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Simulating the effects of targeted fuel removal under alternate land use and climate pathways

Alex N. Neidermeier [a,*], Maik Billing [b], Thales A.P. West [a], Kirsten Thonicke [b], Peter H. Verburg [a]

[a] Environmental Geography Group, Institute for Environmental Studies (IVM), Vrije Universiteit Amsterdam, the Netherlands
[b] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, P.O. Box 60 12 03, D-14412, Potsdam, Germany

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ABSTRACT

Climate and land-use change increasingly influence European fire regimes, creating new challenges for wildfire management. Fuel management strategies, such as prescribed burning and thinning, can alter the composition and distribution of fuels to mitigate wildfire risk. However, the effectiveness of fuel management depends on complex interactions among fuel types and the conditions governing wildfire ignition and spread. Alongside field studies, modelling provides opportunities to explore management priorities under different socioeconomic and climatic conditions. Here, we used a series of fuel-management sensitivity experiments to simulate the response of future wildfire behavior in Europe to five scenarios targeting different fuel size classes (1-, 10-, 100-, and 1000-hour fuels) under alternative land-use and climate futures. Land use was modelled under Shared Socioeconomic Pathways 1 and 3 using CLUMondo, and the resulting scenarios were used as inputs to the fire-enabled dynamic global vegetation model LPJmL-SPITFIRE together with corresponding climate projections. Results show that management targeting 1-hour (fine) fuels produced the largest reductions in burned area, rate of spread, and fire intensity, followed by mixed-fuel management. In contrast, removal of 10-, 100-, and 1000-hour (coarse) fuels did not consistently reduce wildfire behavior within the modelling framework. Treatment responses varied regionally, with southern Europe, the Baltics, and the Carpathian region showing higher sensitivity. We conclude that future wildfire behavior in Europe is particularly sensitive to the management of fine and mixed fuels, and that regionally adapted approaches targeting these fuel classes are likely to provide the greatest potential for reducing wildfire activity under future climate and land-use change.

1. Introduction

Global concerns over wildfires have increased in recent years in light of their record-setting frequency, variability, extent, and intensity (Andela et al., 2017; Cattau et al., 2022). In Europe, new wildfire regimes are largely driven by changes in climate and land use, especially temperature rise, variability in precipitation patterns (Abatzoglou et al., 2019), abandonment of agricultural lands (Sil et al., 2019), and changes to the wildland urban interface (Bar-Massada et al., 2023). Under these conditions, wildfire risk is increasing in parallel with the exposure of key infrastructures, the vulnerability of people and assets (anthropogenic and ecological), changing weather conditions, increasing ignition risks, and changes in the condition and arrangement of combustible fuels (Chuvieco et al., 2023). These risks challenge emergency response systems and endanger ecosystems and human lives assets (Galizia et al., 2021).

Fuel management has emerged as a key adaptation strategy to alter wildfire behavior in fire-prone landscapes. Vegetative fuels—such as grasses, shrubs, and trees—vary in their size, moisture content, flammability, and spatial distribution, all of which strongly influence fire dynamics (Agee and Skinner, 2005; Salis et al., 2018). Variables such as wind speed, soil moisture, vegetation type, and fuel class (e.g., 1-, 10-, 100-, and 1000-hour fuels) determine fire spread and intensity. Such variables are also conceptualized in models such as the classic Rothermel Fire Spread Model (Rothermel, 1972; Andrews, 2018; Campbell-Lochrie et al., 2023). Fuel management strategies, including prescribed burning and mechanical thinning, aim to alter fuel characteristics to reduce fire risk (Mena et al., 2016; Salis et al., 2016; Benali et al., 2021; Rouet-Leduc et al., 2021). Prescribed burning targets fine surface fuels such as grasses and leaves, while thinning targets coarser

* Corresponding author.
E-mail address: a.neidermeier@vu.nl (A.N. Neidermeier).

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fuels such as branches and trees (Brodie et al., 2024; Davis et al., 2024). The effects of fuel management can be complex due to the interactive effects of fuel structure on fire behavior, moisture retention, and nutrient cycling (e.g., Cabon et al., 2018; Giuditta et al., 2018; Ogaya et al., 2020). Although investigations continue on the best strategies to manage wildfire behavior, management of fine surface fuels has been indicated as especially effective (Agee and Skinner, 2005; Ager et al., 2010; Salis et al., 2016; Calleja et al., 2019; Rouet-Leduc et al., 2021; Brodie et al., 2024). Beyond efficacy in the management of wildfire behavior, fuel management decisions are subject to many other considerations, such as financial resources (Fernandes, 2013; Lecina-Diaz et al., 2023), biophysical limits on the fuel strategies (Neidermeier et al., 2023), cultural preferences (Alló and Loureiro, 2020), and ecosystem service provision (Campos et al., 2022; Neidermeier et al., 2025). The effectiveness of fuel management is strongly influenced by the quantity, composition, and spatial arrangement of fuels across landscapes. These characteristics are not static, but are shaped by land-use decisions and socioeconomic change. Processes such as agricultural abandonment, reforestation, urban expansion, and changing forest management practices can alter fuel continuity and accumulation, thereby modifying both wildfire risk and the effectiveness of fuel treatments. Consequently, evaluating fuel management under future conditions requires consideration of the land-use trajectories that shape future fuel landscapes. Effective and ecologically appropriate fuel management strategies are thus needed, which hold under future climate and socio-economic conditions and address Europe's new fire regimes (Fernandes, 2013; Abatzoglou et al., 2020; Dupuy et al., 2020; Kreider et al., 2024; Preinfalk and Handmer, 2024).

Vegetation and wildfire spread models offer an opportunity to simulate and assess fuel management choices under such climatic and socioeconomic changes via scenario development (Abatzoglou et al., 2020). Research on simulating wildfire dynamics has largely relied on statistical and machine learning algorithms (Hantson et al., 2016) or fire-enabled Dynamic Global Vegetation Models (DGVMs; Hantson et al., 2020; Forrest et al., 2024). Fire-enabled DGVMs simulate components relevant to wildfires, such as fuel characteristics, ignition probability, and vegetation composition, under different land use and climate scenarios (Forkel et al., 2019; Teckentrup et al., 2019). The Lund-Potsdam-Jena managed Land (LPJmL) is one such 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). To include the role of wildfire in the Earth system, LPJmL has been coupled to the process-based SPITFIRE fire model (Spread and InTensity of FIRE; Thonicke et al., 2010, with its latest update described in Oberhagemann et al., 2025). Past applications of LPJmL-SPITFIRE have been used to simulate fire emissions (Thonicke et al., 2010), tree species' performance under climatic and wildfire pressures (Boulanger et al., 2022), and the risks to forest regrowth from wildfire (Drüke et al., 2023), amongst others.

Socioeconomic factors and land-use change are gaining recognition as key drivers of wildfire risk in Europe (Abatzoglou et al., 2020; Chuvieco et al., 2023; Preinfalk and Handmer, 2024; Vilar et al., 2021), and a point for improvement in wildfire modelling (Wu et al., 2015; Teckentrup et al., 2019). Because fuel management acts on vegetation and fuel loads that are themselves shaped by land-use change, the effectiveness of fuel treatments is likely to vary across alternative socioeconomic futures. Evaluating fuel-management sensitivity under contrasting land-use scenarios therefore provides insight into whether treatment effectiveness remains consistent as landscapes change through time.

While fire-enabled DGVMs often rely on future population projections as a proxy for land use (e.g., Wu et al., 2015) or globally derived land-use scenarios (e.g., HYDE estimates from Klein Goldewijk et al., 2017), these approaches miss key factors needed to accurately model land-use trends relevant to wildfire behavior in the European context. These trends include regionally specific shifting agricultural patterns, especially abandonment in southern Europe, which has meanwhile been linked to the expansion of shrub and tree cover, leading to more continuous and flammable landscapes (Moreira et al., 2011; Viedma et al., 2015; van der Zanden et al., 2017; Sil et al., 2019). Increasing forest cover through reforestation can also increase fuel loads or introduce fire-prone species, increasing fire risk in fire-prone areas (Pantera et al., 2018).

Such fire-relevant land-use developments can be captured in land-use change models and projected in scenarios that capture likely socio-economic developments and policy implementation, aligned with climate change trajectories. One such land-use model is CLUMondo, a spatially explicit land-use change model that has been used in many global and European-specific applications to simulate land use under different socioeconomic and management scenarios (e.g., Asselen and Verburg, 2013; van der Zanden et al., 2017; Malek and Verburg, 2018; Venier-Cambron et al., 2024). Thus, the development and incorporation of more nuanced, regionally specific land-use scenarios in the modelling of future European wildfire risk can create a wider evidence base for fuel management choices (Abatzoglou et al., 2020; Loehman et al., 2020; Vilar et al., 2021; Preinfalk and Handmer, 2024).

To effectively manage future wildfire risk in Europe, fuel management options must be evaluated within the context of changing land-use systems and climate conditions, as both shape future fuel availability and distribution. While fuel reduction is widely advocated as a wildfire adaptation strategy, the relative influence of different fuel classes on wildfire behavior under alternative future conditions remains poorly understood. Here, we use LPJmL-SPITFIRE to evaluate the sensitivity of future wildfire behavior to five stylized fuel-management scenarios targeting different fuel classes. Rather than simulating operational fuel treatments at local scales, these scenarios are designed to explore how management of different fuel classes influences wildfire behavior under contrasting land-use and climate futures. To do so, we simulate fuel-management scenarios under two CLUMondo-derived land-use pathways aligned with SSP1-RCP2.6 and SSP3-RCP7.0 and compare their effects on burned area, surface fire intensity, rate of spread, and fuel bulk density relative to a baseline scenario without additional fuel management. In doing so, we provide insight into which fuel classes exert the strongest influence on future wildfire behavior and how this sensitivity varies across European landscapes.

2. Methods

Overview

This study evaluates the sensitivity of future wildfire behavior to five fuel-management scenarios across Europe (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, the United Kingdom, Switzerland, and Norway; hereafter the "study area") for the period 2025–2050. The scenarios were designed to target different fuel classes represented in LPJmL-SPITFIRE (1-hour, 10-hour, 100-hour, and 1000-hour fuels) through a series of stylized fuel-removal schedules based on common land-management practices and the model's fuel structure (Fig. 1; Section 2.1). Future land-use change was simulated using CLUMondo under two Shared Socioeconomic Pathways (SSP1 and SSP3; Section 2.2). The fuel-management scenarios were subsequently implemented in LPJmL-SPITFIRE and simulated to 2050 under the corresponding land-use trajectories and five climate model projections (Section 2.3). Scenario outcomes were evaluated relative to a baseline simulation without additional fuel management using four wildfire-behavior metrics: burned area, surface fire intensity, rate of spread, and fuel bulk density (Section 2.4).

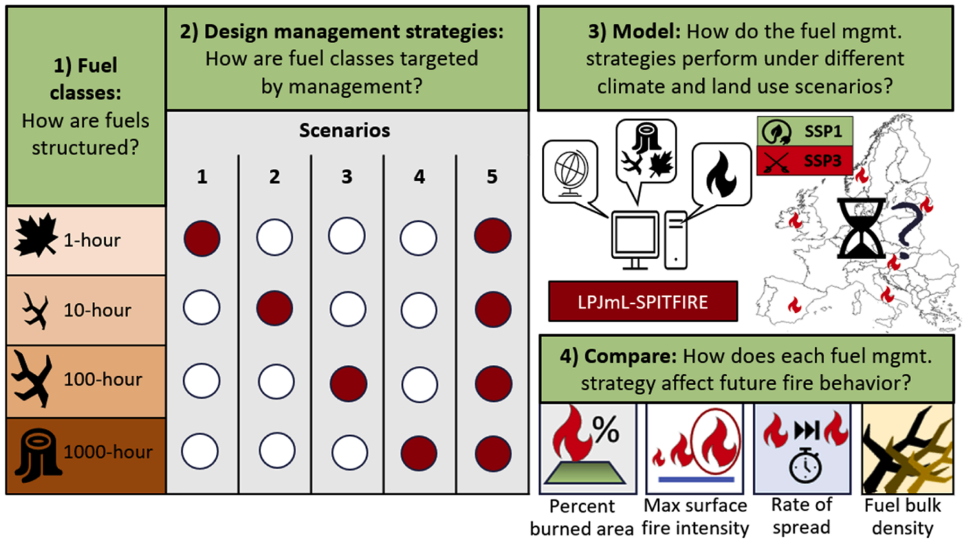


Fig. 1. Conceptual workflow. Scenarios are designed around four fuel classes defined by their burning lag time (1-hour, 10-hour, etc.). The five fuel management scenarios are simulated using LPJmL-SPITFIRE under SSP1 & SSP3 for Europe to the year 2050. Four metrics are evaluated: burned area, surface fire intensity, surface fire rate of spread, and fuel bulk density.

2.1. Fuel management scenario design

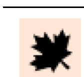
Representation of fuel classes in LPJmL-SPITFIRE

In LPJmL-SPITFIRE, fuel classes are defined according to their diameter sizes (Thonicke et al., 2010), which in turn affects their burning lag time (Table 1). 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 (i.e., leaf fall) and tree mortality (both due to wildfire and other causes). Because it is simulated as part of the DGVM, vegetation growth, turnover, and decomposition of dead fuel also affect the availability of fuels that change dynamically over space and time (see Section 2.3, Thonicke et al., 2010; Oberhagemann et al., 2025, for details).

Linking fuel classes to management activities

Fuel removal amounts and schedules were based on a literature review, expert consultation, and analysis from Neidermeier et al. (2023). Our objective was not to simulate operational fuel management programs, but rather to evaluate the sensitivity of wildfire behaviour to the management of different fuel classes under alternative land-use and climate futures. To facilitate comparison among fuel classes and future scenarios, treatment timing, intensity, and spatial extent were standardized across the study area. The selected removal rates were intended to represent plausible upper-end treatment intensities while remaining broadly consistent with common fuel-management practices in Europe.

Table 1
Description of fuel classes used in LPJmL-SPITFIRE, their illustrative contributions to fuel dynamics, and fuel scenario(s) in which the respective percentage was removed. Icons in the first column represent the respective fuel class.

	Fuel Class	Description	Contribution to Fuel Dynamics	Relevant Scenario
	1-hour fuels	Leaves and twigs	Primary influence on fire ignition and spread. High surface-area to volume ratio. Removal increases overall fuel bulk density.	Scenarios 1 & 5: 20% removal every year
	10-hour fuels	Woody, small branches	Contributes to fire spread and some heating.	Scenarios 2 & 5: 15% removal every year
	100-hour fuels	Large branches	Contributes to fire spread and heating.	Scenarios 3 & 5: 5% removal every 10 years
	1000-hour fuels	Tree boles or trunks	Contributes to fire intensity and smoldering. Low surface-area-to-volume ratio.	Scenarios 4 & 5: 5% removal every 10 years

The fuel-management scenarios were designed to correspond to the fuel classes represented in LPJmL-SPITFIRE. One-hour fuels were assumed to be primarily managed through activities such as prescribed burning and were reduced by 20% annually in treated areas (Table 1; Fig. 1). Ten-hour fuels were assumed to be primarily targeted through mechanical removal (e.g., thinning) and were reduced by 15% annually. In contrast, management of 100- and 1000-hour fuels was assumed to occur less frequently because of logistical, economic, and ecological constraints identified in the literature and through expert consultation. These fuel classes were therefore reduced by 5% at 10-year intervals.

The resulting scenarios should be interpreted as stylized sensitivity experiments rather than management prescriptions. By standardizing treatment implementation across Europe, differences in simulated wildfire behaviour can be more directly attributed to variation in fuel classes, land-use trajectories, vegetation dynamics, and climate conditions. While this approach does not capture the diversity of management practices implemented across European landscapes, it provides a consistent framework for evaluating the relative influence of different fuel classes on future wildfire behaviour.

Fuel removal schedules

Fuel-removal schedules were informed by literature examining how treatment timing influences objectives such as wildfire risk reduction, wildlife conservation, and vegetation management (Hall et al., 2012; Valkó and Deák, 2021). To facilitate comparison among scenarios, fuel removals were implemented on May 1 of the relevant year in LPJmL-SPITFIRE. For fuel management scenarios 1 and 2, we annually removed 20% and 15% of 1- and 10-hour fuels, respectively, from all parts of the study area. For fuel management scenarios 3 and 4, we removed 5% of 100- and 1000-hour fuels, respectively, from all parts of the study area on a decadal basis. For scenario 5, we simulated a mixed-fuel removal approach in which a percentage of fuels from all four fuel classes were removed following the previously described schedules (Fig. 1).

2.2. Land-use data integration

An integrated land-use dataset was used for the years from 1960 to 2050, which incorporates historic and future land-use projections. Historic land-use data were derived from the HILDA+ dataset (Winkler et al., 2020), chosen for its full coverage of the study area, detailed historical assessment, and tailored focus on European land use. Future land-use projections were developed using CLUMondo, a spatially explicit land-use model (Asselen and Verburg, 2013). CLUMondo is the latest generation in the CLUE model framework, which uses exogenously generated demands for goods and services (e.g., crops or livestock), local spatial characteristics and suitability, and algorithms to simulate many of the factors relevant to simulating future land-use scenarios (Schulze et al., 2019; Dou et al., 2023). CLUMondo translates changes in the demand for land-based goods and services into spatial patterns of land-use change, including both land cover change as well as changes in land use intensity (Malek et al., 2018).

The future scenarios were developed under two potential socioeconomic pathways, SSP1 ("Sustainability") and SSP3 ("Regional Rivalry"), for the 20252050 period (O'Neill et al., 2014, 2017). We used a version of these scenarios simulated by Dou et al. (2023) where European demands for agricultural commodities and wood production differ between the scenarios based on world-level simulations of trade and economic change in the agricultural sector as simulated by the partial-equilibrium model GLOBIOM (IBF-IIASA, 2023). In SSP1, the effects of relevant global policies aimed at a more sustainable future, such as the Green Deal (Daigneault et al., 2019; Korhonen et al., 2020) are included in the derivation of these demands. Population is anticipated to increase in Europe, especially in the north and west, with a preference for village and peri-urban lifestyles. Agriculture shifts to more diverse, sustainable systems, and natural landscape protection is favored. Regional differences in productivity see southern Europe facing reduced yields, while northern and western areas experience growth in crop production. The associated climate projection, Representative Concentration Pathway (RCP) 2.6, assumes a high effort to reduce emissions and increase renewable energy and emissions capture. In contrast, SSP3 anticipates an overall decrease in population, especially in the southern and eastern regions of Europe (Fig. S1). Livestock and crops are 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. In our scenarios, SSP3 is 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. For the spatial land-use allocation, CLUMondo was run at 1 km^2 spatial resolution but aggregated to a 9 $\times$ 9 km grid to match the DGVM model design. Model settings were similar for both scenarios for this study. Hence, the results reflect differences in the demand, demography and global trade context simulated by the GLOBIOM model.

2.3. Simulation of stylized fuel scenarios in LPJmL-SPITFIRE

Model overview

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 (daily temperature, precipitation, and radiation), atmospheric carbon dioxide concentration, nitrogen, and soil texture input data. Vegetation composition and productivity result from light and water supply, and are influenced by nutrient and carbon dioxide fertilization effects, resulting in vegetation changes over space and time (LPJmL version 5.7, Lutz et al., 2019; von Bloh et al., 2018).

To initialize LPJmL, a so-called "spin-up" is performed in which all processes, including water flows, the nitrogen cycle, and carbon stored in living biomass and soil, are brought into equilibrium with contemporary climate and land-use conditions. To achieve this, LPJmL starts from bare ground and repeats a shuffled sequence of the first 30 years of the initial simulation period over several thousand years. Simulation results are thus driven by the modelling algorithm of the LPJmL framework and therefore do not require vegetation maps to initialize vegetation distribution or prescribed carbon pools. Through the spin-up, model components are brought into equilibrium-like conditions, and the results obtained from historic and future simulations are purely influenced by climate and land-use driving changes in ecosystem processes.

To simulate the ignition and spread of wildfires, LPJmL is coupled to the Spread and InTensity of FIRE (SPITFIRE) fire model (Thonicke et al., 2010). LPJmL-SPITFIRE has been extensively evaluated against observations of vegetation, carbon dynamics, and fire activity at global scales (Thonicke et al., 2010; Wu et al., 2015; Drüke et al., 2019; Oberhagemann et al., 2025). Recent validation of LPJmL-SPITFIRE demonstrated reasonable reproduction of interannual burned-area variability and fire behavior metrics across major fire regions, although known biases remain in parts of southern Europe, including overestimation of burned area in southern Spain and underrepresentation of fire activity in Portugal (Oberhagemann et al., 2025). Fire spread in LPJmL-SPITFIRE is calculated based on the Rothermel equation (Rothermel, 1972), which is regulated by windspeed and fuel characteristics (e.g., fuel availability, composition, and humidity). Simulated fire regimes depend on an interplay of potential ignitions, fire weather, and fuel loads (Thonicke et al., 2010). The coupled model LPJmL-SPITFIRE operates on daily timesteps with a 9-km spatial resolution. Recent model updates that were applied in this study can be found in Oberhagemann et al. (2025).

Each cell within LPJmL-SPITFIRE is characterized by the proportion of natural vegetation, which determines the maximum potential burnt area in each grid cell. Natural vegetation in this study is restricted to forest, shrubland, and bare land uses. As a consequence, when land-use conversions cause a reduction in the amount of natural vegetation (e.g., a conversion from forest to agriculture land use), the potential maximum burnt area also decreases, and vice versa (Fig. 2). As each land use in the study simulations represents a proportion of a cell's total land use, natural vegetation can consequently comprise a proportion of a cell. This implies that a cell can partially contribute to the total burned area if it is composed of a mix of natural and other vegetation.

Fuels in LPJmL-SPITFIRE are classified as live or dead as an output of model vegetation dynamics. Live fuel characteristics are determined by tree and grass dynamics, which influence the probability of fire spread and post-fire effects. Dead fuel production in the model is related to vegetation productivity through tree mortality and leaf shedding. The amount of dead fuel can also increase in cases where fires trigger tree mortality, but leave woody material or whole trees to contribute to the pool of dead biomass in different sizes. In this study, only dead fuels are targeted for removal and are considered to be uniformly distributed in a cell. Thus, there is no clustering of specific fuel types within a cell, and fuels are removed equally within all grid cells.

Finally, vegetation and wildfire dynamics operate independently in each cell in LPJmL-SPITFIRE with consequences for the representation of landscape-scale ecological processes in the model. Seed dispersal and fire spread across simulations cells, for example, are not simulated. Furthermore, the effects of fuel removal on wildfire behavior and vegetation dynamics do not affect dynamics in neighboring cells.

Simulation protocol

For each simulation, we performed a spin-up of the natural vegetation for 2500 years. Reshuffled input data were used for the years 1960–1990 for which contemporary climate data is available (see explanation of spin-up in the section above). Then, we conducted a 390-year land-use spin-up to bring simulated vegetation and human activity into an equilibrium state. From this equilibrium state, the model ran from 1960 until 2014 using historic climate and land-use input. The simulations then branch to reflect the two SSP scenarios (SSP1 and

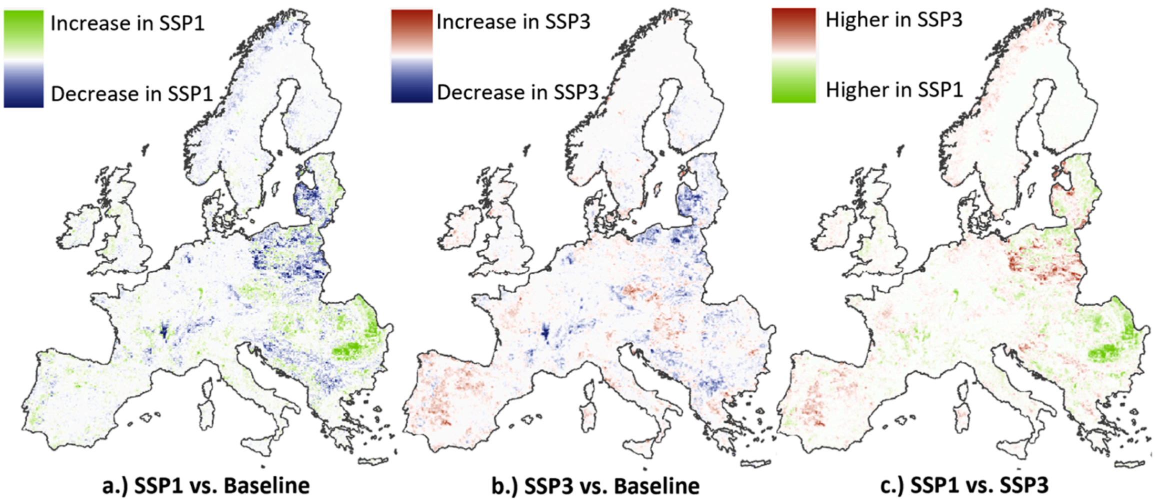


Fig. 2. Natural vegetation determines the maximum potential burned area in LPJmL-SPITFIRE and includes forest, shrubland, and bare land (as simulated in CLUMondo). Figure (a.) is the change in natural vegetation (burnable vegetation) from 2020 to 2050 under the SSP1 baseline scenario; (b.) the change in natural vegetation from 2020 to 2050 under the SSP3 baseline scenario; and (c.) the difference in natural vegetation between the SSP1 and SSP3 baseline scenarios in 2050. As each land use is given as a percent cover within a cell, a cell may be partially burnable.

SSP3) and, within each SSP, five fuel management scenarios (Fig. 1). We additionally ran a baseline scenario that included no fuel management for each SSP for comparison. To close the water and carbon balance in the model, the removed carbon from the fuel scenarios was transferred to the heterotrophic respiration carbon pool, while the corresponding water content was allocated to the evaporation flux.

All scenarios were simulated using data from five climate models ACCESS-CM2 (Ziehn et al., 2020), CanESM5 (Swart et al., 2019), MPI-ESM1-2-HR (von Storch et al., 2017), CNRM-ESM2-1 (Séférian et al., 2019), and EC-EARTH3 (EC-Earth-Consortium, 2019). This selection of models was chosen to reflect the uncertainty of the climate system through a range of plausible future climate patterns and resulting fire weather conditions (Hetzer et al., 2024). Simulation outputs were averaged across the five climate models using Climate Data Operators (Schulzweida, 2023).

2.4. Evaluation of simulation results

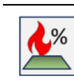
To ensure that the instant removal of fuels did not introduce unexpected behavior into the model, we conducted several model checks using single-cell simulations. These checks focused on the following key variables: fuel levels; soil moisture; and fuel moisture, immediately before and after fuel removals in different locations. The results showed the expected changes in fuel levels and no significant changes in soil and fuel moisture, confirming that the simulated fuel removal did not produce unintended side effects on model performance or behavior.

For each fuel removal scenario, we evaluated the change from the baseline (each SSP with no fuel modifications) for four metrics produced by LPJmL-SPITFIRE: burned area; surface fire intensity; rate of spread; and fuel bulk density (Table 2, Table S1). Rasters representing monthly averages were first calculated for all of the metrics. All monthly rasters from 2025 to 2050 were then summed for each metric to create a cumulative raster. Each cumulative raster was then subtracted from the baseline raster (no fuel removal) to determine the absolute difference between each scenario and its baseline (Figs. 3 and S3). Statistics on the mean, maximum, minimum, and standard deviation of the cumulative rasters for each metric and scenario were then taken (Table S1, Fig. 2).

3. Results

We first review the results of each of the baseline scenarios, in which no fuel management is simulated, under SSP1 and SSP3 for cumulative burned area, fuel bulk density, rate of spread, and maximum surface fire intensity during the 2025–2050 study period at the EU-level. We then analyze the results for each of the fuel removal scenarios targeting 1-hour, 10-hour, 100-hour, and 1000-hour fuels in comparison to the baselines and highlight spatial trends within the EU (Figs. 2, 3, & S3). Inter-model standard deviation in burned area across the five climate projects is included as supplementary information (Fig. S6).

Table 2
Summary of the metrics produced by LPJmL-SPITFIRE used to evaluate the five fuel management scenarios, including associated icon, measurement unit, definition, and illustrative contribution to fire dynamics.

Symbol	Metric	Units	Definition	Contribution to fire dynamics
	Burned Area (BA)	Hectares	Total area burnt in the natural vegetation stand	Removes fuels from the system, changes fuel moisture
	Max. Surface Intensity (Intensity)	kW/m^2	Maximum heat released per unit area per time	Direct relationship with the proportion of coarse fuels
	Rate of Spread (ROS)	m/s	Velocity of the flaming front of a surface fire	Increased by e.g., 1-hr fuels, low fuel moisture, and wind
	Fuel Bulk Density (FBD)	kg/m^3	Density of fuels averaged over dead and live fuels	Increasing FBD decreases rate of spread

3.1. Scenario 0: baseline scenario evaluation

Baseline land-cover distributions differed between the SSP1 and SSP3 scenarios, with distinct regional contrasts across Europe. Forest cover increased between 2020 and 2050 under SSP1 in parts of the Carpathian region, and decreased in Poland (Fig. S2). Cropland extent meanwhile decreased across the time period under SSP1 within the Carpathians, which may indicate reforestation or agricultural abandonment. Other land uses had relatively little change across the time period under SSP1. SSP3 had overall greater spatial heterogeneity and changes in cover of each land use. In Northern Europe, Sweden gained forest cover, and shrublands expand significantly along the border between Sweden and Norway. Croplands were lost in stretches of eastern Europe and the Mediterranean, especially in concentrated areas of

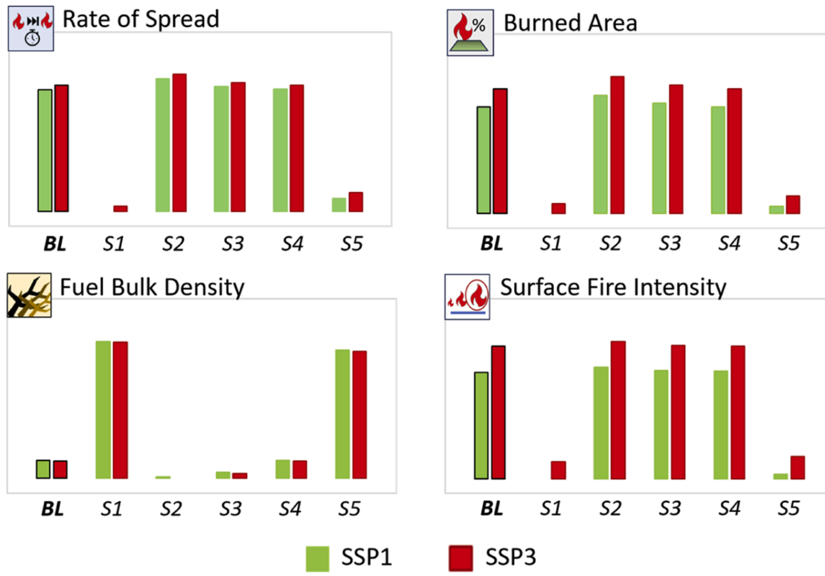


Fig. 3. Comparison of metrics of fire behavior response in the baseline (**BL**) and five fuel management scenarios (S1-S5, targeting 1-,10-,100-, and 1000-hour fuels, respectively) under SSP1 (green bars) & SSP3 (red bars). Each bar represents the mean value of the aggregated yearly data for the 2025–2050 study period (Table S1), normalized (0–10, 0 being lowest and 10 highest) by metric to facilitate comparison. Burned area, surface fire intensity, and rate of spread were most reduced under Scenario 1; fuel bulk density was most reduced under Scenario 2. Note that burned area only occurs within natural vegetation (Fig. 2).

Spain. Portugal lost some forest cover, gaining shrublands, grassland, and limited croplands. The trends differ in neighboring Spain, in which some areas lose shrublands and forest in favor of grassland, while other smaller areas lose cropland in favor of forest. Grassland increased more extensively under SSP3 across much of Spain, regions north of the Alps, eastern Europe, and Greece, with broader dominance across Mediterranean areas.

These land-use conversions also affected the amount of natural vegetation cover (e.g., total forest, shrub, and bare cover) which determines the maximum potential area which can burn in each cell (Fig. 2). Although the total amount of natural vegetation was only slightly higher in 2050 under the SSP1 baseline scenario compared to the SSP3 baseline scenario (0.28% greater than SSP3), the changes in natural vegetation differed spatially between SSPs. Under the SSP1 baseline scenario, natural vegetation increased markedly in most parts of Eastern Europe between 2020 and 2050 due to increases in forest and shrub cover, but decreased in the Baltic region and Poland. Under SSP3, natural vegetation also decreased in the Baltic region and Poland between 2020 and 2050, but increased in the Iberian Peninsula. In comparing SSP1 and SSP3, natural vegetation gains are overall favored most in Eastern Europe (especially in the Carpathian region due agricultural abandonment and the increased demand for forest products) under SSP1 and in Poland under SSP3 (due to retention of forest cover, loss of croplands, and slight increase in shrubland cover).

Burned area, surface fire intensity, and rate of spread were overall higher under the SSP3 baseline, while fuel bulk density was slightly higher under SSP1 (Fig. 3, Table S1). Despite these general differences, fire behavior metrics varied spatially across Europe under the baseline scenarios. The rate of spread decreased between 2020 and 2050 in northern Norway and much of western Europe under both SSPs, and several areas in Poland also experienced declines in rate of spread. In contrast, burned area increases were largely restricted to southern Europe, particularly across the Iberian Peninsula. In the eastern portion of the Carpathian Mountains, the rate of spread was higher under SSP1 than under SSP3. In regions where the rate of spread increased, fuel bulk density either did not change or decreased over time, consistent with the inverse relationship between rate of spread and fuel bulk density embedded in the Rothermel Fire Spread Equation (Fig. S3). The confinement of burned area increases to southern Europe is likely also attributable to enhanced fire weather conditions (Hetzer et al., 2024).

Comparing between SSPs, burned area was higher in the Iberian Peninsula under SSP3, while eastern Europe was higher under SSP1 (Fig. S4). Surface fire intensity was higher under SSP3 in Norway, eastern Europe, and the UK (amongst other areas), but higher under SSP1 in central areas of the Iberian Peninsula. Surface fire rate of spread was higher in Norway, the UK, and parts of southern Europe under SSP3, but higher in much of eastern Europe, the central Iberian Peninsula, and the Baltic region under SSP1. Fuel bulk density differences were mixed between SSPs.

3.2. Scenario 1: annual removal of 20% of 1-hour fuels

The simulated removal of 1-hour fuels in Scenario 1 had the largest effect on reducing the cumulative rate of spread, surface fire intensity, and burned area in the study period under both SSPs across Europe (Figs. 3 and S5; Table S1). As in the baseline scenarios, these metrics were slightly higher under SSP3 than under SSP1, and thus may be attributable to differences in land use and climate between SSPs. Conversely, cumulative fuel bulk density was highest under Scenario 1, with little difference between SSP1 & SSP3. This is in keeping with the underlying principles of the Rothermel Equation and internal logic of the LPJmL-SPITFIRE model, which models, among other factors, an inverse relationship between fuel bulk density and fire rate of spread.

Spatially, decreases in the rate of spread are widespread across Europe under SSP1, except for the Alps and Sweden, which have little variation from the baseline. These patterns are nearly identical to those simulated under SSP3 for the rate of spread. Burned area was most reduced in southern and eastern Europe under both SSPs (Figs. 4 and S5). This is in keeping with the baseline scenarios, in which these areas saw the largest increases in burned area. Increases in fuel bulk density occurred over most of Europe, other than Norway, Scotland, and patches within the Iberian Peninsula, which increased less sharply. In places where fuel bulk density was lower, intensity was largely higher.

3.3. Scenario 2: annual removal of 15% of 10-hour fuels

The removal of 10-hour fuels in Scenario 2 produced the largest increases in cumulative burned area, rate of spread, and surface fire

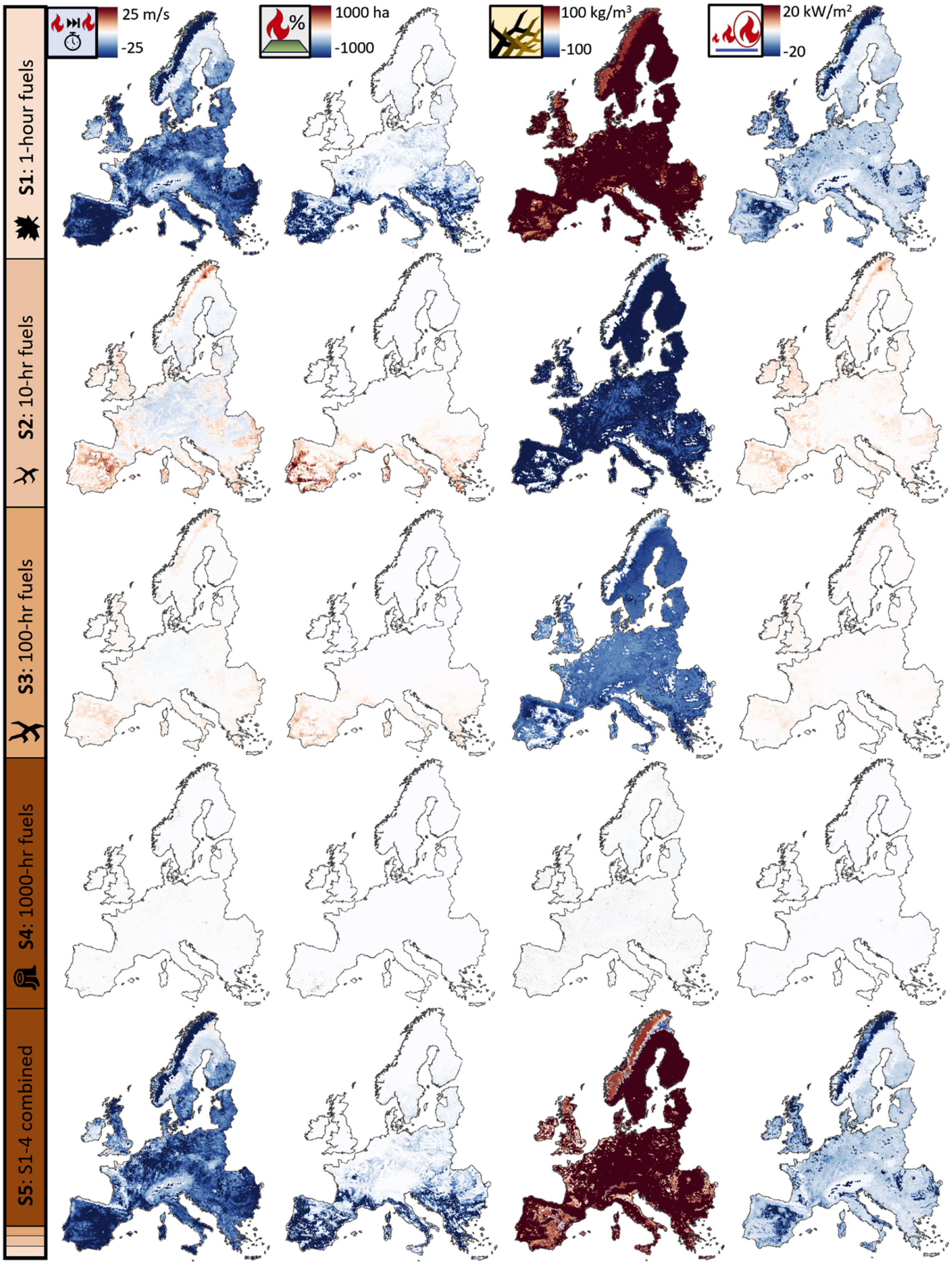


Fig. 4. Comparison of (left to right columns) the cumulative rate of spread, burned area, fuel bulk density, and surface fire intensity for the five fuel management scenarios between 2025 and 2050, under SSP1 (see Fig. S4 for SSP3 results). Blue denotes a decrease from the baseline cumulative amount for the metric, and red an increase. Outcomes for each metric are reporting only within natural vegetation (Fig. 2).

intensity under both SSPs in the study period (Fig. 3 and S5, Table S1). As in the baseline scenarios, these metrics were slightly higher under SSP3, indicating that land use and climate likely produce heightened fire conditions under SSP3. Cumulative fuel bulk density was lowest in this scenario under both SSPs, but slightly higher under SSP1 as compared to SSP3 (as in the baseline scenarios).

Spatially, patterns of change for the metrics were similar between SSPs. Rate of spread increased most in Norway and central-eastern regions of the Iberian Peninsula, while central Europe had a widespread, small reduction. Fuel bulk density displayed the anticipated inverse relationship with rate of spread: areas with increased fuel bulk density had a reduced rate of spread. This relationship did not correlate directly with changes in burned area, which increased most in central-western regions of the Iberian Peninsula and other areas in southern Europe where ignitions in seasonally dry climates likely flourished with increased fire weather. A small increase in fire intensity was simulated in many parts of Europe, except in Poland and Baltic areas, where no measurable difference was found.

3.4. Scenario 3: decadal removal of 5% of 100-hour fuels

The results in Scenario 3 were similar to those simulated with removal of 10-hour fuels in Scenario 2, but at a reduced magnitude. Cumulative burned area, rate of spread, and surface fire intensity under both SSPs were largely the same as the baseline scenarios, indicating that this fuel treatment was not effective in changing wildfire behavior (Fig. 3 & S5, Table S1). These metrics were slightly higher under SSP3 as compared to SSP1. Cumulative fuel bulk density was also similar to baseline levels and slightly lower under SSP3 as compared to SSP1.

Spatially, in line with the results simulated under Scenario 2, the rate of spread increased slightly in Norway and parts of the Iberian Peninsula. These areas also had the smallest reduction in fuel bulk density. Fuel bulk density otherwise decreased across the continent, but to a lesser degree than in Scenario 2. Burned area increases were isolated to the Iberian Peninsula, while changes to fire intensity were slight and isolated to Norway and the Iberian Peninsula.

3.5. Scenario 4: decadal removal of 5% of 1000-hour fuels

In Scenario 4, the simulated results also mirrored those of Scenarios 2 & 3, but at a reduced magnitude. Cumulative burned area, rate of spread, and surface fire intensity were largely the same as the baseline under both SSPs (Fig. 3 & S5, Table S1). These metrics were slightly higher under SSP3 in comparison to SSP1. Cumulative fuel bulk density was also similar to baseline levels and slightly lower under SSP3 as compared to SSP1. Spatially, the simulated results did not differ from the baseline. This matches the assumption in the Rothermel Fire Spread model that 1000-hour fuels do not affect fire spread and the resulting LPJmL-SPITFIRE modelling conditions, which do not include 1000-hour in its calculation.

3.6. Scenario 5: mixed fuel removal (combination of scenarios 1–4)

The mixed fuel removal scenario simulated in Scenario 5 showed a significant net reduction in cumulative mean burned area, rate of spread, and surface fire intensity under both SSPs (Fig. 3 & S5; Table S1). These reductions were similar but comparatively slightly lower than those simulated in Scenario 1.

Spatially, reduction patterns in the rate of spread, burned area, and intensity are nearly identical to Scenario 1, except for slight differences in eastern Europe near the Carpathians and eastern Norway. In the Carpathian region, the rate of spread is slightly lower in Scenario 5 as compared to Scenario 1. Overall, fuel bulk density was slightly lower in Scenario 5 as compared to Scenario 1, and it even decreases compared to the baseline in eastern Norway and a few isolated spots in the eastern Carpathians and Iberian Peninsula.

3.7. Assessment of uncertainty

To assess uncertainty associated with climate forcing, we examined the mean inter-model standard deviation in burned area across the five climate projections (Fig. S6). Variability was highest in southern Europe, particularly across the Iberian Peninsula and parts of the Mediterranean region, corresponding to areas with the greatest simulated wildfire activity. Elsewhere, inter-model variability was comparatively low, suggesting broad agreement among climate models regarding the spatial distribution of future burned area.

4. Discussion

Our simulations indicate that wildfire behaviour is particularly sensitive to the management of fine fuels and mixed-fuel treatments, although treatment responses varied across regions and future scenarios. These findings are broadly consistent with empirical studies showing that fuel-management approaches targeting surface fuels, including prescribed burning, grazing, shrub reduction, and understory management, can reduce wildfire spread and severity (e.g., Fernandes et al., 2013; Casals et al., 2016; Salis et al., 2016; Alcasena et al., 2018; Calleja et al., 2019; Sil et al., 2019; Ascoli et al., 2021; Rouet-Leduc et al., 2021). Many of these interventions primarily act on fine fuels, which play an important role in ignition and fire propagation. The importance of reducing surface fuels has also been highlighted outside Europe. For example, Davis et al. (2024) found that prescribed burning and combined prescribed burning–thinning treatments were generally more effective at reducing subsequent wildfire severity than thinning alone. While our fuel-management scenarios do not directly represent operational treatments, the consistency between these empirical findings and our modelling results suggests that management of fine fuels may exert a disproportionate influence on wildfire behaviour relative to treatments focused solely on larger fuels.

At the same time, relatively few studies have explicitly evaluated the relative influence of different fuel classes on wildfire behaviour, particularly at continental scales and under future land-use and climate change. By isolating the response of wildfire behaviour to different fuel classes within a common modelling framework, our results provide insight into how the effectiveness of fuel management may vary across alternative future landscapes. Furthermore, we found that rate of spread, fire intensity, and burned area were generally higher under SSP3 than SSP1, likely reflecting increasingly severe fire weather conditions projected under higher-emission futures (Abatzoglou et al., 2019; Dupuy et al., 2020; Hetzer et al., 2024).

We identified substantial spatial variation in treatment response across both the fuel-management scenarios and future land-use pathways. Regional differences in treatment effectiveness appear to arise from interactions among land-use change, natural vegetation dynamics, baseline fire activity, and fuel characteristics represented within the modelling framework. For example, land abandonment and forest expansion increased natural vegetation cover in parts of the Carpathian region under SSP1 and in portions of the Iberian Peninsula under SSP3, altering the amount and distribution of burnable vegetation. These changes influenced the sensitivity of wildfire behaviour to fuel management and demonstrate how future socioeconomic pathways may affect treatment outcomes.

The strongest treatment responses generally occurred in southern Europe, where baseline wildfire activity and fire weather were already elevated. In contrast, much of northern Europe exhibited weaker responses because baseline burned area remained comparatively low, limiting the influence of fuel treatments on total area burned. Although fuel treatments influenced fuel bulk density, rate of spread, and fire intensity across multiple regions, reductions in burned area were largely concentrated in southern Europe. Uncertainty in simulated burned area was also greatest in these areas (Fig. S6), reflecting higher overall wildfire activity and greater divergence among climate projections. Nevertheless, the spatial distribution of treatment effects remained consistent with the underlying wildfire patterns represented by the modelling framework.

These findings suggest that fuel-management effectiveness depends not only on the fuel classes targeted, but also on the broader landscape context in which treatments are applied. Consequently, management strategies may be most effective when focused on fire-prone regions experiencing vegetation expansion through processes such as agricultural abandonment or reforestation. More broadly, the results highlight the importance of considering future land-use trajectories alongside fuel-management interventions when developing long-term wildfire adaptation strategies (Neidermeier et al., 2025).

4.1. Fuel schedule design and regionally adapted management

Representing the full complexity of Europe's diverse vegetation structures, phenologies, management objectives, economic constraints, and sociocultural contexts presents a substantial challenge for continental-scale fuel management modelling The fuel-management scenarios developed here were therefore intended as stylized sensitivity experiments rather than operational management prescriptions. The selected treatment schedules reflect broad differences in the practical feasibility of managing different fuel classes, with fine fuels typically treated more frequently through approaches such as prescribed burning, grazing, or understory management, while larger woody fuels are generally managed less frequently because of logistical, ecological, and economic constraints. To isolate the influence of fuel classes and future land-use and climate conditions, treatment timing and implementation were standardized across the study area, including the use of a common treatment date.

While this simplification does not capture the diversity of management practices employed across Europe, it provides a consistent framework for evaluating the relative sensitivity of wildfire behaviour to different fuel classes. The approach also allows broad patterns in treatment response to be identified across large geographic areas, highlighting regions where fuel management may have greater or lesser influence on future wildfire behaviour. Consequently, the results should be viewed as a starting point for more detailed landscape-scale analyses that incorporate region-specific vegetation dynamics, management objectives, and implementation constraints (Thompson et al., 2022).

Further tailoring of fuel removal schedules and reapplication intervals to local management goals and regional ecological phenologies could enhance treatment efficacy, support spatial prioritization, optimize resource use, protect sensitive ecological processes (e.g., breeding and reproduction), and align with or strengthen legal frameworks (Bowman et al., 2016; Fuentes et al., 2018; Valkó and Deák, 2021; Campos et al., 2022; Hellicar and Kirschel, 2022; Cordeiro Pereira et al., 2024). For example, in our study, we established a conceptual link between fuel classes and fuel management types—specifically prescribed burning and thinning—but focused solely on the removal of dead fuels. Including live fuels in future scenario development would be especially relevant for evaluating the role of grazing, pastoralism, and wild ungulates in fuel management, which have been shown to reduce fire risk in Europe (Fuhlendorf et al., 2009; Mena et al., 2016; Rouet-Leduc et al., 2021; Neidermeier et al., 2023).

Testing of alternate fuel removal schedules could further adapt fuel management schemes to local conditions, such as better accounting for phenological differences across Europe. In our study, we opted to remove fuels on the same day in spring at different annual application intervals (Table 1). However, vegetation in northern Europe is typically in early post-winter growth in May, but is often much further along in development in this stage of late-spring in Southern Europe (see Sections 2.2 and 2.3; Forkel et al., 2014). Alternative schedules could differentiate removal timing by region, test both within-year (e.g., spring versus autumn fuel removal) and between-year (e.g., biannual application of prescribed burn instead of annual applications) schedules, and target different combinations of fuel classes (e.g., 1-hour and 10-hour; 1-hour and 100-hour).

Our research also focused primarily on reducing fuels to mitigate wildfires. However, other forms of land-use change and management also impact wildfire, such as wildfire suppression. Future research could thus explore the inclusion of fire suppression initiatives, which are an important first line of defense in fire suppression and firefighting in Europe (Moreira et al., 2020). This could include the inclusion of an algorithm in such modelling exercises to simulate suppression actions, such as in a recent study by the US Forest Service (Finney et al., 2025).

4.2. Understanding fire dynamics in the Rothermel equation as implemented in LPJmL-SPITFIRE

Wildfire behavior and spread in ecosystems is an inherently complex phenomenon. Studies using fire-enabled vegetation models such as ours provide an important testing ground to understand the dynamics of this complexity and explore how management choices may perform under future climate and socioeconomic conditions (Hantson et al., 2016; Abatzoglou et al., 2020). Paramount to understanding the results produced by DGVMs such as LPJmL-SPITFIRE is the implementation of the Rothermel Fire Spread Model (Rothermel, 1972; Thonicke et al., 2010; Oberhagemann et al., 2025). Via the empirical relationships between variables defined in the Rothermel Fire Spread Model, LPJmL-SPITFIRE is used in our study to explore the effects of fuel removals on wildfire behavior metrics, such as fuel bulk density. Fuel bulk density is determined in this modelling approach by the relative proportions of the fuel classes in a cell and has an inverse relationship with the rate of spread. Thus, when coarser fuels are removed, fine fuels proportionally receive more weight, based on the averaging effect of each of the fuel classes in the calculation of fuel bulk density (Table 2). We would therefore expect that removal of fine fuels would increase fuel bulk density and decrease the rate of spread. In our results, fuel bulk density indeed increased from the removal of 1-hour (fine) fuels, and decreased with 10-hour, 100-hour, and 1000-hour fuel removal under both SSPs. This in turn correlated with an inverse effect on the rate of spread and surface fire intensity (Fig. 3).

These findings are particularly important for interpreting the coarse-fuel removal scenarios. Within LPJmL-SPITFIRE, reductions in coarse fuels decrease fuel bulk density and thereby increase simulated rates of spread through the Rothermel-based fire spread formulation. However, this result should not be interpreted as direct evidence that coarse-fuel removal universally increases wildfire risk. In real ecosystems, coarse fuels can influence fire behavior through mechanisms not fully represented in the model, including changes in fuel continuity, vertical structure, canopy connectivity, and fuel moisture dynamics. The following limitations should therefore be considered when interpreting the response of the coarse-fuel scenarios.

The Rothermel Fire Spread Model necessarily simplifies certain components of wildfire behavior dynamics, which may impact how our study findings can best be interpreted and used. While the importance of fine fuels for fire spread is supported by both empirical and modelling studies, the magnitude and direction of the response to coarse-fuel removal are likely more sensitive to the specific fire-spread representation used in LPJmL-SPITFIRE. Consequently, our results provide stronger evidence regarding the relative effectiveness of fine-fuel management than the precise impacts of coarse-fuel removal alone. For example, the model is primarily focused on surface fuels, which are assumed to be evenly distributed within a cell in the implementation of LPJmL-SPITFIRE (Oberhagemann et al., 2025). This implies that certain elements known to be critical to wildfire behavior and spread are not explicitly included in the model function. Such elements include spacing between fuel types, the ability for wind to move through a fuel complex, vertical fuel structures (e.g., ladder fuels), and canopy interactions, amongst others (Cruz and Alexander, 2010; Atchley et al., 2021; Campbell-Lochrie et al., 2023). Wildfire effects on forest canopies are especially of interest to understand impacts on tree mortality and would be an important area of study for integration into models such as LPJmL-SPITFIRE (Cruz and Alexander, 2010; Hevia et al., 2018; Barker et al., 2019). A differentiation in fuel moisture dynamics according to the fuel size class would be an important further addition to increase model realism. Research indicates that the removal of coarse dead fuels, which likely hold more moisture than finer fuels, resulted in decreased fuel moisture (Hood et al., 2017). Thus, the retention of coarse fuels, which may inhibit fire spread under non-drought or extreme heat conditions, is not represented in our study (Kuhn-Régnier et al., 2021). If included, we would expect current simulated effects of coarse-fuel removal to increase fire spread effects of remaining fine fuel. From a management perspective, these results suggest that prioritizing treatment of fine fuels may yield greater reductions in wildfire behavior than interventions focused exclusively on larger woody fuels, particularly in regions expected to experience increasing fire activity. The fuel-management scenarios examined here should also therefore be interpreted as sensitivity experiments designed to explore the relative influence of different fuel classes under future land-use and climate conditions, rather than direct evaluations of operational fuel treatments. Future modelling efforts should evaluate spatially targeted management strategies, incorporate more detailed representations of fuel structure and treatment implementation, and explore how management effectiveness changes under alternative socioeconomic pathways.

Finally, it is important to note that we simulated only two trajectories of socioeconomic development and climate pathways based on SSP1 and SSP3. Our results provide evidence that the effects of climate change will increase wildfire in many regions of Europe under either SSP (Fig. S3), as greenhouse gas emissions released since the industrial revolution continue to accumulate and challenge critical earth system functions. Even a green development pathway such as SSP1 through which the 2-degree target would be met, can increase vegetation and thus fuels under more variable and intense precipitation and fire weather conditions, leading to more destructive and destabilizing wildfires. However, the magnitude of wildfire is clearly mitigated by climate and land management. Consequently, we posit that in addition to land and fuel management, active mitigation of climate change is a critical factor in mitigating wildfire risk.

5. Conclusion

Using a series of stylized fuel-management scenarios, we evaluated the sensitivity of future wildfire behaviour in Europe to the management of different fuel classes under contrasting land-use and climate futures. Across both SSP1-RCP2.6 and SSP3-RCP7.0, wildfire behaviour was most responsive to management of 1-hour (fine) fuels and mixed-fuel treatments, which consistently produced the largest reductions in burned area, rate of spread, and surface fire intensity. In contrast, management scenarios targeting coarse fuels alone (10-, 100-, and 1000-hour fuels) did not consistently reduce wildfire behaviour within the modelling framework. Treatment responses varied substantially across Europe, reflecting interactions among fuel characteristics, baseline wildfire activity, land-use change, and climate conditions. Regions experiencing high wildfire activity or increasing natural vegetation cover, including parts of southern Europe and the Carpathian region, exhibited the greatest sensitivity to fuel management. These findings suggest that the effectiveness of fuel management depends not only on the fuel classes targeted, but also on the broader landscape context in which treatments are applied. While the scenarios examined here are not intended as operational management prescriptions, they provide insight into the relative influence of different fuel classes on future wildfire behaviour. The results highlight the importance of considering future land-use trajectories alongside fuel-management interventions, particularly in regions undergoing revegetation through processes such as agricultural abandonment or reforestation. Future research should evaluate regionally adapted treatment schedules, additional management constraints and interventions, and improved representations of fuel structure, moisture dynamics, and fire behaviour within vegetation-fire models. Overall, our findings suggest that incorporating a fire and fuels perspective into long-term land-use planning can help support wildfire adaptation efforts under a range of future socioeconomic and climatic conditions.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT to assist with language editing, manuscript organization, and the drafting and revision of text. The AI tool was not used to generate, analyze, or interpret data, and all scientific content, conclusions, and decisions were reviewed and verified by the authors. The author(s) reviewed and edited the output as needed and take full responsibility for the content of the published article.

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CRediT authorship contribution statement

Alex N. Neidermeier: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maik Billing:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Thales A.P. West:** Writing – review & editing, Supervision, Conceptualization. **Kirsten Thonicke:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Peter H. Verburg:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ecolmodel.2026.111747.

Data availability

Research Link Provided (https://dataverse.nl/dataset.xhtml?persistentId=doi:10.34894/ALZTYS).

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