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

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Executive Summary

This deliverable presents different analyses regarding future climate conditions and how they will affect fire regimes and fire risk, done at different scales: European Territory level, Pilot Site level (PS4-Barcelona), and for the United Kingdom.

All analyses show that in the future the climatic conditions will increase fire risk and behaviour, either indicating an increase in the emissions expected from fires at European level, an expansion of the fire prone areas in Barcelona and their difficulty to control the fires, or an increase of extreme fire behaviour during the summer months in the UK. When different climate scenarios were considered, they also showed that the worse the scenario, the stronger the increase of fire risk in the future.

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List of Acronyms

List of Acronyms	
AUC	Area Under the Curve
BASE	Burnt Area Simulator for Europe
CMIP6	Coupled Model Intercomparison Project Phase 6
DFMC	Dead Fuel Moisture Content
DGVM	Dynamic Global Vegetation Model
DMC	Duff Moisture Code
EGIF	Spanish Forest Fires Records
FAPAR	Fraction of absorbed photosynthetically active radiation
FFMC	Fine Fuel Moisture Code
FWI	Fire Weather Index
GLM	Generalised Linear Model
GPP	Gross Primary Production
HDI	Human Development Index
PS	Pilot Site
SEDAC	Socioeconomic Data and Applications Center
SSP	Shared Socioeconomic Pathway
UK	United Kingdom

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1 Introduction

1.1 Purpose of the document

This deliverable is part of the Task 3.2: Estimation of future fire risk, Activity 3.2.2: Estimation of impacts to future exposure. The purpose of this document is to present the analyses performed by different partners participating in this activity regarding future climate conditions, and how they will affect fire regimes, fire prone areas and fire exposure, as well as ecosystem and forests characteristics and services.

These analyses were performed at different scales: at European level, at Pilot Site level (specifically in Pilot Site 4: Barcelona), and in the United Kingdom, a temperate region that has shown, in the past few years, extreme fires outside the historical fire regimes. Other analyses originally intended for this deliverable, and more related to human exposure to fire emissions, were relocated to Deliverable 3.6, as they were considered to better substantiate the work performed and overall topic of concern of that deliverable. Complementary, the Annex presents a particular analysis performed for Bulgaria that was part of Activity 3.1.3 of the project and could not be included in its corresponding deliverable due to a lack of time.

1.2 Structure of the Document

The current introduction is followed by three sections, conclusions, and references. In the different sections we:

(1) show how the future fire regimes will impact ecosystem services at the European extent;

(2) analyse future fire prone areas in the pilot site in Barcelona;

(3) evaluate the current and future risk exposure levels in United Kingdom.

The document then includes the conclusions of the deliverable.

Annex A presents a summarised description of current and future characteristics of the Bulgarian forests, as well as a detailed analysis of the simulation of the Razdel Fire, which was not able to be included in Deliverable 3.3, as originally intended.

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2 Impacts of future fire regimes and land-use change on ecosystem services supply at European scale

To understand future fire regimes and land use change we used CMIP6 climate models applied to the fire-enabled Dynamic Global Vegetation Model (DGVM) LPJmLv5.6. The climate change scenarios followed a sustainable Socioeconomic Pathway (SSP) scenario SSP1 in combination with 2-degree-goal climate scenario RCP2.6 (SSP126, hereafter) and SSP3 and RCP7.0 (SSP370, hereafter). For each climate scenario, scenario realisations conducted by five climate models, namely ACCESS-CM2, CanESM5, CNRM-ESM2-1, MPI-ESM1-2-HR, EC-EARTH3, were used to force LPJmLv5.6. We selected these climatic models because they cover the lower, medium and upper bound of changes in the drought code as part of the Canadian Fire Weather Index (FWI; see D3.1 and section 6 in D3.4 for more details). This study was focus on aboveground and belowground biomass and carbon emissions. These components are fundamental to several ecosystem services, including carbon sequestration, soil fertility, climate regulation, and biodiversity maintenance.

The aspects of intensity, frequency, seasonality, and behaviour of wildfires are implicitly considered through the climate models and the calculations of the FWI index, as this index is a comprehensive measure of the meteorological conditions that influence the probability and fire regime. Given that the study uses the LPJmLv5.6 model, it is likely that land-use change dynamics, such as the conversion of forests to agricultural lands, urban expansion, or reforestation, are included in this model, as these are common factors that affect fire regimes.

In the study, two distinct socio-economic and climate scenarios were used to understand future fire regimes and land use changes, applying CMIP6 climate models to the fire-enabled Dynamic Global Vegetation Model (DGVM) LPJmLv5.6. These scenarios are known as SSP126 and SSP370.

SSP126 (Sustainable Scenario):

- Socio-Economic Pathway: SSP1, which follows a sustainable pathway.
- Climate Scenario: RCP2.6, targeting a 2-degree Celsius global warming goal.
- Characteristics: This scenario assumes a world that adopts sustainable practices, leading to lower greenhouse gas emissions. It envisions significant advancements in renewable energy, increased energy efficiency, and widespread adoption of sustainable agricultural and land use practices. The overall impact on climate change is mitigated, resulting in more moderate changes in fire regimes.

SSP370 (Fragmented World Scenario):

- Socio-Economic Pathway: SSP3, which depicts a fragmented world with high challenges to both mitigation and adaptation.
- Climate Scenario: RCP7.0, which assumes higher greenhouse gas emissions.
- Characteristics: This scenario assumes a world with regional rivalry, where countries focus on their own interests and economic growth is uneven. It leads to higher emissions due to less coordination in climate policies, greater reliance on fossil fuels, and limited progress in sustainable development.

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This results in more extreme changes in climate and fire regimes, with increased intensity and frequency of fires.

Climate Models Used

For each scenario, the study utilized realizations conducted by five different climate models, selected to cover a range of changes in the drought code as part of the Canadian Fire Weather Index (FWI). The models used are:

- ACCESS-CM2
- CanESM5
- CNRM-ESM2-1
- MPI-ESM1-2-HR
- EC-EARTH3

These models were chosen to represent lower, medium, and upper bounds of drought conditions, providing a comprehensive view of potential future fire regimes.

Temporal and Spatial Scope

The study covers the period from 2000 to 2100, with calculations of the Fire Impact Index performed at a spatial resolution of 9 km. This index evaluates the impact of fire on aboveground and belowground biomass by measuring fire-induced carbon emissions relative to biomass, allowing the assessment of fire exposure and its effects on terrestrial ecosystems over time.

By comparing the two scenarios (SSP126 and SSP370) and using a range of climate models, the study provides insights into how different socio-economic pathways and climate policies might influence future fire regimes and land use changes, highlighting the importance of sustainable practices in mitigating adverse impacts on ecosystems.

2.1 Calculation of the Fire Impact Index

We have calculated the Fire Impact Index on aboveground and belowground biomass, as a crucial variable for understanding fire exposure and its impact on terrestrial ecosystems. The Fire Impact Index significance lies in its ability to quantify the relationship between fire-induced carbon emissions and both aboveground and belowground biomass. This allows us to assess the fire's impact on vegetation and soil over time, across the two climatic scenarios SSP126 and SSP370 and the five climate models.

The Fire Impact Index is estimated based on the carbon accumulated in vegetation (VegC, gC/m2) and released by fire (FireC, gC/m2) variables developed in the LPJmLv5.6-SPITFIRE model (Billing et al., 2023), which provides detailed information on vegetation and fire-induced carbon emissions. The resulting variable provides a ratio of fire-induced carbon emissions per aboveground and belowground biomass, enabling us to evaluate fire's relative impact on different ecosystem components.

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The carbon accumulated in vegetation and released by fire was estimated using the following method: The Burnt Area Simulator for Europe (BASE) model was developed by fitting Generalised Linear Models (GLMs) to the ESA FireCCI51 burned area data over the European territory at the 9 km resolution of the climate and land use scenarios. The FireCCI51 dataset was processed in combination with the ESA LandcoverCCI to derive the burned area fraction per grid cell within an aggregated land cover termed “Woodlands and Shrublands,” excluding croplands, grasslands, and mosaic classes to focus on 'wildlands' (though this term is used cautiously as most European vegetation is managed). The predictor variables used in BASE included tree cover, FAPAR, GPP, and the Fire Weather Index (FWI), among others. BASE was integrated with the LPJmLv5.6 model, using its vegetation state variables for future scenarios. The model's structure emphasized FWI and GPP interaction to reproduce seasonal burning patterns, and included the Human Development Index (HDI) and tree cover as significant predictors to capture trends and spatial patterns in burnt areas.

2.2 Results of the analysis

Figure 1 shows an example for the future scenarios with the climatic model ACCESSCM2 for Europe, where fire emissions are substantially higher under the SSP126 than the SSP370 scenario. This is also noticeable in the rest of the climatic models but is not shown in this document to avoid redundancy. We can also observe how the fire emissions due to biomass burning and the mean fire emissions projected increased over time, from the period 2000-2025 to the period 2071-2100 (see Figure 2). The 10 “.RData” files available at https://fireurisk.satways.net/datasets/662a3bdae4b0cdb62c50c3eb contain the yearly results separated by scenarios and climatic models for the convenience of future analysis and research.

The observations from Figure 1 align with the underlying dynamics explained in the text. The fire emission to biomass ratio being higher suggests efficient combustion in the scenarios, while the lower total fire emissions indicate that there is less biomass available to burn in absolute terms. This disparity can be explained by the presence of more fine fuels and less dense vegetation in certain areas, leading to efficient burning but lower overall biomass to be burned. It is important to notice that the higher emissions in areas with less biomass are not necessarily due to fewer fires or lower combustion efficiency. Instead, it is because open systems with less tree cover have conditions that promote fire spread and intense burning of surface fine fuels, which leads to higher emissions. The drier microclimate and abundance of readily combustible fine fuels in these areas enhance the efficiency and extent of combustion, resulting in greater emissions.

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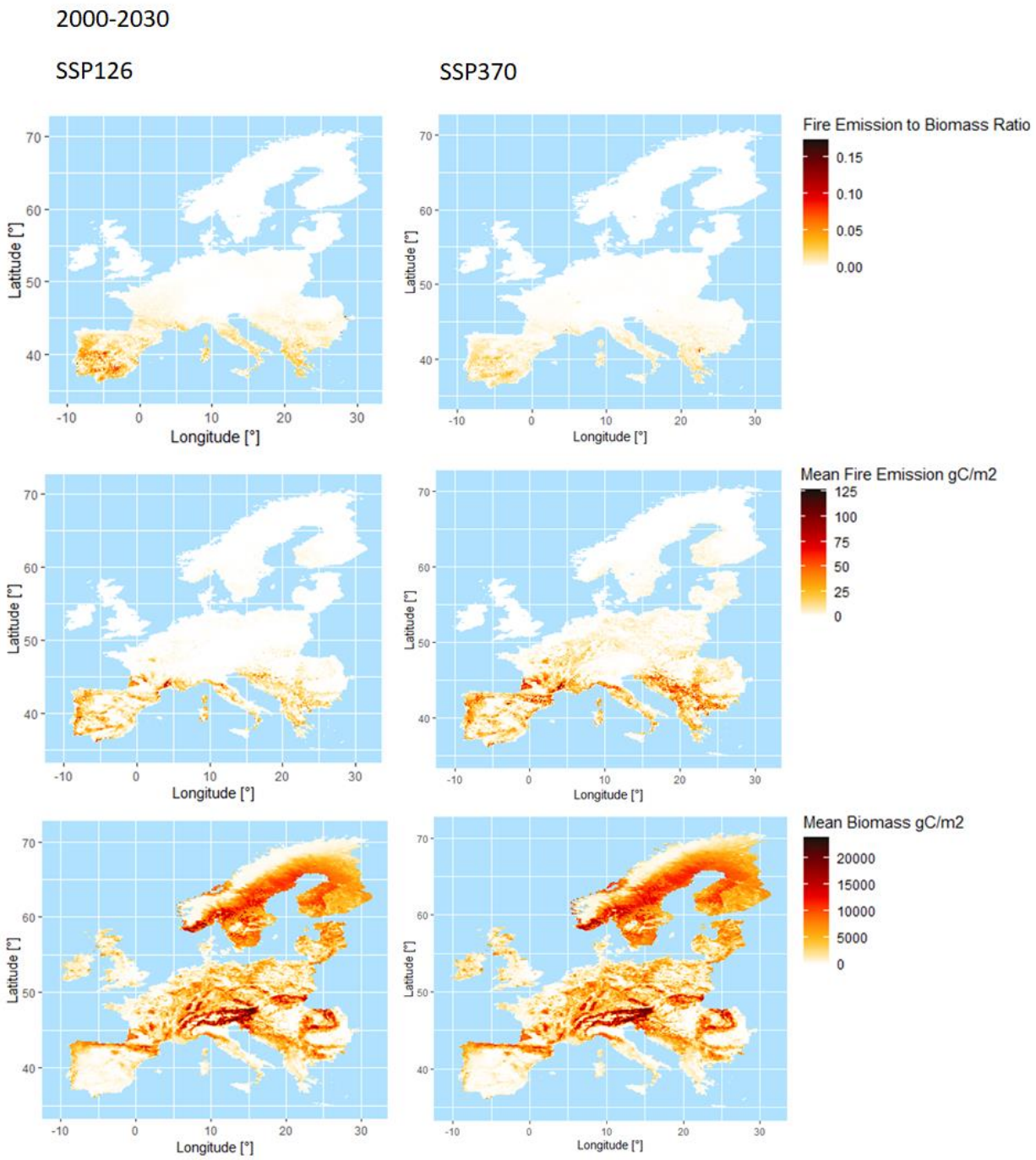


Figure 1: Example of the Fire Impact Index (fire emissions to biomass ratio) calculated as the ratio of carbon stored in above- and belowground living biomass and carbon released by fire in the future climate SSP126 and SSP370 using the model circulation ACCESSCM2 for the period (2000-2030).

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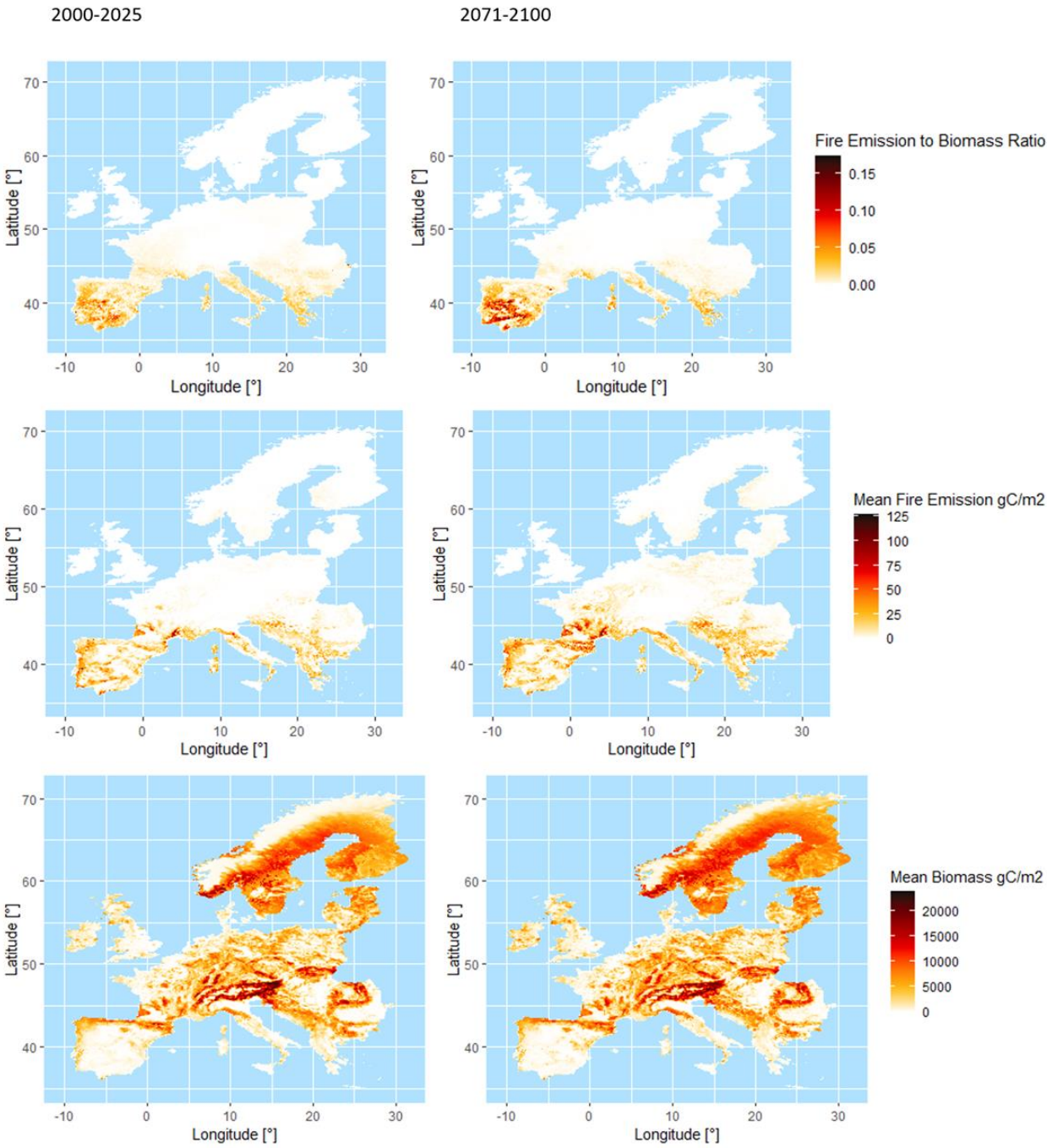


Figure 2: Example of the Fire Impact Index (fire emissions to biomass ratio) calculated as the ratio of carbon accumulated in vegetation and carbon released by fire in the future climate SSP126 (RCP2.6) using the model circulation ACCESSCM2 for the period 2000-2025 and the period 2071-2100.

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The creation of map projections for future scenarios under SSP126 and SSP370 for fire emission to biomass ratio across Europe holds significant importance for a variety of environmental and policy-driven reasons. SSP126 represents a pathway where mitigation strategies successfully limit global warming to well below 2°C, while SSP370 corresponds to a scenario with much higher emissions leading to around 3.5°C of warming. By generating these maps, researchers and policymakers can visualise and anticipate the spatial distribution and intensity of fire emissions relative to biomass, providing crucial insights into the potential future impact of different climate policies and natural resource management strategies.

The utility of these cartographic projections lies in their capacity to inform effective environmental management and disaster preparedness. For instance, areas predicted to experience a higher fire emission to biomass ratio under SSP370 can be targeted for more stringent fire prevention measures, land management reforms, and community awareness programs. Conversely, regions appearing less affected under SSP126 could serve as models for successful mitigation practices. These maps enable governments (at different levels), NGOs and organised Civil Society, as well as local communities to allocate resources more efficiently and implement proactive strategies tailored to the specific risks and challenges projected for their areas.

In practical application, these cartographic outputs are instrumental in shaping long-term planning and legislative frameworks. They can influence decisions on land use, forestry management, urban planning, and infrastructure development. Moreover, by highlighting the potential consequences under different global warming scenarios, they foster greater environmental awareness and advocacy for stronger climate action. The visual nature of these maps also makes the complex data more accessible to a broader audience, facilitating better understanding and engagement among stakeholders at all levels, from local to international, in addressing the challenges posed by future fire emissions in the context of ongoing climate change.

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3 Future fire ignition and initial attack models to evaluate extension of fire prone areas in PS Barcelona

The main objective of this activity was to anticipate extreme wildfire conditions by providing a synthetic product depicting the chances of a fire event starting (ignition) and escaping containment at the initial attack phase, extending WP1 models to future conditions under different scenarios in one of the pilot sites of the project, i.e. PS4-Barcelona. This pilot site comprises the province of Barcelona, in north-eastern Spain.

3.1 Methods for future risk estimation

To perform the analysis, empirical models of ignition likelihood and effectiveness of the initial attack stage (containment) were combined (Figure 3).

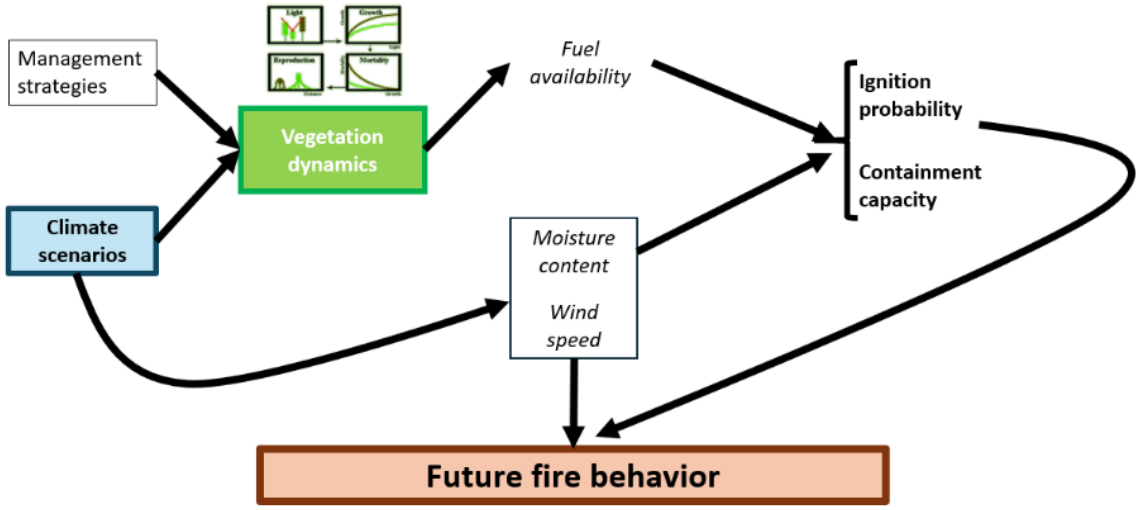


Figure 3: Conceptual scheme for estimating the extension of fire prone areas in Barcelona-PS4.

Machine learning techniques were applied to calibrate binary regression models using historical wildfire ignition data and a geospatial layer depicting the main drivers of ignition and containment. To analyse the containment capacity, we created a binary response following these criteria: From the EGIF database (Spanish Forest Fires Records), we categorised occurrences with a burned area equal to or less than 10 hectares as 1 (contained), while those with an area equal to or greater than 50 hectares were categorized as 0 (escaped). For prediction, we utilised a set of variables commonly used in containment modelling (i.e. Rodrigues et al., 2020), including viewshed from towns, road accessibility, cost distance to paths and tracks, distance to heliports, viewshed from roads, and vegetation height. Additionally, we included two weather-related variables: Dead Fuel Moisture Content (DFMC) and wind speed, leveraging climate projections downscaled by Activity 3.1.1 to extrapolate future results.

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To analyse fire occurrences and predict ignitions, we retained data from EGIF labelled as 1 (occurrence), while setting up a spatial point random sample of equal size labelled as 0 (no occurrence). Independent variables included distance to wildland-agricultural and wildland-urban interfaces, distance to roads, fuel maps. As temporal dynamic variables, we incorporated population density projections from SEDAC (Socioeconomic Data and Applications Center, https://sedac.ciesin.columbia.edu/) and DFMC from Meteogrid downscaling, enabling future projection using Meteogrid's climatic and demographic projections, as with the containment approach.

As the goal was to inform disaster risk reduction authorities by pointing at future wildfire risk zones and prioritizing intervention in high-risk areas, predictions of wildfire ignitions and contention capacity were implemented under diverse population growth and climate warming scenarios. Most geographic variables in the models were kept static, and dead fuel moisture content and wind speed were modified according to climate scenarios. We provide insights into four future SSP scenarios: SSP126, SSP245, SSP370, SSP585, by synthesizing ignition and containment products into comprehensive management zones depending on estimated probability of ignition and success at initial attack.

3.2 Results of the analysis

Results demonstrated high predictive capability for modelling human-caused wildfire ignition (AUC>0.80), but a more moderate ability to predict containment (AUC≈0.70). Road accessibility predominantly influenced the spatial pattern of ignition and containment, with DFMC modulating the temporal probability of ignition and both DFMC and wind speed affecting containment capacity.

Spatial and temporal projections revealed a clear trend of reduced containment capacity and increased ignition likelihood in moderate and worst SSPs (Figure 4 to Figure 6). Due to spatial resolution limitations, understanding the spatial pattern for PS Barcelona was challenging (Figure 4A and B). The model showed some sensitivity to i.e. coastal pixels that produced functions difficult to explain (increase up to 2060 and decrease afterwards). However, our conclusions on trends stem from a more robust geographically extended analysis conducted in the eastern region of Spain (Figure 4C and D) with the same dataset, in cooperation with the Firepathsproject framework (PID2020-116556RA-I00 funded by MCIN/AEI/10.13039/501100011033).

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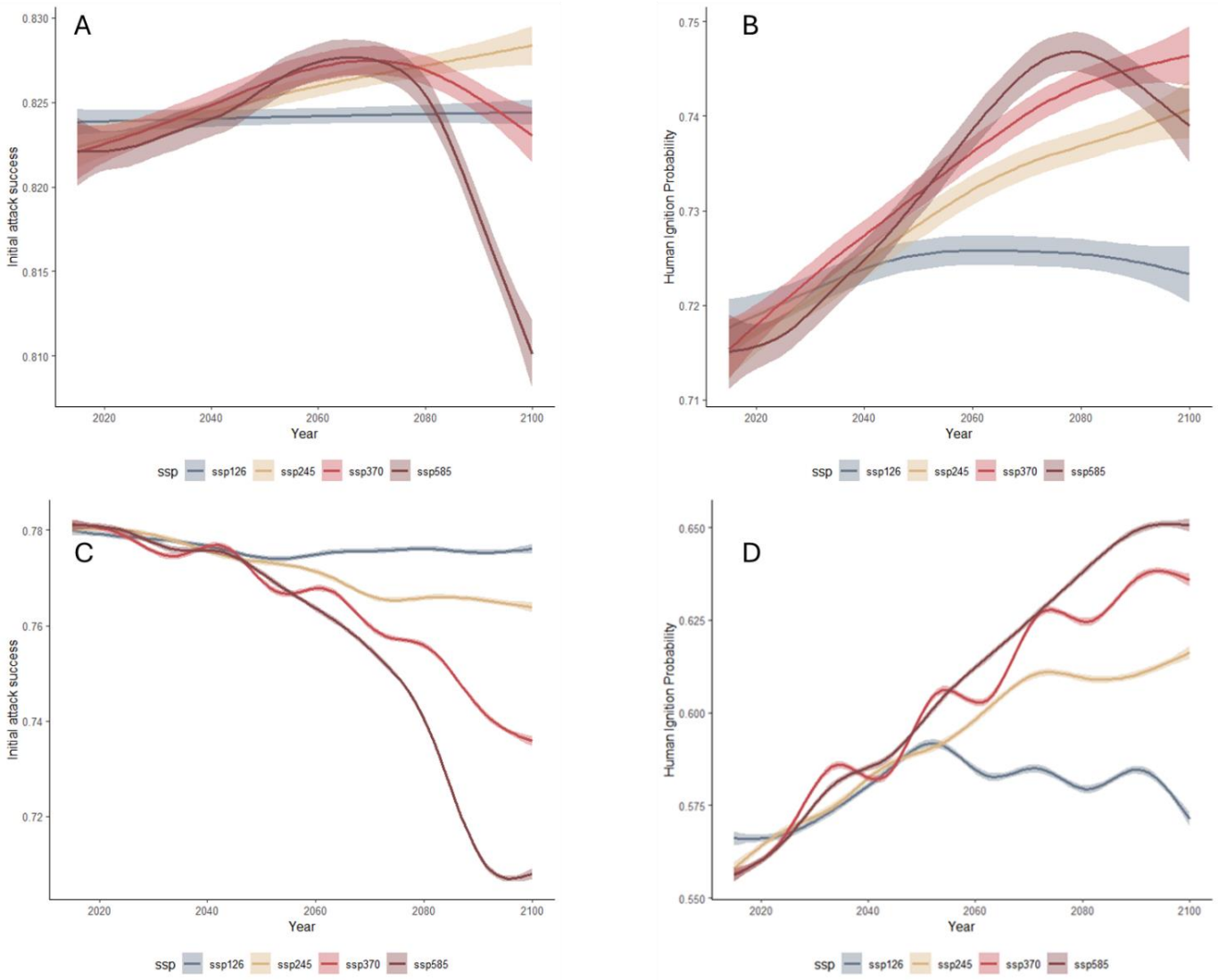


Figure 4: Temporal projection of Human ignition probability and Containment success probability under the different SSP A) Containment success probability in PS4, B) Human Ignition probability in PS4, C) Containment success probability in East of Spain, D) Human Ignition probability in East of Spain.

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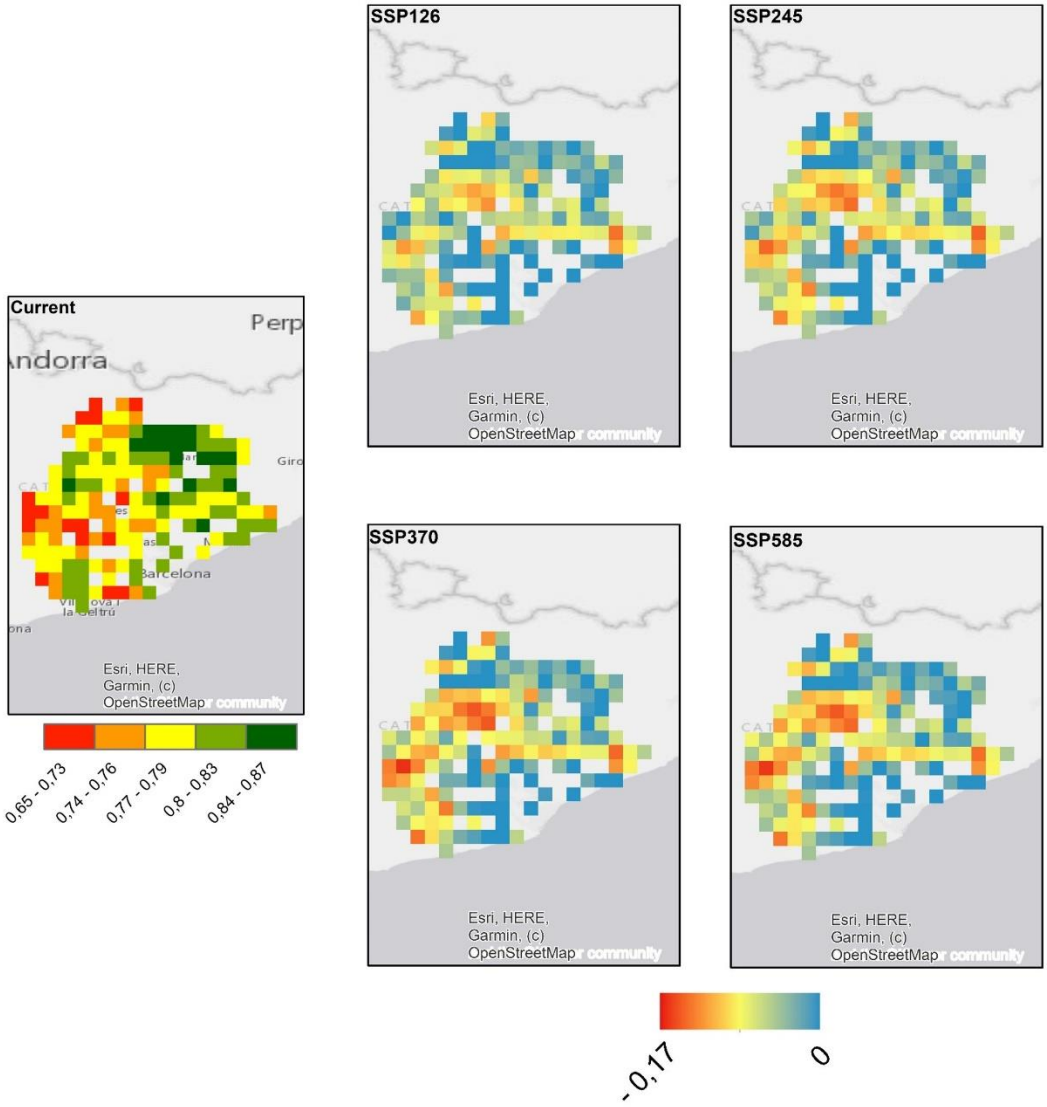


Figure 5: Spatial changes in probability of containment success. Current plot represents the current probability of containment whereas the others represent the difference between the current situation and the projected under each SSP.

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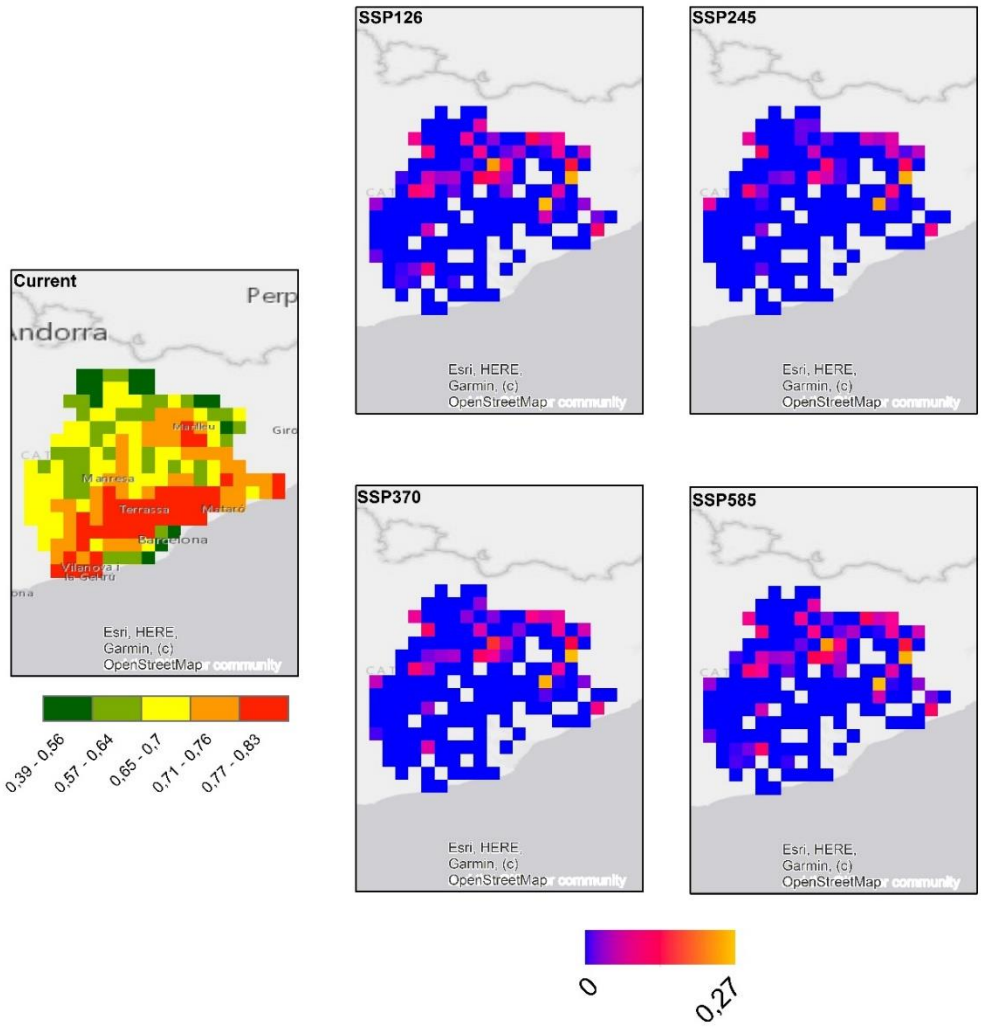


Figure 6: Spatial changes in probability of ignition. Current plot represents the current probability of ignition whereas the others represent the difference between the current situation and the projected under each SSP.

3.3 MEDFATE model with future scenarios to derive fuel impacts

The conceptual scheme for the extension of fire prone areas in Barcelona-PS4 also considers the effects of vegetation dynamics in future fuel availability and fire behaviour. This activity aimed to assess the evolution of fire danger under different emission and forest management scenarios through the explicit interaction of the climate-vegetation-fire system. At the core of the process lied the modelling of vegetation dynamics, at stand scale, according to different trajectories of climatic evolution to characterize the state and typology of fuels and the subsequent simulation of potential crown and surface fire behaviour during the 21st century.

Vegetation dynamics were projected to the future by selecting several feasible forest management scenarios:

1. No management (No_manag), with no intervention,

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2. Business-as-usual (bau), which implies the selective removal of the biggest trees per plot every 15 or 20 years,
3. Carbon Stock (carbon), trees must reach a larger than usual diameter at harvest, which requires longer rotations,
4. Drought adaptation (adap), which requires early and intense thinning to improve tree vigour and resilience,
5. Fire risk reduction (fire), which creates fuel discontinuities in strategic areas.

Climatic data was taken from seven General Circulation Models and the four SSP used in the previous section. The simulations (28 scenarios) were run for 114 plots, using the MEDFATE program (De Cáceres et al., 2021). Results found for the prediction of the probability of occurrence of extreme behaviour fires indicated a continued trend towards increased meteorological danger (Fire Weather Index, FWI) and fire hazard (Flame length) in SSP 245, 370, and 585 scenarios. An accelerated trend with a peak between 2040-2080 in DFMC (dead fine fuel moisture content, 1h) was apparent in SSP 370 and 585 scenarios.

Simulations included both plots burned and unburned recently; understanding the behaviour of fire, in both burned and control (unburned) areas, is essential as fire behaviour varies significantly between these zones due to differences in fuel characteristics and fire history. In burned areas, management strategies usually aim at risk mitigation, such as systematic understory thinning and shrub control, which appear to be the most effective alternatives. These strategies help reduce fuel loads and create defensible space, mitigating the future risk of severe fires (Figure 7). Conversely, in areas that have not experienced recent fires, management practices must adapt to the prevailing climatic conditions (Figure 8 and Figure 9). This adaptation involves assessing the current fuel conditions and considering the potential impact of climate change on fire behaviour. Flexibility and proactive management approaches are essential for effectively mitigating fire risk in these areas.

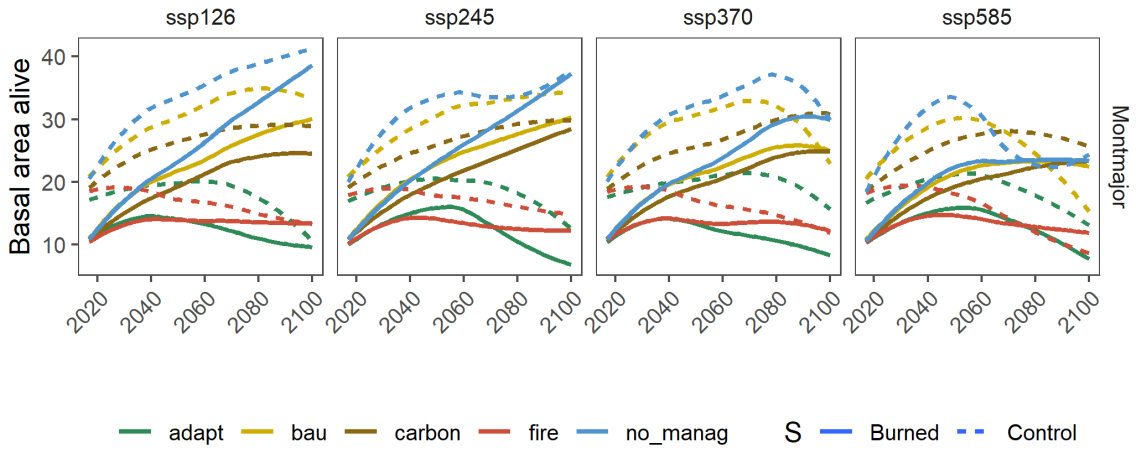


Figure 7: Temporal evolution of basal area under the different SSP in the burned and control plots of the Montmajor fire – PS4.

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Figure 8: Projection of vegetation dynamics and surface fire behaviour (flame length, m) in the burned and control plots of the Montmajor fire – PS4 for the different SSP.



Figure 9: Projection of vegetation dynamics and crown fire behaviour (flame length, m) in the burned and control plots of the Montmajor fire – PS4 for the different SSP.

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3.4 Conclusions of the analysis

The combined analysis of wildfire ignition and containment prediction models, and the MEDFATE management scenarios, highlight the critical need for integrated and adaptive management strategies to prevent future wildfire risks. The ignition prediction model demonstrated high reliability (AUC > 0.80), while the containment success model was moderately reliable (AUC ≈ 0.70). Road accessibility was identified as a significant factor influencing both ignition likelihood and containment success. Additionally, DFMC and wind speed were crucial, with DFMC increasing ignition probability and both DFMC and wind speed decreasing containment capacity. Projections under various SSP scenarios indicate a trend towards reduced containment capacity and increased ignition likelihood, particularly in severe scenarios (SSP245, SSP370, SSP585). This highlights the challenges in maintaining effective containment and managing ignition risks in the future, exacerbated by increased meteorological danger reflected in the Fire Weather Index and elevated fire hazard expressed by flame length. Effective management in burned areas involves systematic understory thinning and shrub control to reduce fuel loads and create defensible spaces, thus mitigating future fire risks. Conversely, in unburned areas, management practices must adapt to changing climatic conditions. Proactive strategies, such as early thinning and creating fuel discontinuities, are essential for effective fire risk mitigation. Overall, these findings emphasize the necessity for flexible, proactive forest management strategies tailored to specific site conditions and future climate projections; no management, or business-as-usual strategies give always the worst outcomes for the future.

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4 Current and future risk exposure levels for UK

The analysis of satellite-based fire activity and vegetation phenology datasets for main fire-prone vegetation types from 2012 to 2023 indicates that phenology, rather than fire weather, was the primary driver of fire occurrence patterns across the UK (Nikonovas et al., in review). Overall, fire activity was highest in March and April when vegetation was in the phenological dormancy phase. During the high greenness phenological phase (summer months), semi-natural grasslands and dwarf shrub-dominated vegetation were highly resistant to burning, resulting in low fire activity, despite typically elevated fire weather conditions at that time of year. However, during two seasons with extreme drought and heatwave events (summers of 2018 and 2022), this phenological fire barrier (greenness) was diminished, leading to widespread burning driven by extreme fire weather conditions. These events placed immense strain on Fire and Rescue Services, resulting in environmental damage and multiple property losses. Future climate predictions suggest that fire-conducive weather conditions for summertime burning will cover larger parts of the UK for longer periods, prompting further research into fire danger prediction systems and improving preparedness for such events.

4.1 Datasets and objectives

We combined datasets from the VIIRS sensor-based active fire detections (VNP14IMGML) (Schroeder et al., 2014) and phenological transition dates (VNP22Q2) (Zhang et al., 2018) products, covering the period from 2012 to 2023, with the UK Centre for Ecology & Hydrology (UKCEH) land cover map (Morton et al., 2020). Our objectives were to i) investigate the current vegetation fire regime in the UK and ii) derive fire occurrence rates for the most significant fire-prone vegetation fuels in different phenological phases. Additionally, we are currently investigating whether the satellite-based vegetation indices dataset VPN13A1 (Didan and Barreto, 2018), combined with the components of the Canadian Forest Fire Weather Index System (Vitolo et al., 2020) can reveal the fire weather levels at which live vegetation becomes flammable during the phenological maturity phase.

4.2 UK Fire regime

During the past decade, vegetation fire activity varied significantly across different types of land covers and regions in the UK. More than half (54%) of the VIIRS vegetation fire detections recorded between 2012 and 2023 (Figure 1) were attributable to land covers dominated by semi-natural grasslands (such as acid grasslands and heather grasslands, with common species like deciduous grass *Molinea caerulea* and bracken ferns) and dwarf shrub-dominated ecosystems (heather and bog land covers, dominated by heather species such as *Calluna vulgaris, Erica cinerea, Erica tetralix*, and gorse shrub *Ulex europaeus* and *Ulex minor*). Detections on agricultural land covers, including arable land and improved grasslands, made up 21% and 15% of the total count, respectively, while fires in deciduous and coniferous woodlands accounted for only 6% and 4%. Temporally, in regions with a higher proportion of semi-natural land covers, fire detection count peaked in the early spring months, whereas in areas primarily consisting of agricultural land and pastures (like improved grasslands), fire activity was higher during the late summer months. A noteworthy observation

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was a secondary increase in fire activity occurring later in the season, particularly in June and July (Figure 10). This late-season peak, although representing a small fraction of the total fire detection counts, is driven by more extreme fire weather conditions typical for that time of year (Figure 11) and drought, potentially posing greater risks compared to the main burning window in early spring.

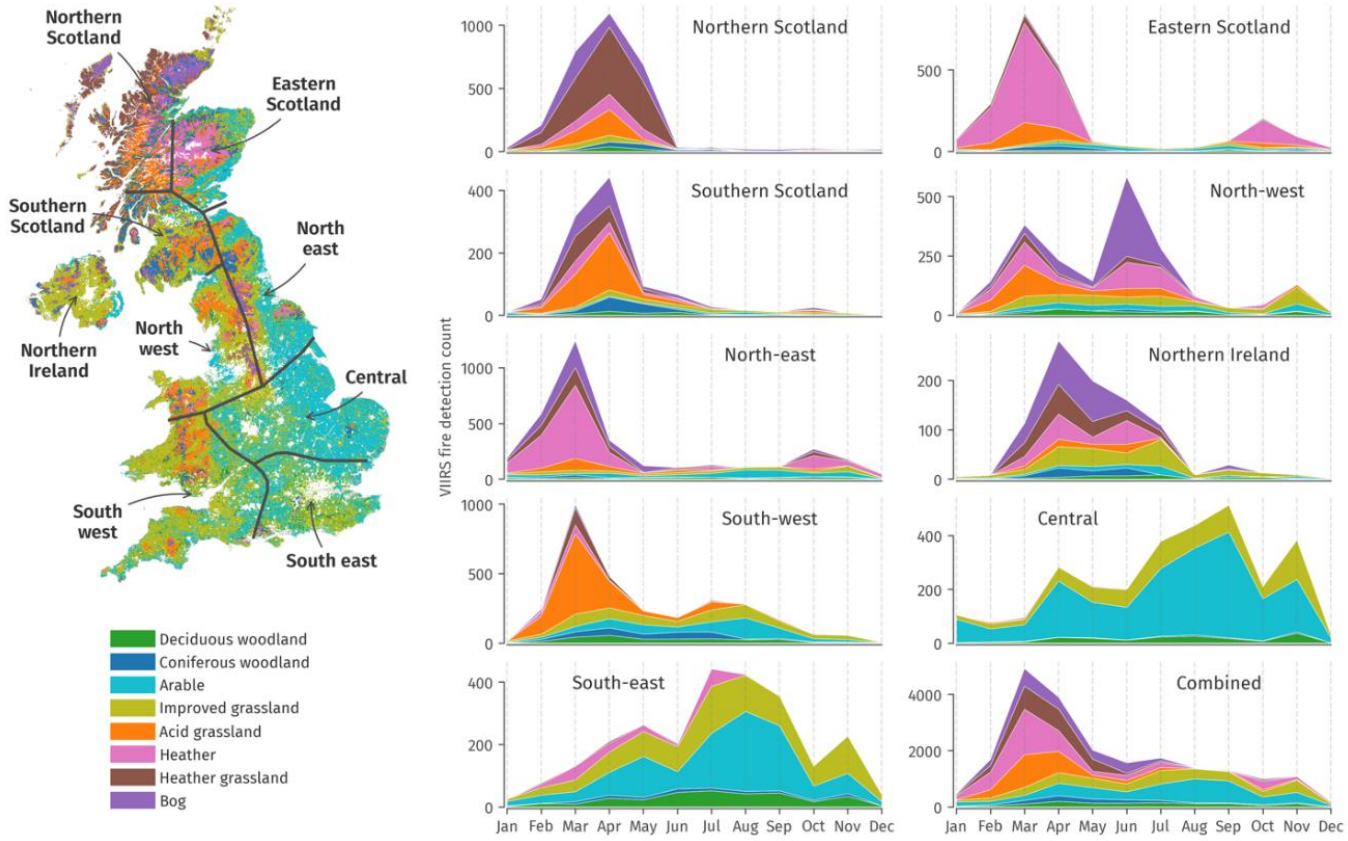


Figure 10: Distribution of the most important vegetation land covers in the UK. Area plots show monthly VIIRS active fire detection counts for different UK regions and land cover types during the 2012-2023 period.

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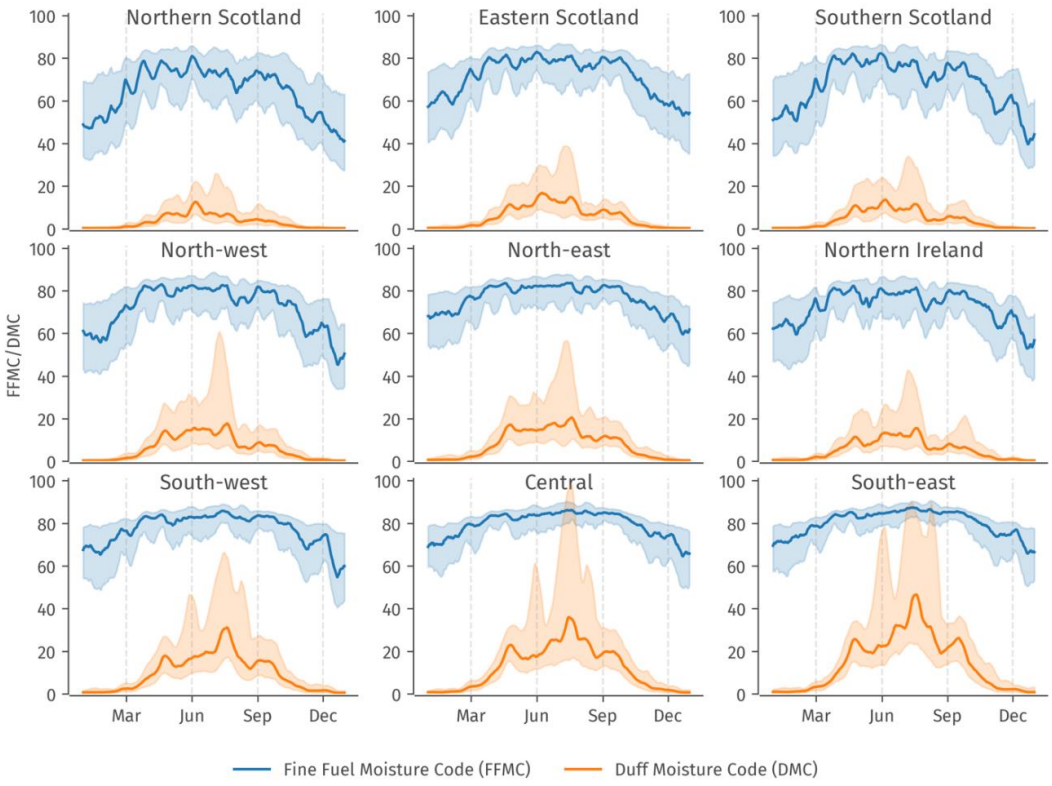


Figure 11: Seasonal variability of Fine Fuel Moisture Code (FFMC) and Duff Moisture Code (DMC) in the study regions. Solid lines show upper quartile values (75th percentile), shaded regions envelope 50th and 99th percentiles of FFMC and DMC values for the 2012 – 2022 period.

4.3 Fire occurrence and phenological phase

The combined analysis of satellite fire detection and phenological datasets revealed that fires in the UK were far more common when host ecosystems were in low greenness state (phenological dormancy, late senescence and early green up phases) compared to the high greenness phase (when vegetation was in the late green-up, maturity and early senescence phenological phases) (Figure 12). For most of vegetation land covers across the UK the timing of reduction in flammability coincided best with the VNP22Q2 product middle of greenup date (see Figure 14 for characteristic timings of middle of greenup and middle of senescence points). The disparity in daily fire occurrence rates between the high- and low-greenness phases (Figure 13 and Figure 13) was particularly large in semi-natural land covers dominated by grass (acid grasslands and heather grasslands) and dwarf shrub vegetation (heather and bog land cover classes). In these ecosystems, fire detection rates were four to six times higher during phenological dormancy compared to the high greenness phase, despite typically elevated fire weather during the latter phase. Over agricultural land covers (arable land and improved grasslands) and woodlands, the difference between the phases was smaller. Nonetheless, fire activity increased during the 2018 and 2022 heatwave episodes in improved grasslands and arable land.

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A substantial number of fire detections recorded during the high greenness phase (Figure 13) were linked to fires in semi-natural grasslands and dwarf shrub ecosystems in 2018, as well as burning events mainly in improved grasslands and arable land during the summer of 2022. Fire activity during the high greenness phenological phase in seasons with less than extreme fire weather was extremely low, and the differences in fire detection rates between the phenological phases mentioned above were much greater in years without drought and heatwave events. This indicates a strong phenological barrier to fire for most vegetation fuels in the UK. In contrast to regions with more extreme fire weather, the current day fire regime in the UK's humid Atlantic climate is thus heavily influenced by vegetation phenology. Seasonally varying effects of vegetation structure and physiology can be the primary factors determining fire occurrence (or rather, a lack thereof) under less extreme fire weather conditions (Cruz et al., 2022). In temperate northwest Europe, grasslands and shrublands are highly resilient to fire during high greenness phases due to the high ratio of live to dead fuels and the high moisture content in live fuels (Davies et al., 2010). This phenological control over fire is particularly pronounced in grasslands, where new growth during the green-up period can act as an on-off switch for fire sustainment. Experimental data from Sweden (Sjöström and Granström, 2023) suggests that the fire season effectively ends when the live grass fraction exceeds 10-20% of the total fuel load.

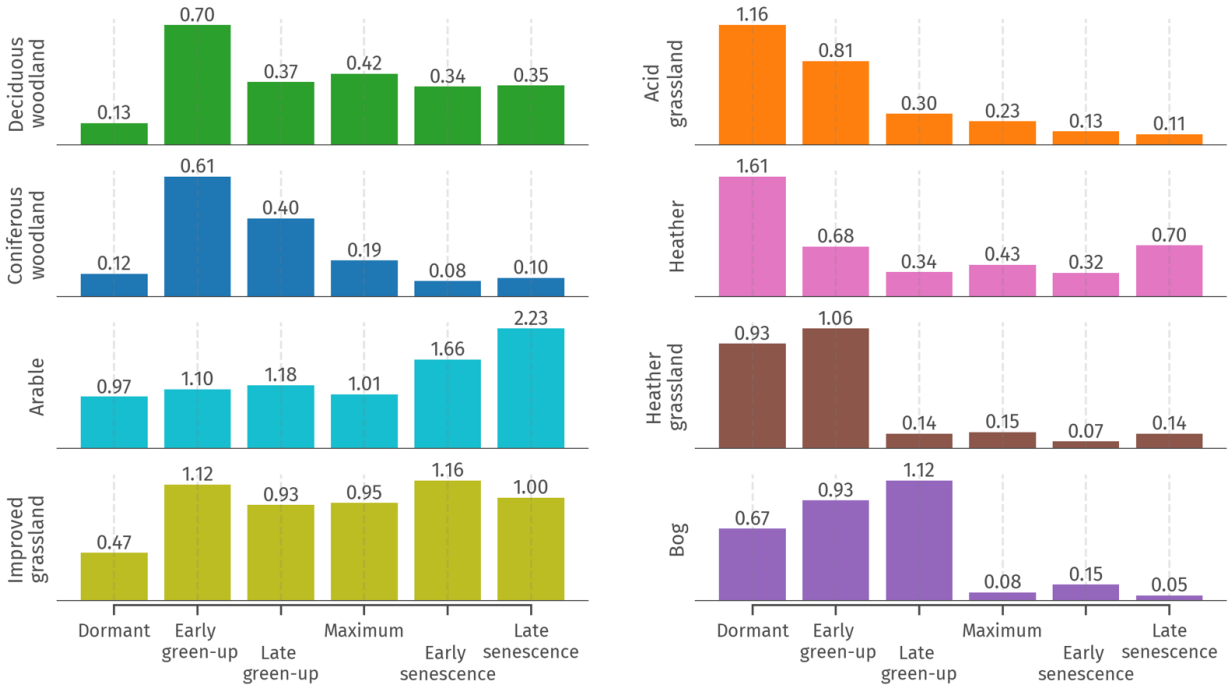


Figure 12: Median rates of active fire detections per day for different phenological phases and land covers pooled over all regions and study years. Early green-up phase represents the period between onset of green-up and middle green-up dates, while detection rates for late green-up phase include active fire pixels between middle of green-up and onset of greenness maximum dates. Senescence phase is also split the same way, using the middle of senescence date. Note that the rates were not normalized by land cover size. As a result, the rates should not be used for comparing different fuels.

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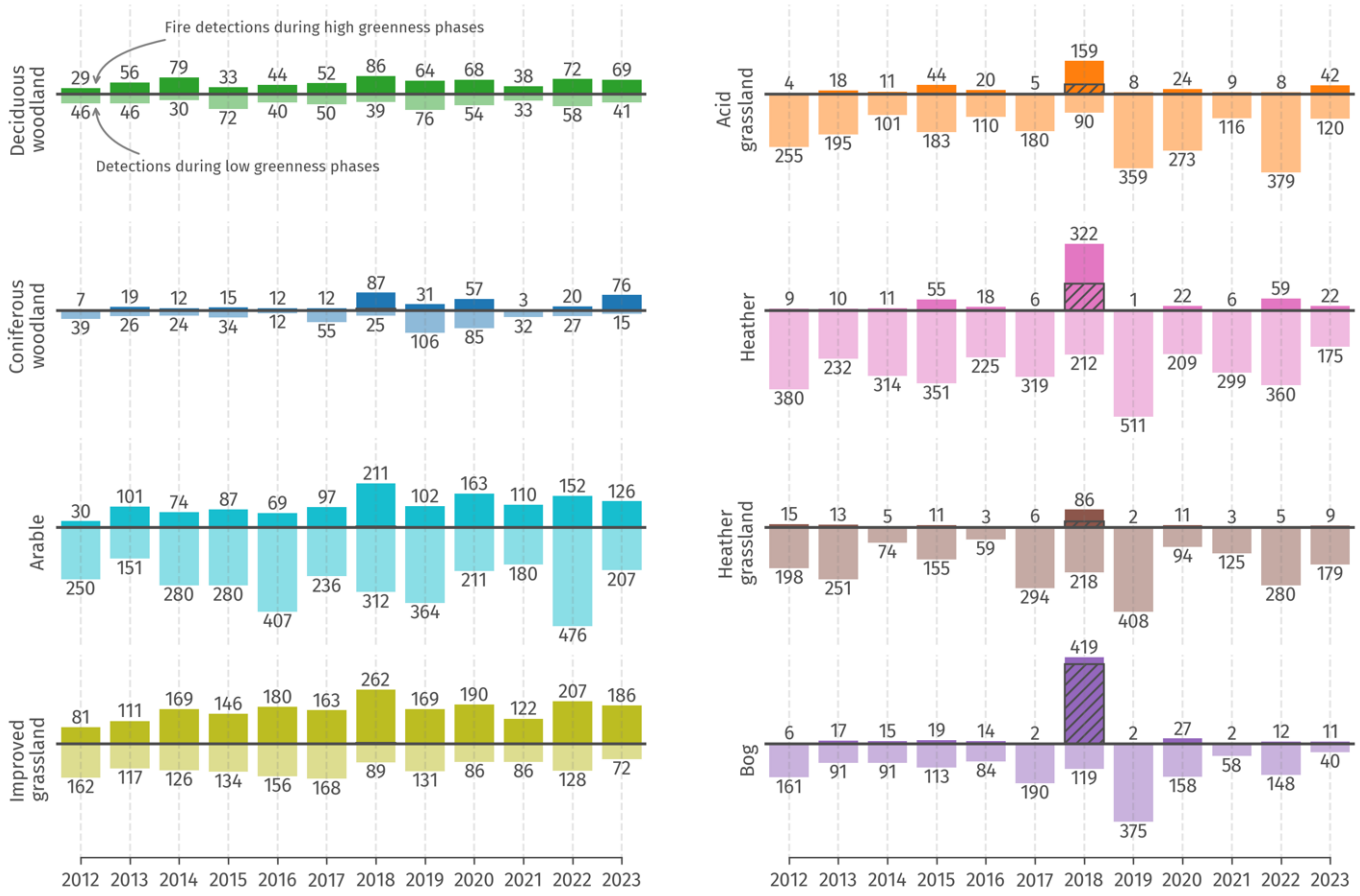


Figure 13: Yearly VIIRS SNP active fire detection counts for high greenness phase (between mid-increase in greenness and mid-decrease in greenness dates) top bars, and low greenness phase (between mid-decrease in greenness and mid increase in greenness dates) bottom bars. Hatched area shows detections attributed to Saddleworth Moor and Winter Hill wildfires, the largest and third largest events respectively in terms of fire detection counts during the record.

4.4 Fire activity modes and associated risks

Under current climatic conditions, the fire regime in the UK is mainly characterised by burning in vegetation that is in a phenological dormancy phase, typically occurring in March and April. While these early season fires are more common compared to those during the summer months, they pose less risk from a firefighting perspective and in terms of potential adverse environmental and human health effects. This is due to fuels and weather factors that influence fire behaviour, severity, and impacts. On average, early season fires occur during low to moderate fire weather conditions (Figure 11), and combustion is driven primarily by fast drying fine dead fuels (1-hour fuels). In semi-natural grasslands dominated by deciduous *Molinia caerulea* grass, the previous year's grass litter is typically 'matted' (blown down) by winter storms (and snow cover in some areas), which reduces fuel depth and, consequently, the rate of fire spread for a given fuel load. Additionally, ground fuels are still saturated by winter rains, preventing combustion of below-surface organic matter,

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including peat. Moreover, many of the early season satellite fire detection counts are attributed to prescribed fires used to modify the structure and age of Calluna vulgaris stands on red grouse game shooting estates and to manage semi-natural pastures dominated by Molinia grass. Prescribed burns, which by definition are planned for and managed, are almost exclusively conducted in upland areas, typically far away from population centres (and the wildland-urban interface), thus presenting little to no threat.

In contrast, extreme drought- and fire weather-driven fire activity spikes during phenological maturity phase are rare, but these have a greater potential to cause adverse effects on human health and lead to environmental damage and property loss. These late-season fires typically occur during periods of elevated fire weather, when extreme fire behaviour is more likely. Unlike in the early season burning window, coarse dead fuels at this time of year have low moisture content, while grass fuels are taller, resulting in greater fuel depth and favouring higher rates of fire spread. Soil water content and associated water tables are typically low during the summer months, increasing the possibility of combustion of below-surface peat, as seen in the large heather and bog wildfires of summer 2018 (Figure 13). The problem is worsened by early senescence and frequent ignitions on agricultural land during the summer months. Arable land and pastures in the UK are often situated at the urban interface, which poses associated threats. These were evident during the 2022 heatwave, when as many as 60 properties were lost primarily due to fires on improved grasslands at the urban interface.

4.5 Phenology as fire risk predictor

The heightened fire risk posed by late-season fires underscores the need to establish the critical fire weather thresholds that determine when a reduction in live fuel moisture and curing is likely to occur. Satellite-based vegetation greenness indices could offer such information on broader scales. Figure 14 illustrates the climatological variability in a vegetation index (in this case EVI2, Jiang et al. 2008) compared to values recorded during seasons with drought and/or heatwave events and recorded fire activity at the time when vegetation greenness should have been at or near maximum. In many cases, mean EVI2 values estimated in the weeks before the date of the first active fire detection during an elevated fire weather season were lower than median values compared to EVI2 recorded at the same time in other years. The decrease in vegetation greenness was more pronounced in grass-dominated land covers compared to heather ecosystems. The sensitivity of NDVI to drought indicators (Figure 15) was highest in improved grasslands and acid grasslands, while in evergreen shrub-dominated land covers, this relationship was subtler. This result was expected as grasslands mainly consist of deciduous vegetation and fine fuels that respond more readily to drought. The analysis suggests that vegetation water stress occurs when both long-term Drought Code and shorter-term memory Duff Moisture Code are high.

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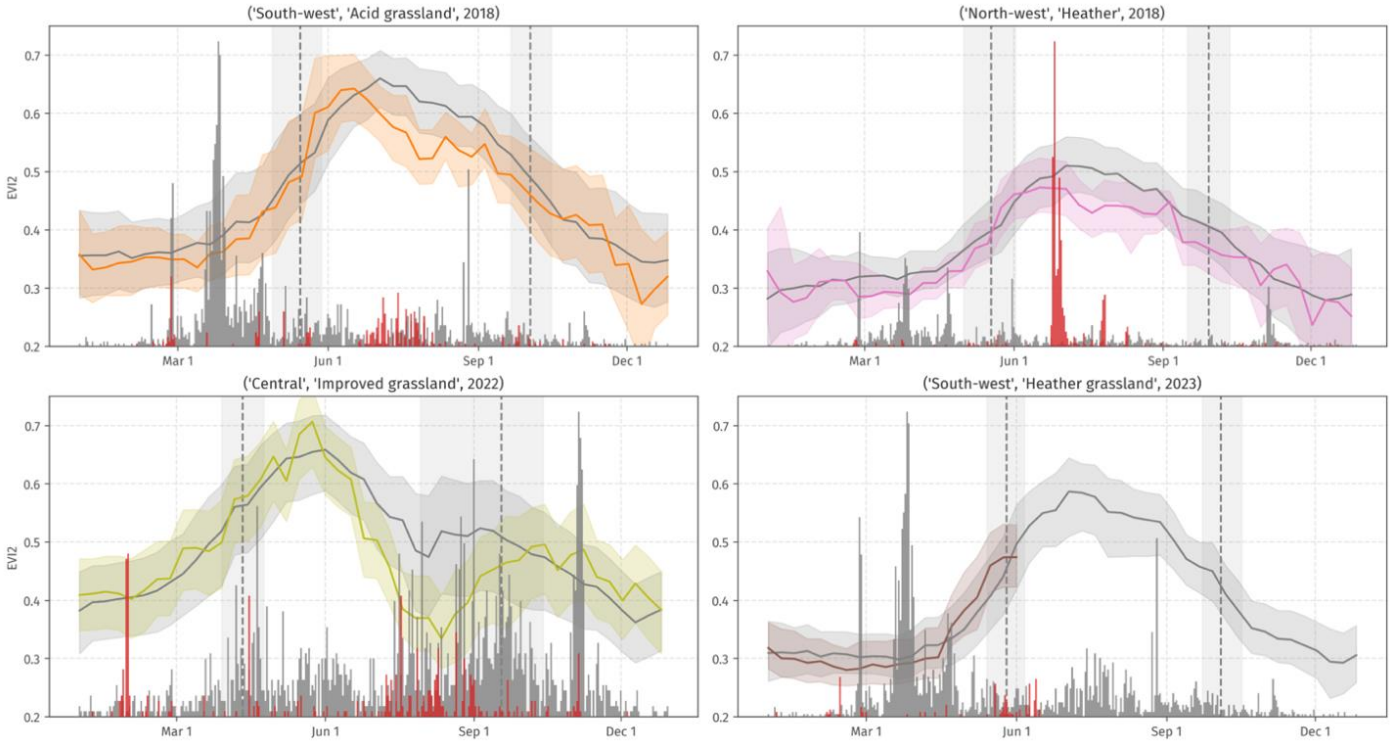


Figure 14: Median EVI2 index (in colour) during years with heatwave and/or drought events versus other years (solid grey lines). Vertical dashed lines indicate median mid-increase in greenness and mid-decrease in greenness phenological transition dates for the land covers. Shaded regions show interquartile range. Red bars show VIIRS fire detections during the extreme weather year, grey bars show fire detections during other years. Four example events are shown in the subplots of the figure visualizing data for different regions and land covers.

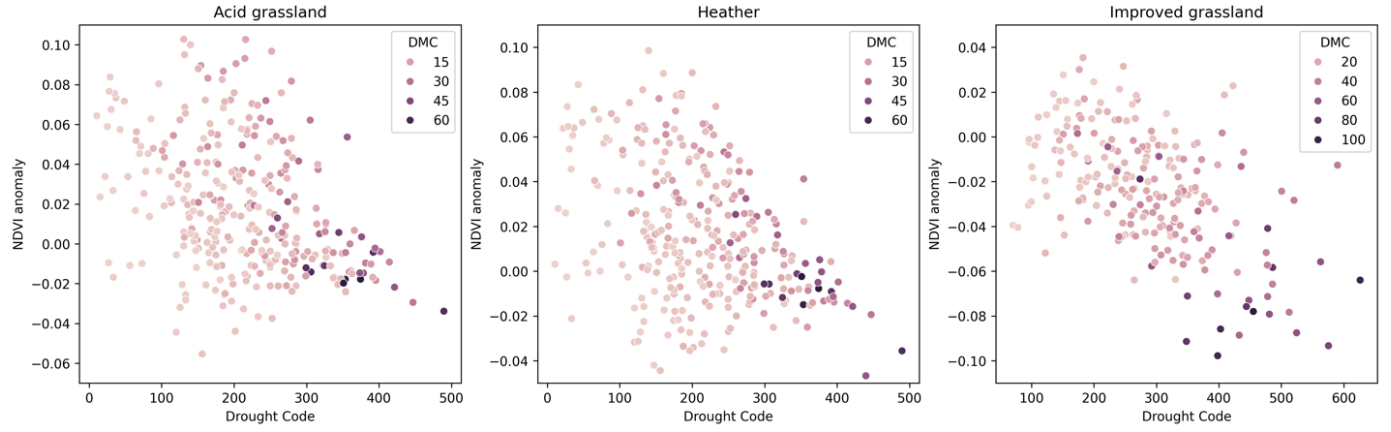


Figure 15: Weekly anomaly in regional NDVI trend for different vegetation fuels in phenological maturity phase as a function of Drought code and Duff Moisture Code (DMC, shown in colour shading).

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4.6 Future fire risk

Our findings thus far suggest that future changes in fire risk exposure in the densely populated UK are more likely to be driven by climatic factors rather than changes in land cover and land use. Future climate projections indicate an increase in the frequency and severity of summer droughts across the UK, particularly in regions in the south of the country (Arnell et al., 2021). Consequently, vegetation that is typically fire-resilient during the phenological maturity phase may become more flammable due to increased water stress. Drought-driven summer fire events with more extreme fire behaviour could become the dominant mode of burning in the UK in the coming decades. This shift may already be occurring in the Central and South-eastern regions, which experience the warmest and driest summers. Large parts of these regions, including areas at the wildland-agricultural-urban interface, are covered by improved grasslands that are particularly susceptible to summer droughts. Transitioning to this mode of burning in regions further west and north of the UK could have significant implications for fire risk exposure in the country. Late-season fires have the potential to overwhelm the resources of emergency responders and fire professionals, as was evident during July 2022 when 14 Fire and Rescue Services across England declared major incidents due to wildfires during the extreme heat. Further research is urgently needed to determine drought severity thresholds and changes in future fire weather for different vegetation fuels and regions across the UK, as well as more broadly across comparable regions in Atlantic/temperate north-west Europe.

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5 Conclusions

The different analyses performed as part of this deliverable show a clear tendency towards an increase in fire risk in Europe in the future, being it higher the higher the expected global warming in the different scenarios used. In the case of the European Territory, the analysis shows an evident increase in emissions due to fires expected to happen in the near future (by 2030) if the SSP370 scenario is realised instead of the SSP126 one. However, this scenario still presages an increase in fire emissions in the medium future (2100).

The two more local analyses (in PS4-Barcelona and in the UK) also reflect this tendency. The estimation of future fire prone areas and their probability of containment in Barcelona show a steady increase in the human ignition probability as the climate scenarios worsen, with a parallel decrease in the probability of containment of the fires, implying an increased risk of big fires in those areas.

Similarly, the analysis of the current and future fire risk in the UK suggest that the expected increase in summer droughts may cause fire events with more extreme fire behaviour in areas and months that were not fire prone in the past, changing the previous fire regimes and endangering population and assets historically not affected by fires.

All these conclusions strengthen the need to advocate for a stronger climate action to contain global warming, and to establish effective reduction and adaptation mechanisms to protect the future population and ecosystems to fires.

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Annex A: Current and future characteristics of the Bulgarian forests, and simulation of a fire with the FlamMap/FARSITE model

Bulgarian forests and forest territories, according to the annual report of the Bulgarian Forestry Executive Agency by the end of 2022, have an area of 4,273,126 ha, where the forested area is 3,926,058 hectares. The area of forest territories is 3,955,790 ha (92.6%). The area of agricultural territories possessing the characteristics of a forest within the meaning of Art. 2 of the Law on Forests ("forests on agricultural territories") is 317,336 ha (7.4%). Figure 16 shows the topographic characteristics of Bulgaria.

According to the Art. 17 of the Regulation № 18 of 7 October 2015 on inventory and planning in forest territories, the departments are divided into sub-departments, which are the smallest territorial unit of the forest territories and serve as the basis of their inventory and management. The sub-departments are relatively constant and uniform and are distinguished depending on their: property; taxation characteristic; management direction; typological affiliation; function and category.

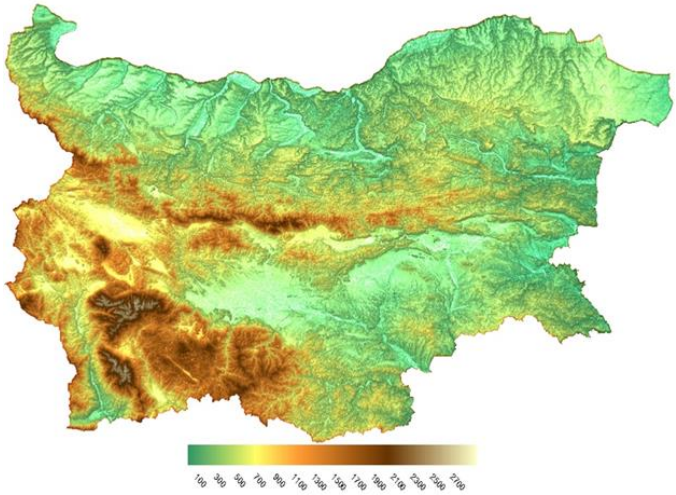


Figure 16: Bulgarian map where the mountain chains and river valley are depicted

Bulgaria is a country with high forest coverage, which by the end of 2022 is 35.37% of the country's territory, and for the last 20 years it has grown by about 5%. There is a Programme of measures for adaptation of Bulgarian forests to climate change. It has been prepared by experts from the Executive Forest Agency under the project “FUTUREforest”, funded by INTERREG IV C Programme. The findings for the Bulgarian climate in the report for the country called “Climate Change Adaptation – Assessment of the Forestry Sector” published on 17th August 2018 under project №: P160511, shows for 2020, 2050 and 2080 in realistic scenarios that the east part of the country will be more affected by heat waves. The De Marton index in combination with the Holdridge model represents the expected draughts in the past, present and future. The Marton index can be easily calculated for the recent and expected climate based on the report Global Water Partnership Central and Eastern Europe (GWP CEE)-Regional Secretariat funding. This methodology ensures that the values, connected with the vegetation coverage, represent the climatic characteristics in local, regional and global

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scales. The Holdridge model connects the spatial distribution of the present vegetation to the factors of the climate system. This model is appropriate for studying the wide distributed structure of the vegetation according to the climate factors and can be used for evaluation of the climate change on the capability of one region or another to maintain the development of different forest types. The Holdridge model is climatic classification scheme, which connects the distribution of the main ecosystem complexes to the climate indexes as bio temperature, annual precipitation and the relation between the potential evapotranspiration to the precipitation. (Figure 17 and Figure 18).

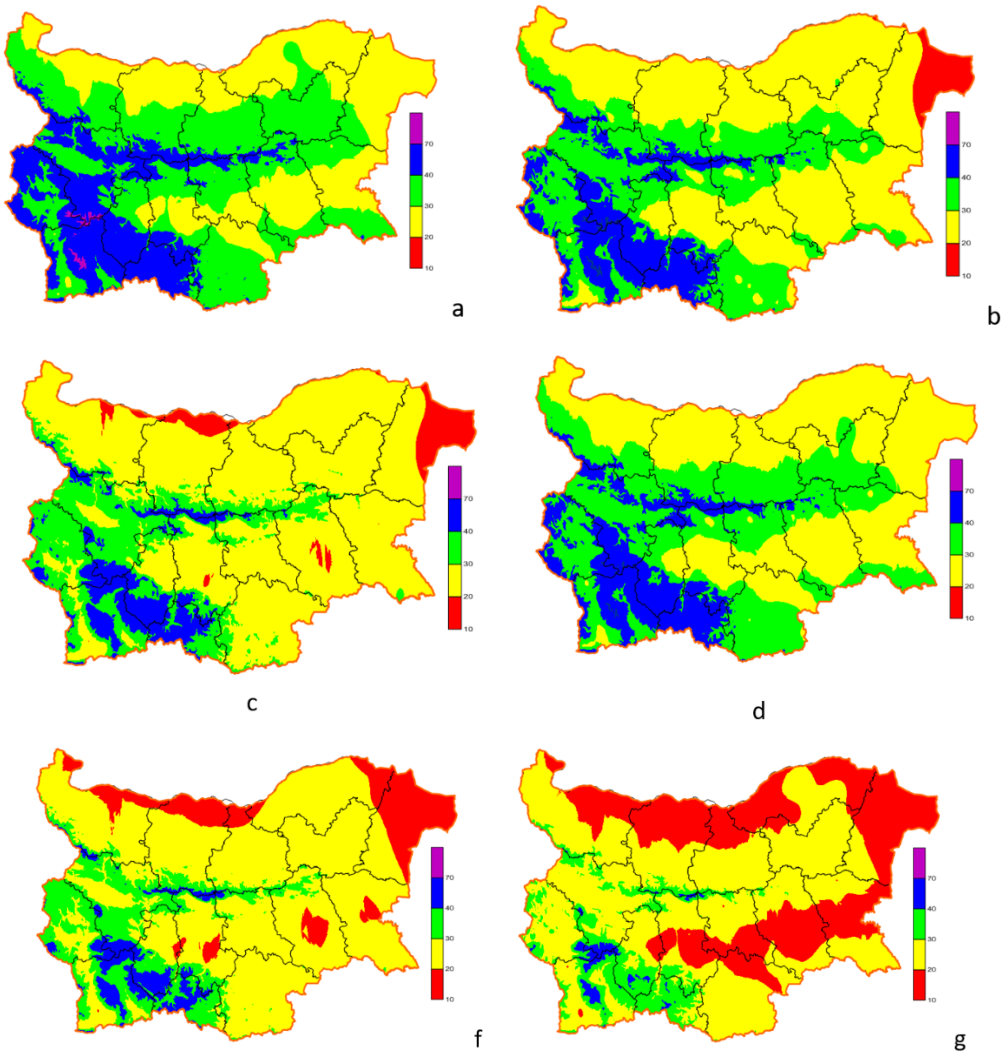


Figure 17: De Marton index for past climate (1961-1990) (a), 2020 (b - realistic scenario), 2050 (c - realistic scenario), 2080 (d - optimistic, f- realistic and g - pessimistic scenarios). Legend: < 20 - deficit in moistening (destruction of vegetation); 21 - 30 - lasting disturbances in moistening, 31-40 - disturbances in moistening for particular years, 41-70- optimal moisture conditions, > 70 - over moistening.

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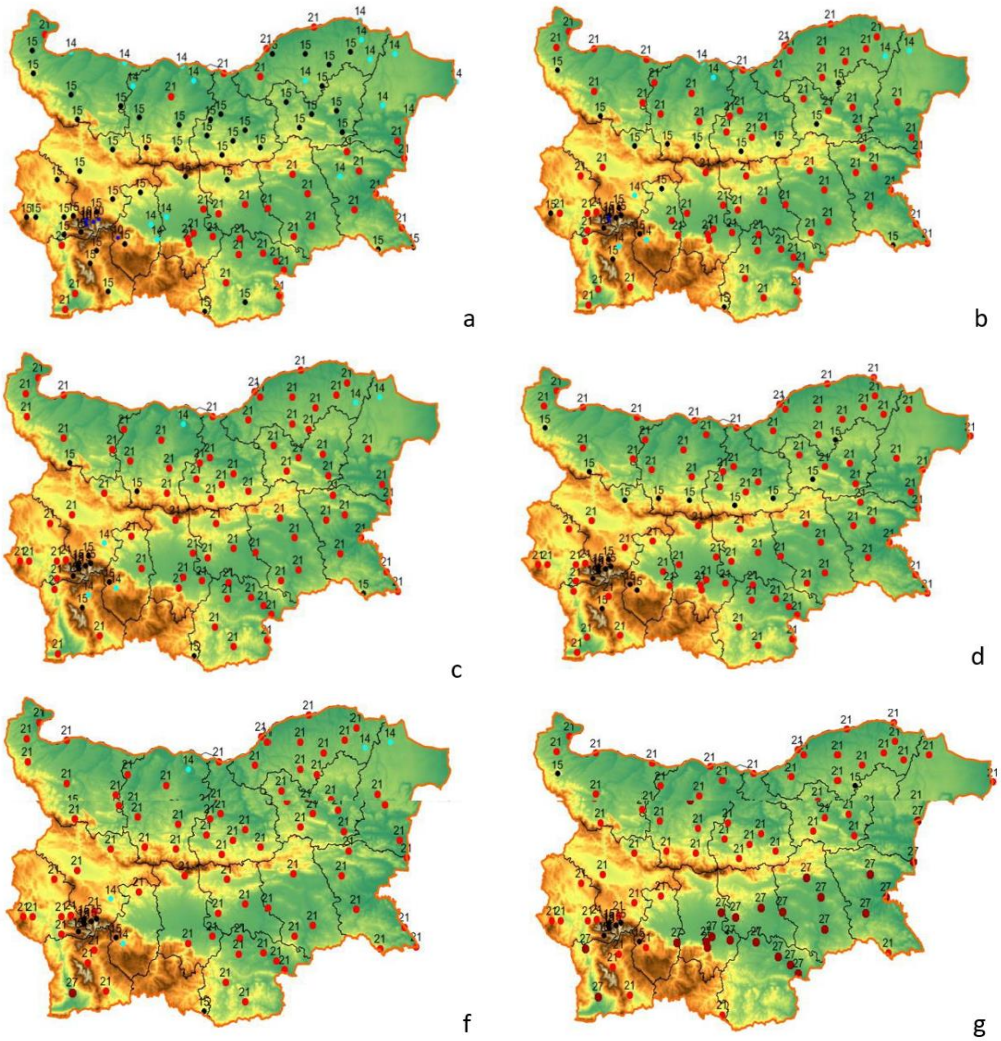


Figure 18: Holdridge classification for the past climate (1961-1990) (a), 2020 (b – realistic scenario), 2050 (c – realistic scenario), 2080 (d – optimistic scenario f – realistic and pessimistic scenario). Legend: 14 – temperate cool step; 15- temperate cool fresh forest, 21- temperate warm dry forest, 27 – subtropical forest land with thorns.

The number of fires in Bulgaria is semi-stable since 2008, with a total BA that has not significantly increased (Figure 19 and Figure 20), observing 2 peaks in the spring and summer time (Figure 21).

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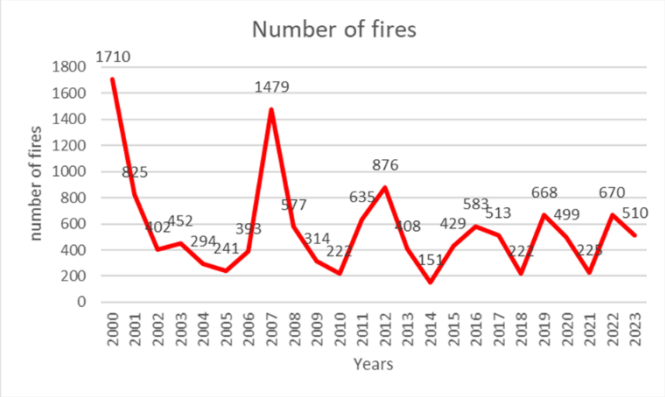


Figure 19: Number of fires in the period 2000-2023

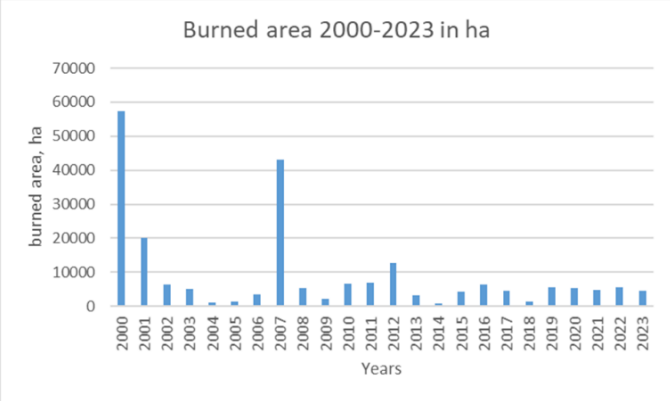


Figure 20: Burned area in the period 2000-2023 in ha

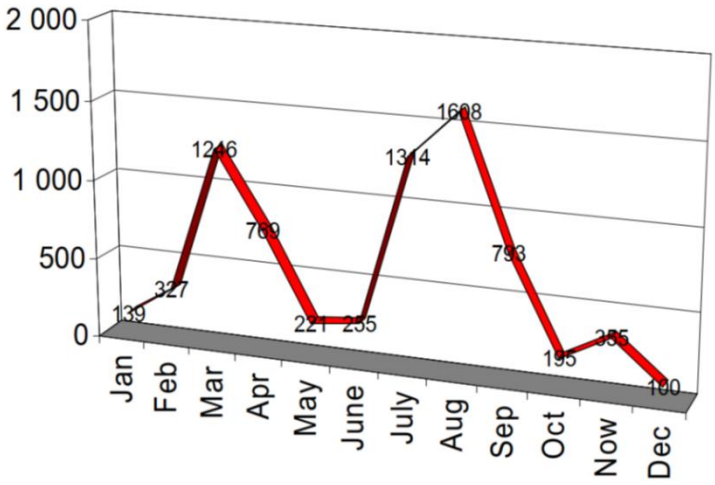


Figure 21: Number of fires in the period 2011-2023 by months

Razdel Fire simulation results

The Fire of Razdel started 2 km south-east of Razdel village, in the municipality of Elhovo, District of Yambol in the South-Eastern Region in Bulgaria. The ignition occurred on the morning of August 10th of 2022. The alert was given at 11:00 of the same day, and the fire was detected by the passage of the Terra MODIS at 11:26. Final total burned area was 797 ha, where 560 ha were forest areas, and 237 ha were grasslands and pastures. The size of the burned forest territory makes that fire the largest forest fire in Bulgaria in the year 2022 (another fire with 1,023 ha total burned area was also recorded during 2022 in another part of the country, but with a smaller part of affected forest zones: 460 ha). Although the fire of the Razdel village did not have an impact on residential zones, it affected considerable areas of NATURA 2000 and there was the risk of the fire crossing the Bulgarian - Turkish border.

The Razdel Fire was active for five days, spreading in two villages: the village of Razdel (affected territory is 667 ha) and the village of Malko Kirilovo (affected territory is 130 ha). Both villages are located under the

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same municipal territory of Elhovo (Figure 22). 95% of the burnt area was reached during the first 60 hours of the fire, approximately around 12:00 on August 12th. The monitoring of the burned area continued until August 14th, several days after the major fire perimeter was suppressed. Smaller fires were active on August 15th and 17th but were considered as separate events. The description of this report focuses mainly on the period between August 10th and 14th. As shown in Figure 23, the area where the fire was propagating was evaluated as a maximum fire danger zone with a red code probability for fire occurrence at the fire ignition date. The red code is the highest degree of fire danger in Bulgaria calculated on a daily basis by the National Institute for Meteorology and Hydrology (NIMH).

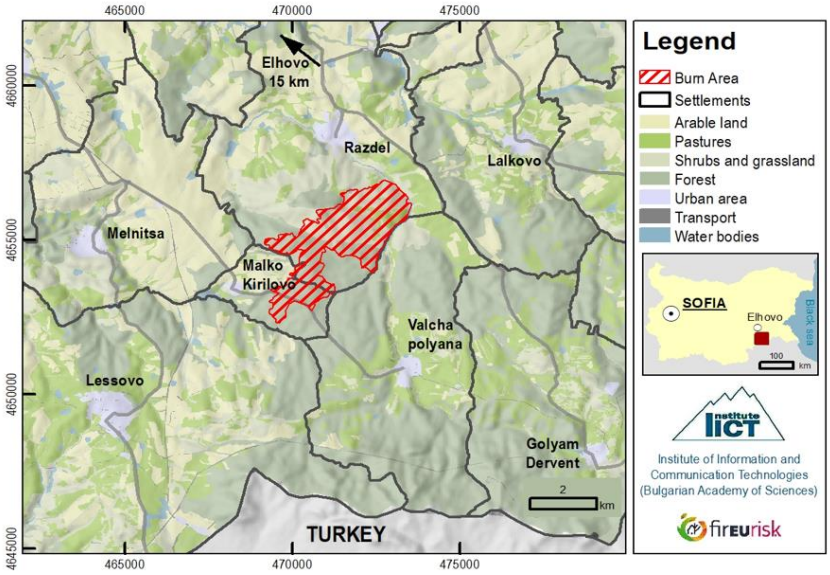


Figure 22: Geographical representation of the Razdel Fire (source IICT - BAS)

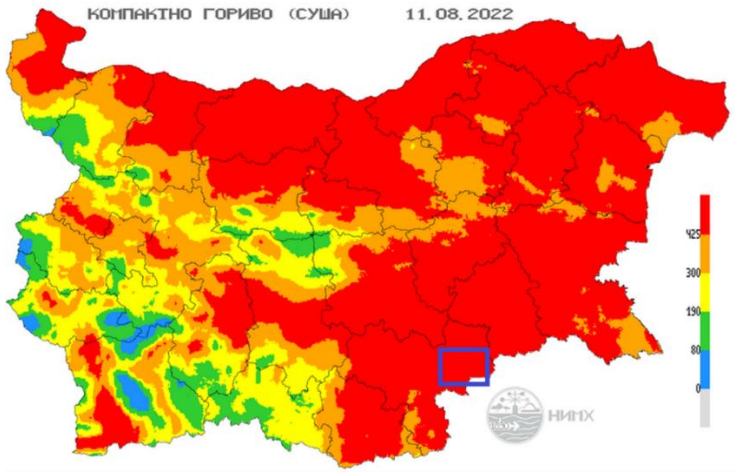
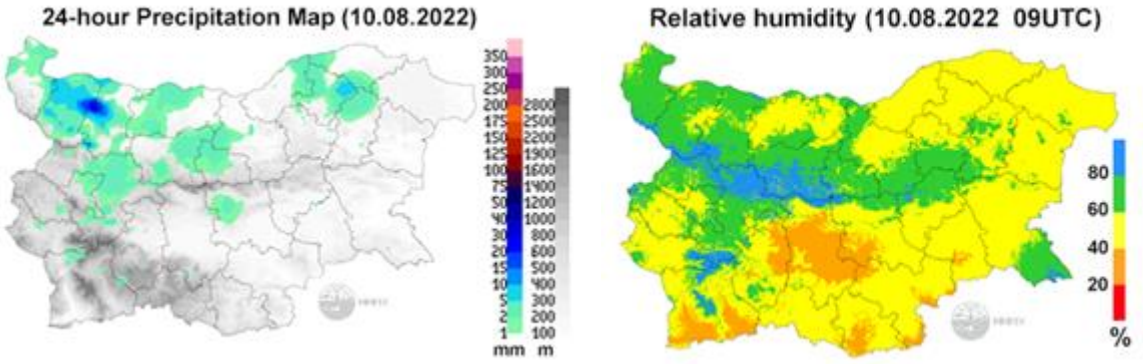


Figure 23: Draught index for the 11 August 2022 (source NIMH)

The forecast for August 10th, provided by the National Institute for Meteorology and Hydrology (NIMH), was for sunny weather with a clear sky (Figure 24), accompanied by strong winds from north-northeast with a

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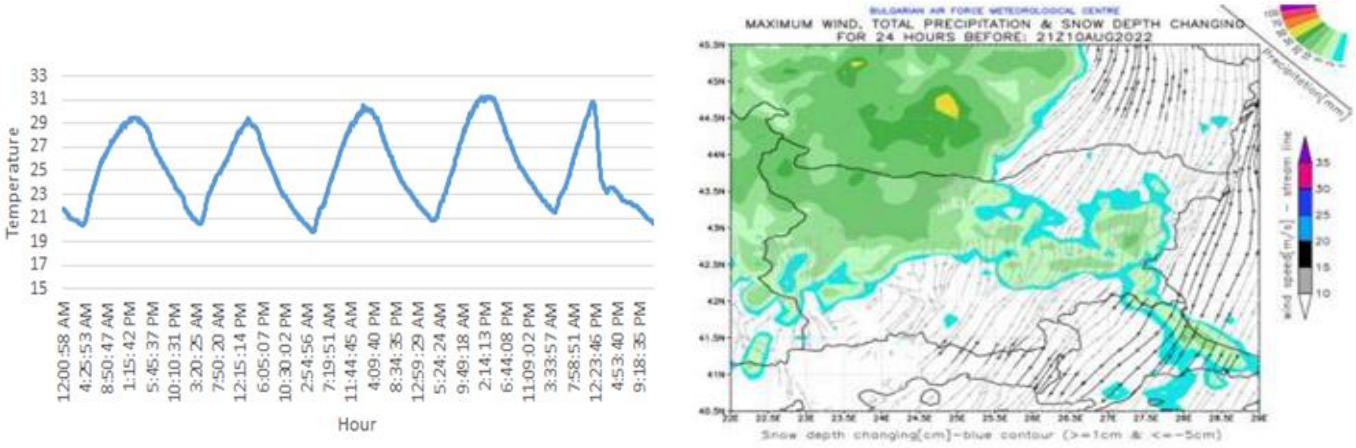
speed of 6 to 9 m/s reaching up to 15 m/s. The forecast for the daily maximum temperatures was 32ºC to 34ºC for the region where the Razdel Fire occurred.



(a) (b)

Figure 24: Meteorological parameters for August 10th, 2022: (a) 24-hour precipitation (mm); (b) Relative humidity (%), data from NIMH

The wind had an important role in the fast fire perimeter spread of the Razdel Fire. As shown in Figure 25b, on August 10th, the wind was expected to be from the northwest reaching in the afternoon 10-15 m/s. This led to the fast spread of the fire in the southwest direction, but stopping the fire after reaching the top of the hill where it turns to the north (close to the village of Razdel). The temperature was the other driver of the fire spread as could be seen in Figure 25a.



(a) (b)

Figure 25: Meteorological influence on fire on August 10th: (a) Hourly meteorological conditions (temperature in ºC) registered by the meter from August 10th to 14th in a station located in Elhovo. (b) Wind forecast for August 10th from NIMH

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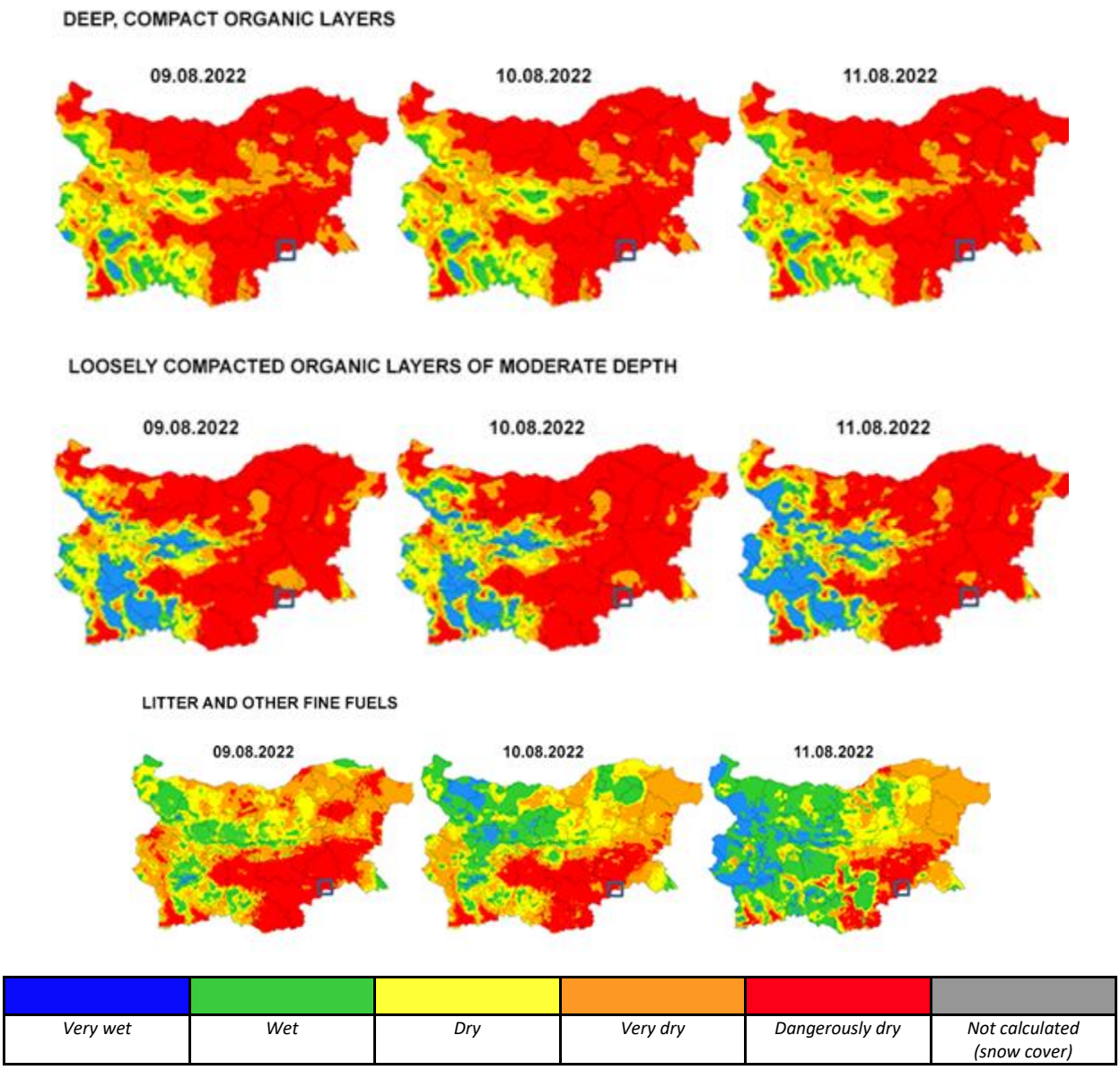


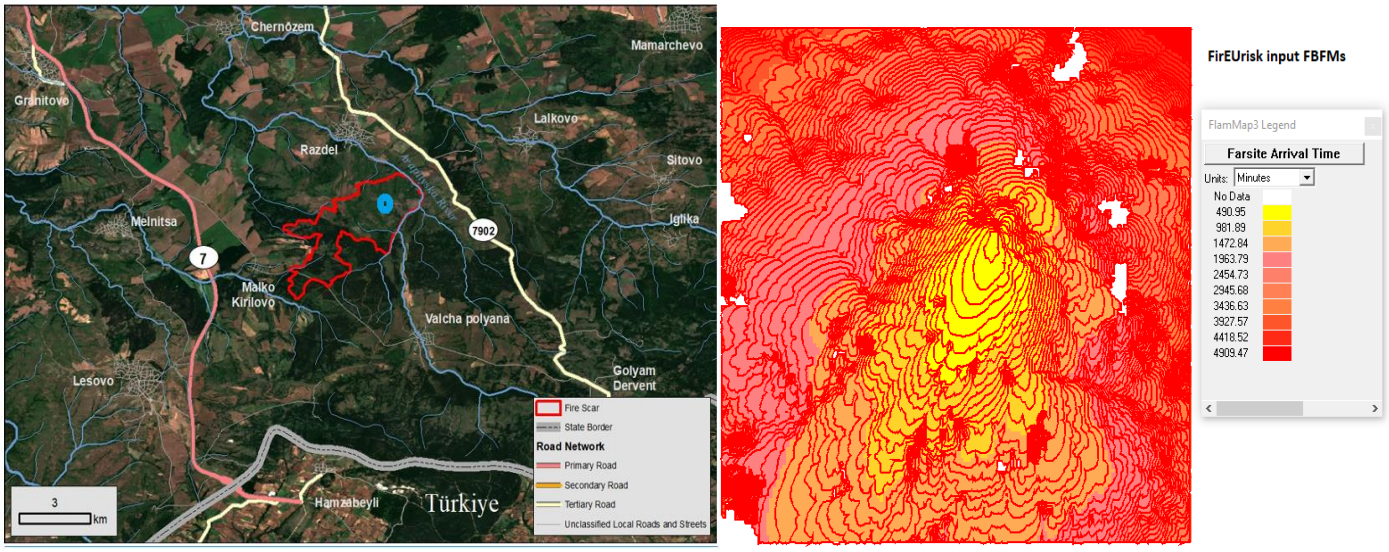
Figure 26: Maps of the fuel moisture conditions for August 9th, 10th, and 11th provided by NIMH based on data from ALADIN (numerical model for a short-range forecast

The fuel moisture content for the first day of the fire event 9-10-11 August 2022 seen on Figure 26, shows that the area was dangerously dry. The conditions were very favourable for ignition occurrence and fast fire spread.

Based on the collected data from the local observations and the National Institute of Meteorology and Hydrology a FlamMap run with the embedded FARSITE simulator for a single fire propagation was run. The simulation landscape file was built with downscaled fuel map on 100m resolution. It has been produced as the FirEUrisk 1km map was elaborated with machine learning techniques and LUCAS points validation. The simulation was run with no fire breaks as it was progressing in the real conditions. The suppression measures

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were not simulated. The shape of the simulated fire is not completely overlapping with the final real burned area, but in its initial fire spread the similarity is fairly good. Simulation result and real burned shape of the fire can be seen on Figure 27.



(a) (b)

Figure 27: a) Real burned shape of the Razdel fire after 5 days of active burning and its ignition point marked as blue dot. b) Simulated Razdel fire run with FARSITE simulation and FirEUrisk fuel models downscaled to 100m resolution.

From the simulation results, we can have as a conclusion that in the grasslands the fire spread was simulated close to the real fire spread driven by wind first in the north and after that in the south. However, the mixed forest areas and the conifer zones where the major part of the suppression measures of this fire were performed do not overlap because no firebreaks were used in the FARSITE simulation. In case of no suppression, the fire might have grown similar to what the simulation result has depicted.

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