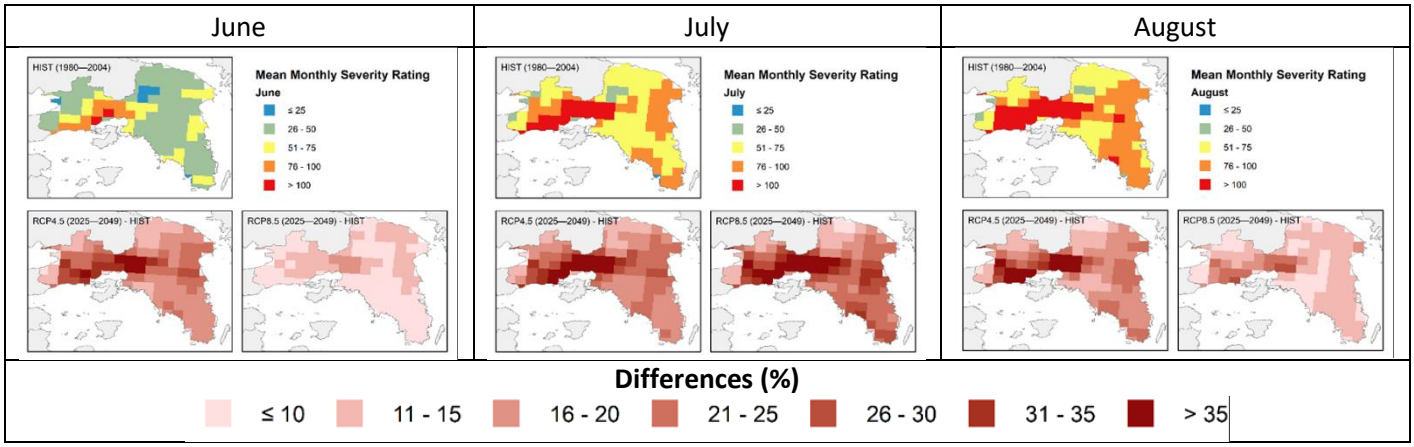


Figure 8.5. Estimation of mean monthly Daily Severity Rate (DSR) change for summer period in the near future for RCP4.5 and RCP8.5 for PS5 (Attica region)

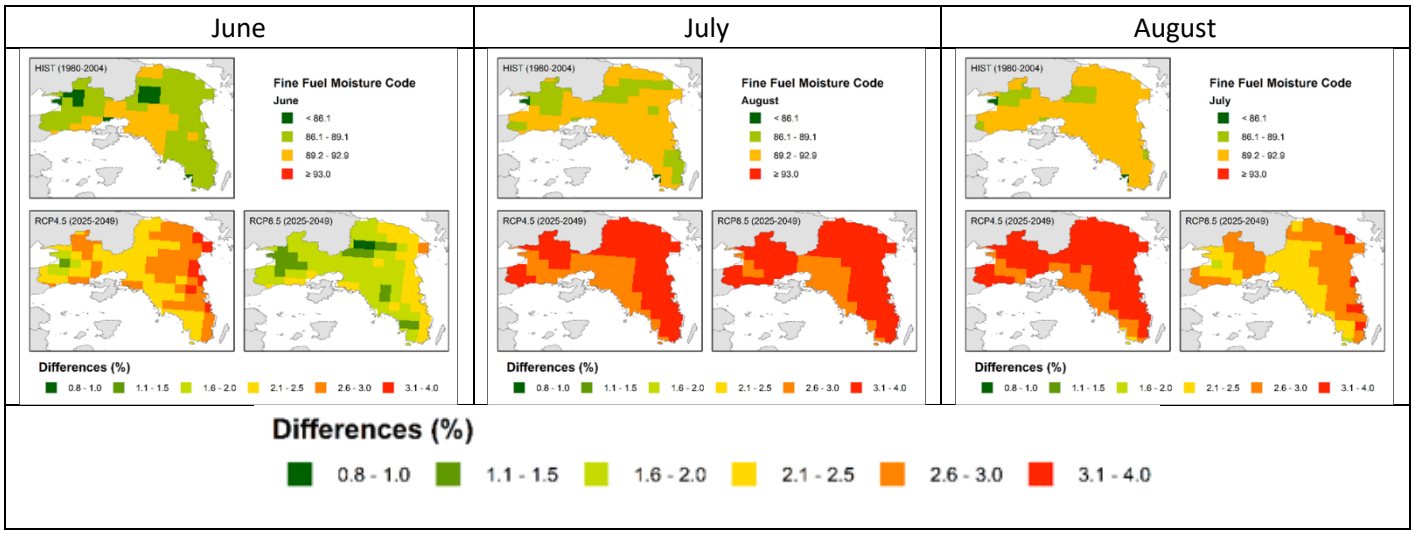


Figure 8.6. Estimation of mean monthly FFMC change for summer period in the near future (2025-2049) for RCP4.5 and RCP8.5 for PS5 (Attica region)

In general, the potential impact of climate change on fire weather danger is evident in all the examined indices in the Attica region under RCP4.5 and RCP8.5. The spatial distribution of the results of FWI (Figure 8.1) indicated an increase of fire weather danger from 10 to 20% in the near future under both scenarios with the highest increase observed in the far future under RCP8.5. Similarly in the monthly analysis (Figure 8.2) during summer period, the month of July was the worst month in terms of fire danger with notable increase under both scenarios with percentage change over 25%. In the Figure 8.3, the increase of extreme fire danger days with FWI>50 in the near future, is evident in the greatest part of the region under both scenarios. Projected higher fire danger conditions were also indicated by mean monthly

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FFMC during summer months (Figure 8.6), mainly in the Eastern part of the Attica region, with July's projections being the highest under both scenarios. Regarding annual DSR future changes (Figure 8.4), the highest increase (of above 40%) was observed in the far future under RCP8.5, being extended in the whole region, while no significant differences were existing under RCP4.5 for both periods (>20% increase). During summer months (Figure 8.5) and under RCP4.5 the percentage differences were higher than that under RCP8.5, particularly in the western part of the region. However, in July the percentage change of DSR marked similar increases of above 26%, under both scenarios spatially expanded to the entire region.

8.3.2.3 Sardinia (DA)

For the Sardinia DA, we used climate data provided by Meteogrid in Deliverable 3.1 - Downscaled CMIP5 and CMIP6 climate scenarios for selected PS and DA. We gathered climate data of four different climate models (ERA5, ACCESS-CM2, EC-EARTH3, MPI-ESM1-2-HR) and two climatic periods were considered: 1985-2014 for historical conditions; 2035-2064 for the "near future" conditions. The results of last timestep will not be reported in this Deliverable but will be available in later months. For future conditions, three different SSPS were considered (SSP1-2.6, SSP2-4.5, SSP5-8.5). For these combinations of models, SSPS and timesteps, we calculated the FWI and related subcodes for the whole island, to analyse potential variations in wildfire danger conditions among and within models, as well as in spatial terms. We then split the modelling domain into three Weather Zones (Northern, Central and Southern Sardinia) adapted from Salis et al. 2021 (Figure 8.7). For each Weather Zone, a representative Climate Data location was identified, with geographic coordinates corresponding to the weather station monitoring network managed by the Environmental Protection Agency of Sardinia. Statistical analyses were done using climate data extracted for these locations This allowed to evaluate the spatial representativeness of each location, and the availability of measured data allowed for a better characterisation of the current climate conditions. We then focused our attention on the days with FWI values greater than or equal to 38, which according to EFFIS correspond to very high wildfire danger conditions. Ather that, days with FWI≥38 were classified based on wind speed (< 10 km h^{-1}, 10-20 km h^{-1}, 20-30 km h^{-1}, > 30 km h^{-1}) and direction (N; NE; E; SE; S; SW; W; NW) classes, and for each Weather Zone (Table 8.3 and 8.4). This analysis was carried out for each climate model, SSPS and timestep. We used wind speed, direction and related frequency as wind inputs for the simulations.

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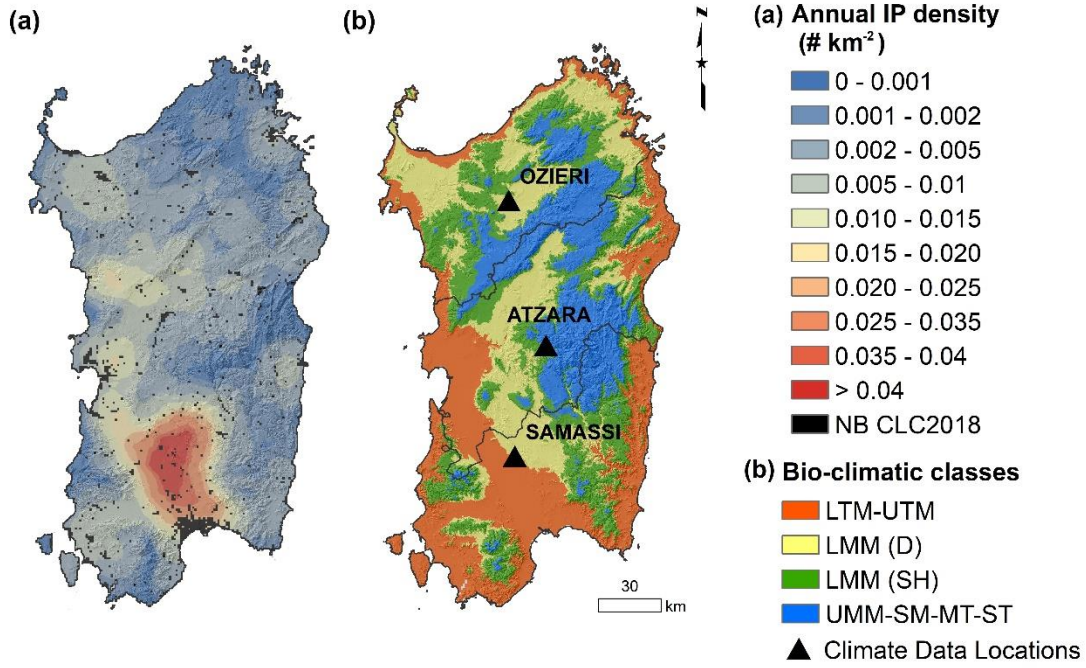


Figure 8.7. (a) Annual wildfire ignition point density (aIPD) of Sardinia, considering the 2003-2022 wildfire database and fire with size >= 1 ha. NB= not burnable fuels according to CLC2018 data. (b) Weather Zones (adapted from Salis et al. 2021) and bio-climatic conditions (Canu et al. 2015) of Sardinia, along with the Climate Data Locations used for the extraction of climate data. LTM = lower ther-momediterranean; UTM = upper thermomediterranean; LMM (SH)= lower mesomediterranean subhumid; LMM (D)= lower mesomediterranean dry UMM = upper mesomediterranean; SM = supramediterranean; MT = mesotemperate; ST = supratemperate.

Table 8.3. Wind speed classes and frequency for climate models, SSPs scenarios and reference years used in the modelling exercise for Sardinia, focusing on days with FWI values greater than or equal to 38. The wind speed data for the 3 main weather zones of Sardinia (North, Center and South) are not showed.

Climate Model and SSP	Years	0-9.99 Km/h	10-19.99 km/h	20-29.99 km/h	>30 km/h
		(% of days)	(% of days)	(% of days)	(% of days)
ACC	1985-2014	73.99	19.42	4.96	1.63
ACC126	2035-2064	75.15	18.81	5.37	0.66
ACC245	2035-2064	72.77	21.36	4.84	1.03
ACC585	2035-2064	75.10	20.71	3.86	0.33
ECH	1985-2014	67.24	30.55	1.71	0.50
ECH126	2035-2064	71.28	26.69	2.02	0.00

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ECH245	2035-2064	69.83	28.18	1.72	0.27
ECH585	2035-2064	68.76	28.78	2.45	0.00
ERA5	1985-2014	71.13	26.20	2.66	0.00
MPI	1985-2014	80.29	19.56	0.15	0.00
MPI126	2035-2064	83.04	16.41	0.55	0.00
MPI245	2035-2064	78.41	21.18	0.41	0.00
MPI585	2035-2064	81.39	18.45	0.16	0.00

Table 8.4. Wind direction classes and frequency for climate models, SSPs scenarios and reference years used in the modelling exercise for Sardinia, focusing on days with FWI values greater than or equal to 38. The wind direction data for the 3 main weather zones of Sardinia (North, Centre and South) are not showed.

Climate Model and SSP	Years	N	NE	E	SE	S	SW	W	NW
		(% of days)	(% of days)	(% of days)	(% of days)	(% of days)	(% of days)	(% of days)	(% of days)
ACC	1985-2014	4.82	7.99	9.87	24.14	9.24	9.38	16.28	18.27
ACC126	2035-2064	5.69	5.38	10.65	19.51	7.18	6.69	18.11	26.80
ACC245	2035-2064	5.70	4.60	11.04	18.14	6.08	6.56	21.17	26.71
ACC585	2035-2064	5.47	7.18	9.81	17.59	5.98	5.57	23.13	25.26
ECH	1985-2014	3.75	2.97	9.03	21.93	15.52	11.24	10.97	24.60
ECH126	2035-2064	4.70	4.24	9.31	16.10	11.67	7.91	15.54	30.53
ECH245	2035-2064	3.97	4.77	6.99	19.01	11.97	8.84	13.90	30.55
ECH585	2035-2064	3.99	4.66	8.21	15.76	10.27	8.51	17.04	31.57
ERA5	1985-2014	3.41	2.35	2.68	19.15	14.86	18.60	16.38	22.56
MPI	1985-2014	5.04	5.66	20.69	28.03	11.93	7.09	5.95	15.63
MPI126	2035-2064	7.23	7.87	17.81	24.74	10.84	6.74	6.24	18.53
MPI245	2035-2064	7.84	7.00	16.11	22.46	13.17	8.35	6.10	18.98
MPI585	2035-2064	7.42	7.79	16.31	22.68	11.31	7.74	5.90	20.83

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8.3.3 Fuel mapping scenarios

The different land use types are used by the fire behaviour simulators in the form of fuels models. Fuel models are a stylised description of the vegetation, in a set of numerical parameters that physically characterise a fuel complex. There are different sets of fuel models in the literature, commonly used to calculate Rothermel 's (1972) surface fire spread model, being the most well-known the 13 standard fuel models (Anderson, 1982) and the new set of 40 models, proposed by Scott & Burgan (2005). Assigning a fuel model to a vegetation complex is a difficult task, usually overcome by experience, but doing so for future scenarios, with scarce information regarding the exact land use structure is very hard. Nevertheless, an exercise of cross matching was attempted for this work. The underlying idea was to firstly assign each Land Use class to one of the FirEUrisk fuel types developed in WP 1. Then, whenever possible, use the crosswalk table proposed in Aragoneses et al. (2023). This process had two complementary phases:

- Future Land Use (LU) scenarios (Developed by VUA for Deliverable 3.2 - Continental land-use change scenarios and stylised fuel management scenarios for the 21st century): Future LU scenarios were simulated using CLUMondo, a spatially explicit and dynamic land system change model using SSP1 (“Sustainability”) and SSP3 (“Regional rivalry”). In brief, CLUMondo is the latest generation in the CLUE model framework used to simulate future land system scenarios based on predefined demands for goods and services (e.g. crops or livestock) while also considering local spatial characteristics and climate change. CLUMondo allocates future changes to land systems based on their allocation suitability using a series of input attribute values specific to certain land systems. These attributes reflect the land system’s individual suitability in local contexts, ability to provision specific goods, potential for a change in land use, susceptibility to neighbourhood effects, and restrictions to conversion. In combination with anticipated regional demands for goods and services produced by exogenous models (e.g., GLOBIOM), CLUMondo optimises potential solutions and allocates the results in a spatially explicit manner. For FirEUrisk, Project Partner 14 VUA developed a hybrid product of historical land use (from HILDA+) and future land use (from CLUMondo) which was scaled up to a 9km resolution (from the original 1km resolution datasets). For this deliverable (D3.6 - Future vulnerability and exposure to future fire, incl. changes along WUI), however, VUA provided the original 1km resolution dataset. Projected land use scenarios are very generic, and hard to reclassify into fuel types or fuel models. A rough approach was used, with the selection of average fuel types and fuel models. As the resolution of the land use projections is 1km, we opted for not having “non-fuel” cells, as it would distort the results of the simulations. Instead, we used fuel types and models that could represent the average condition more properly. Without any information on the type of forest represented, we selected “mixed” forests to represent this class.

- Using Dynamic Global Vegetation Models (DGVMs) scenarios to refine fuel type identification: DGVMs simulate the establishment, growth and mortality of natural and managed (agriculture, pastures and managed forests) vegetation and fire (ignition, spread and effects on vegetation). The dataset used contains simulated vegetation and fire variables using the LPJmLv5.6-SPITFIRE coupled vegetation-fire model. LPJmL is a DGVM, which simulates impacts of climate change and vegetation including carbon, water and energy fluxes, on land. SPITFIRE is a process-based fire model that is developed at the Potsdam Institute for Climate Impact Research (PIK) simulating ignitions, fire spread, fuel combustion and plant mortality at 9km scale covering the years 2000-2100. The models were forced

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with 5 climate models from the SSP1-2.6 and SSP3-7.0 climate scenarios (its downscaling to ~9km grid cell resolution) as well as the land-use projections corresponding to those climate scenarios (provided at ~9 km grid cell resolution). The variables provided in this dataset are at monthly and annual temporal resolution. The simulated changes in fire and vegetation spatio-temporal patterns are the result of changes in climate and land-use and subsequent fire-vegetation feedbacks. For PS3 (central region of Portugal), the DGVM projections, bands 6 (temperate summer-green broadleaved trees) and 11 (C3 temperate grasses) are the only ones that are representative. These two were deemed helpful in further refining the fuel type and fuel model attribution to each of the land use classes from the previous phase. For each of the reference years and each of the SSP scenarios, both bands were reclassified as follows:

a. Band 6 reclassified to 600 where percentage of cover is higher than 50%.
b. Band 11 reclassified to 1100 where percentage of cover is higher than 50%.

Note that using the threshold of "higher than 50%" eliminates the possibility of having a selection of band 6 and band 11 in the same cell. After the reclassification, and for each reference year and each SSP, a new raster was created from the sum of Band 6, Band 11 and Land Use. The new values for the pixels help identify the unique combination of input rasters. For example, a sum of 606 represents a cell with "Low-intensity forest" (class 6 from the Land Use layer) and "temperate summer-green broad-leaved trees" (reclassified band 6 (600) from DGVM). A value of 1107 represents "Medium-intensity forest" (class 7 from the Land Use layer) and "C3 temperate grasses" (reclassified band 11 (1100) from DGVM). The primary dataset used for the fuel type reclassification was Land Use and the DGVM bands were used to distinguish a few particular cases of forest type (broadleaves and conifers) and the understory when grasses are present. **Erro! A origem da referência não foi encontrada.** resumes the reclassification rules established. The first 21 classes are the ones representing the primary Land Use types reclassification. From class 600 onward the different combinations of Land Use and DGVM are shown, although the only ones that were used were i) the combination of "low, medium and high intensity forest" (from LU) with "temperate summer-green broad-leaved trees" (from DGVM) and ii) the combination of "low and medium intensity forest" (from LU) with "temperate grasses" (from DGVM). These are shown in blue in the table. All other combinations were not considered, as they do not offer enough reliability, so the original "Land Use" reclassification was used. To characterise High-intensity forest, a relation to FirEUrisk "Closed mixed forest" was established, but in terms of fuel model, instead of the TU5 (Very High Load, Dry Climate Timber-Shrub) of the reclassification proposed by Aragoneses *et al.* (2023), we opted for a grass-shrub model (GS2). This seemed more realistic when performing the initial simulation tests. Without any information regarding the structure of the forests, no crown fuels were included in the simulations. See table 8.5 for further details.

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Table 8.5 Correspondence table to assess Scott & Burgan fuel models. Classes 0 to 21 represent the main classification using Land Use projections. Classes in the range of 600 and 1100 represent the combinations between LU and DGVM. In blue combinations effectively used, all other in these range were discarded.

Value	Land Use projections	DGVM projections	FirEURisk Fuel type	Scott & Burgan Fuel Model
0	Water	–	Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
1	Low-intensity urban (village landscape)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
2	Medium-intensity urban (peri-urban)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
3	High-intensity urban areas		Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
4	Low-intensity permcrops		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
5	High-intensity permcrops		Woody cropland	GR2 (Low Load, Dry Climate Grass)
6	Low-intensity forest		Open mixed forest	SH7 (Very High Load, Dry Climate Shrub)
7	Medium-intensity forest		Open mixed forest	SH7 (Very High Load, Dry Climate Shrub)
8	High-intensity forest		Closed mixed forest	GS2 (Moderate Load, Dry Climate Grass-Shrub)
9	Low-intensity grassland		Low grassland [0-0.3 m)	GR2 (Low Load, Dry Climate Grass)
10	Medium-intensity grassland		Medium grassland [0.3-0.7 m)	GR4 (Moderate Load, Dry Climate Grass)
11	High-intensity grassland		High grassland [≥ 0.7 m)	GR7 (High Load, Dry Climate Grass)
12	Low-intensity cropland		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
13	Medium-intensity cropland		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
14	High-intensity cropland		Woody cropland	GR2 (Low Load, Dry Climate Grass)
15	Forest/shrub and cropland mosaic		Medium shrubland [0.5-1.5 m)/ Low grassland [0-0.3 m)	GS2 (Moderate Load, Dry Climate Grass-Shrub)
16	Forest/shrub and grassland mosaics		Low shrubland [0-0.5 m)/ Medium grassland [0.3-0.7 m)	GS1 (Low Load, Dry Climate Grass-Shrub)
18	Medium-intensity agricultural mosaic		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
19	High-intensity agricultural mosaic		Woody cropland	GR2 (Low Load, Dry Climate Grass)
20	Shrub		Medium shrubland [0.5-1.5 m)	SH5 (High Load, Dry Climate Shrub)
21	Bare and rocks		Low grassland [0-0.3 m)	GR1 (Short, Sparse, Dry Climate Grass)
600	Water	Temperate summergreen broad-leaved tree	Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
601	Low-intensity urban (village landscape)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
602	Medium-intensity urban (peri-urban)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
603	High-intensity urban areas		Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
604	Low-intensity permcrops		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
605	High-intensity permcrops		Woody cropland	GR2 (Low Load, Dry Climate Grass)
606	Low-intensity Forest		Open broadleaf deciduous forest	SH5 (High Load, Dry Climate Shrub)
607	Medium-intensity Forest		Open broadleaf deciduous forest	SH5 (High Load, Dry Climate Shrub)
608	High-intensity forest		Closed broadleaf deciduous forest	GS2 (Moderate Load, Dry Climate Grass-Shrub)
609	Low-intensity grassland		Low grassland [0-0.3 m)	GR2 (Low Load, Dry Climate Grass)
610	Medium-intensity grassland		Medium grassland [0.3-0.7 m)	GR4 (Moderate Load, Dry Climate Grass)
611	High-intensity grassland		High grassland [≥ 0.7 m)	GR7 (High Load, Dry Climate Grass)

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612	Low-intensity cropland		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
613	Medium-intensity cropland		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
614	High-intensity cropland		Woody cropland	GR2 (Low Load, Dry Climate Grass)
615	Forest/shrub and cropland mosaic		Medium shrubland [0.5-1.5 m)/ Low grassland [0-0.3 m)	GS2 (Moderate Load, Dry Climate Grass-Shrub)
616	Forest/shrub and grassland mosaics		Low shrubland [0-0.5 m)/ Medium grassland [0.3-0.7 m)	GS1 (Low Load, Dry Climate Grass-Shrub)
618	Medium-intensity agricultural mosaic		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
619	High-intensity agricultural mosaic		Woody cropland	GR2 (Low Load, Dry Climate Grass)
620	Shrub		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
621	Bare and rocks		Woody cropland	GR2 (Low Load, Dry Climate Grass)
1100	Water	C3 temperate grasses	Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
1101	Low-intensity urban (village landscape)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
1102	Medium-intensity urban (peri-urban)		Urban discontinuous fabric	SH2 (Moderate Load Dry Climate Shrub)
1103	High-intensity urban areas		Nonfuel	GR1 (Short, Sparse, Dry Climate Grass)
1104	Low-intensity permcrops		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
1105	High-intensity permcrops		Woody cropland	GR2 (Low Load, Dry Climate Grass)
1106	Low-intensity forest		Open mixed forest	TU1 (Low Load Dry Climate Timber-Grass-Shrub)
1107	Medium-intensity forest		Open mixed forest	TU1 (Low Load Dry Climate Timber-Grass-Shrub)
1108	High-intensity forest		Closed mixed forest	GS2 (Moderate Load, Dry Climate Grass-Shrub)
1109	Low-intensity grassland		Low grassland [0-0.3 m)	GR2 (Low Load, Dry Climate Grass)
1111	Medium-intensity grassland		Medium grassland [0.3-0.7 m)	GR4 (Moderate Load, Dry Climate Grass)
1112	High-intensity grassland		High grassland [≥ 0.7 m)	GR7 (High Load, Dry Climate Grass)
1113	Low-intensity cropland		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
1115	Forest/shrub and cropland mosaic		Medium shrubland [0.5-1.5 m)/ Low grassland [0-0.3 m)	GS2 (Moderate Load, Dry Climate Grass-Shrub)
1116	Forest/shrub and grassland mosaics		Low shrubland [0-0.5 m)/ Medium grassland [0.3-0.7 m)	GS1 (Low Load, Dry Climate Grass-Shrub)
1118	Medium-intensity agricultural mosaic		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
1119	High-intensity agricultural mosaic		Woody cropland	GR2 (Low Load, Dry Climate Grass)
1120	Shrub		Herbaceous cropland	GR4 (Moderate Load, Dry Climate Grass)
1121	Bare and rocks		Woody cropland	GR2 (Low Load, Dry Climate Grass)

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For the Sardinia DA, the surface fuels were derived from three different maps of land use (Figure 8.8): the Corine Land Cover 2018 (CLC 2018) and the land use (LU) scenarios, developed by VUA, consisting of the baseline map for the year 2015 (BSL 2015) and the future land use for the year 2050-SSP3 (LU 2050 SSP3). The Corine Land Cover and the 2015 baseline map were associated to historical conditions, the LU 2050-SSP3 map to future conditions. The SSP1 scenario was not considered for two main reasons: 1) the projected increase in urban and anthropic areas was in our opinion too high; 2) limited time to perform the whole set of simulations. The bioclimatic map of Sardinia (Canu et al. 2015) was also considered, but in this case the mesomediterranean class was subdivided into a dry mesomediterranean class and a sub-humid mesomediterranean class, to better consider spatial fuel moisture variability. The land use maps were resampled to 150 m and intersected with the bioclimatic map of the island: we then performed a reclassification to assign to each forest land use class & bioclimatic condition either a standard or custom surface fuel model (Anderson, 1982; Arca et al., 2009; Salis et al., 2013; Scott and Burgan, 2005), as shown in Table 8.6. The estimation of canopy metrics such as canopy cover, canopy bulk density, canopy base height, and canopy height for forest areas was conducted using data obtained from the National Inventory of Forests and Forest Carbon Sinks.

Table 8.6. Summary of the fuel type incidence (in % over the regional area) and reference surface fuel model used in Sardinia.

Fuel Types	Surface Fuel Model	CLC - 2018	BSL - 2015	LU - 2050 SSP3
		%	%	%
Rocks	NB1 (Scott and Burgan 2005)	0.22	0.57	0.57
Urban	NB1 (Scott and Burgan 2005)	2.91	5.30	7.12
Water	NB1 (Scott and Burgan 2005)	1.18	3.75	3.75
Grasslands	FM3 (Anderson 1982)	2.63	2.47	1.04
Permanent crops	GR4 (Scott and Burgan 2005)	2.67	3.29	9.00
Croplands	FM1 (Anderson 1982)	24.38	22.57	15.90
Agr. Mosaics	FM2 (Anderson 1982)	19.66	15.35	1.04
Thermomed Shrubs	SH5 (Scott and Burgan 2005)	8.75	4.02	6.36
Thermomed Forests	SH7 (Scott and Burgan 2005)	2.17	5.52	5.16
Mesomed Shrubs	SH2 (Scott and Burgan 2005)	20.07	8.45	20.54
Mesomed Forests	CMM (Arca et al. 2009, Salis et al. 2013)	15.37	28.70	29.53

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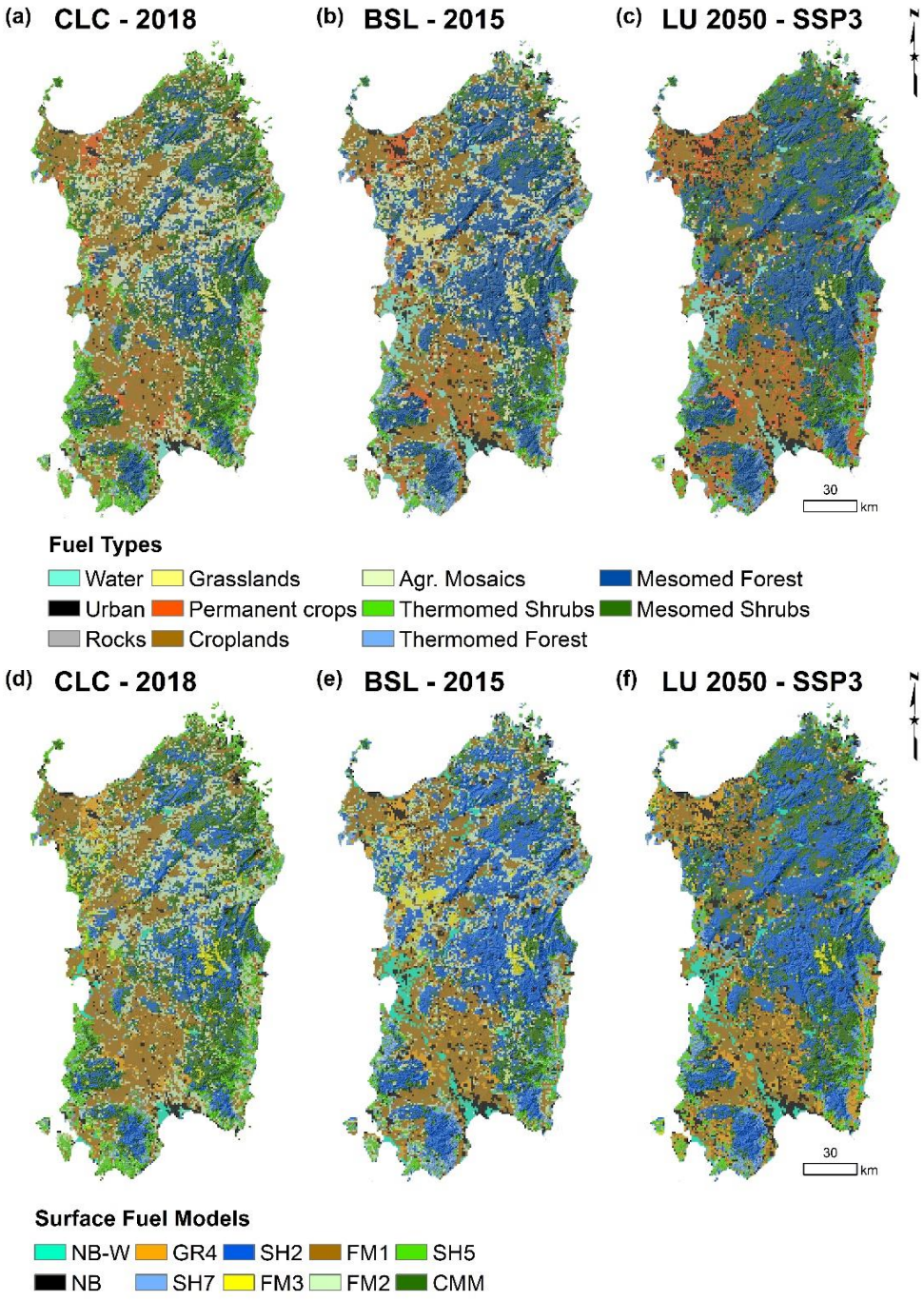


Figure 8.8. Vegetation types (a,b,c) and fuel models (d,e,f) of the study area (Sardinia DA) *considering CLC 2018, BSL 2015 and LU 2050 SSP3 scenarios*

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8.3.4 Fuel moisture scenarios

FMC is an important parameter when assessing fire behaviour. In modelling it is necessary to describe FMC in all the different fuel size classes and phenological states (live and dead). For its assessment, projections FFMC of the Canadian Fire Weather Index (FWI) were obtained from the Senckenberg Biodiversity and Climate Research Centre. The subindices were run with several climate models, including CNRM-ESM2 and MPI-ESM1-2, among others. These models can differ in how dry or wet they project the future to be, and where the changes occur. The subsets reflect the range of all climate models. These subsets are identified as "lower" for the wetter climate projections, "medium" for a model within the range, and "upper" for the driest projections. Following the same procedure as with climate variables, the summer period for the reference years was used for the FFMC analysis (1st June to 30th September). FlamMap requires FMC to be entered per fuel model. To accomplish this, The FFMC spatial variation was tabulated with the fuel maps and a statistical analysis per fuel model was produced. The “upper” datasets were used, as they represent the projections for driest scenarios, therefore the “worst case scenario”. FFMC is directly related to the dead fine fuels (1Hr) moisture content. Having this in mind, two fuel moisture scenarios were created, using FFMC percentiles 90 and 95, assuming they represent very high and extreme fire danger, respectively. These scenarios were created starting from the FFMC projections and following the approach described in Deliverable 1.1 for the remaining classes (Table 8.7).

Table 8.7. Rules to estimate FMC based on FFMC values (adapted from FirEUrisk A1.1.5)

1 Hr	10 Hr	100 Hr	Live Herbaceous	Live Woody
=101-FFMC	= 1 Hr + 1	=10 Hr + 1	If 1 Hr ≤ 4.5 then LH = 30% If 1 Hr ≤ 7.5 then LH = 60% If 1 Hr ≤ 10.5 then LH = 90% If 1 Hr > 10.5 then LH = 120%	= LH *2 = LH *1.5 = LH * 1.33 = LH * 1.25
Dimitrakopoulos et al. (2011)	Based on Scott & Burgan (2005)		Based on Scott & Burgan (2005) and Pettinari & Chuvieco (2017)	

For Sardinia DA, dead and live fuel moisture values were estimated by using the FFMC and the Drought Code (DC) as proxies of fuel moisture conditions. Considering that we focused our analysis on the days with FWI ≥38, in the most of cases FFMC and DC presented values corresponding to low and very low fuel moisture conditions, which reflect the conditions commonly associated to large wildfire spread in Sardinia. The dead fuel moisture values by using the data from Salis et al. 2021, 2015, 2023 and Pellizzaro et al. 2005, 2007, using fuel moisture data collected in Sardinia from field observations and fuel moisture sticks and corresponding to low/very low fuel moisture. These values ranged from 7 to 13% (1-h time lag dead fuels) to 11–17% (100-h time lag dead fuels), with a gradient from the driest to the moistest areas of the island, according to the Sardinia bioclimatic map. Live fuel moisture values were set using a time series of data collected in northern Sardinia from 2003 to 2024 and previous studies (Pellizzaro et al. 2007, 2009; Salis et al. 2015; Chuvieco et al. 2011) by considering the driest periods of the fire season (which is generally represented by the July–August months). Live FMC values ranged from 65% to 100%.

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8.4 Results

8.4.1 Central region of Portugal (PS3)

Table 8.8. Burn probability for the different scenarios for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Median	PCT95	PCT99
Burn Probability	SSP1	High	2020	0	0.0094	0.0010	0.0011	0.0007	0.0031	0.0056
			2030	0	0.0100	0.0011	0.0012	0.0007	0.0035	0.0066
			2040	0	0.0226	0.0023	0.0024	0.0017	0.0066	0.0131
			2050	0	0.0229	0.0021	0.0024	0.0014	0.0067	0.0123
		Very high	2020	0	0.0102	0.0011	0.0012	0.0008	0.0035	0.0057
			2030	0	0.0204	0.0025	0.0024	0.0018	0.0072	0.0117
			2040	0	0.0226	0.0023	0.0024	0.0017	0.0066	0.0131
			2050	0	0.0241	0.0025	0.0026	0.0018	0.0073	0.0134
	SSP3	High	2020	0	0.0187	0.0028	0.0028	0.0019	0.0086	0.0121
			2030	0	0.0205	0.0029	0.0030	0.0019	0.0094	0.0129
			2040	0	0.0205	0.0027	0.0029	0.0018	0.0091	0.0131
			2050	0	0.0204	0.0026	0.0028	0.0017	0.0087	0.0127
		Very high	2020	0	0.0203	0.0036	0.0032	0.0026	0.0107	0.0142
			2030	0	0.0208	0.0037	0.0034	0.0025	0.0109	0.0146
			2040	0	0.0216	0.0034	0.0034	0.0023	0.0111	0.0153
			2050	0	0.0217	0.0031	0.0031	0.0020	0.0099	0.0139

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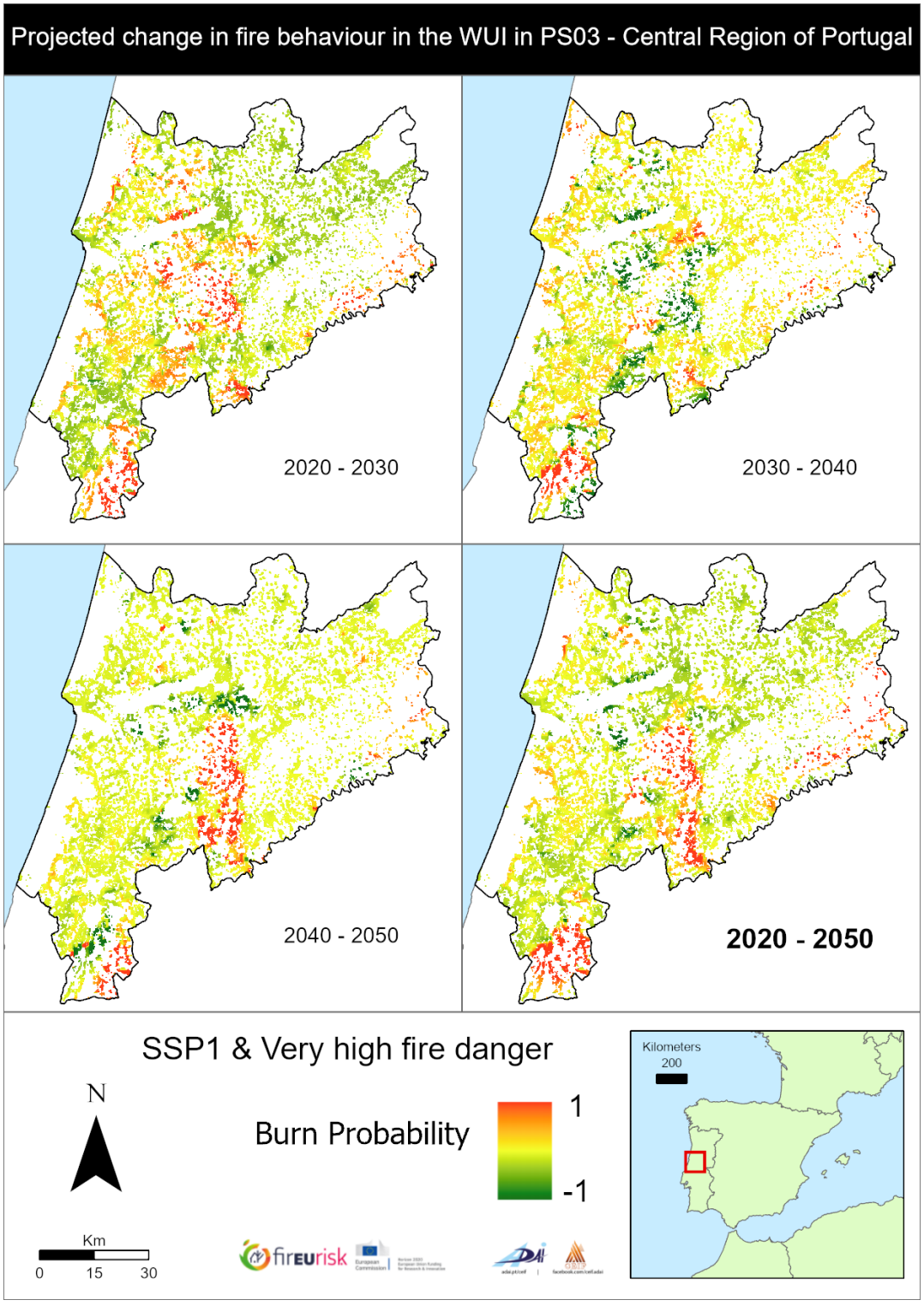


Figure 8.9. Burn probability changes between the reference years, for SSP1 and very high fire danger, for PS3 (Central region of Portugal)..

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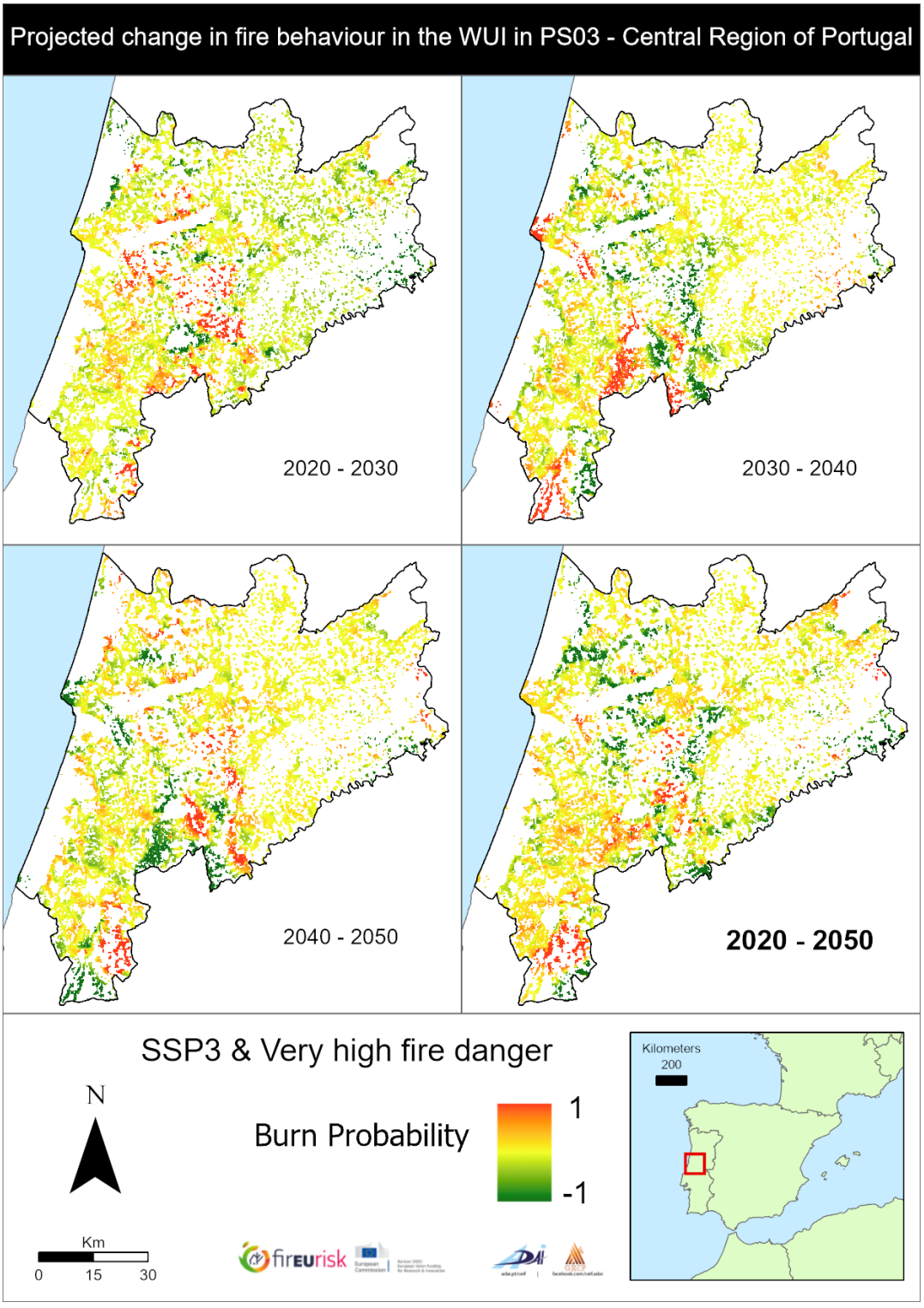


Figure 8.10. Burn probability changes between the reference years, for SSP3 and very high fire danger, for PS3 (Central region of Portugal)..

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Table 8.9. Burn probability changes between 2020 and 2050, for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Burn Probability	SSP1	High	0	+0.0135	+0.0011	+0.0013	+0.0007	+0.0036	+0.0068
		Very high	0	+0.0139	+0.0014	+0.0014	+0.0010	+0.0039	+0.0077
	SSP3	High	0	+0.0017	-0.0002	+0.0001	-0.0002	+0.0001	+0.0005
		Very high	0	+0.0015	-0.0006	-0.0001	-0.0005	-0.0008	-0.0003

Table 8.10. Conditional flame length for the different scenarios, for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Median	PCT95	PCT99
Conditional Flame Length (m)	SSP1	High	2020	0	5.1	1.0	0.5	0.9	1.8	2.9
			2030	0	6.0	1.1	0.5	1.0	1.9	3.1
			2040	0	6.5	1.4	0.5	1.3	2.3	3.6
			2050	0	5.6	1.4	0.5	1.3	2.3	3.6
		Very high	2020	0	5.1	1.0	0.5	1.0	1.9	2.9
			2030	0	6.1	1.3	0.6	1.2	2.3	3.6
			2040	0	6.5	1.4	0.5	1.3	2.3	3.6
			2050	0	6.5	1.5	0.5	1.4	2.4	3.7
	SSP3	High	2020	0	5.3	1.4	0.7	1.3	3.2	3.9
			2030	0	5.8	1.5	0.8	1.3	3.4	4.1
			2040	0	5.5	1.6	0.9	1.3	3.6	4.2
			2050	0	5.4	1.6	0.9	1.2	3.6	4.1
		Very high	2020	0	5.9	1.7	0.7	1.5	3.3	4.1
			2030	0	6.0	1.7	0.8	1.5	3.5	4.2
			2040	0	5.9	1.8	0.9	1.5	3.8	4.5
			2050	0	5.5	1.7	0.9	1.4	3.6	4.2

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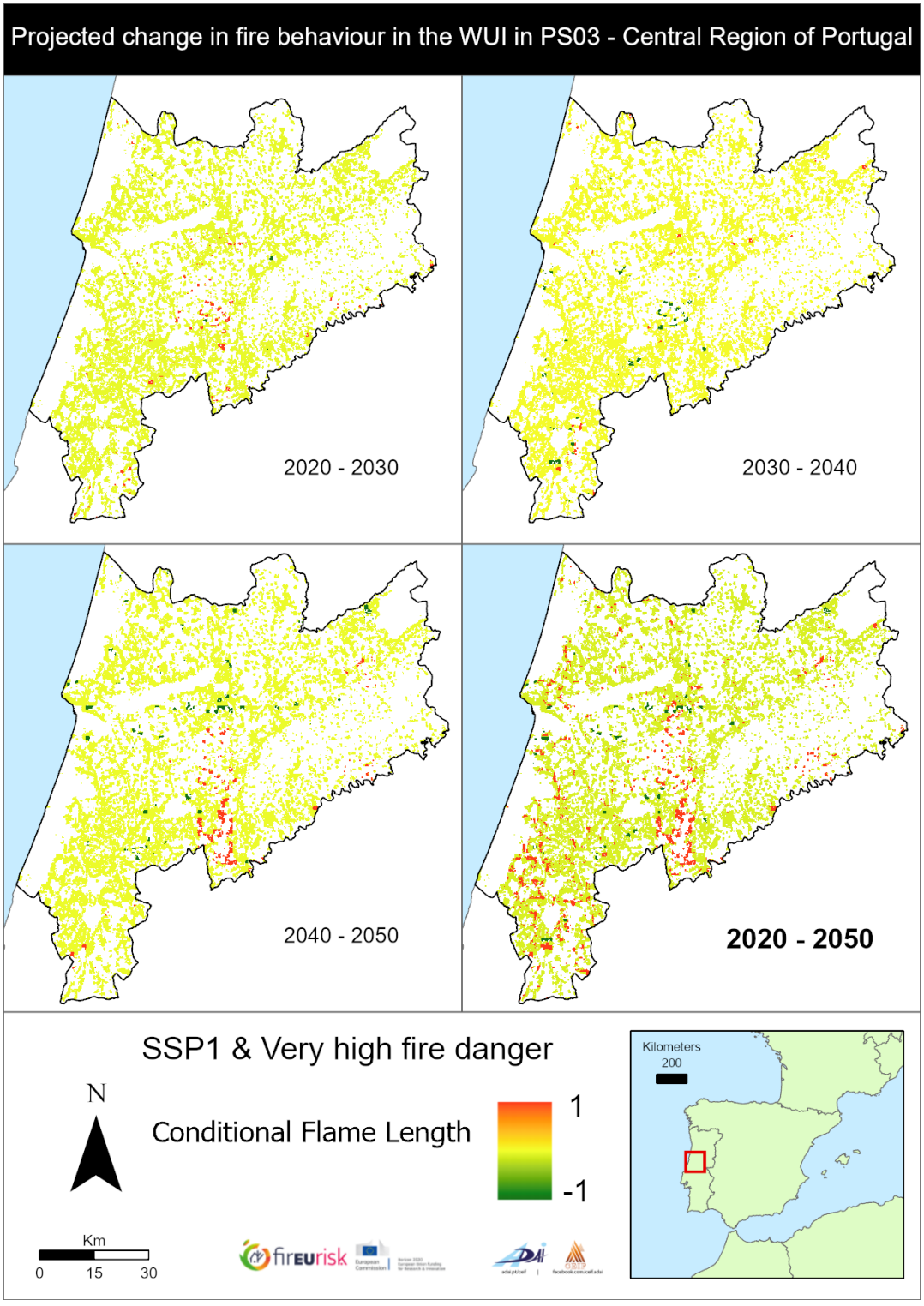


Figure 8.11. Conditional flame length changes between the reference years, for SSP1 and very high fire danger for PS3 (Central region of Portugal)..

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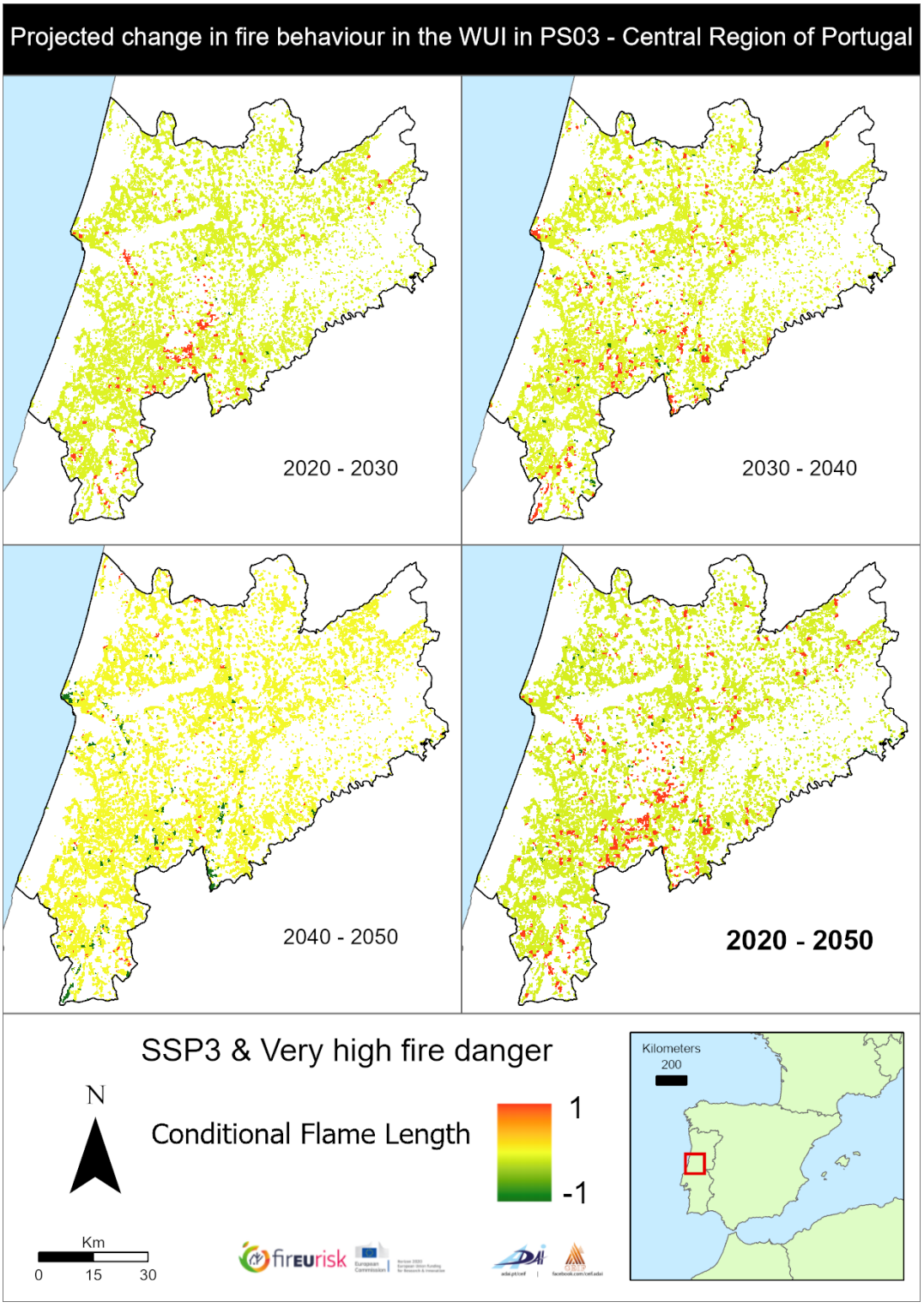


Figure 8.12. Conditional flame length changes between the reference years, for SSP3 and very high fire danger for PS3 (Central region of Portugal)..

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Table 8.11. Conditional flame length changes between 2020 and 2050 for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Conditional flame length (m)	SSP1	High	0	+0.5	+0.4	+0.0	+0.3	+0.5	+0.7
		Very high	0	+1.4	+0.4	+0.0	+0.4	+0.5	+0.8
	SSP3	High	0	+0.1	+0.1	+0.2	-0.0	+0.4	+0.2
		Very high	0	-0.3	+0.0	+0.2	-0.1	+0.3	+0.1

Table 8.12. Fire Intensity Level (FIL) for the different scenarios for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Majority	Majority %	Median	PCT95	PCT99
Fire Intensity Level	SSP1	High	2020	0	6	2.1	0.8	2	61	2	4	5
			2030	0	6	2.3	0.8	2	70	2	4	5
			2040	0	6	2.8	0.8	3	56	3	4	5
			2050	0	6	2.7	0.9	3	48	3	4	5
		Very high	2020	0	6	2.1	0.9	2	56	2	4	5
			2030	0	6	2.7	0.9	3	42	3	4	5
			2040	0	6	2.8	0.8	3	56	3	4	5
			2050	0	6	2.9	0.8	3	60	3	4	6
	SSP3	High	2020	0	6	2.8	1.0	2	41	3	5	6
			2030	0	6	2.9	1.2	2	40	3	5	6
			2040	0	6	3.0	1.3	2	40	3	5	6
			2050	0	6	3.0	1.3	2	41	3	5	6
		Very high	2020	0	6	3.2	1.0	3	59	3	5	6
			2030	0	6	3.2	1.1	3	46	3	5	6
			2040	0	6	3.3	1.2	3	46	3	6	6
			2050	0	6	3.2	1.2	3	44	3	5	6

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Table 8.13. Fire Intensity Levels in percentage of WUI area for PS3 (Central region of Portugal).

Socio Economic Path		SSP1								SSP3							
Fire danger (percentile)		High				Very high				High				Very high			
Year		2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Fire Intensity (% of WUI area)	1	20.8	20.2	6.9	4.8	4.3	4.3	3.8	3.2	4.9	3.8	5.1	3.5	4.5	3.1	4.1	3.1
	2	60.6	55.9	70.1	40.6	27.5	27.5	37.4	23.7	41.4	24.2	40.1	21.6	40.2	21.4	41.3	12.8
	3	13.5	18.3	16.8	41.7	55.9	55.9	47.8	60.0	28.2	44.3	29.6	45.8	32.8	46.4	36.0	59.0
	4	2.8	3.3	3.5	8.8	8.0	8.0	6.5	8.4	8.2	9.7	8.2	9.9	10.0	13.7	9.4	12.9
	5	2.2	2.2	2.3	3.3	3.4	3.4	3.7	3.7	13.4	13.6	13.1	13.1	9.4	12.0	7.3	9.7
	6	0.2	0.1	0.5	0.8	0.9	0.9	0.8	1.0	3.8	4.3	3.9	6.0	3.1	3.4	1.9	2.4

Table 8.14. Fire Intensity Level changes between 2020 and 2050 for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Fire Intensity Level	SSP1	High	0	+0.5	+0.4	+0.0	+0.3	+0.5	+0.7
		Very high	0	+1.4	+0.4	+0.0	+0.4	+0.5	+0.8
	SSP3	High	0	+0.1	+0.1	+0.2	-0.0	+0.4	+0.2
		Very high	0	-0.3	+0.0	+0.2	-0.1	+0.3	+0.1

Table 8.15. Rate of spread for the different scenarios. Rate of spread refers to the speed of fire progression (m/min) for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Median	PCT95	PCT99
Rate of spread (m/min)	SSP1	High	2020	0	59	6	7	4	21	29
			2030	0	88	6	7	4	20	32
			2040	0	96	9	9	7	29	42
			2050	0	82	8	8	6	27	40
		Very high	2020	0	60	7	7	5	23	31
			2030	0	92	10	11	7	35	49
			2040	0	96	9	9	7	29	42
			2050	0	100	9	9	7	30	44
	SSP3	High	2020	0	93	11	11	7	33	43
			2030	0	91	11	11	7	35	43
			2040	0	86	11	10	7	33	41
			2050	0	58	10	10	7	32	39
		Very high	2020	0	102	13	12	9	41	52
			2030	0	104	13	13	8	42	54
			2040	0	97	12	11	8	37	45
			2050	0	65	12	11	7	35	42

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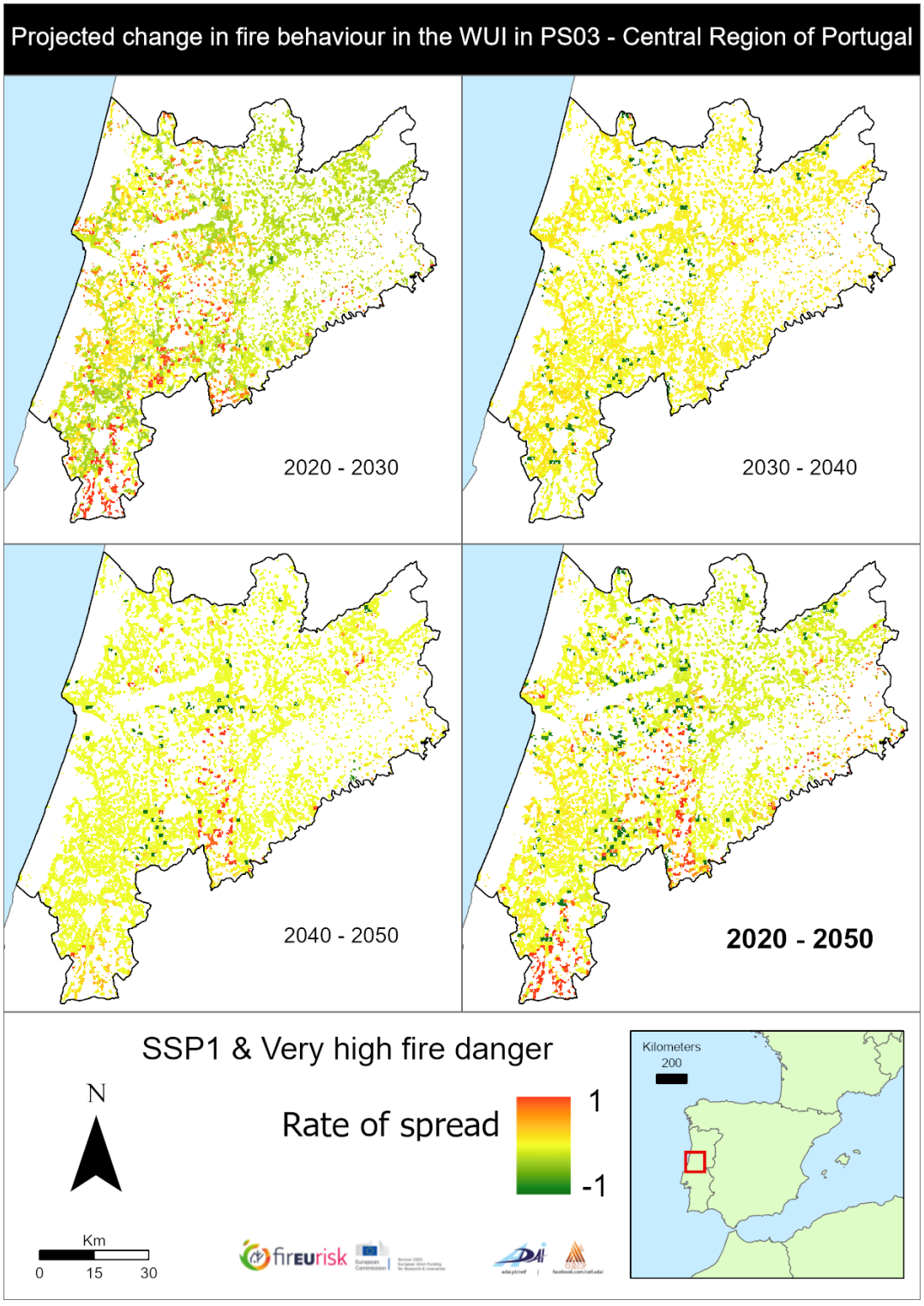


Figure 8.13. Rate of spread changes between the reference years, for SSP1 and very high fire danger for PS3 (Central region of Portugal).

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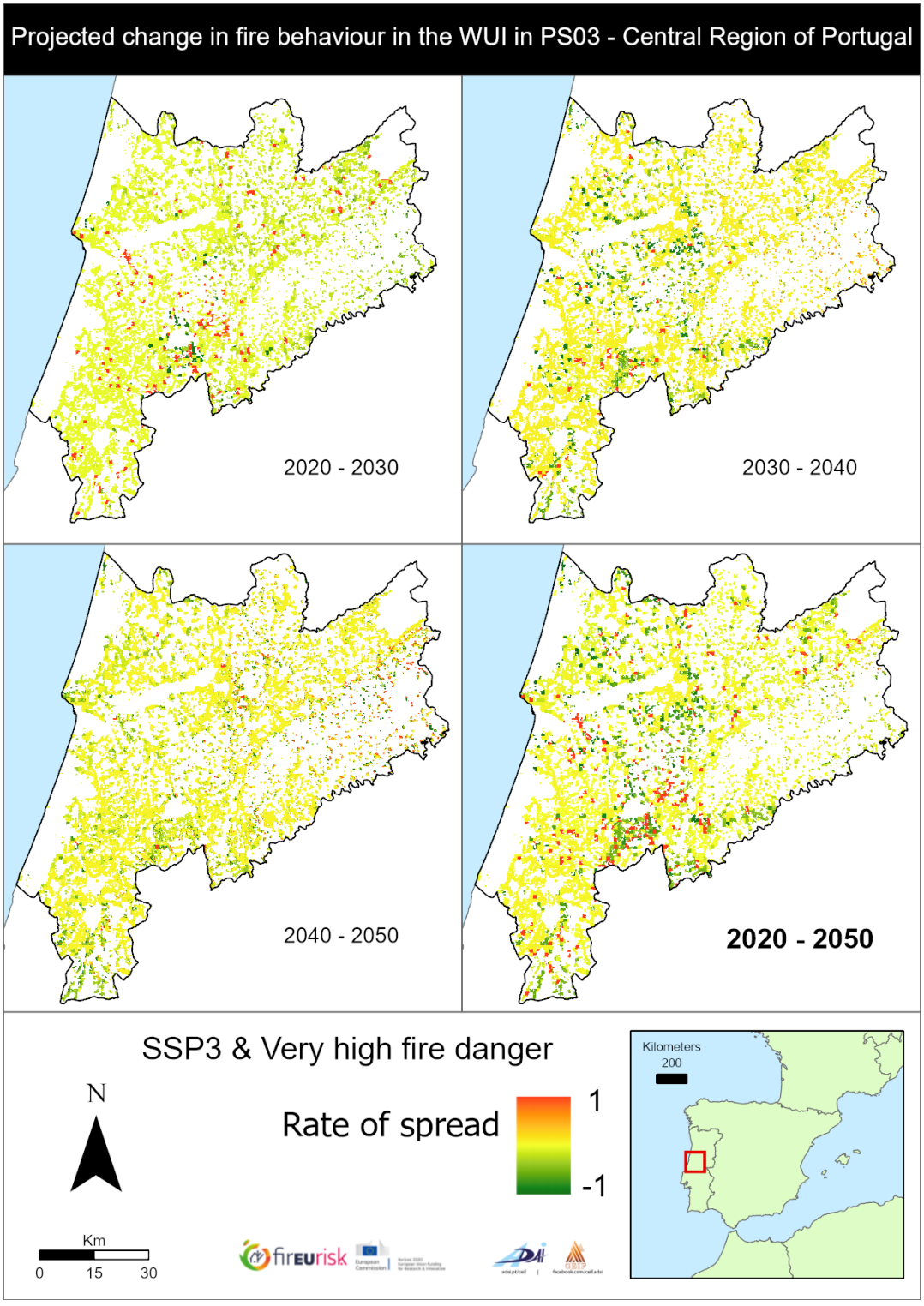


Figure 8.14. Rate of spread changes between the reference years, for SSP3 and very high fire danger for PS3 (Central region of Portugal)..

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Table 8.16. Rate of spread changes between 2020 and 2050 for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Rate of spread (m/min)	SSP1	High	0	+23	+2	+1	+2	+6	+12
		Very high	0	+41	+2	+2	+2	+7	+13
	SSP3	High	0	-36	-0	-0	-1	-2	-5
		Very high	0	-37	-1	-2	-1	-6	-10

Table 8.17. Fireline Intensity for the different scenarios for PS3 (Central region of Portugal). Fireline intensity, expressed in Kw/m, is an indicator of the difficulty of suppression and the type of wildfire.

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	M ax	Mean	Std	Median	PCT95	PCT99
Fireline Intensity (Kw/m)	SSP1	High	2020	0	18998	700	1486	348	2240	9181
			2030	0	27161	832	1959	371	2162	12905
			2040	0	32208	1284	2170	811	3259	13579
			2050	0	25369	1162	1897	712	3611	10881
		Very high	2020	0	19213	805	1655	445	2444	9871
			2030	0	28309	1314	2493	676	3754	15010
			2040	0	32208	1284	2170	811	3259	13579
			2050	0	33579	1385	2276	862	3975	13165
	SSP3	High	2020	0	31252	1714	2930	713	9364	13948
			2030	0	30515	1998	3304	689	10140	14594
			2040	0	28761	2306	3646	679	11008	14101
			2050	0	18223	2247	3525	656	10544	13432
		Very high	2020	0	34195	2134	3196	963	10479	14796
			2030	0	34720	2419	3582	982	11013	15877
			2040	0	32352	2649	3910	946	11962	15608
			2050	0	20806	2563	3756	885	11509	14599

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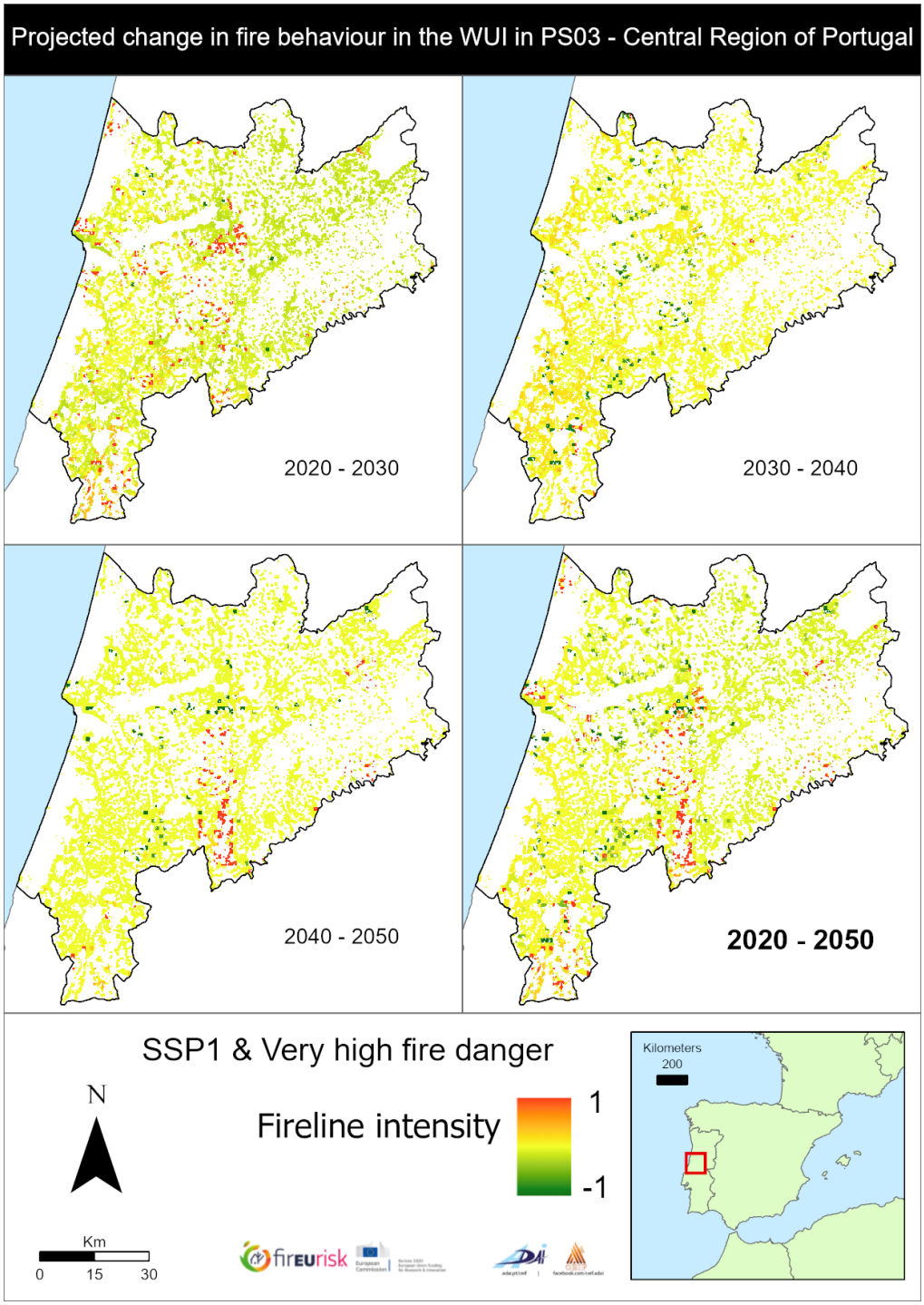


Figure 8.15. Fireline Intensity changes between the reference years, for SSP1 and very high fire danger, for PS3 (Central region of Portugal).

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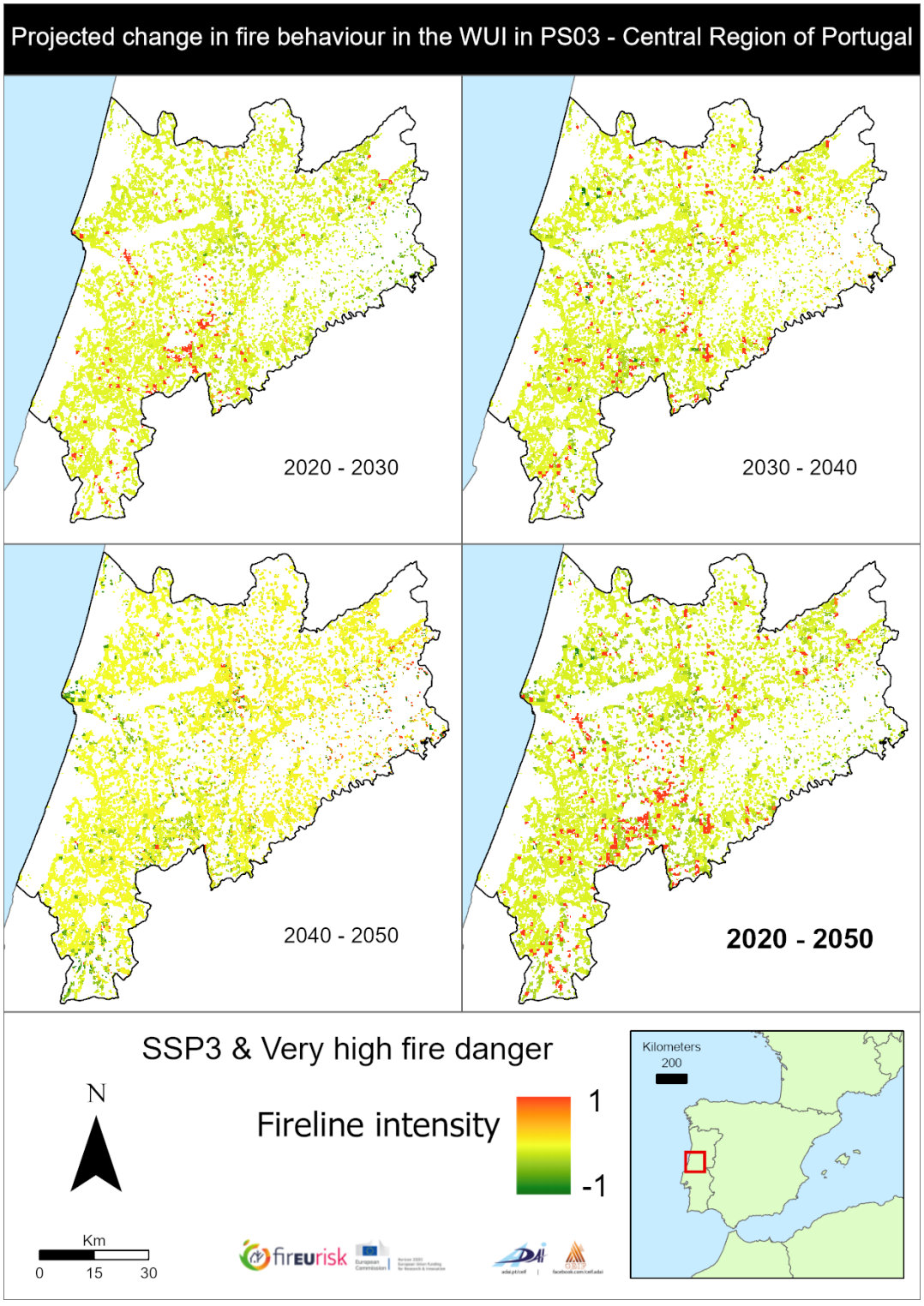


Figure 8.16. Fireline Intensity changes between the reference years, for SSP3 and very high fire danger, for PS3 (Central region of Portugal).

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Table 8.18. Fireline Intensity changes between 2020 and 2050, for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Fireline Intensity (Kw/m)	SSP1	High	0	+6371	+462	+411	+365	+1371	+1700
		Very high	0	+14366	+580	+621	+417	+1530	+3293
	SSP3	High	0	-13030	+533	+595	-57	+1180	-516
		Very high	0	-13389	+429	+560	-78	+1031	-196

Table 8.19. Flame Length for the different scenarios for PS3 (Central region of Portugal). Together with fireline intensity, flame length is often used to assess fire suppression capacity.

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Median	PCT95	PCT99
Flame Length (m)	SSP1	High	2020	0.0	7.2	1.3	0.9	1.1	2.7	5.2
			2030	0.0	8.5	1.4	0.9	1.2	2.7	6.0
			2040	0.0	9.2	1.8	0.9	1.7	3.2	6.2
			2050	0.0	8.2	1.8	0.9	1.6	3.4	5.6
		Very high	2020	0.0	7.2	1.4	0.9	1.3	2.8	5.3
			2030	0.0	8.7	1.8	1.0	1.6	3.4	6.5
			2040	0.0	9.2	1.8	0.9	1.7	3.2	6.2
			2050	0.0	9.4	1.9	0.9	1.7	3.5	6.1
	SSP3	High	2020	0.0	9.1	1.9	1.3	1.6	5.2	6.2
			2030	0.0	9.0	2.0	1.4	1.6	5.4	6.4
			2040	0.0	8.7	2.1	1.6	1.6	5.6	6.3
			2050	0.0	7.1	2.1	1.5	1.5	5.5	6.1
		Very high	2020	0.0	9.4	2.2	1.3	1.8	5.5	6.4
			2030	0.0	9.5	2.3	1.4	1.8	5.6	6.6
			2040	0.0	9.2	2.4	1.5	1.8	5.8	6.6
			2050	0.0	7.5	2.3	1.5	1.8	5.7	6.4

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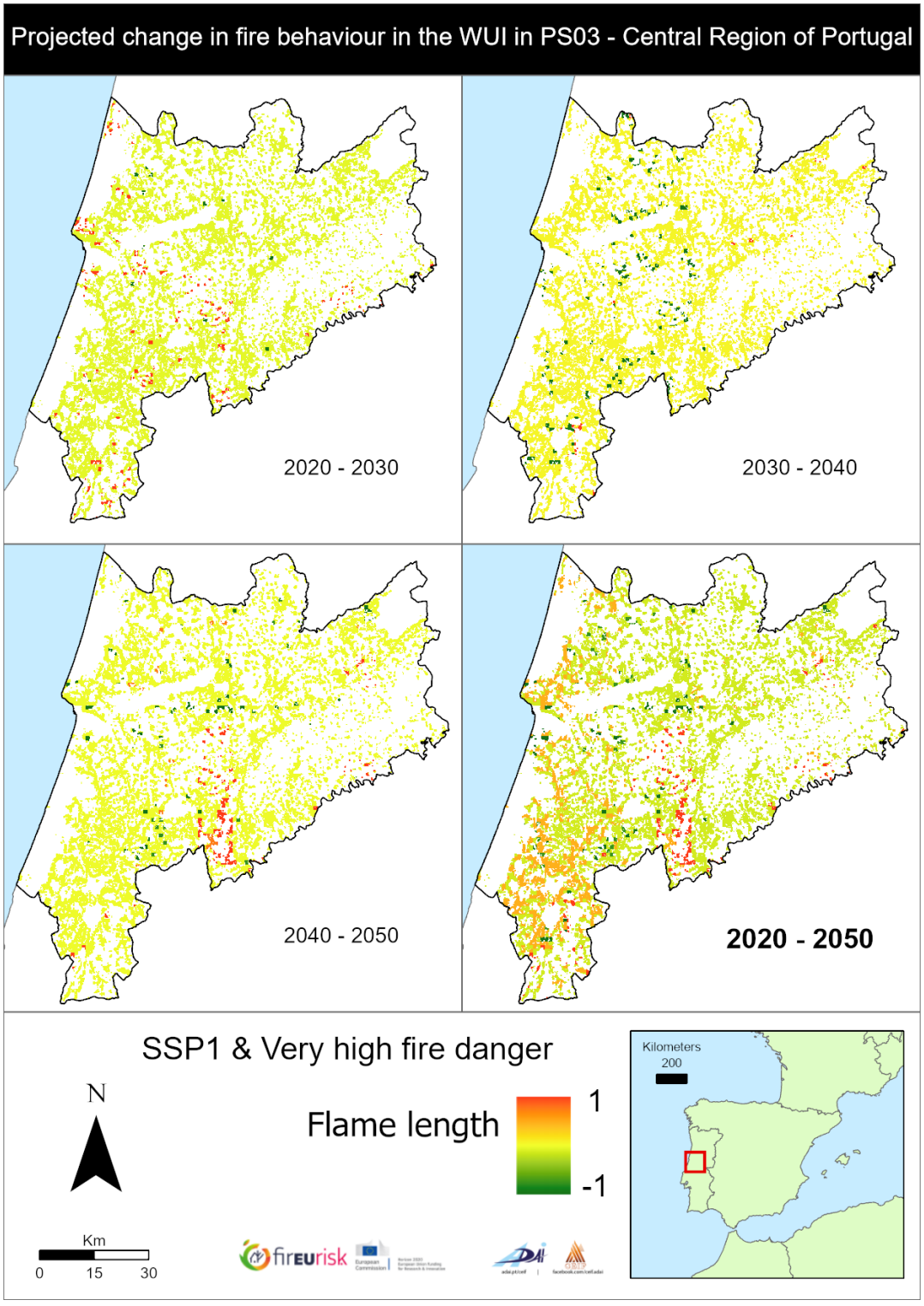


Figure 8.17. Flame Length changes between the reference years, for SSP1 and very high fire danger for PS3 (Central region of Portugal).

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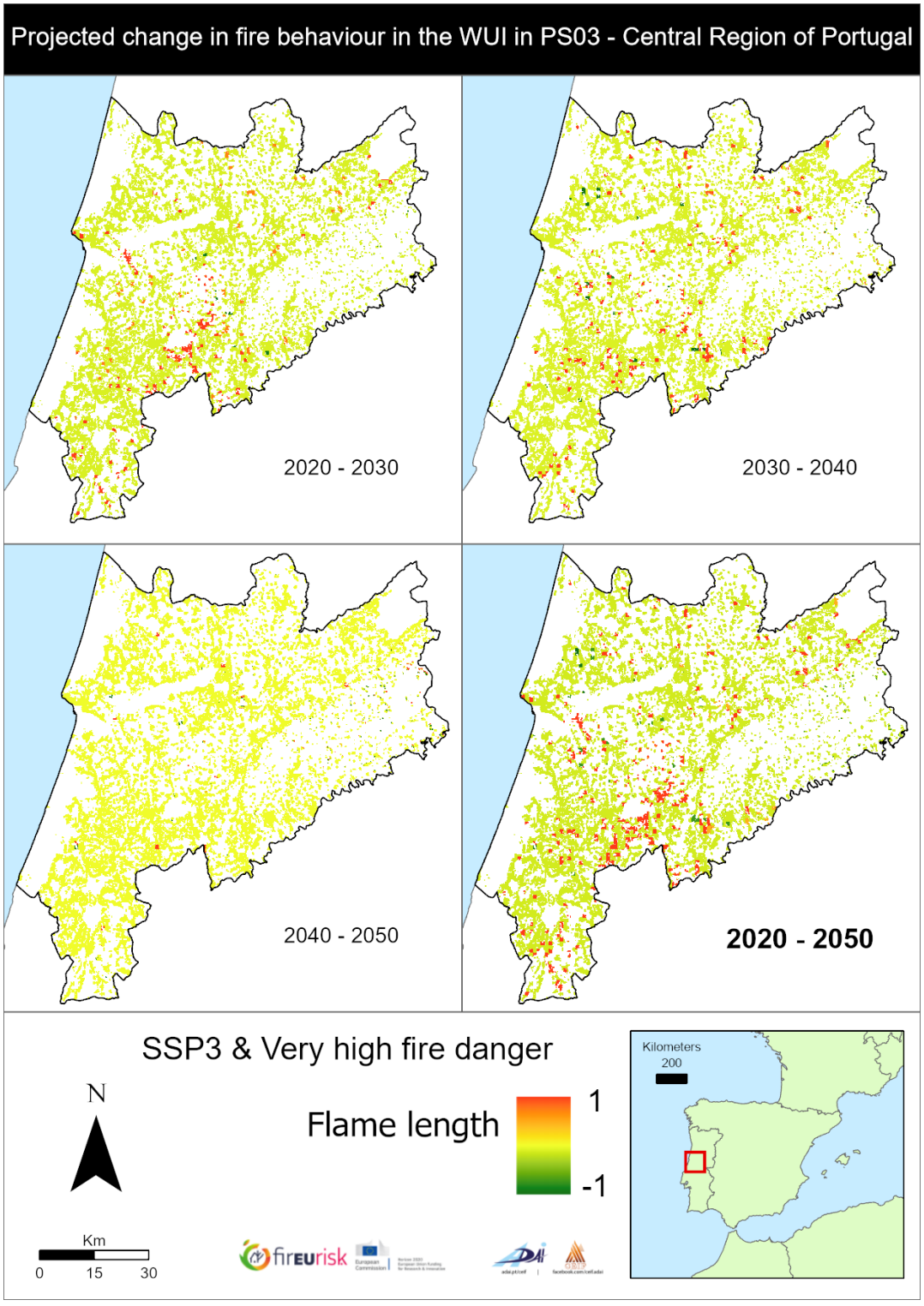


Figure 8.18. Flame Length changes between the reference years, for SSP3 and very high fire danger for PS3 (Central region of Portugal).

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Table 8.20. Flame Length changes between 2020 and 2050 for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Flame Length (m)	SSP1	High	0	+1.0	+0.5	-0.0	+0.4	+0.7	+0.4
		Very high	0	+2.1	+0.6	+0.0	+0.5	+0.7	+0.8
	SSP3	High	0	-2.0	+0.2	+0.3	-0.1	+0.3	-0.1
		Very high	0	-1.9	+0.1	+0.3	-0.1	+0.2	-0.0

Table 8.21. Heat Released for the different scenarios for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Year	Min	Max	Mean	Std	Median	PCT95	PCT99
Heat Released (KJ/m^2)	SSP1	High	2020	0.0	36382	5675	2868	5209	6050	19297
			2030	0.0	37967	5747	2891	5319	6050	19297
			2040	0.0	37967	7211	3914	5319	11387	18472
			2050	0.0	37967	7577	3888	6004	11387	20259
		Very high	2020	0.0	36382	9303	5496	6344	16545	21403
			2030	0.0	37967	9303	5496	6344	16545	21403
			2040	0.0	37967	9088	5489	6004	16029	28896
			2050	0.0	37967	9460	5616	6344	16545	28896
	SSP3	High	2020	0.0	37967	8623	5531	6004	20259	28896
			2030	0.0	37967	9893	6415	6004	20259	28896
			2040	0.0	37967	9203	6103	6004	20259	28896
			2050	0.0	37967	10484	6804	6004	20259	28896
		Very high	2020	0.0	37967	10181	6967	6004	28896	28896
			2030	0.0	37967	11421	7466	6004	28896	28896
			2040	0.0	37967	10228	7000	6004	28896	28896
			2050	0.0	37967	11460	7486	6004	28896	28896

Table 8.22. Heat Released changes between 2020 and 2050 for PS3 (Central region of Portugal).

Variable	Socioeconomic Path	Fire danger (percentile)	Min	Max	Mean	Std	Median	PCT95	PCT99
Heat Released (KJ/m^2)	SSP1	High	+1585	+1901	+1021	+795	+5337	+963	+1585
		Very high	+1585	+157	+120	0	0	+7493	+1585
	SSP3	High	0	+1861	+1273	0	0	0	0
		Very high	0	+1280	+519	0	0	0	0

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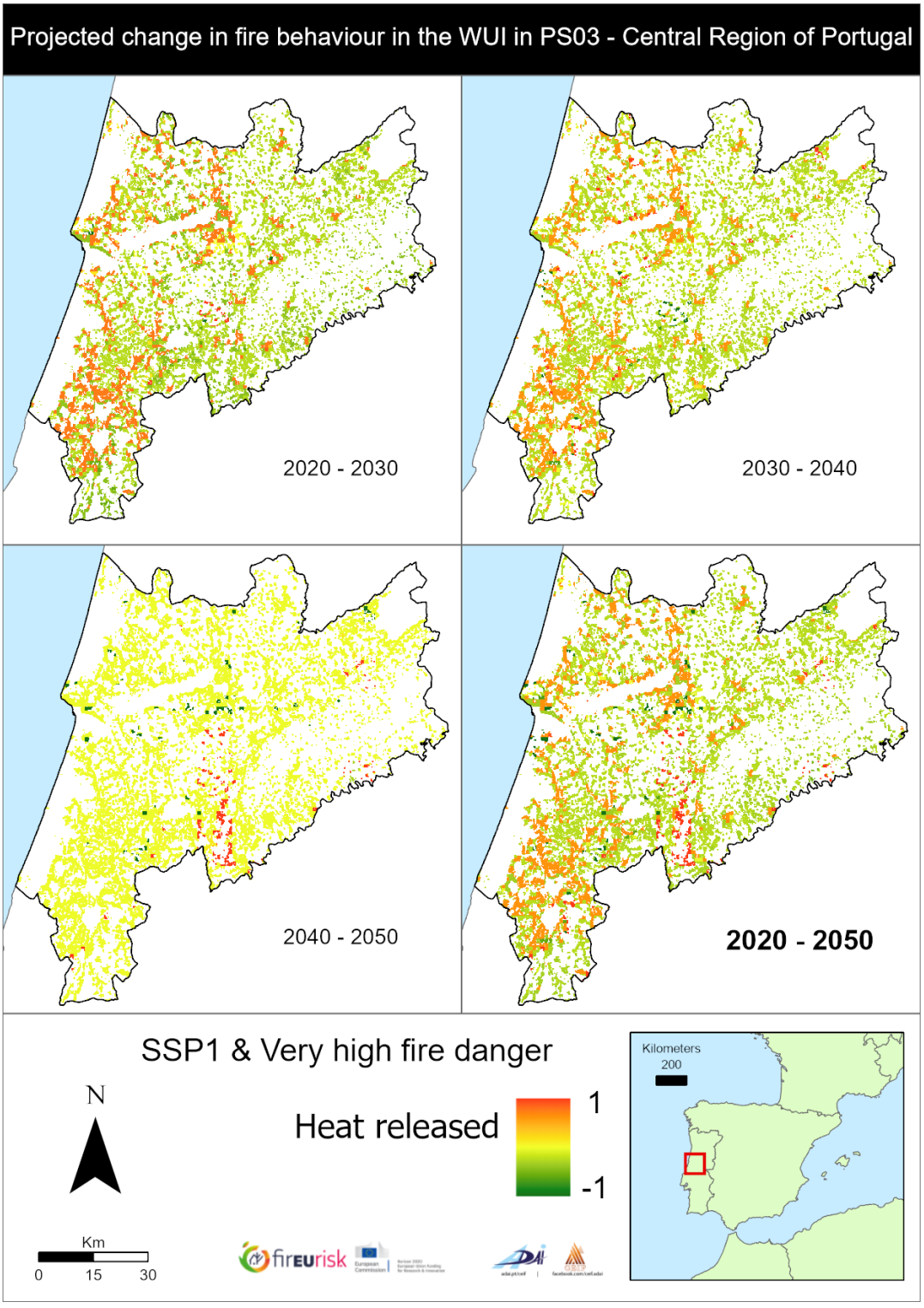


Figure 8.19. Heat Released changes between the reference years, for SSP1 and very high fire danger, for PS3 (Central region of Portugal).

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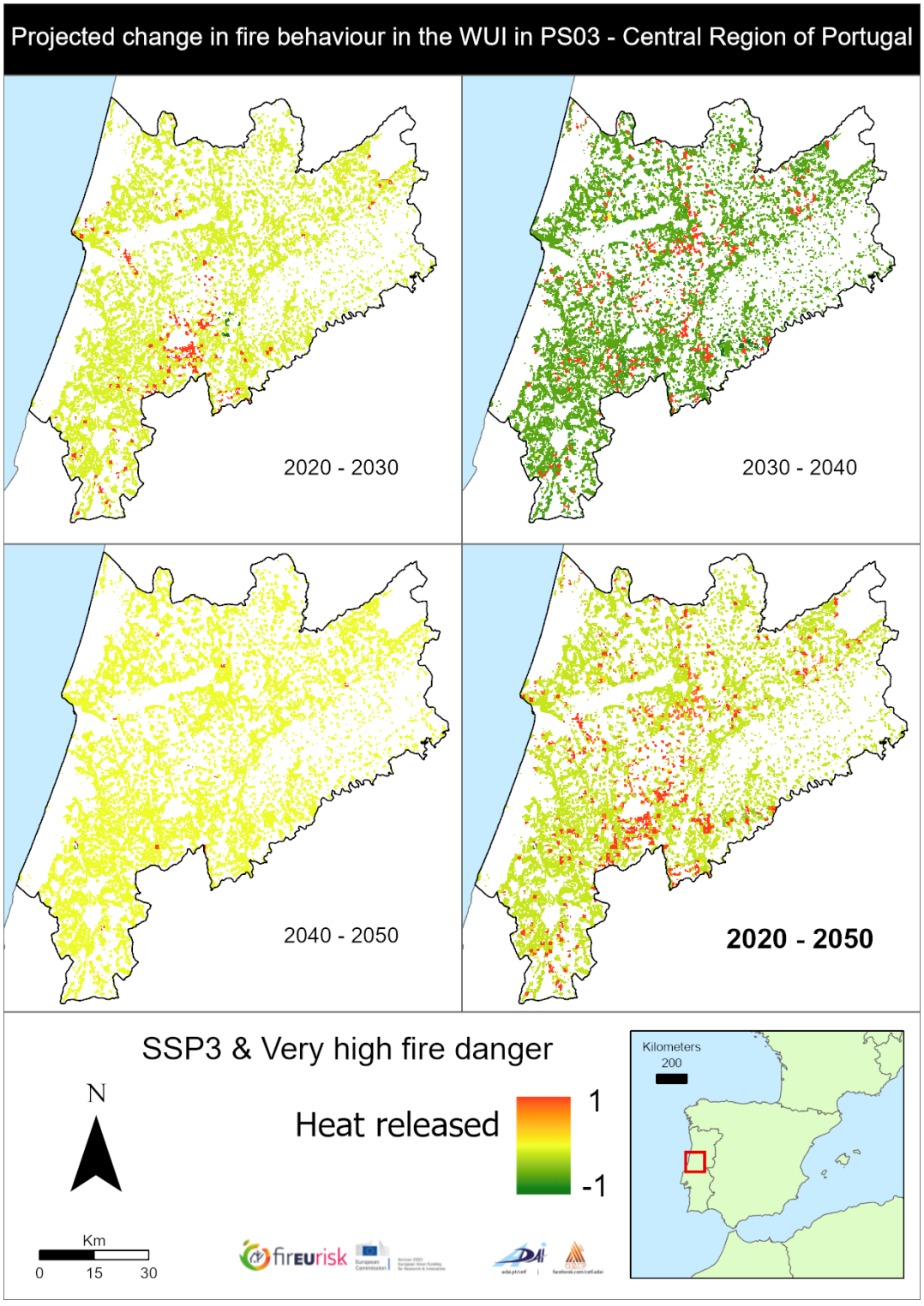


Figure 8.20. Heat Released changes between the reference years, for SSP3 and very high fire danger, for PS3 (Central region of Portugal).

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8.4.2 Attica Region of Greece (PS5)

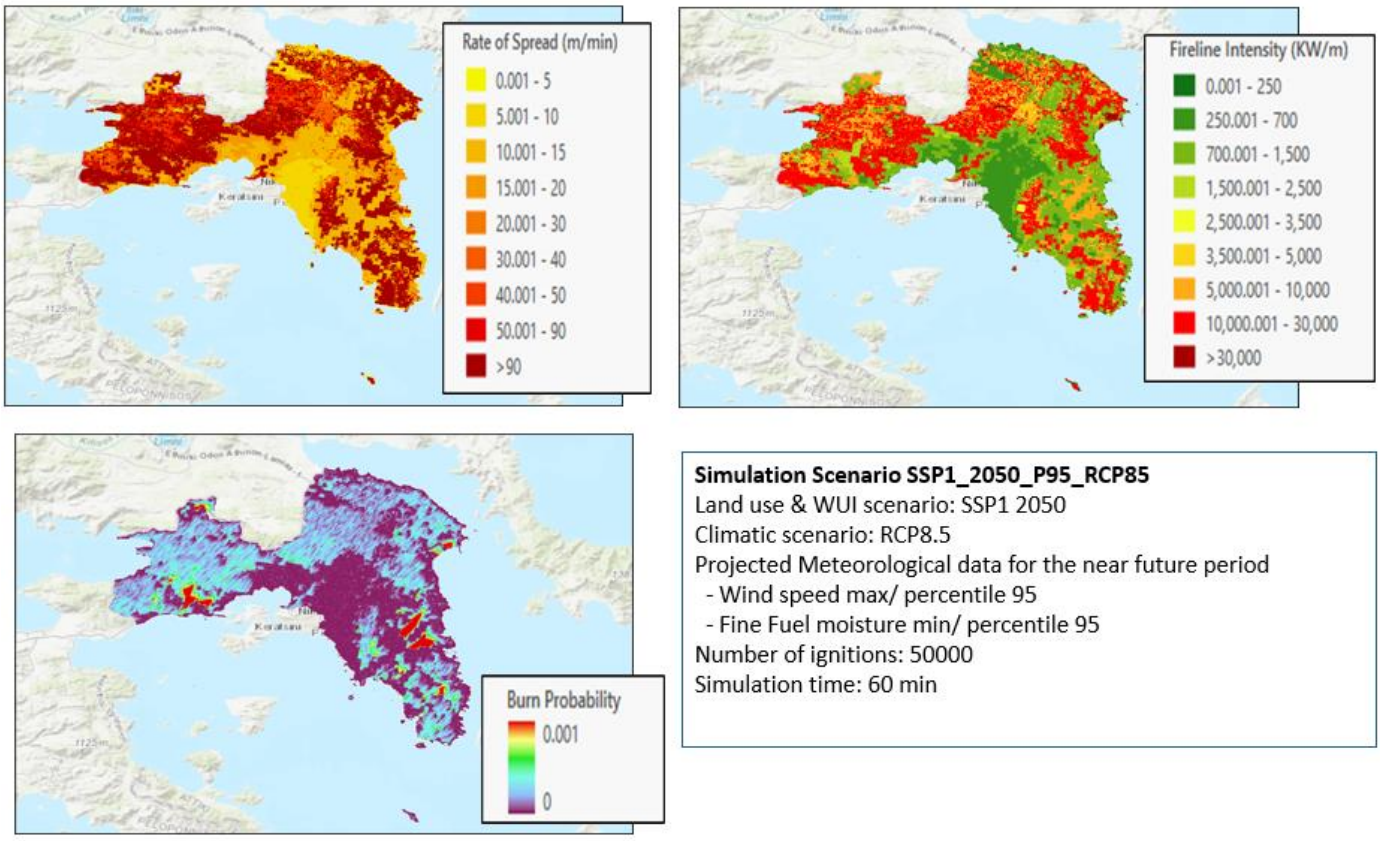


Figure 8.21: Maps of Rate of Spread, Fireline intensity and Burn Probability for the simulation scenario SSP1_2050_P95_RCP85, 60 min simulation time for PS5 (Attica region)

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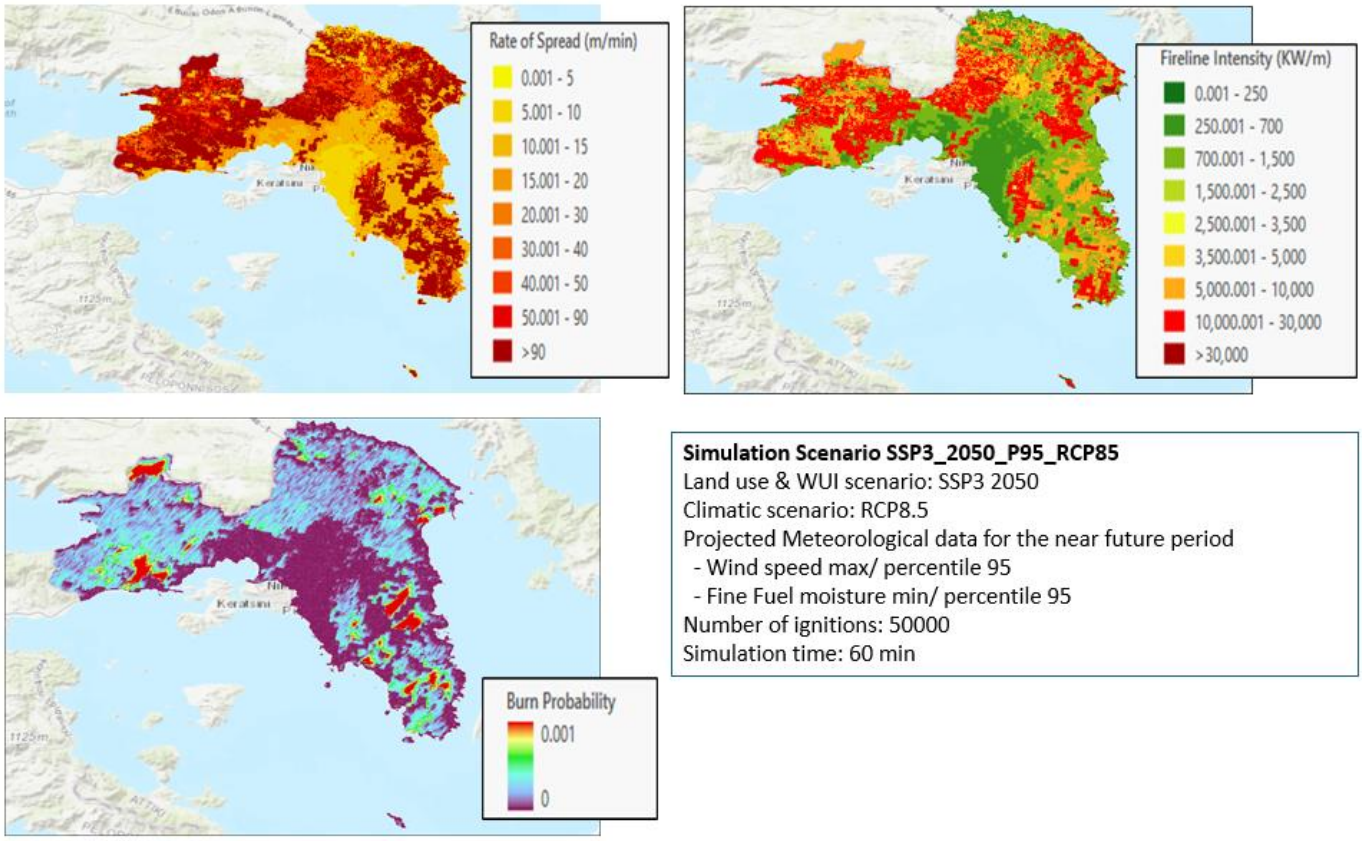


Figure 8.22: Maps of Rate of Spread, Fireline intensity and Burn Probability for the simulation scenario SSP3_2050_P95_RCP85, 60 min simulation time, for PS5 (Attica region).

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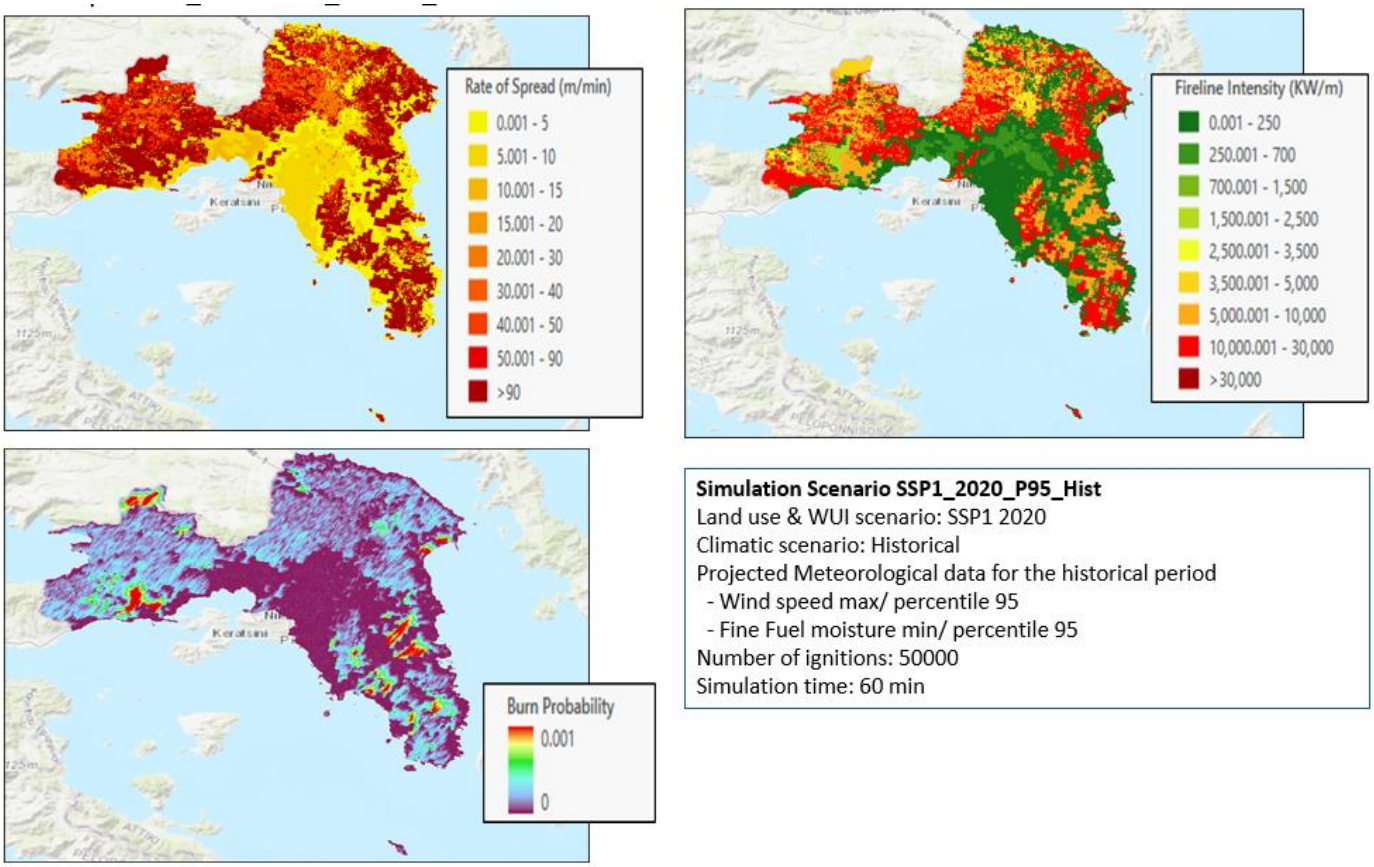


Figure 8.23: Maps of Rate of Spread, Fireline intensity and Burn Probability for the simulation scenario SSP1_2020_P95_Hist, 60 min simulation time for PS5 (Attica region).

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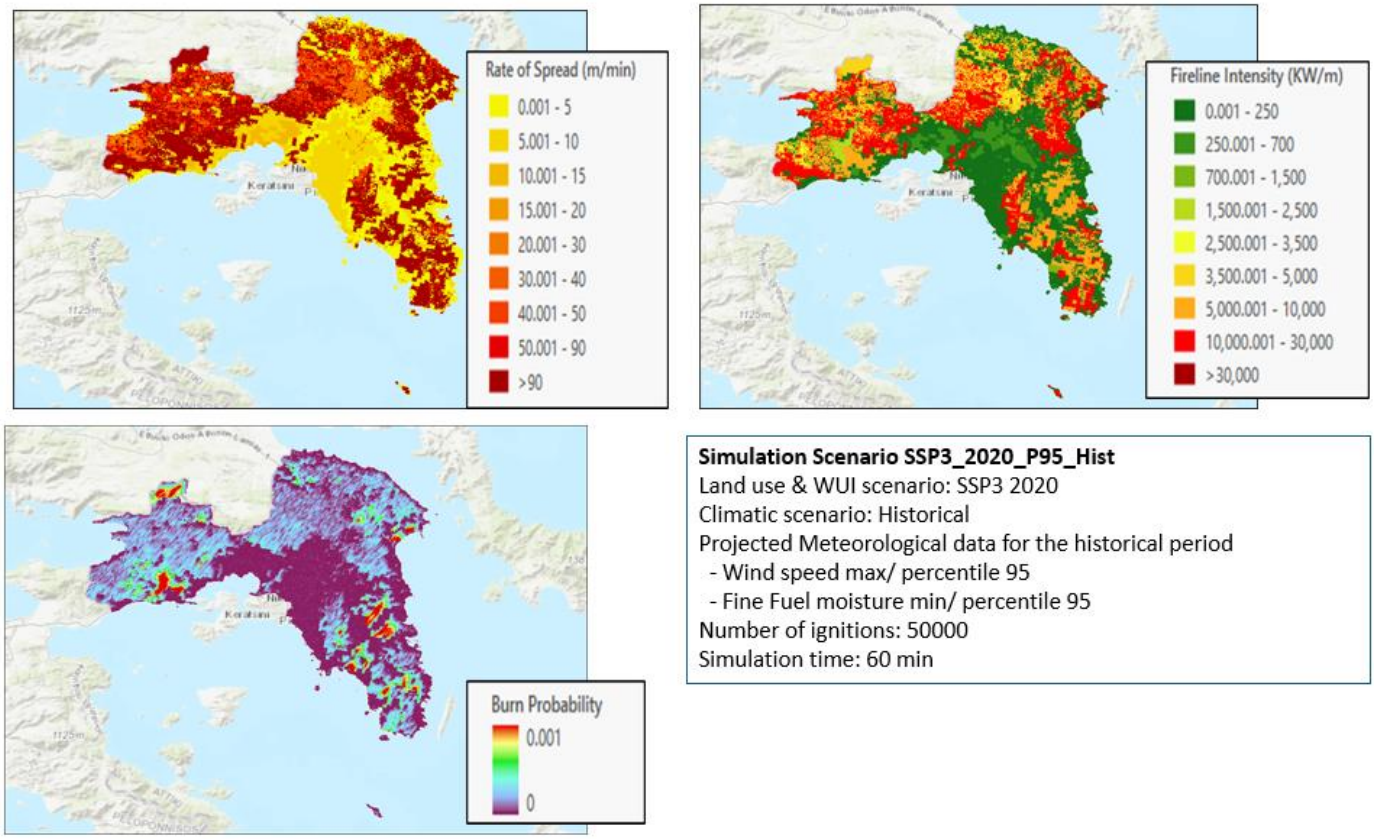


Figure 8.24. Maps of Rate of Spread, Fireline intensity and Burn Probability for the simulation scenario SSP3_2020_P95_Hist, 60 min simulation time for PS5 (Attica region).

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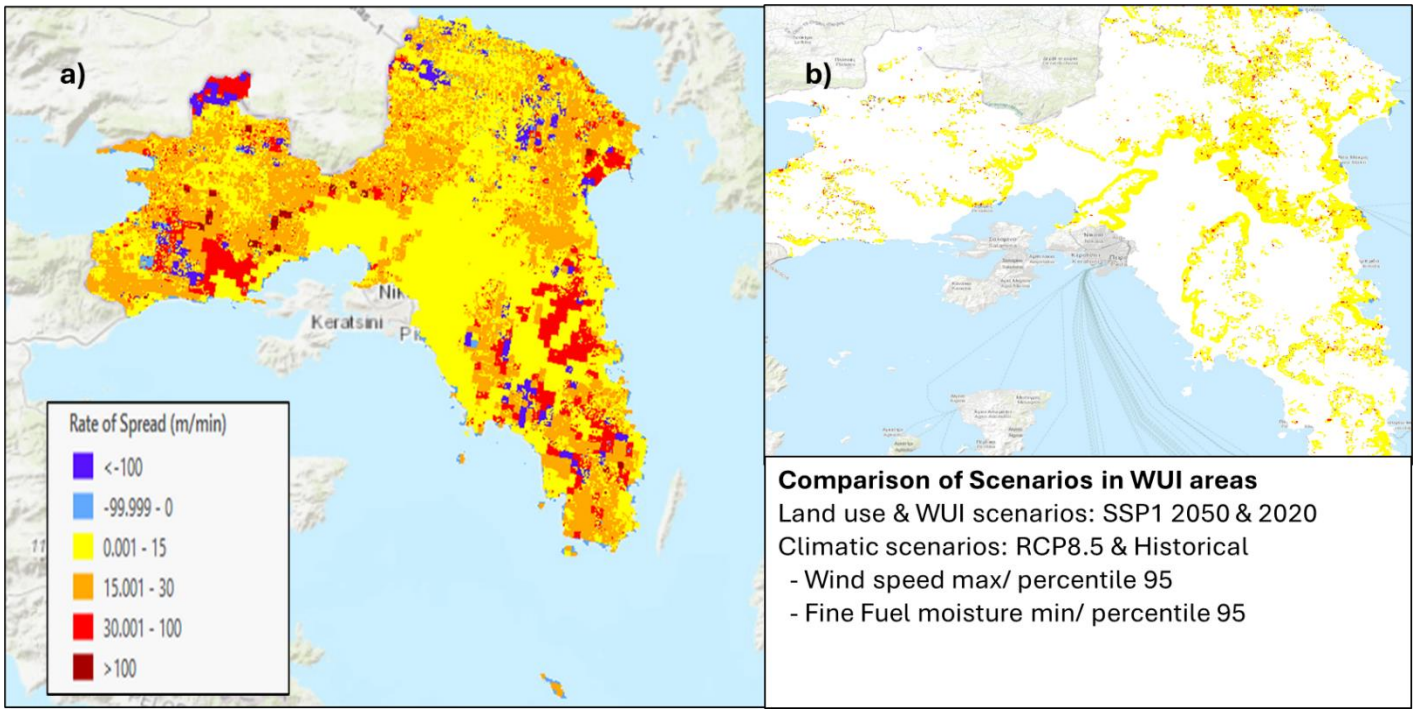


Figure 8.25. Maps of future changes of Rate of Spread a) for the whole area and b) only within the WUI areas, based on the simulation scenarios SSP1_2050_P95_RCP85 and SSP1_2020_P95_Hist, for PS5 (Attica region).

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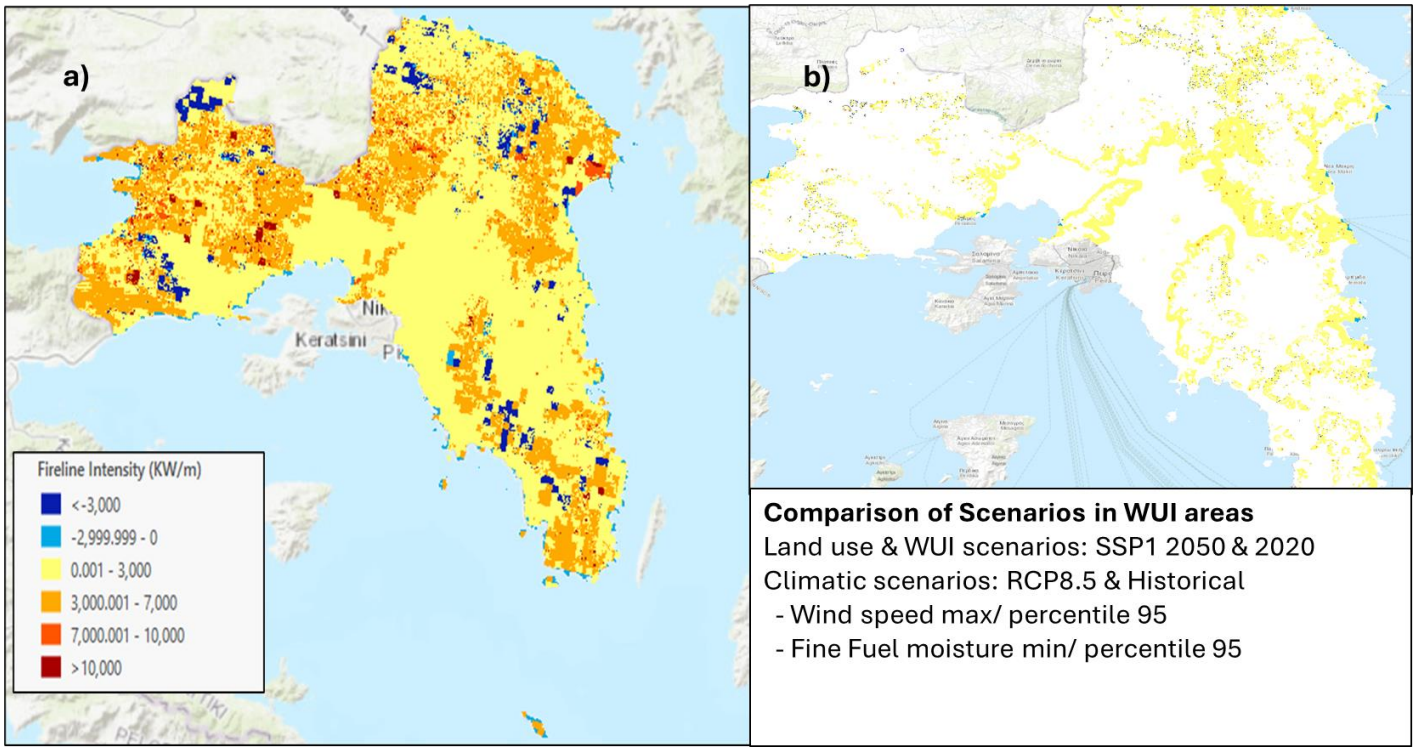


Figure 8.26. Maps of future changes of Fireline intensity a) for the whole area and b) only within the WUI areas, based on the simulation scenarios SSP1_2050_P95_RCP85 and SSP1_2020_P95_Hist, for PS5 (Attica region)

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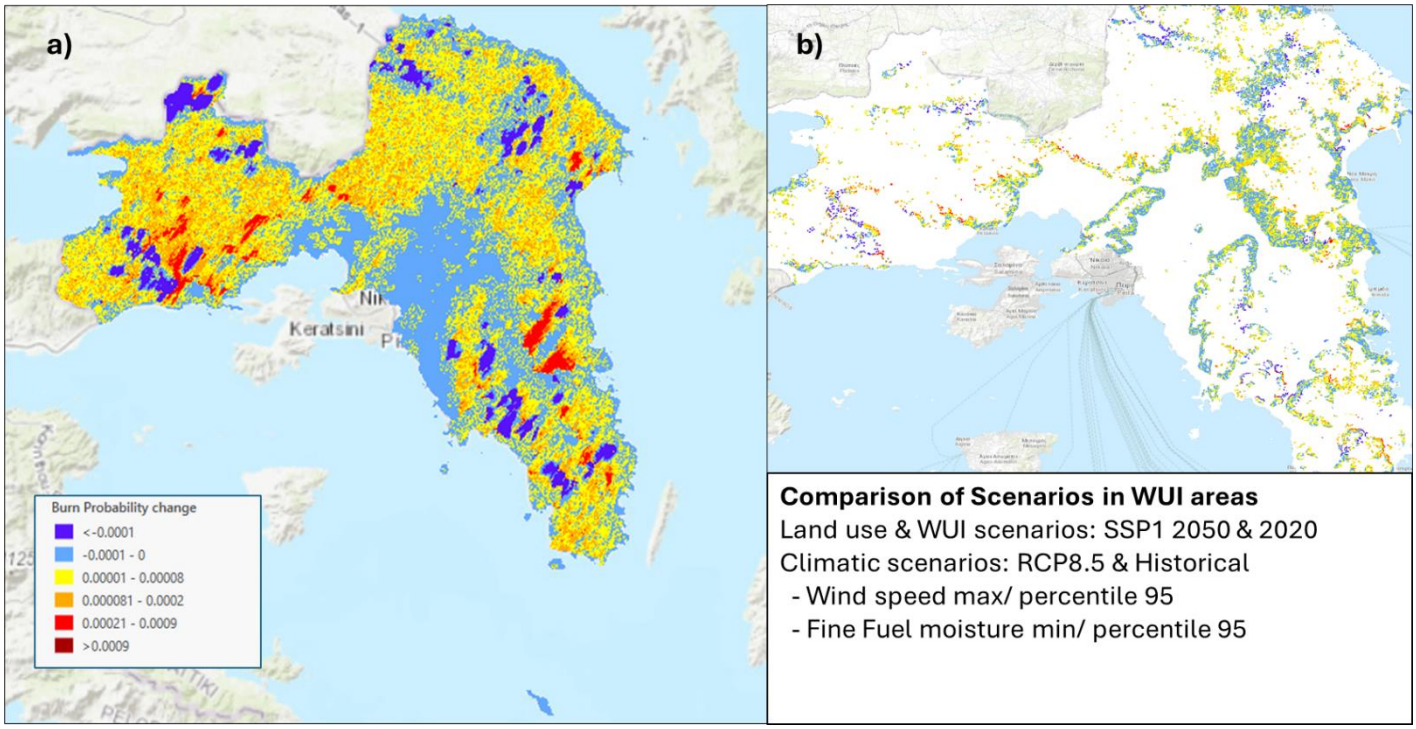


Figure 8.27. Maps of future changes of Burn Probability a) for the whole area and b) only within the WUI areas, based on the simulation scenarios SSP1_2050_P95_RCP85 and SSP1_2020_P95_Hist, for PS5 (Attica region).

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Table 8.23. Rate of Spread (m/min) within the WUI areas for each scenario, for PS5 (Attica region).

Scenario	Min	Max	Mean
ssp3-2050_p95_rcp45	1	402	18.2
ssp3-2050_p95_rcp85	2	420	18.6
ssp3-2050_p90_rcp85	1	383	14.1
ssp3-2050_p90_rcp45	1	380	14.02
ssp1-2050_p95_rcp45	2	361	18.18
ssp1-2050_p95_rcp85	2	364	18.38
ssp1-2050_p90_rcp45	2	361	12.2
ssp1-2050_p90_rcp85	2	364	12.4
ssp3-2020_p90_hist	1	359	15.77
ssp3-2020_p95_hist	1	353	17.70
ssp1-2020_p90_hist	1	355	6.49
ssp1-2020_p95-hist	1	352	7.42

Table 8.24. Fireline Intensity (kw/m) within the WUI areas for each scenario, for PS5 (Attica region).

Scenario	Min	Max	Mean
ssp3-2050_p95_rcp45	134	54,313	1217.76
ssp3-2050_p95_rcp85	136	55,388	1231.18
ssp3-2050_p90_rcp85	86	48,564	821.50
ssp3-2050_p90_rcp45	87	48,345	817.45
ssp1-2050_p95_rcp45	134	54,351	1243.07
ssp1-2050_p95_rcp85	136	55,388	1252.86
ssp1-2050_p90_rcp45	86	46,231	723.23
ssp1-2050_p90_rcp85	86	48,345	753.15
ssp3-2020_p90_hist	14	49,265	779.5
ssp3-2020_p95_hist	16	54,910	870.59
ssp1-2020_p90_hist	14	38,800	240.3
ssp1-2020_p95-hist	16	42,086	271.67

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Table 8.25. PS5 - Burned areas in hectares for each scenario in 60 minutes simulation time, for PS5 (Attica region).

Scenario	Average burned area (ha)	Standard Deviation (ha)	Maximum burned area (ha)
ssp1_2050_P95_rcp45	78.56819	94.77604	862
ssp1_2050_P95_rcp85	79.08237	95.04732	864
ssp1_2050_P90_rcp45	67.4523	89.5573	772
ssp1_2050_P90_rcp85	68.258	89.997	783
spp3_2050_P95_rcp45	93.16724	111.8069	862
ssp3_2050_P95_rcp85	93.90798	112.6723	865
ssp3_2050_P90_rcp45	85.4561	105.3428	768
ssp3_2050_P90_rcp85	86.1327	106.2861	786
ssp1_2020_P90_Hist	68.24484	84.83461	599
ssp1_2020_P95_Hist	71.47342	90.45642	671
ssp3_2020_P90_Hist	70.14436	88.51605	599
ssp3_2020_P95_Hist	73.45815	94.1777	671

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8.4.3 Sardinia (DA)

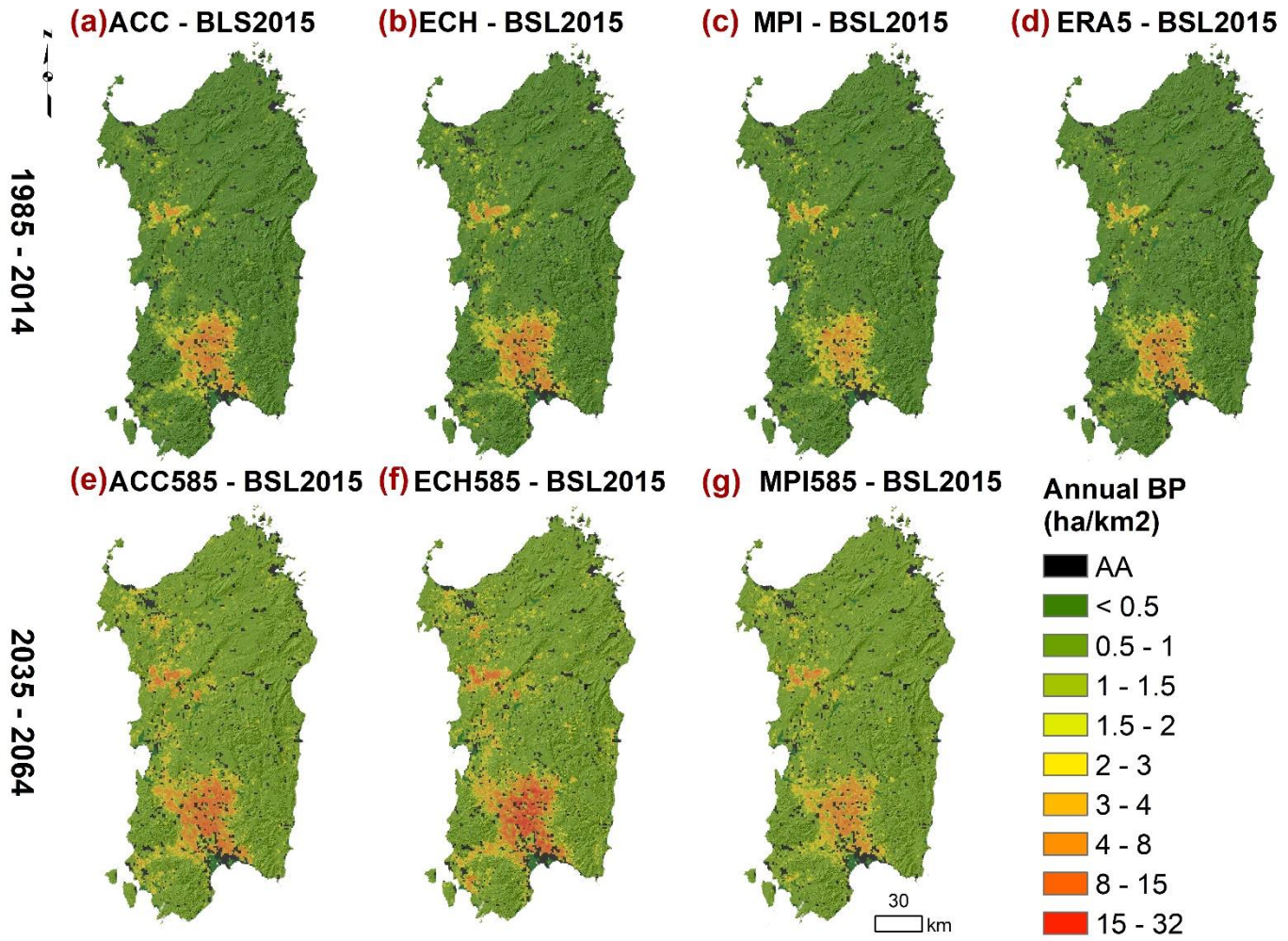


Figure 8.28. Maps of simulated aBP considering four climate models (ACC, ECH, MPI and ERA5) for both historical (1985-2014) and future (2035-2064) climate conditions, for Sardinia. The simulations were carried out using BSL2015 as reference land use for the landscape file.

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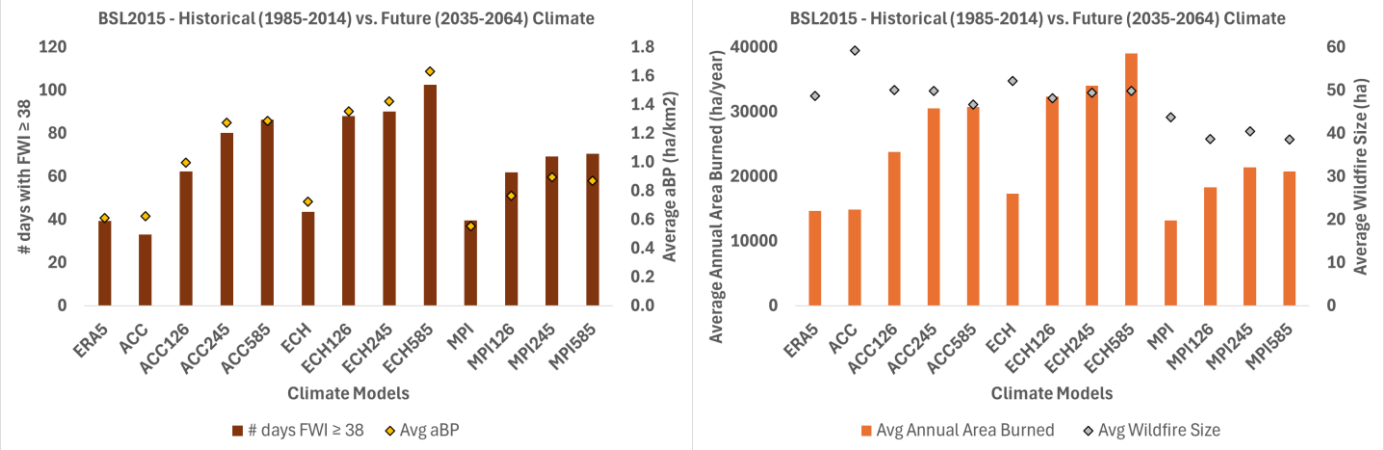


Figure 8.29. Role played by historical vs. future climate data and climate models on wildfire danger and average aBP (left figure) and on average annual area burned and average wildfire size (right figure) for the whole Sardinia, considering the 13 wildfire spread simulation modelling exercises performed using BSL2015 as reference for land uses and fuels.

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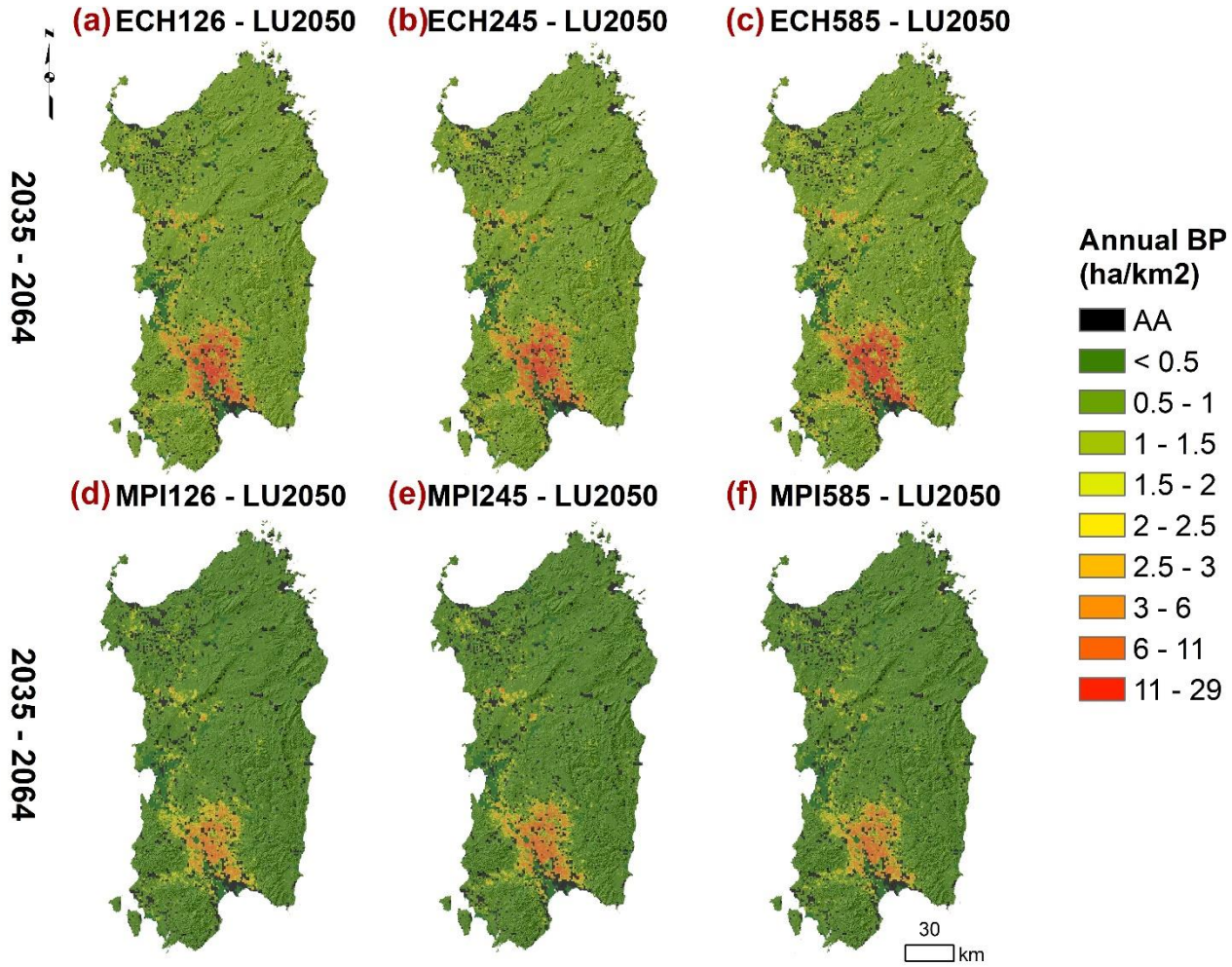


Figure 8.30. Maps of simulated aBP considering three different SSPs scenarios (126, 245, 585) for given climate models (ECH, upper figures, and MPI, bottom figures) for future (2035-2064) climate conditions, and LU2050-SSP3 as reference input for the creation of the landscape file, for Sardinia.

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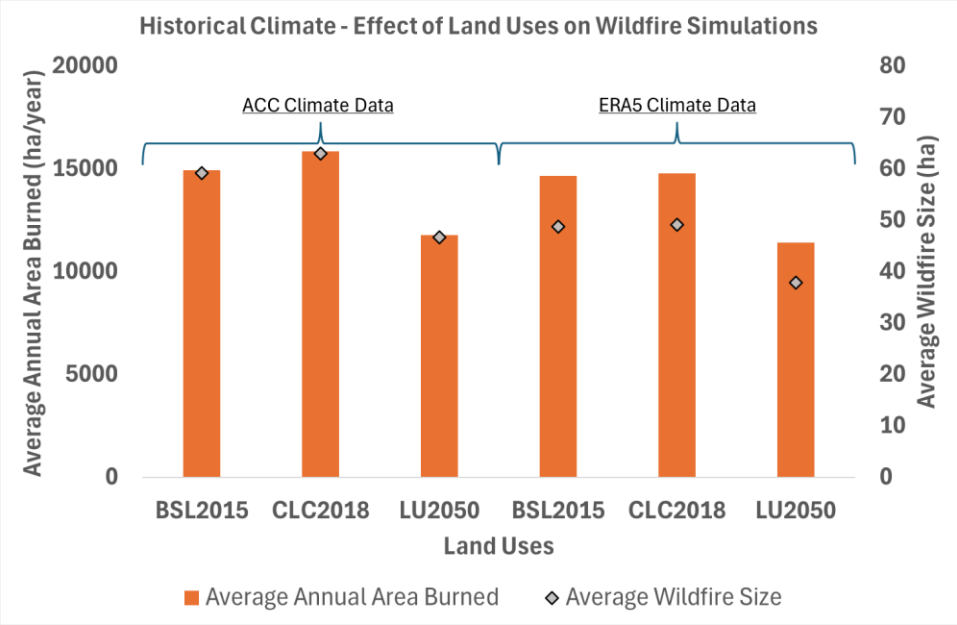


Figure 8.31. Role played by land uses on average annual area burned and average wildfire size for the whole Sardinia, considering the wildfire spread simulation modelling exercises performed using ACC and ERA5 climate models and historical conditions (1985-2014 data).

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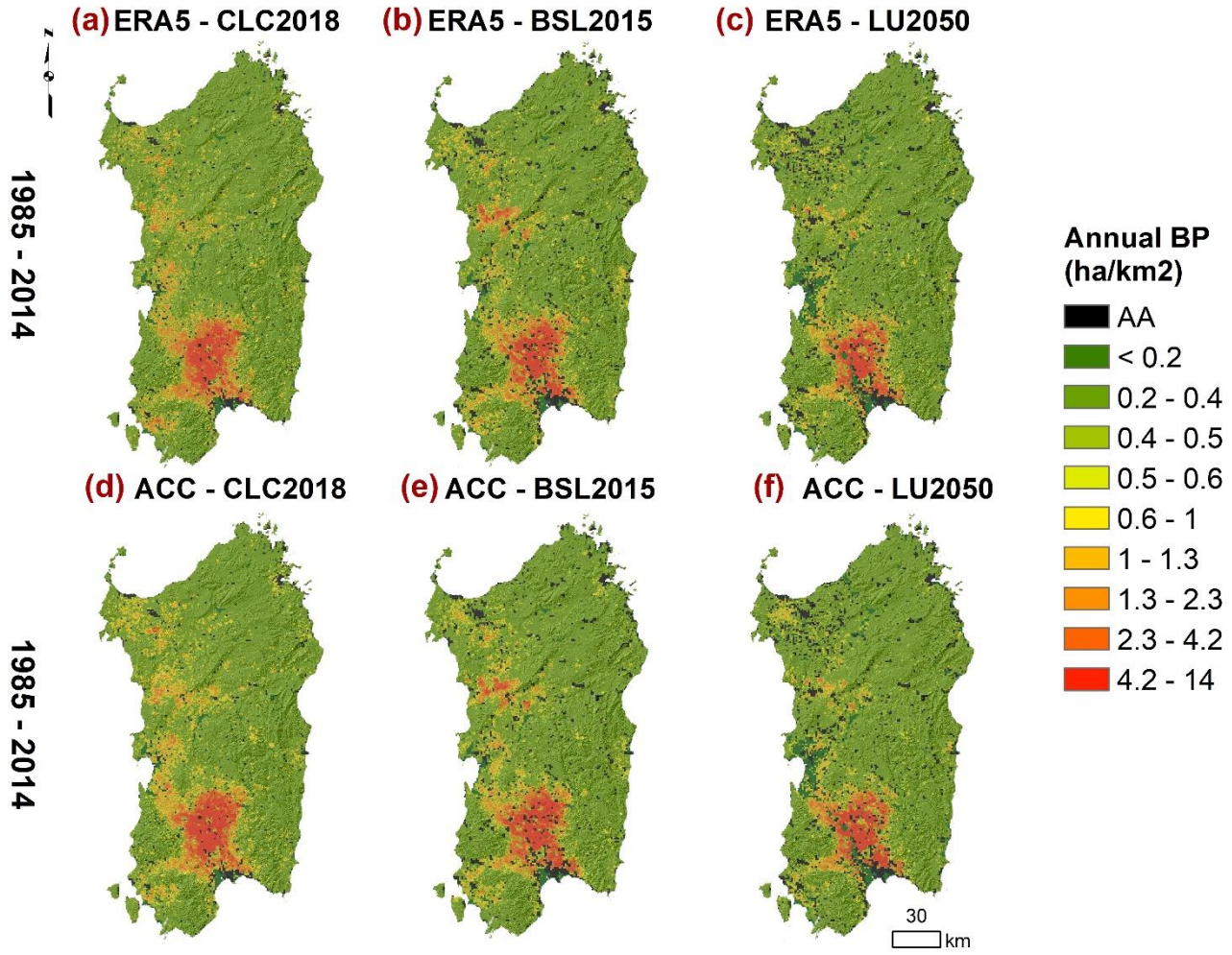


Figure 8.32. Maps of simulated aBP considering ERA5 (upper figures) and ACC (bottom figures) climate models for historical (1985-2014) climate conditions, for Sardinia. The simulations were carried out using BSL2015, CLC2018 and LU2050-SSP3 as input for the creation of the landscape file.

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Table 8.26. Summary of wildfire spread simulation outputs for the whole Sardinia, considering the 39 scenarios of climate and land use conditions tested, for Sardinia DA

Climate Model	Years	Land Use	High Fire Danger (FWI ≥ 38)	Avg aBP	Avg Annual AB	Avg FS	Avg CFL	90P CFL	Avg Cr. Fires
			Avg Annual # days	(ha/km2)	(ha/yr)	(ha)	(m)	(m)	(ha/yr)
ACC	1985-2014	CLC2018	33	0.66	15860	63	1.34	2.37	1092
ACC	1985-2014	BSL2015	33	0.62	14930	59	1.09	2.19	488
ACC	1985-2014	LU2050-SSP3	33	0.49	11771	47	1.12	2.18	667
ACC126	2035-2064	CLC2018	62	1.04	24810	52	1.27	2.25	1563
ACC126	2035-2064	BSL2015	62	1.00	23847	50	1.05	2.07	692
ACC126	2035-2064	LU2050-SSP3	62	0.75	17981	38	1.07	1.99	956
ACC245	2035-2064	CLC2018	80	1.31	31239	51	1.27	2.25	1906
ACC245	2035-2064	BSL2015	80	1.28	30544	50	1.04	2.13	846
ACC245	2035-2064	LU2050-SSP3	80	1.00	23887	39	1.06	2.03	1203
ACC585	2035-2064	CLC2018	86	1.35	32272	49	1.26	2.29	1898
ACC585	2035-2064	BSL2015	86	1.29	30786	47	1.04	2.07	897
ACC585	2035-2064	LU2050-SSP3	86	0.98	23496	36	1.06	2.06	1245
ECH	1985-2014	CLC2018	44	0.72	17157	52	1.22	2.26	1041
ECH	1985-2014	BSL2015	44	0.73	17357	52	1.01	2.09	491
ECH	1985-2014	LU2050-SSP3	44	0.54	12894	39	1.03	1.92	645
ECH126	2035-2064	CLC2018	88	1.37	32839	49	1.19	2.21	1946
ECH126	2035-2064	BSL2015	88	1.35	32377	48	0.99	2.07	860
ECH126	2035-2064	LU2050-SSP3	88	1.03	24580	37	1.01	1.88	1222
ECH245	2035-2064	CLC2018	90	1.46	34855	51	1.20	2.20	2044
ECH245	2035-2064	BSL2015	90	1.42	34067	49	0.99	2.16	933
ECH245	2035-2064	LU2050-SSP3	90	1.07	25587	37	1.03	1.85	1264
ECH585	2035-2064	CLC2018	103	1.67	39891	51	1.21	2.22	2401
ECH585	2035-2064	BSL2015	103	1.63	39084	50	1.00	2.10	1062
ECH585	2035-2064	LU2050-SSP3	103	1.27	30263	39	1.03	2.04	1515
ERA5	1985-2014	CLC2018	39	0.62	14785	49	1.19	2.21	862
ERA5	1985-2014	BSL2015	39	0.61	14665	49	0.98	2.09	397
ERA5	1985-2014	LU2050-SSP3	39	0.48	11409	38	1.01	1.82	570

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MPI	1985-2014	CLC2018	40	0.54	12975	43	1.22	2.20	808
MPI	1985-2014	BSL2015	40	0.55	13247	44	1.04	2.08	438
MPI	1985-2014	LU2050-SSP3	40	0.50	11991	40	1.25	2.07	830
MPI126	2035-2064	CLC2018	62	0.76	18274	39	1.16	2.16	979
MPI126	2035-2064	BSL2015	62	0.77	18341	39	0.96	1.90	424
MPI126	2035-2064	LU2050-SSP3	62	0.58	13876	29	1.00	1.92	645
MPI245	2035-2064	CLC2018	69	0.91	21727	41	1.17	2.20	1155
MPI245	2035-2064	BSL2015	69	0.90	21411	41	0.96	2.13	551
MPI245	2035-2064	LU2050-SSP3	69	0.69	16518	31	1.00	1.85	775
MPI585	2035-2064	CLC2018	71	0.86	20623	38	1.14	2.16	1099
MPI585	2035-2064	BSL2015	71	0.87	20824	39	0.95	1.92	513
MPI585	2035-2064	LU2050-SSP3	71	0.66	15877	29	0.99	1.82	741

Table 8.27. Summary of wildfire spread simulation outputs, focusing on Sardinia WUI areas, considering 13 scenarios of climate and land use conditions for Sardinia DA.

Climate Model	Years	Land Use	Avg aBP	Avg Annual AB	AB WUI/ AB	Avg CFL	90P CFL	Avg Cr. Fires
			(ha/km2)	(ha/yr)	(%)	(m)	(m)	(ha/yr)
ACC	1985-2014	BSL2015	0.38	1024	6.86	0.91	2.19	20
ACC126	2035-2064	LU2050-SSP3	0.46	1230	6.84	0.94	1.96	57
ACC245	2035-2064	LU2050-SSP3	0.60	1607	6.73	0.94	1.98	66
ACC585	2035-2064	LU2050-SSP3	0.61	1639	6.98	0.93	1.97	74
ECH	1985-2014	BSL2015	0.46	1235	7.12	0.84	1.92	20
ECH126	2035-2064	LU2050-SSP3	0.63	1691	6.88	0.89	2.07	72
ECH245	2035-2064	LU2050-SSP3	0.65	1747	6.83	0.9	2.09	74
ECH585	2035-2064	LU2050-SSP3	0.76	2027	6.7	0.91	1.97	90
ERA5	1985-2014	BSL2015	0.40	1061	7.24	0.8	1.94	17
MPI	1985-2014	BSL2015	0.39	1035	7.82	0.97	2.14	29
MPI126	2035-2064	LU2050-SSP3	0.38	1029	7.41	0.87	1.82	42
MPI245	2035-2064	LU2050-SSP3	0.45	1197	7.25	0.87	1.79	48
MPI585	2035-2064	LU2050-SSP3	0.44	1178	7.42	0.86	1.78	48

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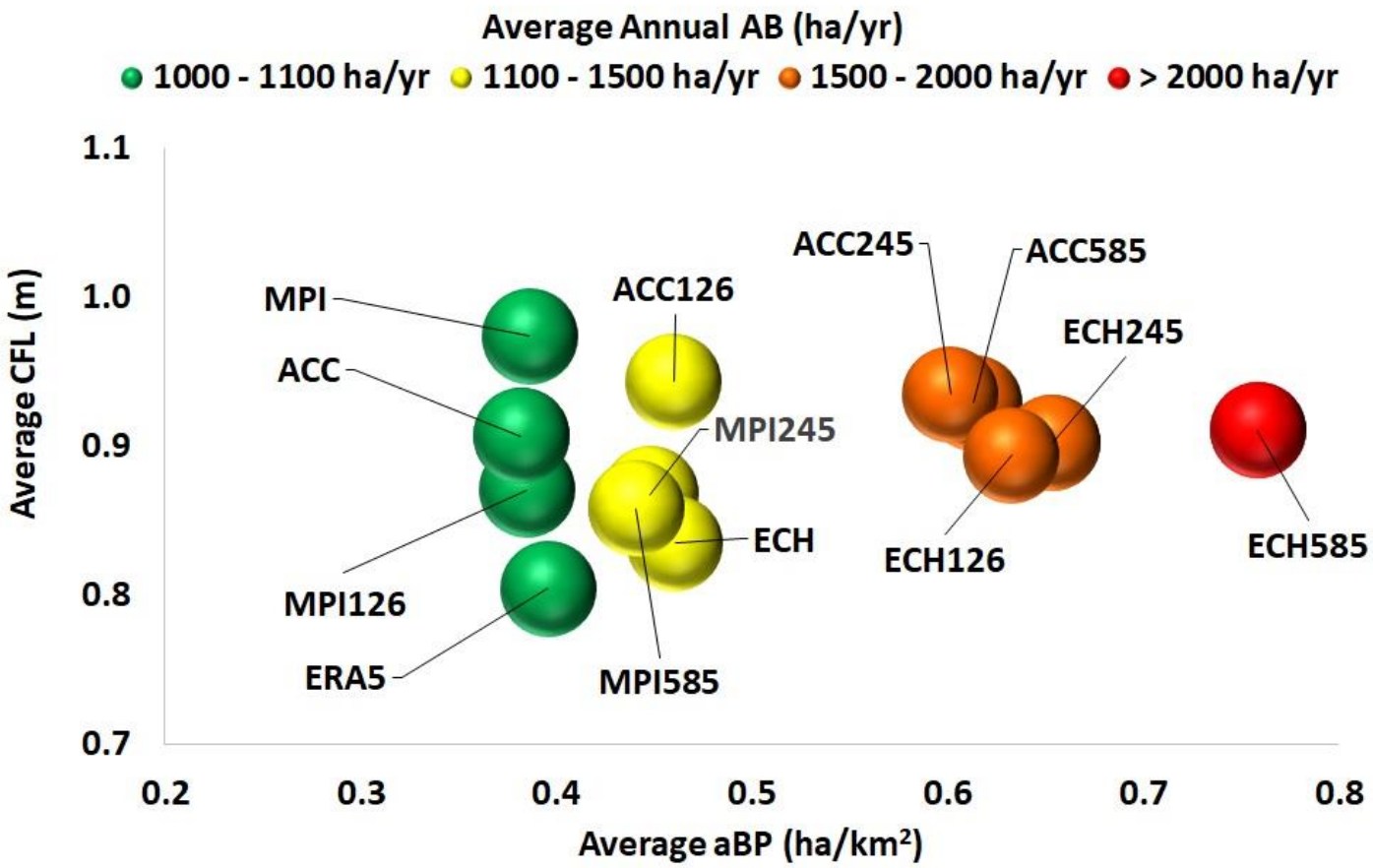


Figure 8.33. Scatterplots of average annual burn probability (aBP) vs. average conditional flame length (CFL (m)) at the WUI level for the 13 scenarios of climate change and WUI projection tested, for Sardinia. The color of the bubbles is related to the average annual area burned at WUIs.

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