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

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Executive Summary

Climate and land use changes are affecting European fire regimes. Characteristics of fuels on the landscape, such as the type, moisture content, and arrangement, affect the characteristics of subsequent wildfires. Fire-enabled dynamic global vegetation models are a useful tool to explore how different fuel management scenarios may affect parameters that affect future fire risk, especially when coupled with improved scenarios of future land use.

This deliverable presents the design and results of a simulation experiment evaluating, for the first time, fuel removal scenarios using a fire-enabled Dynamic Global Vegetation Model (DGVM) for the European Territory. The experiment was conducted under two combined climate and land-use change scenarios: Shared Socioeconomic Pathway 1 (SSP1, “Taking the Green Road”) and SSP3 (“Regional Rivalry”) which align with the Representative Concentration Pathways RCP2.6 and RCP7.0, respectively. The experimental design provides insights into the potential outcomes of near-term fuel management actions while assessing the model's functionality under varying socioeconomic and climate pathways. Our findings suggest that societal decisions shaping socioeconomic trajectories, along with the spatial targeting of specific fuel classes, can significantly influence future fire risks.

This research builds on data developed in Deliverables 2.3, 2.4, 3.3 & 3.4. In Deliverable 3.4, improved future land use scenarios developed in Deliverable 3.3 were included as input data in the Lund-Potsdam-Jena managed Land model (LPJmL) DGVM and coupled with a process-based fire model, SPITFIRE. The results of Deliverable 3.4 are used in this deliverable as baselines to evaluate the effects of five fuel management scenarios on four metrics relevant to fire risk and fuel dynamics—burned area, maximum surface fire intensity, rate of spread, and fuel bulk density—under SSPs 1 & 3. These fuel management scenarios targeted different fuel sizes, ranging from fine fuels (e.g., leaves) to coarse fuels (e.g., whole trees) which can be associated with specific fuel management tactics, such as prescribed burn and mechanical removal (based on research associated with deliverables 2.3 and 2.4).

Key Take Aways

Targeting fine fuels (i.e., 1-hour fuels such as grasses and leaves) is likely most effective for reducing burned area in Europe. However, coarser fuels, such as large branches and mature trees should still be managed carefully in wildland-urban interfaces and to make areas accessible to fire response teams in the event of emergencies.

Whether Europe’s future follows a more sustainable pathway along the lines of SSP1 or a more tumultuous and nationalistic one similar to SSP3, fire will be present with the potential to undermine efforts to mitigate climate change. This means that landscapes and priorities must also be viewed from a fire perspective, with an eye towards targeted fuel treatments that make the best use of resources.

Decisions on fuel treatment require a thorough assessment of local factors, including costs and incentive opportunities, interest or opposition by local stakeholders, and socioeconomic trends. Further research is needed to better negotiate the potential trade-offs between fire risk, biodiversity, ecosystem services, and unintended effects.

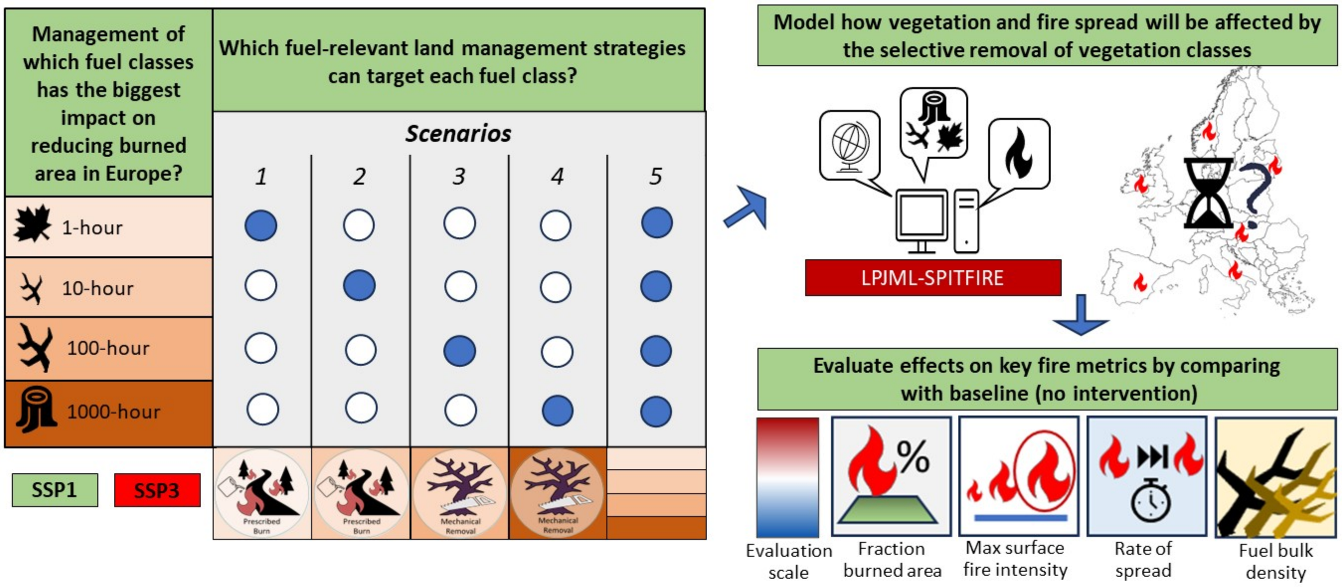

Figure 1: Graphical Abstract. Overview of the research organization and outputs. Left: Scenarios are designed around four fuel classes (left column) which can be related to fuel management strategies (bottom row—prescribed burn and mechanical removal). The scenarios are processed using LPJmL-SPITFIRE, a fire-enabled Dynamic Global Vegetation Model. Four outputs are then evaluated to understand the effects of the fuel management interventions on burned area, fire intensity, surface fire rate of spread, and fuel bulk density for the European Territory.

Links to Key Related Deliverables*:

[D2.3 – Guidelines for Land Management Strategies: Applicability, socioeconomics and environmental concerns](#)

[D3.2 – Continental land-use change scenarios and stylised fuel management scenarios for the 21st century](#)

[D3.3 – Improved fire regime simulations using hybrid functions in fire models and in fire-enabled DGVMs](#)

[D3.4 – Simulated fire and vegetation dynamics at three spatial scales](#)

******Note that Deliverable 2.4 is pending upload to the FirEUrisk website: https://fireurisk.eu/deliverables/*

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Table 1: List of acronyms

List of Acronyms	
ACCESS-CM2	Australian Community Climate and Earth System Simulator, Coupled Model 2
C	Carbon
CO_2	Carbon dioxide
DGVM	Dynamic Global Vegetation Model
EU	Europe(an)
GCM	Global Circulation Model
GLOBIOM	Global Biosphere Management Model
ha	hectares
HW	Heartwood
kg	kilogram
kW	kilowatts
LPJmL	Lund-Potsdam-Jena managed Land DGVM
LU(C)	Land use (change)
PFT	Plant Functional Type
RCP	Representative Concentration Pathway
SPITFIRE	Spread and InTensity of FIRE process-based fire model, embedded in LPJmL
SSP	Shared-Socio-economic pathway
SW	Sapwood

1 Introduction

Climate and land-use changes are reshaping fire regimes across Europe. The characteristics of a fuelscape—the type, quality, and arrangement of fuels on the landscape—significantly influence wildfire behaviour, including the area burned, rate of spread, surface intensity, and carbon emissions. To evaluate the potential trade-offs of policies like the European (EU) Green Deal and traditional practices such as prescribed fire use, it is essential to develop models that simulate the impacts of these strategies on land-use change and fuel distribution. Such models are critical for informing adaptive management and preparation efforts across European landscapes.

Dynamic Global Vegetation Models

Previous research in Europe has used Dynamic Global Vegetation Models (DGVMs) coupled with wildfire spread models to understand how fire may behave in future landscapes. These models simulate an ecological system which is composed of attributes relevant to ecological function and fire dynamics. Input attributes include climate conditions, atmospheric CO_2 concentrations, nutrients, soil types, ignitions models (from humans and lightning), from which locally adapted vegetation (characterized by plant functional types), stand structures, and fuel characteristics emerge. After running the process-based vegetation and fire spread model, fire and vegetation dynamics are derived. These include burned area, fire intensity, surface fire spread, and fuel bulk density, amongst others (Thonicke et al., 2010). Although these models have made important contributions to understanding potential trajectories for fire system dynamics, they have thus far not assessed the potential effects of fuel management (e.g., reductions in burned area, fire size, fire intensity, and vegetation recovery) on simulated outcomes.

Land use and fire risk

Understanding land use is also critical for exploring future fire risk, as changes in land use significantly affect fuel composition and distribution across landscapes. Policies like the EU Green Deal's Biodiversity Strategy for 2030, which aims to plant 3 billion trees (European Commission, 2021), offer benefits for biodiversity, conservation, and carbon sequestration but also introduce trade-offs. Large-scale reforestation can compete with other land uses, alter forest canopy structures, and potentially increase fire risk, especially if maladapted or highly flammable species, like eucalyptus in Portugal, are introduced (Pantera et al., 2018). Similarly, urbanization trends may expand the wildland-urban interface—a known contributor to wildfire risk in Europe—while also driving land abandonment, which can increase fire fuel loads as unmanaged agricultural lands revert to shrub and tree cover (Sil et al., 2019a; van der Zanden et al., 2017; Viedma et al., 2015). Accurate models are essential to evaluate these trade-offs and predict how land-use changes affect fire risk.

1.1 Purpose and objectives of the document

In this study, we novelly develop and test scenarios in which fuels are selectively removed from European landscapes under two different socioeconomic and climate pathways. The purpose is thus to assess fuel classes, land-use management strategies, and fire dynamics across Europe in response to changing climate, population, and land-use scenarios. By testing and analysing fuel removal interventions under future climate pathways, we aim to provide critical insights into how targeted strategies can mitigate fire risk and enhance socio-ecological resilience. The findings will highlight opportunities to reduce future burnt area while identifying regions most vulnerable to fire and those that would benefit most from tailored fuel management approaches. In this context, the study has three main objectives:

- **Integrate climate, population, and land-use change scenarios** to estimate future fire regimes and assess their impacts on socio-ecological vulnerability and exposure, enabling effective adaptation measures. (FirEUrisk O10)
- **Deploy forward-looking land-use models** to evaluate the effectiveness of adapted management strategies under alternative climate and land-use futures and assess their influence on the geography of wildland-urban interfaces. (FirEUrisk O10)
- **Test fuel removal scenarios** using LPJmL-SPITFIRE under SSP1-RCP2.6 and SSP3-RCP7.0 to quantify the limits of climate change on fire risk mitigation and explore adaptation measures for optimized wildfire management in Europe.

1.2 Structure of the document

After the background and context given in the introduction, the document details the methods used to explore stylized fuel management scenarios in Section 2. This includes a description of the design and decision process for the development of the fuel removal scenarios, as well as a brief background of the process by which future land use scenarios are developed (with further detail available in Deliverable 3.2). This section also includes descriptions of the terminology, fuel classes, evaluations metrics (Figs. 2 & 3), and protocol under which the scenarios were simulated in the DGVM. The results in Section 3 are then structured in three parts, beginning with comparisons of the cumulative differences between the scenarios in comparison to the baseline, an assessment of spatial differentiation across Europe, and the model outcome with respect to adapting to future fire regimes in Europe. Finally, we discuss potential underlying mechanisms in the DGVM which may contribute to the results in Section 4, with insights on how to interpret and use the results.

2 Methodology for development of stylized fuel management scenarios

This study consists of three main parts (Executive Summary, Graphical Abstract)—the development of fuel management scenarios which selectively remove fuels (Sections 2.1), land use scenarios which link historic and future projections (Section 2.2 with more detail in Deliverable 3.2) and coupled dynamic fire and vegetation modelling (Section 2.3, noting that the baseline scenarios were developed in Deliverable 3.3, a link for which can be found in the Executive Summary). The following sections give an overview of each of these components, with descriptions of the parameters, settings, and assumptions used to run them.

2.1 Design of the fuel removal schedule

The fuel model

Five fuel removal scenarios were designed to explore management potential in Europe in a way which can be simulated in the structure of LPJmL-SPITFIRE. This first required interpreting fuel removal vis-a-vis the fuel model used by LPJmL-SPITFIRE. In landscape-scale fire models and fire spread predictions, fuel classes are defined according to their diameter sizes. Because simulated tree architecture does not provide that level of detail, the fuel model used in LPJmL-SPITFIRE consists of fuel classes defined by their proportion in aboveground living biomass (Table 2), which in turn affects their burning lag time. One-hour fuels are characterized by leaves and small twigs; 10-hour fuels by woody and small branches; 100-hour by larger branches; and 1000-hour by tree boles and trunks. The fuel contained in each fuel class is derived from dead aboveground biomass from leaves and wood that occur as a result of leaf turnover (leaf fall) and tree mortality not related to fire. Because it is simulated inside the DGVM, vegetation growth and turnover, but also decomposition of dead fuel additionally affect availability of fuel for burning.

Matching the fuel model to fuel management practices

Fuel removal amounts and schedules were based on the literature review and analysis described in Deliverables 2.3 and 2.4 (see Executive Summary for links). Within this scheme, we determined that 1-hour fuels can be targeted by prescribed burning, for example, which can at most be carried out on a yearly basis at a relatively high amount of removal (here, 20% removal within a 9x9km cell). Ten-hour fuels may also be managed through prescribed burning, but at a lower level of removal (here, 15% removal within a 9x9km cell). The literature and expert opinion characterize longer management return intervals for 100- and 1000-hour fuels for logistic, financial, and ecological reasons (here, 5% every 10 years). These values represent the maximum potential for fuel removal.

Table 2: Description of fuel classes as defined in LPJmL-SPITFIRE for fuel removal and contributions to fuel dynamics (technical input from Andrews, 2018). These icons are used throughout the deliverable to represent the fuel classes.

	Fuel Class	Description	Contribution to fuel dynamics	Scenario
	1-hour fuels	leaves and twigs, i.e. leaf mass plus 4.5% of the carbon stored as heartwood (HW) and sapwood (SW)	Greatest influence on fire spread. High surface-area to volume ratio. Removal increases overall fuel bulk density.	Scenarios 1 & 5: 20%, every year
	10-hour fuels	Woody, small branches, i.e. 7.5% of HW and SW	Influence on fire spread	Scenarios 2 & 5: 15%, every year
	100-hour fuels	large branches, i.e. 21% of HW and SW	Influence on fire spread	Scenarios 3 & 5: 5%, every 10 years
	1000-hour fuels	boles or trunks, i.e. 67% of HW and SW	Direct relationship with fire intensity. Low surface-area-to-volume ratio.	Scenarios 4 & 5: 5%, every 10 years

Scheduling of fuel removal

The time of year in which fuels are removed can support different management goals, such as fuel reduction or protecting breeding wildlife and sensitive periods in vegetation cycles. We opted to remove fuels on May 1st of the respective year as the literature indicates that this is an appropriate and effective time to carry out many fuel removal activities. Finally, although other studies using LPJmL-SPITFIRE extend to the year 2100, we limit the study period here to the year 2050. This choice was made based on limitations for the extension of the future land use scenarios. In short, the future land use scenarios are based on many complex global socioeconomic assumptions. Extending the scenarios to 2050 keeps the study results within an acceptable level of uncertainty. See Section 2.2 for more detail on the development of the land use scenarios and Section 4 for a discussion of the implications of this choice and potential for further studies.

2.2 Preparation of future land use scenarios

Tailored scenarios for historic and future land use were developed for the years from 1960-2050 in Deliverable 3.2 to fit in a model chain that includes global economic models, spatial land use models, and fire risk assessment. Historic data was extracted from the HILDA+ dataset (Winkler et al., 2020). Future land use projections were developed using CLUMondo. 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 (Asselen and Verburg, 2013). CLUMondo takes a land systems approach, allowing for a more nuanced interpretation of land uses. This includes simulation of changes in cropland, grazing, and settlement intensity as well as incorporation of mosaic land systems. In combination with anticipated regional demands for goods and services produced by exogenous models, CLUMondo optimizes potential solutions and allocates the results in a spatially explicit manner (Malek et al., 2018; Schulze et al., 2019). As CLUMondo systematically runs each year's input of demands and suitability for a region, CLUMondo allocates a corresponding land system to each grid cell, subject to the input conversion rules supplied to the model.

The future scenarios were developed under two potential socioeconomic pathways, SSP1 ("Sustainability") and SSP3 ("Regional Rivalry"). The scenarios and projected demands to the year 2050 are based on the productivity change produced by GLOBIOM ("GLOBIOM - Global Biosphere Management Model," n.d.), a bottom-up, partial equilibrium, integrated assessment model developed by the International Institute for Applied Systems Analysis which integrates global trade and global demand-supply. *SSP1, "Sustainability,"* explores the effects of relevant policies aimed at a more sustainable future, such as the Green Deal (Daigneault et al., 2019; Korhonen et al., 2020; Popp et al., 2017), on different forest management scenarios and corresponding land demands. The associated climate projection, Representative Concentration Pathway (RCP) 2.6, which assumes a high effort to reduce emissions and increase renewable energy and emissions capture, was used to account for changing climatic conditions. In contrast, *SSP3* anticipates an overall decrease in population, especially in the south and east regions of Europe (Fig. 2). Livestock and crops are also anticipated to decrease under SSP3, especially in the south. Agricultural production is more polarized overall, as farms are assumed to become larger and adopt conventional practices. Demand for permanent crops increases significantly for all of Europe, especially the south, while demand for forest products decreases as biofuel energy sources are increasingly adopted. SSP3 in our scenarios are associated with RCP7.0, which indicates mixed renewable and fossil fuel energy generation, limited public transportation options, and an overall low effort to curb emissions. Full details of the rationale and procedure for the development of the future land use scenarios can be found in Deliverable 3.2, "Continental LUC scenarios & stylized fuel management scenarios."

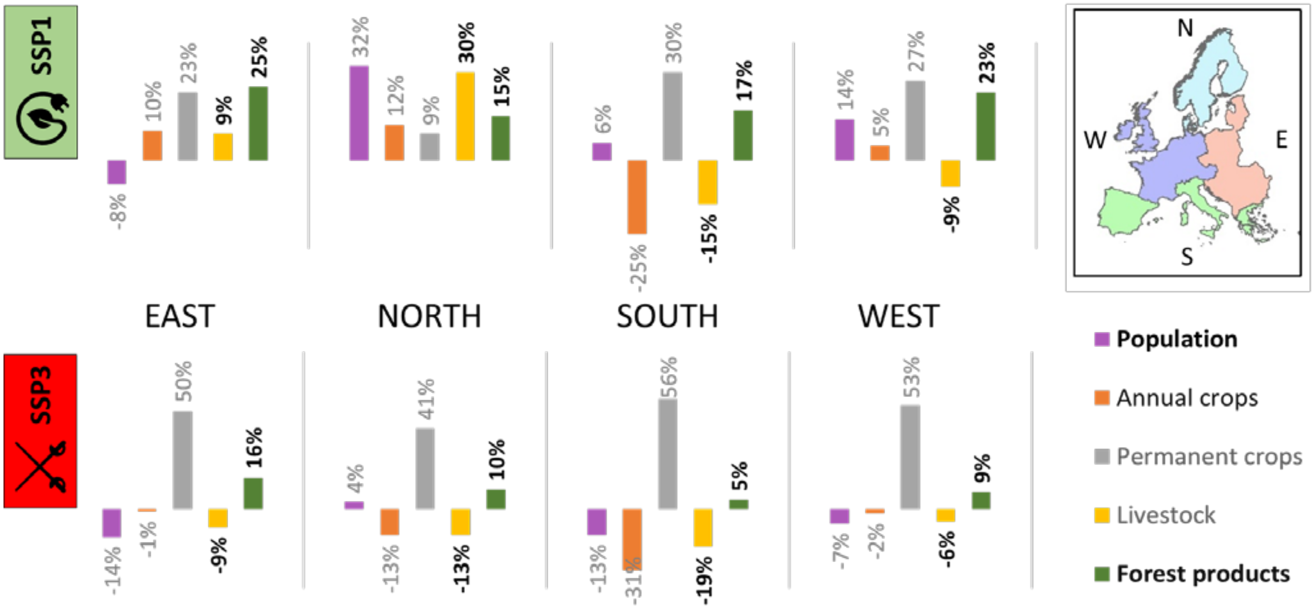


Figure 2: Summary of differences between the percent land cover change to be met in CLUMondo for each SSP scenario by the year 2050. CLUMondo was run separately for each of the four regions of Europe (east, north, south, and west—see inset map). These percent cover changes are derived from demands for goods from GLOBIOM, an exogenous macroeconomic model.

2.3 Simulation of stylized fuel scenarios in LPJmL-SPITFIRE

2.3.1 Integration of land use and fuel management into LPJmL-SPITFIRE

The Lund-Potsdam-Jena managed Lands (LPJmL) model is a DGVM that simulates both natural and agricultural ecosystems, as well as land-atmosphere exchange flows of carbon and water on a global scale (Schaphoff et al., 2018). Vegetation dynamics are driven by climate input data (daily temperature, precipitation and radiation), atmospheric CO_2 concentration and soil texture data. In LPJmL, each grid cell can be characterized by the proportion of natural vegetation and other land covers, such as various crop types and managed grasslands. By incorporating land use scenarios as input to the model, the proportion of natural vegetation within each grid cell can change over time. In SPITFIRE, fires are assumed not to spread into neighbouring managed land stands or to neighbouring grid cells. As a consequence, the size of the natural stand determines the maximum potential burnt area. When land use change causes a reduction in the size of the natural stand, the potential burnt area thus decreases. Conversely, if a land use change scenario causes an increase in natural vegetation, such as from land abandonment, the potential burnt area can increase.

At the beginning of the simulation period, LPJmL-SPITFIRE starts from bare ground, i.e. climate and soil input data as well as all necessary parameter are read by the model and saplings of each PFT are established after the algorithm checked their capacity to survive under the local climate. As a consequence, a so-called spin-up period is required, where under a given contemporary climate all carbon stored in living biomass, soil and litter is brought into equilibrium. All simulated processes, incl. water balance, processes related to the nitrogen cycle as well as fire are in equilibrium with contemporary climate conditions. When conduction simulation experiments using land-use change scenarios, a second spin-up period that emulates the effect of long-term, but small-scale land-use change is conducted.

In that sense, the LPJmL DGVM is unique as it does not require vegetation maps to initialize vegetation distribution, or uses prescribed carbon pools. Simulation results are purely the effect of the modelling algorithm of its framework and no carry-over effects because of model-driven adjustments to the climatic or land-use driver is perturbing the results of the transient scenario simulations. This setting allows to assess our systems understanding of ecosystem functioning and its related fire disturbance and the implication for related water and biogeochemical cycles.

LPJmL is coupled to the Spread and InTensity of FIRE (SPITFIRE) fire model (Thonicke et al., 2010). SPITFIRE simulates the ignition and spread of wildfires in the natural vegetation of each cell. The coupled model LPJmL-SPITFIRE operates on daily timesteps with a spatial resolution of 9x9km. Fire spread is calculated based on the Rothermel equation (Rothermel, 1972), which is regulated by windspeed and the availability, composition, and humidity of fuels. Simulated fire regimes in LPJmL-SPITFIRE depend on an interplay of potential ignitions, fire weather, and fuel loads (Thonicke et al., 2010). Details of this framework, including additional model description, are provided in Deliverable 3.4 and 3.3. Recent model updates can be found in Oberhagemann et al. (2024).

The fuel classes are dealt with differently in LPJmL-SPITFIRE with consequences for their contribution to fuel dynamics upon removal (Table 2). Uniform distribution of a fuel class is assumed within the natural stand of a cell (no clusters of 1-hour fuels in the corner of a natural stand for example). Notably, only dead fuels are targeted for removal in these simulations (see Section 4 for a discussion of the implications). Firefighting aimed at reducing burned area is also not considered by the fire model, i.e. effects of fuel removal will have to be seen without the additional effects of fighting fires. In terms of interactions between cells, we note that LPJmL-SPITFIRE does not consider process interactions between cells, such as seed dispersal or fire spread. However, within cells, the interaction of vegetation and fire dynamics produces dead fuels of different sizes. Tree and grass demography also determine live fuel characteristics which all influence the probability of a spreading fire and the simulated post-fire effects within the natural stand of a 9x9 km grid cell. Fuels in the study's fuel management scenarios are thus removed from natural stands but equally across all grid cells in the study region with the intention of determining key areas for fuel management measures.

2.3.2 Simulation protocol

For each simulated scenario, we performed a spin-up of the natural vegetation by starting the simulation from bare ground and running the model for 2500 years with reshuffled input data for the years 1960-1990 (years for which contemporary climate data is available; see explanation of spin-up in the section above). Thereafter, we conducted a 390-year land use spin-up to bring simulated vegetation and human activity into an equilibrium state. From this equilibrium state, we ran the model from 1960 until the end of simulation year 2014. The simulations then branch to reflect the two SSP scenarios (SSP126 and SSP370) and then again for each of the five fuel management scenarios under each SSP.

All scenarios were simulated using the ACCESS-CM2 (Australian Community Climate and Earth System Simulator, Coupled Model 2) climate model. This specific configuration was chosen because the outputs fell in the middle range of results from previous experiments using the Global Circulation Model (GCM) conducted in Deliverable 3.4. This medium sensitivity ensures that the simulations avoid extreme deviations that could compromise the validity of the results. Additionally, removed carbon was transferred to the heterotrophic respiration carbon pool, while the corresponding water content was allocated to the evaporation flux. CO_2 fertilization was enabled including the effects of nitrogen limitation on the CO_2 uptake of plants. All other model inputs were chosen as described in Deliverable 3.4. The baseline results exactly correspond to the simulations results presented in Deliverable 3.4 for ACCESS-CM2.

2.4 Evaluation of simulation results

To ensure that the instant removal of fuels did not introduce unexpected behavior into the model, we conducted several sanity checks using single-cell simulations. These checks focused on key variables, such as fuel levels, soil moisture, and water fluxes from the litter to the soil layer, immediately before and after the fuel removal in different locations. The results showed no significant changes in these variables, confirming that the artificial fuel removal did not produce unintended side effects on model performance or behavior.

To evaluate the effect of each of the fuel removal scenarios, we defined four evaluation metrics—burned area, surface fire intensity, rate of spread, and fuel bulk density (Table 3). These parameters reflect not only the effect of the selective removal of different fuel classes on reducing the amount of area burned, but also help to characterize the impact and dynamics of fires. The evaluation metrics were then compared to the respective baseline simulations, in which no fuel removal was implemented, under SSP1 (baseline 1) and SSP3 (baseline 2) for the evaluation period (2025-2050). The comparison between the baselines and the management scenarios under each SSP during the evaluation period (2025-2050) was carried out in one of two ways:

1) For burned area, surface intensity, and rate of spread, all monthly outputs (rasters) were summed (Fig. 6 – 10).
2) For fuel bulk density, the initial 10-year average of the monthly totals was compared with the final 10-year average of the monthly totals (Fig. 6 – 10).
3) For fuel load, the fuel loads from the years 2015 to 2025 (historical period) and 2040-2050 (future period) for each simulation were averaged (Fig. 11-14).

Table 3: Overview of evaluation metrics produced by fuel management scenarios in LPJmL-SPITFIRE. These icons are used throughout the deliverable to illustrate the respective processes.

		Units	Definition	Contribution to fire dynamics	Evaluation method
%	Burned Area	ha	Area burnt is calculated in hectares. It can also be expressed as fraction burnt within a 9x9km grid cell that burned. Both can be written to output files.	Removes fuels from the system, changes fuel moisture and affects rate of spread	Summed monthly output from the years 2025-2050
	Max. Surface fire Intensity	kW/m^2	Maximum surface fire intensity	Direct relationship with proportion of coarse fuels	Summed monthly output from the years 2025-2050
	Rate of Spread	m/s	Flaming front of a surface fire	Direct relationship with proportion of fine fuels and fuel moisture (main influence)	Summed monthly output from the years 2025-2050
	Fuel Bulk Density	kg/m^3	The mass-weighted average over dead and live fuels	Inverse relationship with fire spread: fine fuels with low fuel bulk density increase fire spread	Average of final 10 years of each scenario compared to avg. of the first 10 years of the baselines.

3 Results

Based on the comparison of the five fuel management scenarios run in LPJmL-SPITFIRE under two SSP scenarios to baseline runs in which no fuel management is applied, we organize the results in three sections. First, the outcomes at the EU level are described which give total burned area, fuel bulk density, rate of spread, and maximum surface fire intensity changes across the 2025-2050 period. The spatial distribution of the results is then evaluated through maps of the differences from the baselines (SSPs 1 & 3 results developed in Deliverable 3.3) across the same time period. The potential drivers of these patterns are explored through a closer look at the fuel distributions per fuel class across the EU territory as produced by LPJmL-SPITFIRE.

3.1 Comparison of scheduled removal outcomes for all scenarios under SSPs 1 & 3

Scenario 1 had the largest overall effect on reducing the mean burned area in the simulated period under both SSPs (Fig. 3), indicating the management of fine fuels may be more critical for reducing burned area under future climate and land-use change. Scenario 5 also showed a substantial reduction in burned area, while Scenario 4 saw a small decrease. Scenarios 2 and 3 projected smaller magnitude increases in burned area. This pattern held for both SSPs but was slightly amplified in SSP3 outcomes, both for the reductions in burned area (scenario 1 and 5) and increases in burned area (scenario 2 and 3). Overall, the differences between the fuel management scenarios had a greater impact than the alternate SSPs until 2050. Under both SSP1 & SSP3, fuel bulk density increased in Scenarios 1 & 4 and decreased in Scenarios 2, 3, & 5. The rate of spread and surface intensity both decreased in Scenarios 1 & 5 but were relatively unchanged in the other scenarios (Figure 4).

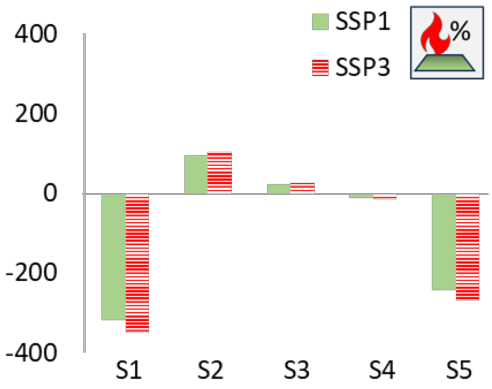


Figure 3: Comparison of mean burned area for the period between 2025 and 2050 for each fuel management scenario (1-5) relative to the respective baseline under SSP1 (green bars) & SSP3 (red, patterned bars). S1 refers to fuel management Scenario 1 (removal of 1-hour fuels). For a definition of fuel management scenarios S2 to S5 see Table 2.

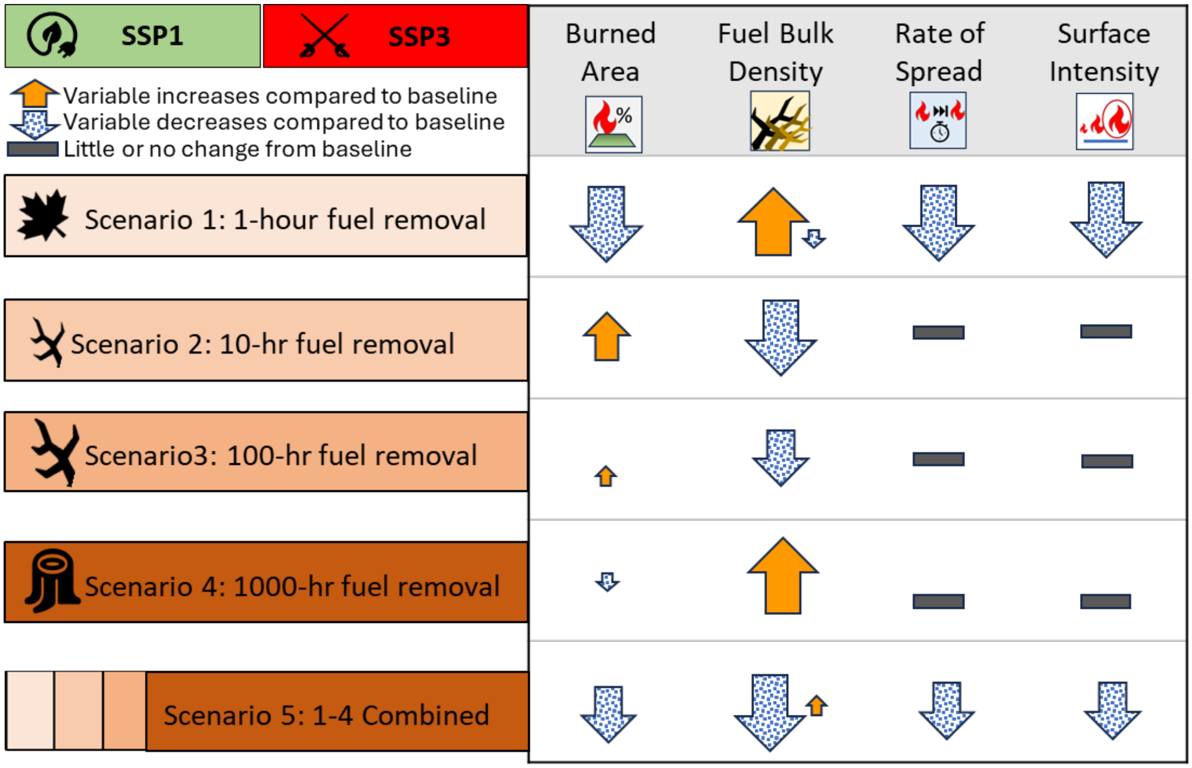
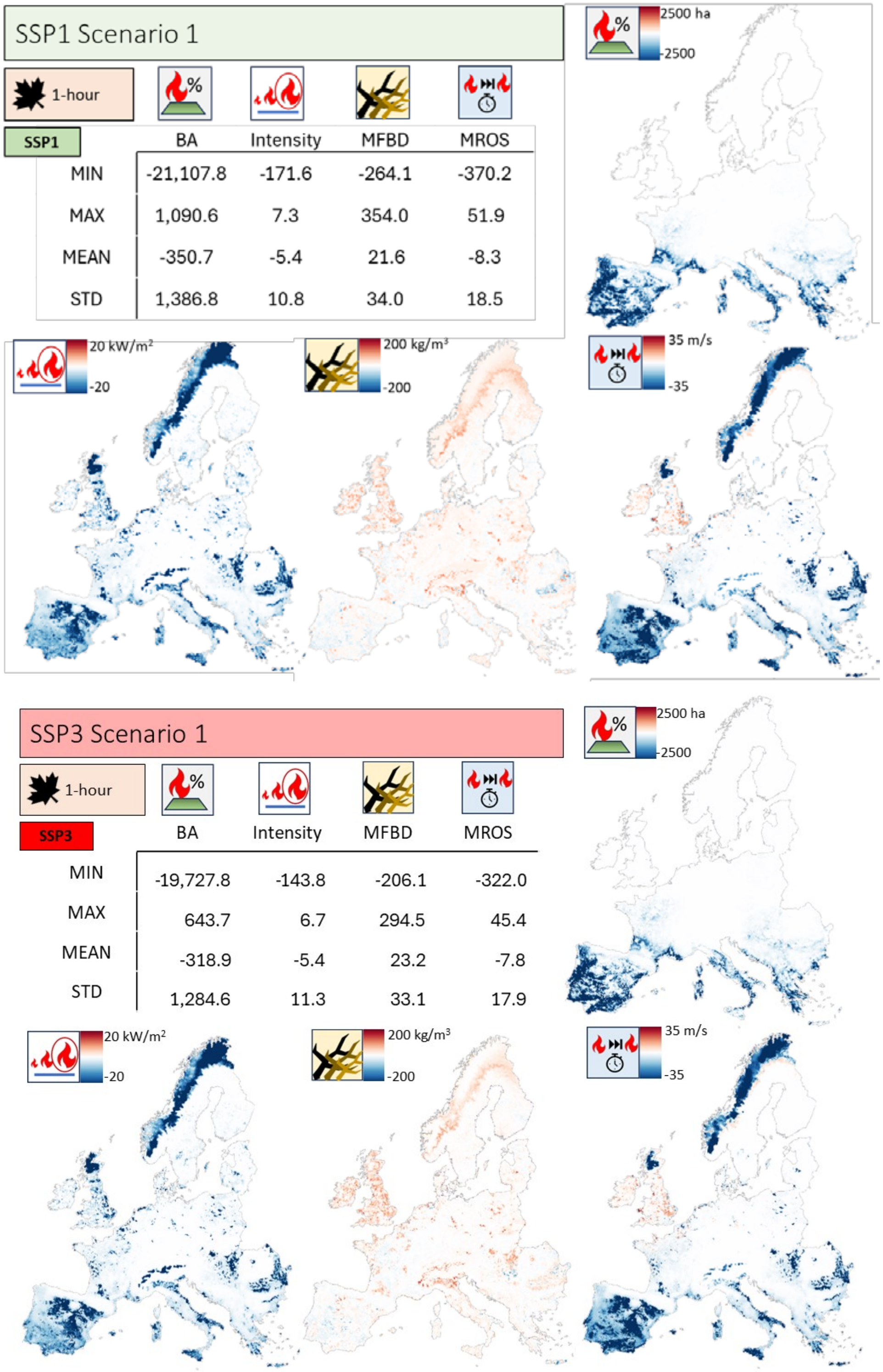


Figure 4: Illustrative comparison of relative outcomes for the five fuel management scenarios under SSP1 & SSP3 as simulated by LPJmL-SPITFIRE for the EU, compared to the baseline scenario of no fuel management from 2025-2050. Arrow sizes indicate relative differences in trends while duel areas represent spatial differentiation of results between regions (see maps in section 3.2 below).

3.2 Spatial characterization of results

The outcomes for burned area, fuel bulk density, rate of spread, and surface intensity differ spatially across Europe, with little variation between SSP1 and SSP3. This may be attributable to conflicting drivers in each SSP. Namely, in SSP1, land is assumed to be better managed, but increases in vegetation and population may, regardless, increase fire risk. In contrast, although land is more poorly managed and land abandonment can be anticipated to increase in SSP3, the thwarting of efforts to protect and increase vegetation and lower population increases as compared to SSP1 may serve to decrease fire risk. We expand further on these drivers and the implications of the results in Section 4. Changes in burned area are largely isolated to Mediterranean areas, especially in the Iberian Peninsula, Italy, and Greece in all scenarios (Figs. 5-9). However, the spatial variation in fuel bulk density, rate of spread, and surface intensity is more dispersed. Fire intensity sharply decreases in central Scandinavia, the UK, central Spain, and parts of Romania in Scenarios 1 & 5. The rate of spread follows a similar pattern for Scenarios 1 & 5, with the exception of central areas of the UK and coasts along the English Channel in continental Europe. The spatial differentiation for fuel bulk density is more mixed across scenarios, with Norway, the UK, and parts of northern Italy displaying opposing trends from the rest of the continent.

3.2.1 Scenario 1: Scheduled removal of 1-hour fuels under SSPs 1 & 3

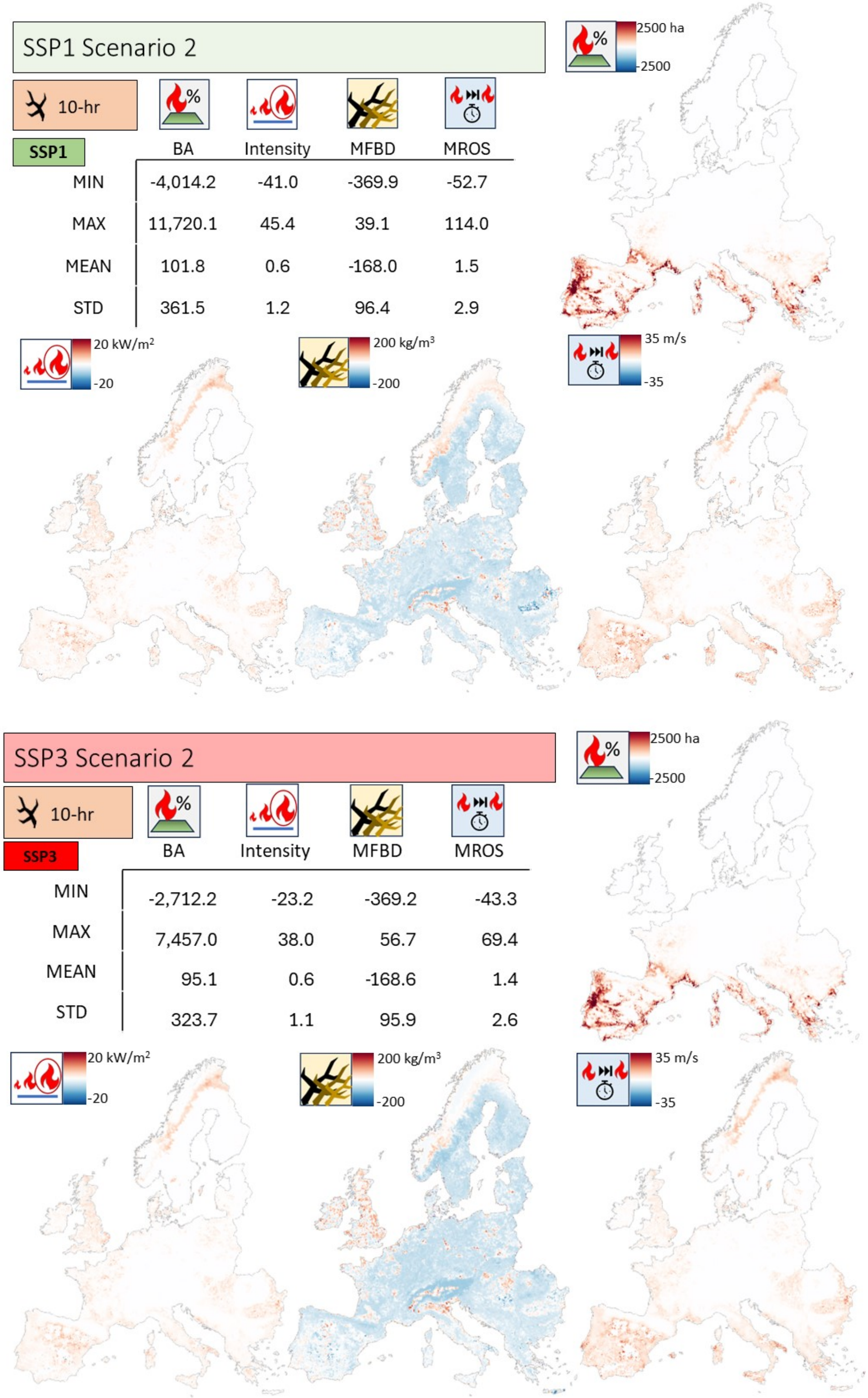


SSP1	BA	Intensity	MFBD	MROS
MIN	-21,107.8	-171.6	-264.1	-370.2
MAX	1,090.6	7.3	354.0	51.9
MEAN	-350.7	-5.4	21.6	-8.3
STD	1,386.8	10.8	34.0	18.5

SSP3	BA	Intensity	MFBD	MROS
MIN	-19,727.8	-143.8	-206.1	-322.0
MAX	643.7	6.7	294.5	45.4
MEAN	-318.9	-5.4	23.2	-7.8
STD	1,284.6	11.3	33.1	17.9

Figure 5: Statistical summary and spatial results of the difference from baseline for Scenario 1 (scheduled removal of 1- hour fuels) under SSP1 (top) & SSP3 (lower) accumulated across the period from 2025-2050. Maps, clockwise: Burned area, rate of spread, fuel bulk density, & surface intensity marked by respective process icons.

3.2.2 Scenario 2: Scheduled removal of 10-hour fuels



SSP1 Scenario 2

10-hr

SSP1	BA	Intensity	MFBD	MROS
MIN	-4,014.2	-41.0	-369.9	-52.7
MAX	11,720.1	45.4	39.1	114.0
MEAN	101.8	0.6	-168.0	1.5
STD	361.5	1.2	96.4	2.9

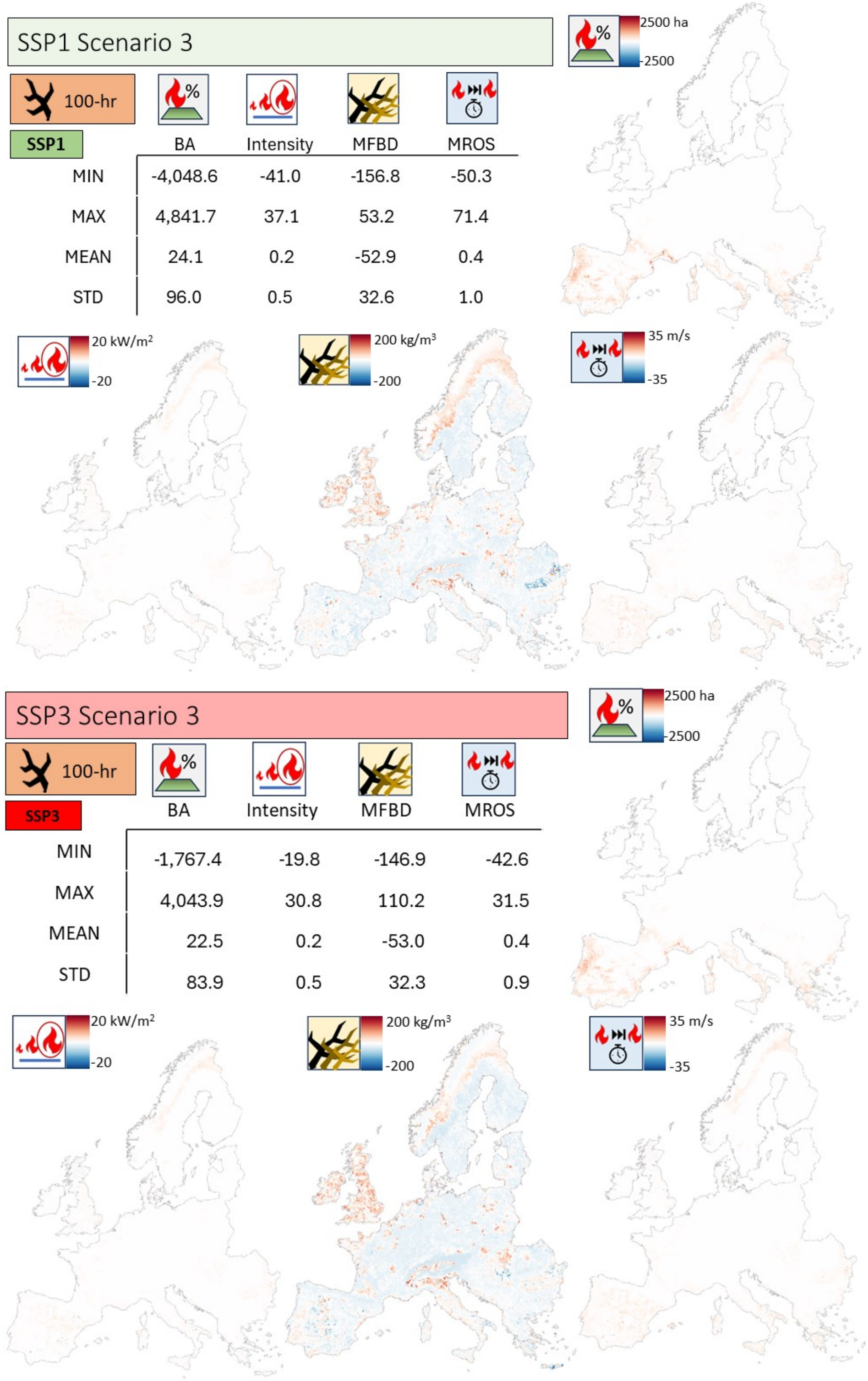
SSP3 Scenario 2

10-hr

SSP3	BA	Intensity	MFBD	MROS
MIN	-2,712.2	-23.2	-369.2	-43.3
MAX	7,457.0	38.0	56.7	69.4
MEAN	95.1	0.6	-168.6	1.4
STD	323.7	1.1	95.9	2.6

Figure 6: Statistical summary and spatial results of the difference from baseline for Scenario 2 (scheduled removal of 10-hour fuels) under SSP1 (top) & SSP3 (lower) accumulated across the period from 2025-2050. Maps, clockwise: Burned area, rate of spread, fuel bulk density, & surface intensity marked by respective process icons.

3.2.3 Scenario 3: Scheduled removal of 100-hour fuels



SSP1 Scenario 3

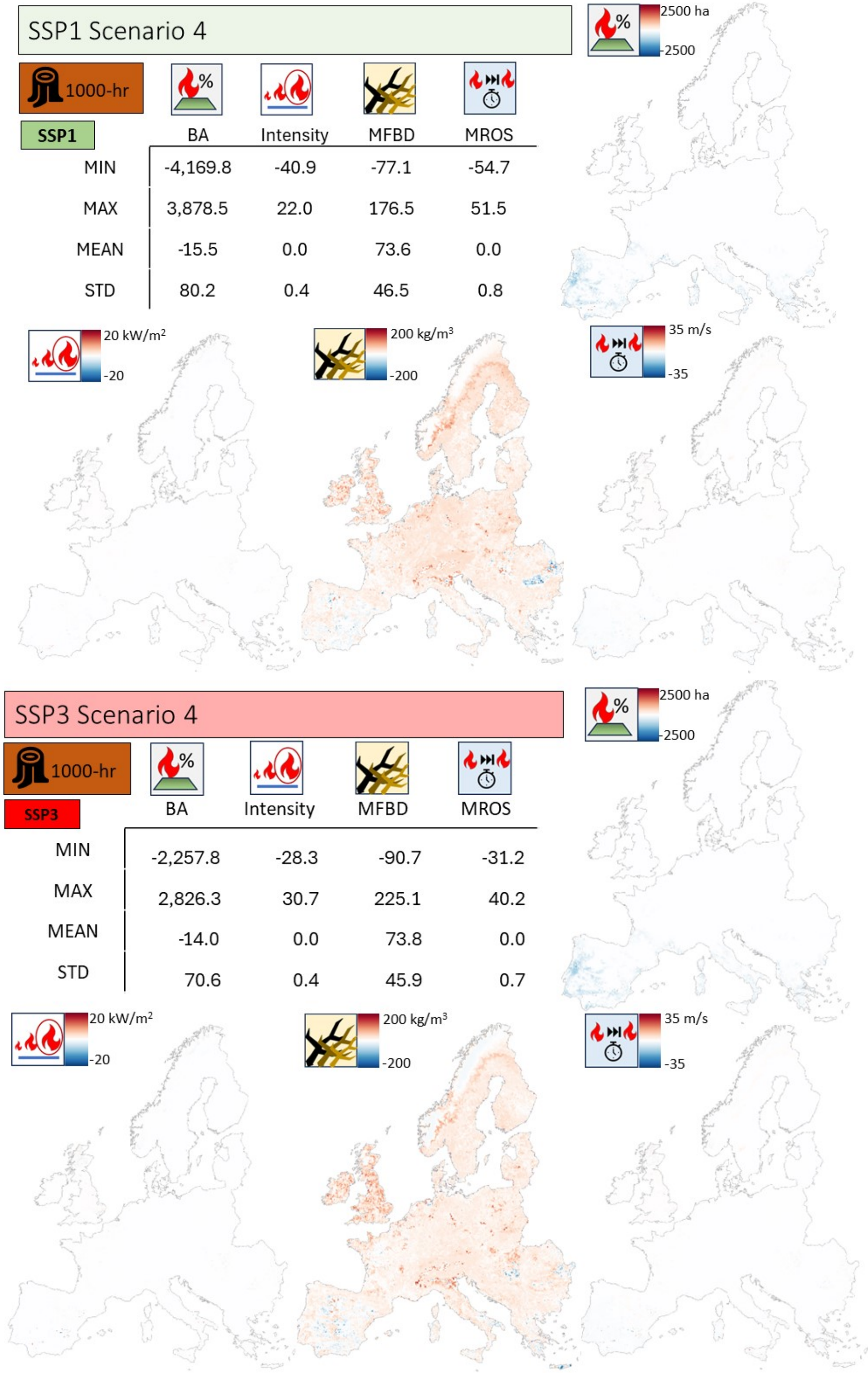
SSP1	BA	Intensity	MFBD	MROS
MIN	-4,048.6	-41.0	-156.8	-50.3
MAX	4,841.7	37.1	53.2	71.4
MEAN	24.1	0.2	-52.9	0.4
STD	96.0	0.5	32.6	1.0

SSP3 Scenario 3

SSP3	BA	Intensity	MFBD	MROS
MIN	-1,767.4	-19.8	-146.9	-42.6
MAX	4,043.9	30.8	110.2	31.5
MEAN	22.5	0.2	-53.0	0.4
STD	83.9	0.5	32.3	0.9

Figure 7: Statistical summary and spatial results of the difference from baseline for Scenario 3 (scheduled removal of 100-hour fuels) under SSP1 (top) & SSP3 (lower) accumulated across the period from 2025-2050. Maps, clockwise: Burned area, rate of spread, fuel bulk density, & surface intensity.

3.2.4 Scenario 4: Scheduled removal of 1000-hour fuels



SSP1 Scenario 4

1000-hr

SSP1	BA	Intensity	MFBD	MROS
MIN	-4,169.8	-40.9	-77.1	-54.7
MAX	3,878.5	22.0	176.5	51.5
MEAN	-15.5	0.0	73.6	0.0
STD	80.2	0.4	46.5	0.8

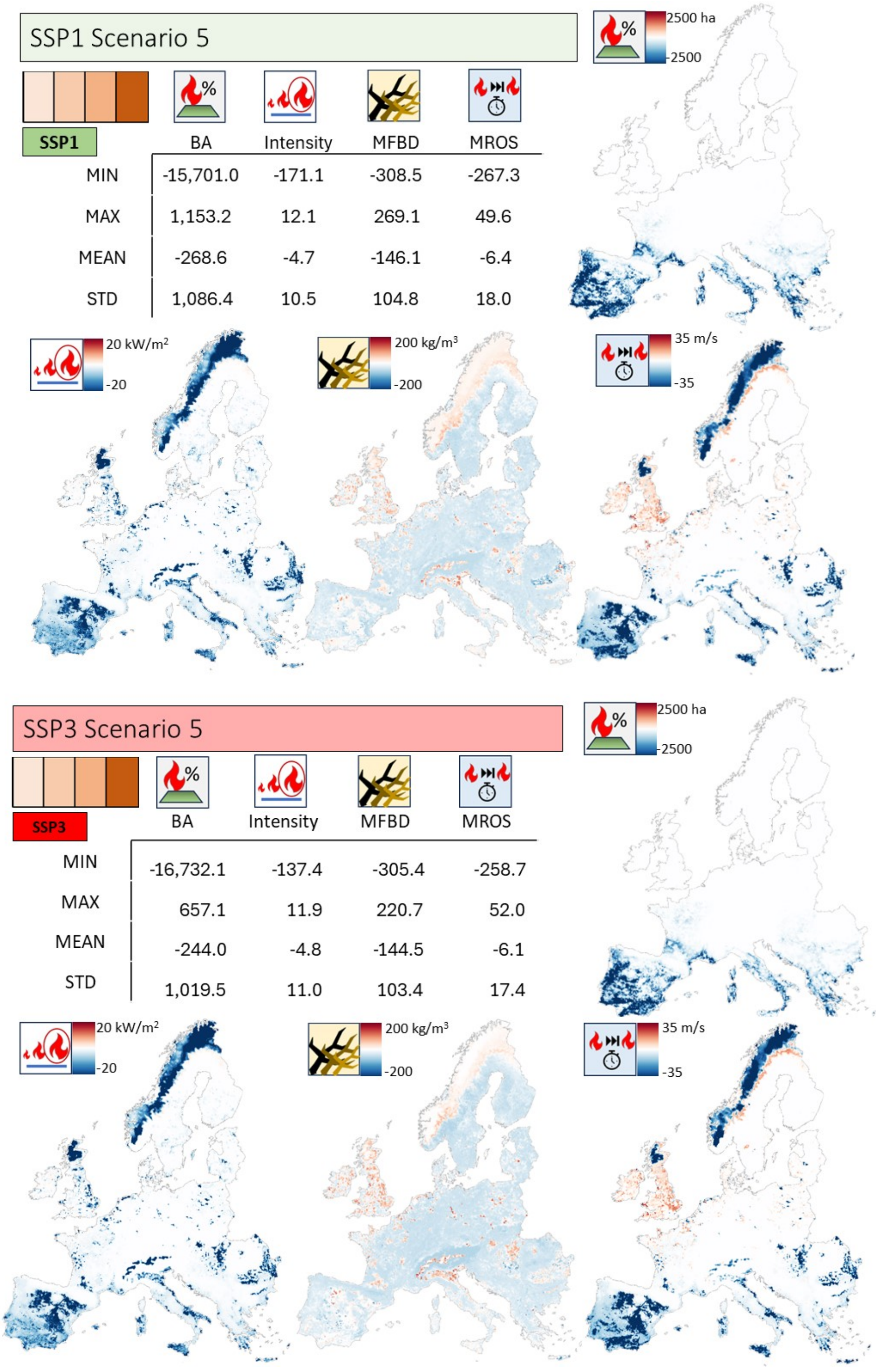
SSP3 Scenario 4

1000-hr

SSP3	BA	Intensity	MFBD	MROS
MIN	-2,257.8	-28.3	-90.7	-31.2
MAX	2,826.3	30.7	225.1	40.2
MEAN	-14.0	0.0	73.8	0.0
STD	70.6	0.4	45.9	0.7

Figure 8: Statistical summary and spatial results of the difference from baseline for Scenario 4 (scheduled removal of 100-hour fuels) under SSP1 (top) & SSP3 (lower) accumulated across the period from 2025-2050. Maps, clockwise: Burned area, rate of spread, fuel bulk density, & surface intensity.

3.2.5 Scenario 5: Scheduled removal from all fuel classes



SSP1	BA	Intensity	MFBD	MROS
MIN	-15,701.0	-171.1	-308.5	-267.3
MAX	1,153.2	12.1	269.1	49.6
MEAN	-268.6	-4.7	-146.1	-6.4
STD	1,086.4	10.5	104.8	18.0

SSP3	BA	Intensity	MFBD	MROS
MIN	-16,732.1	-137.4	-305.4	-258.7
MAX	657.1	11.9	220.7	52.0
MEAN	-244.0	-4.8	-144.5	-6.1
STD	1,019.5	11.0	103.4	17.4

Figure 9: Statistical summary and spatial results of the difference from baseline for Scenario 5 (scheduled removal from all fuel classes) under SSP1 (top) & SSP3 (lower) accumulated across the period from 2025-2050. Maps, clockwise: Burned area, rate of spread, fuel bulk density, & surface intensity.

3.3 Impacts of fuel management scenarios on fuel loads across Europe

1-hour fuels

These fuels exhibit widespread coverage across Europe (Fig. 11). Without intervention to remove 1-hour fuels, fine fuel loads are projected to increase until 2050, particularly in the mountainous regions of boreal and temperate Europe. This trend is also observed, though at a smaller scale, in parts of the Mediterranean region, such as Italy, with increases reaching up to 0.1 kgC/m² (Fig. 11, panel B). However, applying a 20% annual removal of 1-hour fuels significantly reduces fine fuel loads—by as much as 0.4 kgC/m² in boreal Scandinavia, central Europe, and along Spain's northern mountainous coastline.

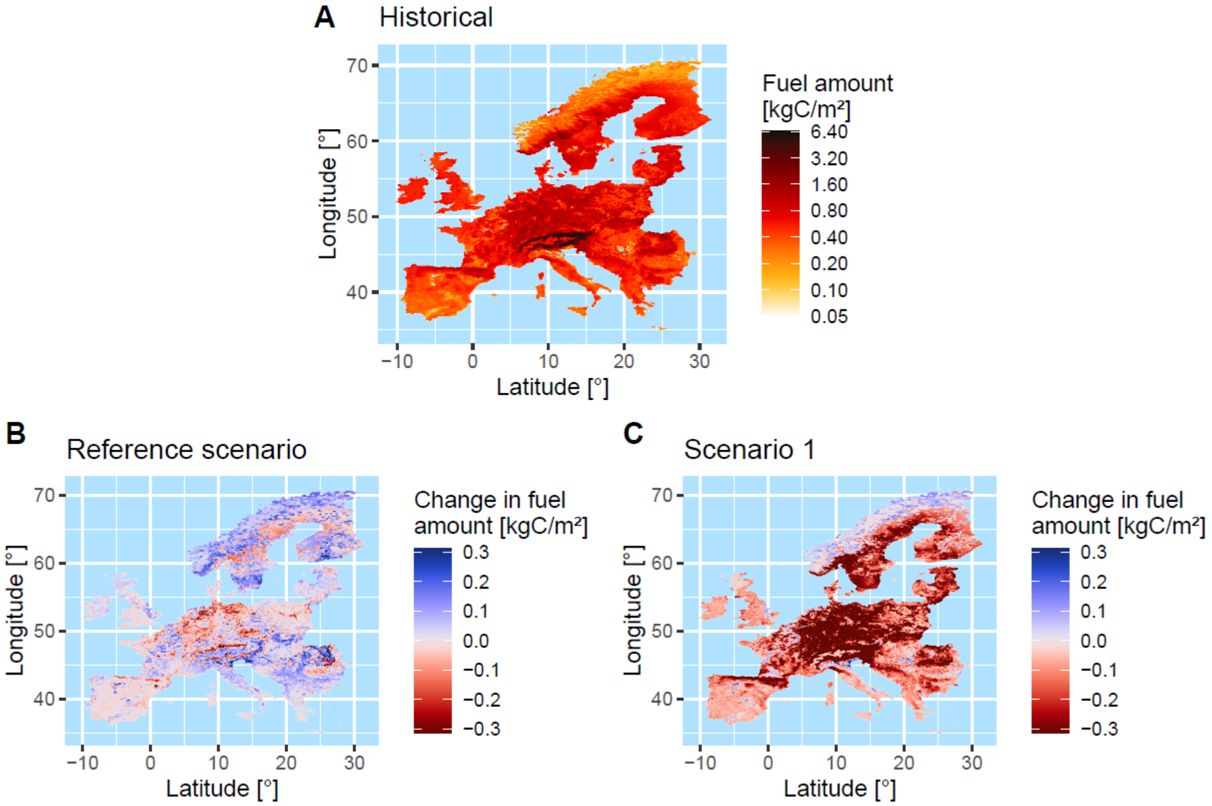


Figure 10: Historical (average between 2015 and 2025) fuel amount of 1-hour fuels [in kgC/m²] (Panel A) and changes of 1-hour fuels by mid-century (2040 - 2050) for the reference scenario (no fuel removal, Panel B) and scenario 1 (Panel C) under SSP1. Scenarios 2, 3 and 4, which do not include 1-hour fuel removal, are not shown.

10-hour, 100-hour, and 1000-hour fuels

The effects of selectively removing coarse fuels are minimal or non-existent in certain regions, such as Norway, most of the Iberian Peninsula, and the UK. Their impact is most notable in Central Europe. Among these, the reduction in 10-hour fuels is less pronounced compared to 100-hour fuels, which in turn have a smaller effect than 1000-hour fuels (Figs. 11–13).

Removing 1000-hour fuels shows distinct regional impacts, particularly in Scandinavia, temperate Europe, and the Balkan Peninsula. However, despite these localized effects, the overall impact on future burned area remains limited. This is primarily because burned area outcomes are dominated by the management of 1-hour fuels, which directly influence fire spread. In contrast, the removal of 1000-hour fuels appear to have minimal indirect effects on surface fire intensity, and, by extension, fuel load.

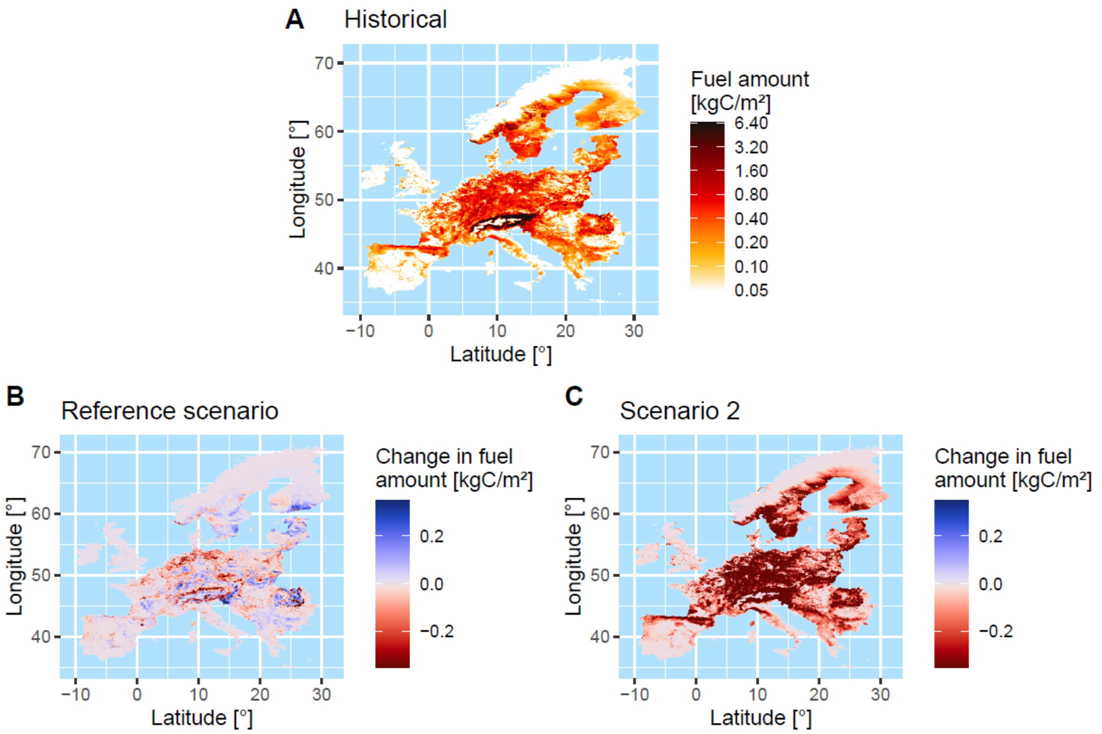


Figure 11: Historical (average between 2015 and 2025) amount of 10-hour fuels [in kgC/m²] (Panel A) and changes of 10-hour fuels by mid-century (2040 - 2050) for the reference scenario (no fuel removal, Panel B) and scenario 2 (Panel C) under SSP1. Scenarios 1, 3 and 4, which do not include 10- hour fuel removal, are not shown.

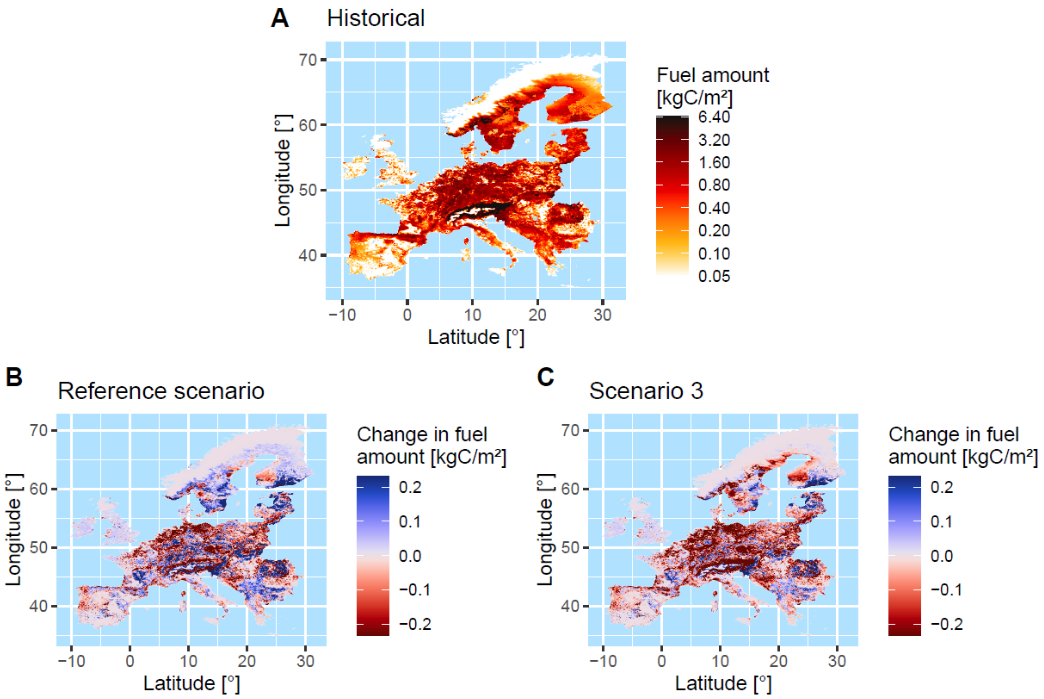


Figure 12: Historical (average between 2015 and 2025) amount of 100-hour fuels [in kgC/m²] (Panel A) and changes of 100-hour fuels by the mid of the century (2040 - 2050) for the reference scenario (no fuel removal, Panel B) and scenario 3 (Panel C) under SSP1. Scenarios 1, 2 and 4 which do not include 100- hour fuel removal, are not shown.

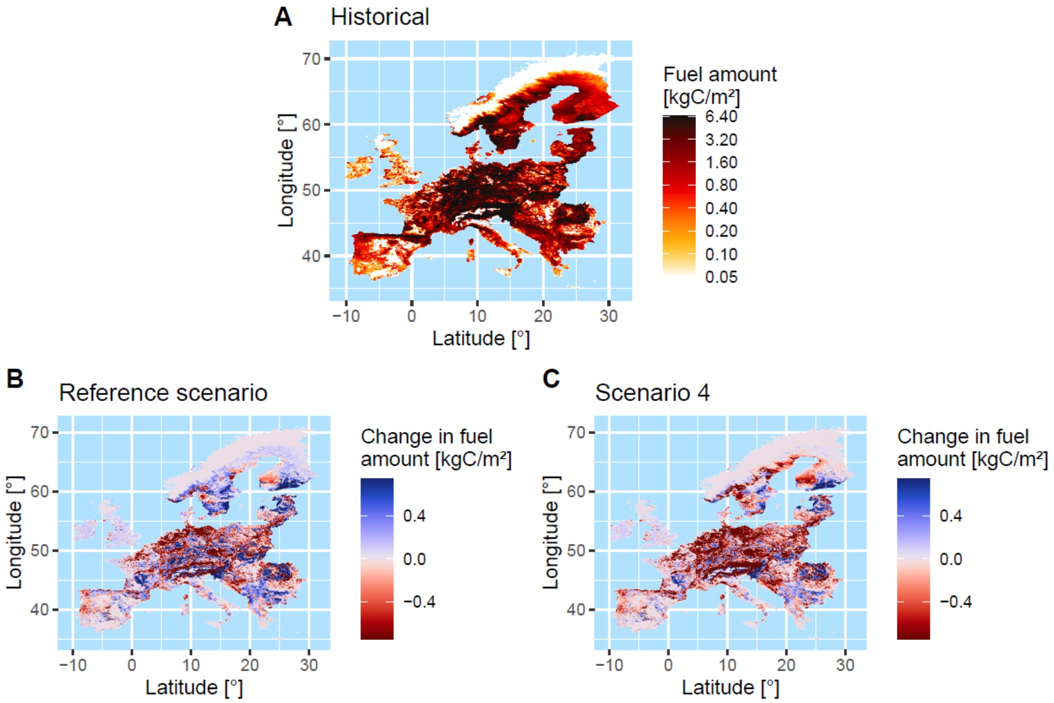


Figure 13: Historical (average between 2015 and 2025) fuel amount of 1000- hour fuels [in kgC/m²] (Panel A) and changes of 1000-hour fuels by mid-century (2040 - 2050) for the reference scenario (no fuel removal, Panel B) and scenario 4 (Panel C) under SSP1. Scenarios 1, 2 and 3, which do not include 1000-hour fuel removal, are not shown.

3.4 Adaptation to future fire regimes

Future fire regimes can best adapt if climate and land use change follow the climate protection and sustainability narrative of the SSP1-RCP2.6 future trajectory. Fuel management can additionally help to reduce future fire risk if concentrated on fine-fuel removal with the largest effect in the Mediterranean region (Figures 14). Because removing dead wood has an effect on fuel composition that affects average fuel moisture and thus fire spread conditions, removing fine fuels versus coarse fuels can have opposite effects, it could increase burned area by 50-100% in many regions in the European Territory (Figure 14). However, since the absolute effect is rather small, removing dead wood (Scenario 2 and 3) would only increase area burned by more than 1000 ha per 9x9km grid cell in the Mediterranean region and southwestern France (Figure 14). The effect of fine-fuel removal (scenario 1) dominates the overall effect of fuel removal and remains so under future climate change under both scenarios, SSP1-RCP2.6 as well as SSP3-RCP7.0 (see also Figure 3). However, local conditions have to be considered when discussing the feasibility of implementing fuel management as well as potentially higher impacts of climate extremes that may override fuel management effects.

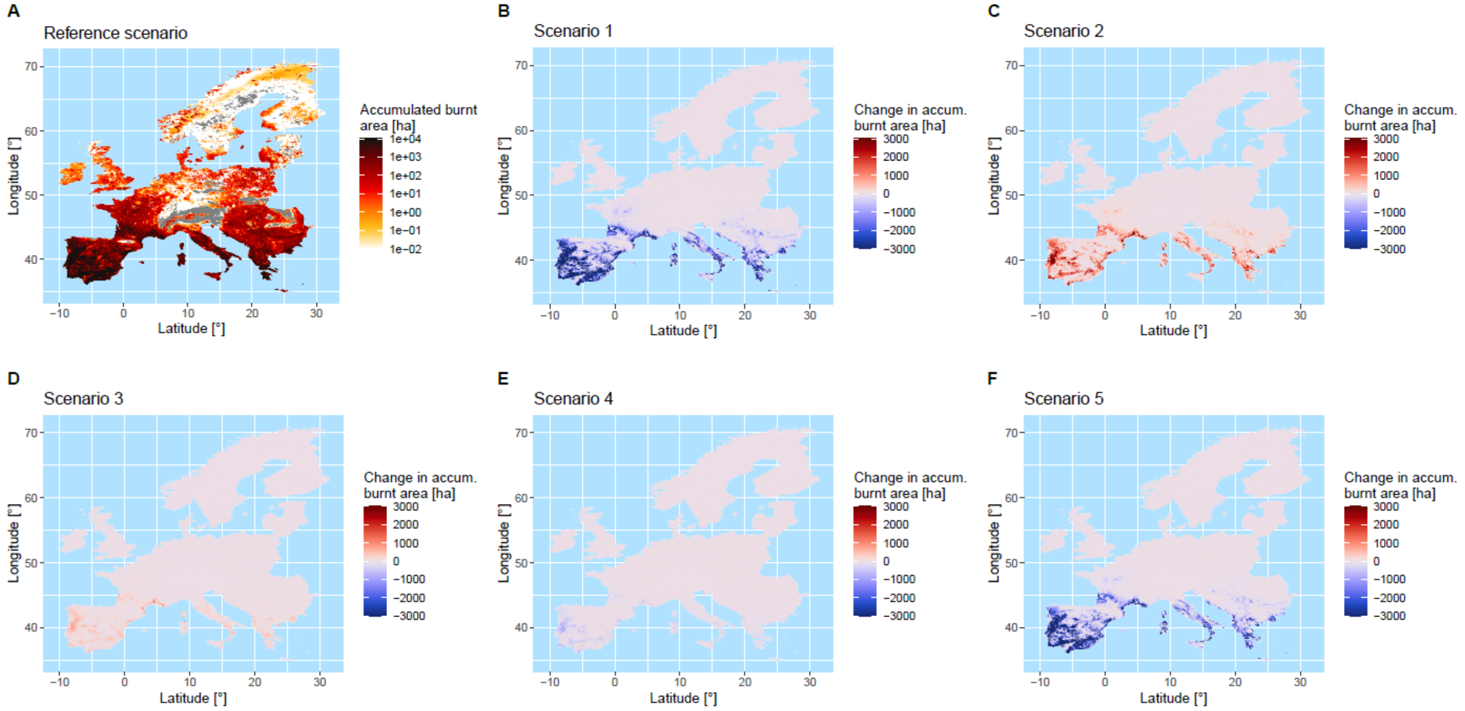


Figure 14: Averages for both SSPs of accumulated burnt area between 2025 and 2050 without fuel removal in hectares (ha) (Panel A). Change in accumulated burnt area (Panels B – F) for each fuel removal scenario in comparison to the reference scenario. Grey areas in panel A refer to grid cells without any simulated fire.

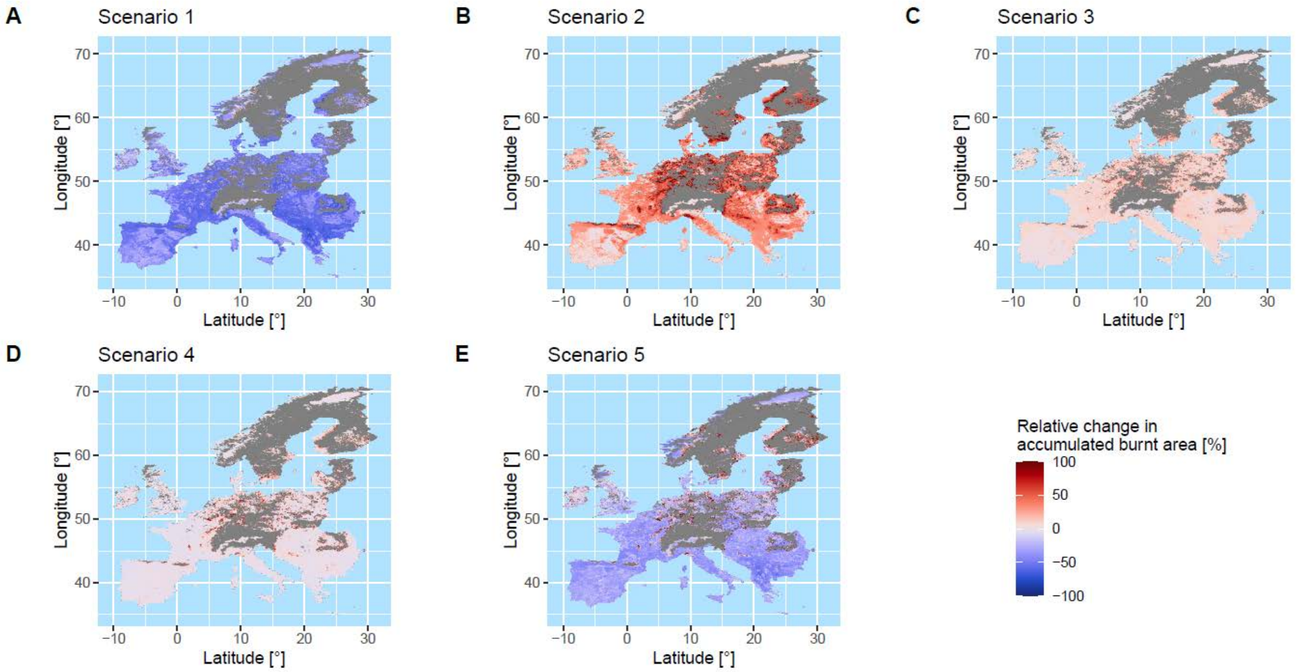


Figure 15: Averages for both SSPs of relative change in accumulated burnt area across the period from 2025-2050 for each fuel removal scenario (1-5) compared to the reference scenario (no fuel removal). Grid cells with accumulated BA less than 0.1ha in the Reference Scenario (Fig. 15, Panel A) are masked out in grey.

4 Discussion & Conclusion

4.1 Interpreting variable interactions and outcomes

Fuels

Results confirmed that fine fuels have the greatest influence on changing fire spread and burned area. In our simulations, only 1-hour fuel removal decreased the rate of spread and burned area. In areas dominated by grasslands, e.g., interior areas in the Mediterranean region, the rate of spread was significantly impacted by managing fine fuels. Removal of 1000-hr fuels did not impact the rate of spread (as could have been expected by impacting surface fire intensity and resulting fuel amount) and actually increased the amount of burned area in the cases of 10- and 100-hour removals.

In terms of fuel bulk density, it was anticipated that removal of fine fuels would increase bulk density while removal of coarser fuel classes would decrease fuel bulk density congruent to the fuel class. This assumption is based on the averaging effect over the fuel bulk densities of each of the fuel classes (fuel bulk density indirectly reduces the impact of grass plant function types (PFTs) compared to the tree PFTs on the weighting of fuel bulk densities), in which fine dead fuels have a higher surface-area-to-volume ratio than coarse fuels (Andrews, 2018). Thus, when coarser fuels are removed, fine fuels get more weight, reducing overall fuel bulk density, increasing the rate of spread, and thereby increasing burned area. In our results, fuel bulk density increased from the removal of 1-hour fuels, as expected, but also from the removal of 1000-hour fuels (however, 1000-hr fuel is not influencing rate of spread). Fuel bulk density decreased with 10- and 100-hour fuel removal as expected, but decreased more from 10-hour removal than from 100-hour fuel removal which could be a result of the amount of fuel simulated by LPJmL in the 10-hr fuel class.

These results can be interpreted from a few angles. Firstly, each fuel class is not evenly distributed across Europe. Coarser fuels are found commonly and in larger densities in central Europe (Fig. 11, 12, & 13) while finer fuels are more widely dispersed in tall and closed forests (Fig. 10). Secondly, in these simulations, we were not able to differentiate fuel moisture levels between the dead fuel classes. However, it is likely that dead, coarse fuels (such as rotting logs on the forest floor) could hold more moisture than finer fuels, such as dead grasses and leaves. Furthermore, by removing fine fuels, the dampening effect on coarser fuels is likely increased. Thus, future studies should look to better reflect the indirect effects of such fuel manipulations on fuel moisture.

The effect of firefighting on burned area and indirectly on the amount of fuel and fuel build-up is an additional point that should be considered in future research. In our study, we were not able to reflect the net effect of this intervention on fuel removal as SPITFIRE does not include a function emulating the effect of firefighting on burned area. Dedicated simulation experiments to explore this issue could consider a baseline scenario with no firefighting (e.g., the experiment outlined in this deliverable) compared to, for example, one in which areas deemed suitable for firefighting are treated when fires break out with corresponding effects on vegetation and emissions. Such a simulation would also need to incorporate a success rate for extinguishment depending on the potential arrival time of firefighters, the intensity of the fire upon arrival, and the conditions under which the fire is burning, for example. Our results, however, are a useful baseline and tool to explore scenarios in which resources are focused on management of fuels prior to wildfires as well as situations where – for whatever reason and even though being very unlikely – firefighting is not possible.

Spatial pattern, land use and combined effects of climate and land-use change

Building on the previous findings, a spatial evaluation of the study results reveals regional nuances in the effectiveness of fuel management strategies. For example, burned area in boreal regions is likely underestimated (Oberhagemann et al., 2024). Consequently, reductions in burned area are most pronounced in the Mediterranean, where fine fuels should be prioritized for removal. However, the role of coarser, woody fuels cannot be overlooked. These fuels contribute to dampening fuel moisture, especially under the region's predominantly dry, fire-prone conditions exacerbated by increasing heat waves and droughts. Strategic removal of coarser fuels in the Mediterranean remains important—not only to address their indirect effects on fire risk but also to maintain accessibility for management activities and wildfire response.

In evaluating the results by SSP scenario, we speculated on the potential for mixed effects on the reduction in burned area based on the scenario storylines, largely due to differences in anticipated land management, vegetation, and population. In line with this thinking, our results did not indicate large differences between the results for SSP1 and SSP3 (Fig. 2). This may be attributable partly to the demands produced by each of the SSPs storylines. In SSP1, increased land management and decreased land abandonment are assumed, which are anticipated to reduce fire risk. This is based on research indicating that land abandonment contributes to fire risk through the increase in unmanaged vegetation, while increases in agricultural land use reduces vegetation and increases fragmentation, i.e. reducing potential burned area (Azevedo et al., 2018; Fayet and Verburg, 2023; Sil et al., 2019b). However, SSP1 indicates a large increase in population, especially in the Mediterranean. Vegetation is also anticipated to increase in SSP1. In combination, this could have consequences for the WUI and the amount of biomass available to burn. In contrast, SSP3 anticipates an increase in land abandonment and decrease in land management, but vegetation and population are anticipated to be lower. Our results indicate that burned area changes, upward and downward, are somewhat magnified under SSP3. Finally, given the nationally focused storyline associated with SSP3, one could anticipate starkly different results along country borders. However, CLUMondo was run essentially as four models for each region of Europe (north, south, east, west). Thus, country specific differences would not be observable. Scaling results for national prioritization and planning, however, is an important area for further research. For example, in the case of removing 1-hour fuels in scenario 1, the average burned area across all of the EU territory is lower under SSP3 compared to SSP1 (Figs. 3 & 6). The removal of 10-hour fuels in scenario 2, although both scenarios see a net increase in burned area, causes more burned area under SSP3 than SSP1 (a difference of 6.7 ha in the average burned area for all of the EU territory—Figs. 3 & 7).

Since plausible land-use change scenarios are only available until 2050, and even though climate change impacts are expected to intensify in the latter half of the 21st century, it is unlikely that climate change will entirely negate the positive effects of fuel management in Europe. Forests recovering from fires and disturbances may temporarily transition to open vegetation, raising questions about whether coarse dead wood can continue to provide or retain moisture effectively. This path dependency warrants further investigation, particularly using fire-enabled DGVMs to assess the long-term impacts of fuel removal under changing climatic conditions. Our findings underscore the importance of integrating fire risk considerations into climate mitigation and adaptation strategies. Decisions in this context must account for potential trade-offs with carbon storage, biodiversity, and ecosystem services.

4.2 Caveats and future research recommendations

In our study, we developed five scenarios for management of dead fuels under two socio-economic pathway scenarios (SSPs) using one climate model until 2050 which represents an advancement on the use of DGVMs to understand how decisions on fuel management may affect future fire risk outcomes. Further research could expand and reconfigure these fuel scenarios to explore different pathways to reducing fire risk. In terms of the targeted fuels, a study which includes the selection of live fuels as well as canopy cover could expand the fuel management options. This would be especially relevant to the use of grazing, pastoralism, and wild ungulates to manage fuels, which have been found to have a beneficial impact on reducing fire risk in Europe (Neidermeier et al., 2023; Rouet-Leduc et al., 2021). Furthermore, this study provides a first attempt to develop a schedule of fuel removal based on the literature and expert input which was applicable for all of Europe. However, development of more scenarios, potentially tailored to regional suitability and vegetation cycles for different fuel management strategies, could further refine the area needed for fuel treatment in order to better prioritize resources and safeguard natural processes such as breeding periods and reproductive cycles for sensitive vegetation. For example, vegetation in May in northern Europe is likely to still be in an early post-winter growth phase, while vegetation in southern Europe may already be much further along in its phenological development. Other removal schedules, both within a year (e.g., efficacy of removal activities in the fall instead of spring) and annual return intervals (e.g., biannual application of prescribed burn instead of annual applications) should also be explored.

4.3 Conclusion

Future fire regimes can be adapted via fine-fuel management that has the overall best effect on reducing burned area under future climate and land-use change. Our findings indicate that fine fuel management (e.g., 1-hour fuels such as grasses and leaves) in the Mediterranean is likely most effective for reducing burned area in Europe under both of the socioeconomic pathways and climate scenarios explored. We highlight that although coarser fuels, such as large branches and mature trees, may be a lower priority, they should still be carefully managed in wildland urban interfaces and to make areas accessible to fire response teams in the event of emergencies. This is especially relevant given the large interannual variability in heat and precipitation which can create unpredictable conditions favoring severe fires in the Mediterranean region. In temperate and boreal Europe, retaining coarse fuels can contribute to ecosystem health through moisture retention, habitat conservation, and carbon storage. Whether Europe's future follows a more sustainable pathway along the lines of SSP1 or a more tumultuous and nationalistic one similar to SSP3, fire will need to be actively and intentionally managed. This means that landscapes and priorities must also be viewed from a fire and fuels perspective, with an eye towards targeted fuel treatments that make the best use of resources. We also note that decisions on fuel treatment require a thorough assessment of local factors, including costs and incentive opportunities, interest or opposition by local stakeholders, and socioeconomic trends. Further research is needed to better negotiate the potential trade-offs between fire risk, biodiversity, ecosystem services, and unintended effects. However, our results provide a useful next step in the use of scenario analysis for fuel management.

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