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

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Executive Summary

Land use and climate change are driving new dynamics for wildfires globally. In Europe, these drivers contribute to changes in fuel structures which affect the behavior, impact, and recurrence interval of wildfires. In response, there is interest in restoring historic fuel-relevant land management strategies (FRLMS) which impact the condition and arrangement of fuels.

This document provides a spatial assessment of opportunities to manage fuels through three fuel-relevant land management strategies (FRLMS)—herbivory, mechanical removal, and prescribed burn—at the landscape-scale in Europe in order to envision a comprehensive fire risk mitigation strategy. It builds on FirEUrisk deliverable 2.3, in which landscape-level policy guidelines were developed based on a literature review and fuzzy cognitive mapping of the enabling factors for the uptake of FRLMS. The biophysical, socioeconomic, and environmental factors which can contribute to the uptake and success of the FRLMS were synthesized for this deliverable (2.4) into a series of spatially-explicit suitability factors for each FRLMS (summarized in Fig 1). Here we provide relevant background information; a summary of the methodology; decision trees for choosing suitable FRLMS (Fig. 1); maps of FRLMS-suitable areas (as published in Neidermeier et al., 2023; Fig. 2); and maps of hot-spots of ecosystem function (here used as an umbrella term which includes biodiversity and carbon storage) and wildfire occurrence (Neidermeier et al., 2024, in review) in Europe. The results are linked to FirEUrisk WP3 as a basis to simulate stylized fuel management schemes under future socioeconomic and climate scenarios.

Key Take Aways



GEOGRAPHY MATTERS
Over a quarter of Europe was found to be suitable for multiple FRLMS in areas of historical fire occurrence. However, conditions in other regions were only suitable for singular FRLMS, such as in parts of southern Europe (prescribed burn), much of northern Europe (herbivory), and eastern Europe (a combination of herbivory and prescribed). *Section 3.2.*



ONE SIZE DOES NOT FIT ALL:
Local factors, including costs and incentives, interest or opposition by local stakeholders, and treatment of high conservation value areas must be properly assessed. *Section 4.*



NAVIGATING TRADE-OFFS
Potential trade-offs between fire risk and ecosystem function must be carefully assessed. Eastern & southern Europe have especially high ecosystem function & fire occurrence. Fuels in pockets of high fire & low ecosystem function are low-hanging fruits for reducing fire risk. *Section 3.3.*



NO SILVER BULLETS
FRLMS such as those studied here are, however, only part of the solution: mitigating climate change and reducing exposure at the wildland urban interface are simultaneously important. *Section 4.*

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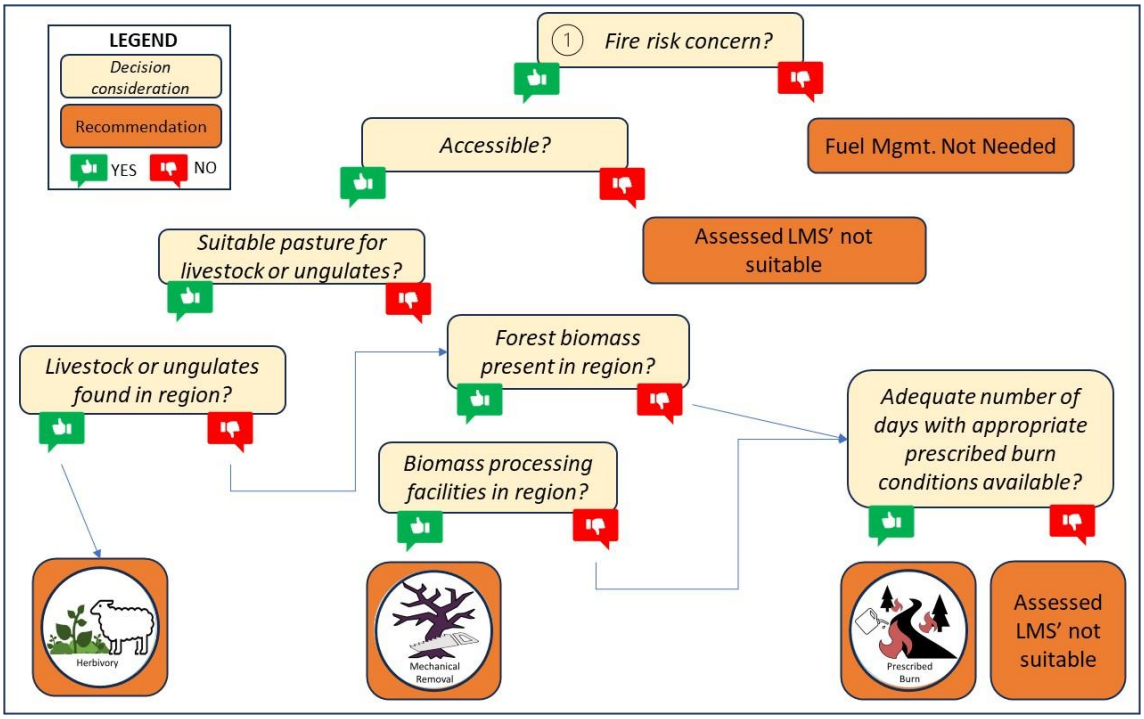


Figure 1: Decision tree of considerations for the use of a land management strategy (FRLMS), beginning with "Fire risk concern?" (top).

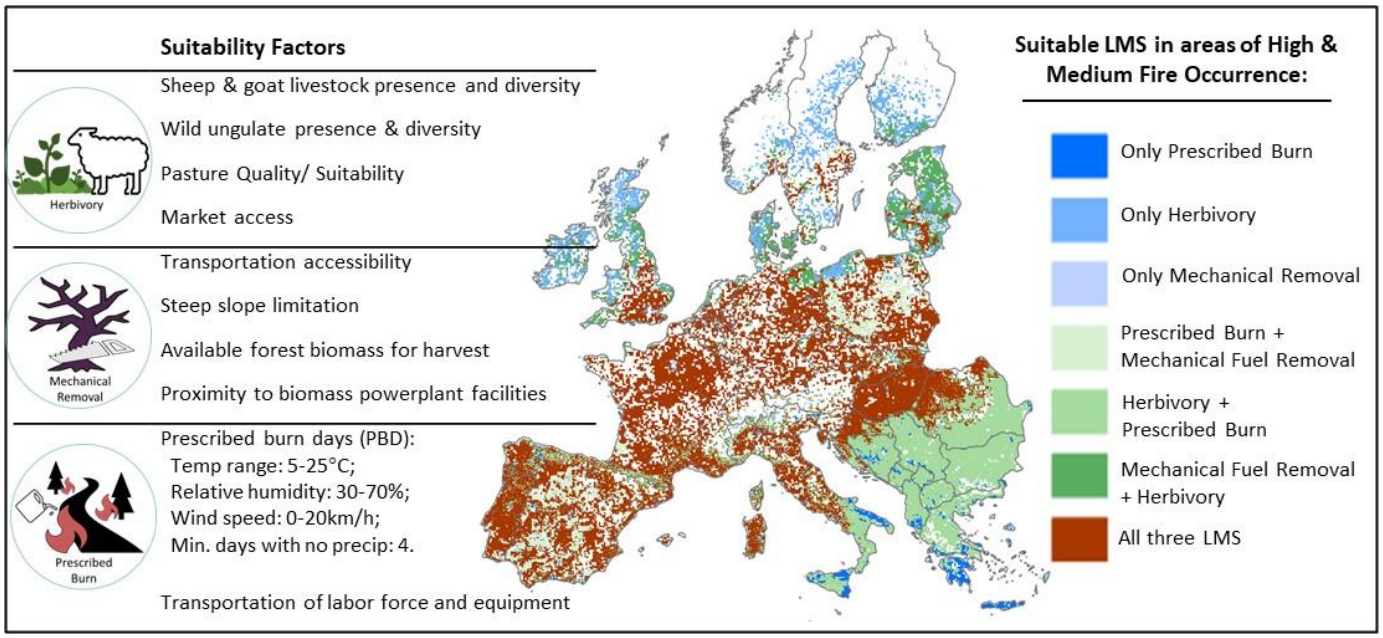


Figure 2: Suitability factors used for each FRLMS (left) and final suitability map (middle). Areas in white had low fire occurrence and/or low FRLMS suitability.

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List of Acronyms

Table 1: List of Acronyms

List of Acronyms	
FRLMS	Fuel-Relevant Land Management Strategies
EU	Europe
GPS	Global Positioning System
WUI	Wildland Urban Interface
PBD	Prescribe Burn Days
SI	Supplementary Information
WDTA	Wildfire Danger by Thermal Anomaly
ERA	Environmental Risk Assessment
FMP	Fuel Management Plan

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1 Introduction

1.1 Background

An historically close relationship has existed amongst people, landscapes, and fire in Europe (Camp et al., 1997; Carnicer et al., 2022; Galizia et al., 2021). Fire has been used traditionally for a variety of reasons, such as by pastoralists to improve fodder for livestock (Varela et al., 2022) and by farmers to clear vegetation from the land (Scherjon et al., 2015; Trauernicht et al., 2015). A complex array of land covers and uses (Azevedo et al., 2018), climate (Carnicer et al., 2022), vegetation types (Loudermilk et al., 2022), and topography (Moreira et al., 2011) drive the fire regimes with which Europe has become familiar over the last centuries (Bowman et al., 2011; Galizia et al., 2021; Kelley et al., 2019; Krebs et al., 2010). However, many parts of Europe face new challenges in dealing with wildfires due to a combination of dynamic and interrelated factors, including: more frequent drought and heat wave events due to climate change (Abatzoglou et al., 2019; Joint Research Centre European Commission, 2020); alterations to the composition, continuity, and condition of fuels across the landscape (Moreira et al., 2011); and shifting wildland urban interface dynamics (Chuvieco et al., 2010).

Although Europe has witnessed a reduction in burned area over the past three decades, certain regions are experiencing an upward trend in both interannual variability and the magnitude of wildfires (European Commission et al., 2022b). Additionally, previously fire-scarce areas, such as central and eastern Europe, are now encountering a greater number of and more severe fires. This phenomenon implies a significant shift in fire patterns throughout the continent (European Commission et al., 2022b). The drivers of such changes are complex and spatially heterogenous across Europe (Azevedo et al., 2018; Sil et al., 2019). For example, increased risk in northern Europe has been attributed to increases in the number of days with fire-prone meteorological conditions (e.g. drought, high winds, high temperatures) due to climate change (European Commission et al., 2020; Jones, Matthew W. et al., 2020; Lozano et al., 2017; Turco et al., 2018).

In southern Europe, fire risk is largely associated with demographic and socioeconomic changes which have resulted in large areas of land abandonment (Estel et al., 2015; van Vliet et al., 2015). Landscape changes associated with land abandonment can lead to different trajectories of development, including spontaneous regrowth with unmanaged, semi-natural vegetation, invasive species or reforestation (Fayet and Verburg, 2023). The new vegetation has the potential to contribute to important ecosystem functions, such as carbon storage and biodiversity (Fischer et al., 2012; Schulp et al., 2008; van der Zanden et al., 2017). These changes may even contribute to the fulfillment of EU policies such as the Green Deal, which attempt to secure a more sustainable future through the provision of certain ecosystem functions (Ascoli et al., 2023; European Commission, 2021; European Environment Agency, 2019). The restoration of such functions, through tree planting, increased habitat connectivity, or granting of protected area status, has implications for land use which can affect fuels and thus fire dynamics (Moreira et al., 2011).

However, these fuelscapes can also become dense, compact, and homogenous, with vegetation largely composed of a similar age and species type (Moreira et al., 2011; Moreno et al., 2014). In combination with dangerous weather conditions for wildfires, driven by climate change, this vegetation can also become a liability (Azevedo et al., 2018; Hermoso et al., 2021; Lasanta, 2019; Moreno et al., 2014; Santana et al., 2018). For example, many

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Mediterranean areas were formerly managed through the use of agropastoral burns and agriculture. In the wake of abandonment, such areas may be colonized by shrubs or pine trees, with decreased species diversity (Fayet et al., 2022; Jones et al., 2016; Lasanta, 2019) and a densification in the spatial organization of fuels. Wildfires in such landscapes, especially given the steep slopes common in the region, are likely to be more difficult to control as compared to those with greater heterogeneity of fuel characteristics (such as a mosaic landscape). This can contribute to a higher magnitude or more frequent interval of wildfire than that which ecosystems have been conditioned to cope in recent history (Adams, 2013). Referred to as megafires in some contexts (Linley et al., 2022), uncharacteristically intense and impactful fires have the potential to burn large patches of forests, degrade seed banks, erode carbon-rich soils (Wunder et al., 2021), and create danger for humans and their assets. Although wildfire provides an integral contribution to many unique, dynamic ecosystems by cycling nutrients and catalyzing succession (McLauchlan et al., 2020), an unusually intense fire can overwhelm an ecosystem's resilience capacity with a long recovery interval which may not match human time frames for biodiversity conservation goals (Warziniack et al., 2019).

Conversely, the implementation of fire management activities has the potential to affect both wildfire dynamics and ecosystem function (Campos et al., 2022; Vorster et al., 2023). Fire suppression, for example, can be a useful tool for fire management, playing a pivotal role in safeguarding lives and assets in the short term. However, in historically fire prone regions, the suppression of fires can yield adverse consequences for fire-adapted species and foster the accumulation of fuels, contributing to more extensive and destructive wildfires (Moreira et al., 2020; Rigolot et al., 2009). Similarly, research on fuel management strategies such as herbivory (e.g., silvopasture and domesticated livestock, mechanical removal (e.g., understory biomass removal), and prescribed burn (e.g., traditional uses for pasture) indicates that they can reduce fire risk by changing vegetation dynamics (Ascoli et al., 2023; Benali et al., 2021; Neidermeier et al., 2023). Larger scale landscape transformations, such as the construction of artificial lakes (Santos et al., 2018), the substitution of fire-prone tree species with less combustible alternatives (Palik et al., 2022), or restrictions on urban development in fire-prone areas (Calkin et al., 2014) can also impact wildfire behavior. These can intentionally or unintentionally make regions less fire prone, better prepared for wildfire response, or decrease the risk of megafires. However, beyond disruption to residents, they may also unlock carbon stored in vegetation and soils, alter habitat extent, quality, and connectivity, or disrupt the facilitation of another ecosystem function congruent to the intensity of application, application timing, and ecological sensitivity of an area (Hall et al., 2012; Patacca et al., 2023).

A nuanced approach to landscape management is thus needed which addresses the intensifying threat of wildfires (European Commission et al., 2020), the importance of maintaining and restoring ecological functions (Roces-Díaz et al., 2022), and the potential trade-offs between them (Campos et al., 2022). Prior research has assessed FRLMS opportunities by way of inventories, analysis, and summaries with a focus on southern Europe (e.g., Moreira et al., 2011), but has not to our knowledge carried out a pan-European spatial assessment of areas in which opportunities exist for these FRLMS. Research on the trade-offs between ecosystem functions and fuel management in Europe has largely focused on local and regional scales, primarily in southern Europe (e.g., Campos et al., 2021; Lecina-Diaz et al., 2023; Regos et al., 2023), which can be difficult to translate to EU-wide policy initiatives. Here, we focus on three common FRLMS in Europe with historical precedence and current relevance: (1) herbivory (specifically, browsing and grazing by goats, sheep, and wild ungulates—see Table 2 for full

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rationales); (2) mechanical fuel removal, including pruning, thinning, and harvest for management and industrial purposes; and (3) prescribed burn. We also include the results of an empirical, continent-wide spatial analysis on recent fire occurrence, above and below ground carbon, species diversity, and structural diversity. Together, the findings offer policymakers tasked with addressing the dual challenges of wildfire and ecosystem function provision a holistic perspective for decision making.

1.2 Document aim and scope

- Provide relevant background information needed to understand the relationship between FRLMS and wildfire risk in Europe;
- Summarize the methodology used to develop suitability maps of FRLMS strategies to manage wildfire risk in Europe;
- Present a decision tree and suitability maps for single and concurrent use of the FRLMS in Europe;
- Highlight potential trade-offs between fuel management and ecosystem function.

2 Methods

2.1 Deriving suitability factors for each FRLMS

We began with a semi-systematic literature review to identify the constraints and opportunities of adopting different fuel-relevant land management strategies to reduce wildfire risk in Europe. Although more than ten strategies were identified over the course of the review, we narrowed our study to strategies which were most frequently identified in the literature (providing the broadest evidence base) and which targeted fuels by way of land management specifically (instead of land-use change actions, e.g., construction of artificial lakes). All references to FRLMS in this text thus refer to those strategies which have the potential to change fuel characteristics across the landscape through land management. These FRLMS were: (1) herbivory (by domesticated and wild herbivores); (2) mechanical fuel removal (including pruning, thinning, and harvest for management and industrial purposes); and (3) prescribed burn. The full methodology and results of the literature review can be found in FirEUrisk Deliverable 2.3 ("Guidelines for Land Management Strategies: Applicability, socioeconomics and environmental concerns") and in the 2023 publication by Neidermeier et al., "Mapping opportunities for the use of land management strategies to address fire risk in Europe".

Using these results, we defined a set of spatially explicit suitability factors for the adoption of the three FRLMS (Tables 2, 3, and 4). In summary, the suitability map for herbivory encompasses areas which (1) have greater presence or diversity of domesticated or wild ungulate grazers or browsers; (2) have greater accessibility to livestock and can allow for transportation of livestock products; (3) have a greater share of suitable pasture. The suitability for mechanical fuel removal, including pruning, silvicultural activities, and extraction for industry, was represented by areas with (1) greater forest biomass availability; (2) greater proximity to documented biomass powerplants; (3) greater accessibility for transportation of raw materials and products; and (4) were located on suitable degrees of slope for machine and labor access. Finally, suitability for prescribed burning encompasses areas with (1) a greater number of days with safe and effective prescribed burn conditions ('prescribed burn days,'

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or PBD); (2) greater accessibility to allow for transport of equipment and labor; and (3) sufficient distance from major settlements (which may be adverse to resulting smoke).

The resulting suitability maps were reviewed by approximately 60 researchers and practitioners specializing in fire management working within the EU Horizons' 2020-funded FirEURisk project via a project-organized session and accompanying optional survey. Feedback was solicited on the appropriateness of each suitability factor, validation of results for the participant's area of expertise and geography, and holistic feedback on the resulting suitability maps. Based on the responses, revisions were implemented regarding the list of livestock species included (specifically, removal of horses and cows due to limited efficacy and potential for recruitment of more flammable fuel types, especially shrubs--Calleja et al., 2019) and the calculation of prescribed burn days (modification of the windows used).

Table 2: Suitability factors (including discarded factors & rationale) for herbivory as an FRLMS.

Suitability Factor	Proxy data	Technical Details	Rationale
Sheep & goat livestock presence and diversity	Number of livestock per pixel from Gilbert et al. 2018	Resolution: 5 arc minutes Spatial & Temporal Coverage: Global, 2010	The literature indicated that certain domesticated livestock can be effective in fuel management, especially sheep and goats which will consume herbaceous vegetation and live woody buds. Although cattle can meaningfully reduce herbaceous live fuel cover, our research indicated that they were associated with shrub recruitment by selectively grazing grasses (Calleja et al., 2019) thus potentially contributing to heightened fire risk and were thus excluded. We assume that livestock will either partially or fully base their diets on natural fodder (versus supplemental food sources) in order to affect fuels. We avoid an assessment of over-grazing by capping maximum suitability at 25 head per pixel (per species).
Wild ungulate presence & diversity	Location of wild ungulates from Linnell et al., 2020	Resolution: Shapefiles Spatial & Temporal Coverage: Europe, various temporal coverage	Wild ungulates were found to meaningfully contribute to fire risk reduction (Lecomte et al., 2019), especially browsers. This is especially important to avoid shrub recruitment (Rouet-Leduc et al., 2021). It was not possible to account for population density due lacking spatial data on population densities or optimal distribution. We therefore only accounted for wild ungulate species diversity by assigning greater suitability to areas in which a larger number of species are present.
Pasture Quality/ Suitability	Pasture suitability index from Velthuizen, H. van, 2007	Resolution: 5 arc seconds Spatial & Temporal Coverage: Global, 2000	To determine areas in which grazers and mixed diet browsers could find sufficient pasture for their diet, we used a global estimate of pasture quality.

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Market access & livestock mobility	Friction map of travel time to cities (accessibility) Weiss et al. 2018	Resolution: 1km Spatial & Temporal Coverage: Global, 2015	Greater market access enables the sale of livestock products which may act as an incentive for its uptake (Elia et al., 2016). Accessibility can also facilitate the transportation of livestock to priority areas for fire risk reduction.
Avoid large city centers	Dou et al. 2021	Resolution: 1km Spatial & Temporal Coverage: Europe, 2015	The literature indicates that grazing opportunities will be limited and less likely to be adopted in large cities. Peri-urban areas may, however, still be able to adopt. We therefore developed a mask of high intensity settlements. To represent this, Settlements here are defined by the amount of impervious surface.
Excluded suitability factors and rationale			
Demographic parameter to simulate abandonment risks	*The literature indicates a relationship between areas with aging populations (>65 years of age) and land/ farm abandonment. Land abandonment, including the loss of grazing, is an important component of fire risk in Europe. However, we opted not to use a demographic age parameter as a proxy for land abandonment so that any area, regardless of the status of land abandonment, can be recommended for the FRLMS. Instead, areas facing land abandonment with opportunity to use grazing as an FRLMS strategy are highlighted as a priority for intervention.*		
Rural/ farmer population density	*Land abandonment and the loss of pastoral systems has an important relationship with fire risk in Europe. Thus, an indicator of farmer presence on landscapes was considered as a data point in this map. However, we opted not to use a rural population density indicator as a proxy for abandonment so that any area can be recommended for the FRLMS. Instead, areas facing land abandonment with opportunity to use grazing as an FRLMS strategy are highlighted as a priority for intervention.*		
Poverty index--Low or medium wealth areas more likely to adopt	*The literature indicates that there can be positive socioeconomic impact from grazing activities in economically disadvantaged areas. A poverty index could therefore be indicated as increasing the likelihood of adoption in more impoverished places. This is likely a potential enabling factor for more livestock raising in areas where it is likely in decline. However, based on the literature, it was not possible to say that more impoverished places are more likely to adopt this FRLMS, especially given the drivers behind agricultural abandonment.*		
Mosaic land systems &/or agroforestry areas	*Landscape heterogeneity seen in agro-silvopastoral systems is identified in the literature as a contributor to fire risk reduction and is one of the broad goals of the use of land management strategies for reducing fire risk. However, we excluded it from our study because it is a goal of these initiatives, but not necessarily a factor indicated the suitability of an area for grazing activities.*		

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Table 3: Suitability factors (including discarded factors) for mechanical removal as an FRLMS

Suitability Factor	Proxy Data	Technical Details	Rationale
Transportation accessibility	Friction map of travel time to cities (accessibility) Weiss et al. 2018	See above.	Forest biomass removal was found to be facilitated by greater accessibility for requisite machinery, access for technicians, and debris removal. This was proxied by a friction map of accessibility.
Steep slope limitation	Slope derived from EU-DEM from Copernicus Land Monitoring Service	Resolution: 25m Spatial & temporal coverage: Europe, NA	The literature indicates that access for the machinery used for removal is significantly eased by lower topographic inclines. We removed (masked) areas of >30% slope from the analysis. In the remaining areas, the slope index was inverted so that the flattest areas were most suitable.
Available forest biomass	Forest biomass availability in tons of dry matter/ hectare/ year from Verkerk et al. 2019	Resolution: 10km Spatial & temporal coverage: Europe, composite data sources (multiple years)	Availability of biomass was identified as a contributor to the feasibility of associated industries. Although biomass stock can come from many vegetation types, data on the availability of all types of biomass in Europe which could be sustainably harvested is not available. We therefore used an estimation of potential forest biomass availability, restricted by current sustainable forest management guidelines and legal limitations (BASE potential—see SI 2 for further details).
Proximity to known biomass power plant facilities	Global Database of Power Plants from World Resources Institute. Byers et al., 2021.	Resolution: NA, GPS coordinates Spatial & temporal coverage: NA	Proximity to known power plants that use biomass for energy provides an economic incentive for mechanical removal of fuels by decreasing the costs associated with transportation to the facility. As a proxy, we created a buffer of increasing suitability around the coordinates of current biomass power plants.
Excluded suitability factors and rationale			
Wildland Urban Interface (WUI)	*In terms of suitability, the WUI is not indicated in the literature review as a specifically suitable area for physical fuel removal, despite its importance for fire risk. However, this is an important area for further study.*		
Poverty/ wealth index	*Funding is documented in the literature as one of major barriers for the use of physical fuel removal (due to the manual labor and equipment needed. However, funding for silviculture, clearing, wood product based industry, park management, etc. can be derived from several sources, such as local authorities, grants, EU initiatives, and individual donors. Therefore, it is not possible to create a meaningful proxy for this indicator.*		
Shrubland areas	*There is evidence in the literature that removal produces the best results for mitigating shrubland expansion in the long term. However, the relationship is between this fact and the likelihood that it will be adopted (i.e. that people will be more likely to use this FRLMS) is unclear.*		

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Table 4: Suitability factors (including discarded factors) for prescribed burn as an FRLMS

Suitability Factor	Proxy Data	Technical Details	Rationale
Prescribed burn days: Max temp 5-25°C; relative humidity 30-70%; wind speed 0-20km/h; Minimum days with no precip: 4.	Developed From Copernicus Climate Change Service (2017): ERA5	Resolution: 0.1 arc seconds Spatial & temporal coverage: Global, 2011-2021	Suitable meteorological conditions for conducting prescribed burns occur within a variable temperature, relative humidity, wind speed, and precipitation envelope. Although assessments of appropriate PBD windows across the globe vary, we set a general window within Europe based on literature findings and feedback from FirEUrisk experts.
Transportation of labor force and equipment	Friction map of travel time to cities (accessibility) Weiss et al. 2018	See above.	The literature documents the need for accessibility for prescribed burn activities in order to transport technicians and equipment and for emergency access in the event of loss of control.
Avoid high and medium settlements	High intensity settlement areas, Dou et al. 2021	Resolution: 1km Spatial & Temporal Coverage: Europe, 2015	Studies have documented an aversion to smoke from prescribe burn by residents living in the vicinity of the activity. We have thus excluded high and medium intensity settlements from this FRLMS map.
Excluded suitability factors and rationale			
Areas of traditional fire use	*The literature indicates that many areas of Europe have a history of using prescribed burn, especially pastoralists who may burn areas in order to encourage the growth of pasture for grazing. It is also indicated that people living in areas of traditional prescribed burn are more open to the use of prescribed burn in their region to reduce fire risk. However, geospatial data of traditional prescribed burn at the EU scale was not found.*		
Fire adapted and fire dependent ecosystems, or species presence	*The literature indicates that some ecosystems are either more prone to fire with sometimes positive and sometimes deleterious ramifications. The positive and negative outcomes can depend on or be mitigated by fire characteristics such as intensity, species compositions, and seasonality, for example. In addition to the difficulty of meaningfully capturing these ecological complexities for this activity, EU wide data was not found. This should rather be a consideration at the local level by coupling management strategies with ecological outcome assessments.*		
Legality of prescribed burn (official and unofficially burning)	*The literature indicates that prescribed burning is in fact illegal in some areas due to the risk of small fires (often for fodder restoration by local pastoralists) becoming out of control and causing negative impacts for ecosystems and nearby human communities. For our study, we would like to locate areas which, for example, are only found to be suitable for prescribed burn as a an FRLMS, but leave them in the results in order to make a policy recommendation (i.e., prescribed burn may be illegal here but it is the only recommended FRLMS).*		

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2.2 Prioritizing by areas of higher fire occurrence

We used the Wildfire Danger by Thermal Anomaly (WDTA) dataset, developed by EFFIS (Joint Research Centre European Commission, 2022a; https://effis.jrc.ec.europa.eu/apps/fire.risk.viewer/), to prioritize the results by areas most affected by wildfire in Europe. This dataset uses observed thermally anomalous events recorded between the years of 2018 and 2021. To discriminate between thermal events from wildfire versus other causes (e.g., volcanoes and manufacturing facilities), the developers used Pareto ranking based algorithms for areas which were known to have historic fires, and which overlapped with known burnable wildland fuels. We resampled the data to a 1-km^2 resolution and normalized it (referred to from here on as "fire occurrence").

All spatial data (suitability factors and fire occurrence) were reprojected and resampled to a 1-km^2 resolution and normalized (0-1). Based on the literature review, large settlements were given a suitability of zero in the final suitability maps for herbivory and prescribed burning. A step-by-step account of the preparation of all data can be found in the SI 1 of Neidermeier et al. 2023 (Neidermeier et al., 2023).

The suitability of each FRLMS was then calculated by averaging the respective rasters. Each FRLMS suitability map and the fire occurrence map were then reclassified into three bins representing low, medium, and high suitability/ occurrence based on equal quantiles (Fig. 8). We then prepared bivariate choropleth maps to compare FRLMS suitability and fire occurrence in Europe by assigning unique values to each suitability or fire occurrence level and summing the respective rasters (Figs. 2 & 3).

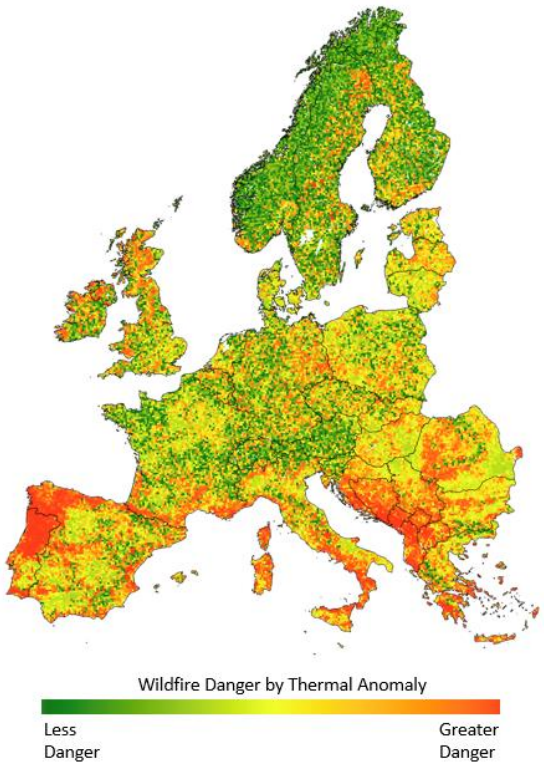


Figure 3: Wildfire Danger by Thermal Anomaly (WDTA; Joint Research Centre European Commission, 2022a).

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2.3 Prioritizing by ecosystem function metrics

Carbon storage

To evaluate above and below ground carbon stocks for Europe, our study used data from Noon et al. (2022) on total manageable carbon. This dataset was built on the global biomass carbon map of Spawn et al. (2020), with the addition of coastal ecosystems and soil organic carbon. To prioritize natural areas, Noon et al. (2022) created a mask which excluded agriculture, urban, and developed areas using the ESA Climate Change Initiative 2018 land cover map dataset.

Biodiversity

As biodiversity indices capture specific facets of biodiversity (Díaz et al., 2020), using multiple indicators can help to reflect different dimensions of biodiversity. We thus used species diversity and structural function as alternate indicators.

For species diversity, we used a dataset developed by Jung et al. (2021). The author's approach was based on complementarity of species ranges and prioritized areas with unique species compositions. It reflects intraspecific variation by creating targets for each species range within biogeographic biomes. The dataset covers all countries included in our study and accounts for species of native plants in addition to over 34,000 bird, mammal, amphibian, and reptile species based on the International Union for Conservation of Nature Red List database, Birdlife International, the Global Assessment of Reptile Distributions database, Botanic Gardens Conservation International, and the Botanical Information and Ecology Network (see Jung et al., 2021, for details).

We also developed a pragmatic structural diversity index which reflects the physical composition of an ecosystem and can be indicative of niches availability for a broad set of species (LaRue et al., 2019; Storch et al., 2018). We developed the structural diversity index using data from Pucher et al. (2022), which covers several dimensions of forest structure at an 8-km^2 resolution. The dataset by Pucher et al. uses forest inventory data from 16 countries and a gap-filling algorithm to create a forest structure dataset which covers all of Europe, including countries which do not currently have publicly available forest inventory data. Areas in which there is no woody biomass have a value of zero in this dataset. We developed the structural diversity index using four metrics—canopy height, diameter at breast height (DBH), age class, and tree species group. For each metric, we first took the standard deviation using a moving window of 3x3 cells (24 km x 24 km). In this way, we gain insight into the heterogeneity of the forest structure. Thus, even-canopied forests of the same age, diameter, and species group would score low (have a lower standard deviation). The rasters of the standard deviation of were normalized (0-1, one representing greater diversity). These were then added together, and the resulting raster normalized. Finally, the data was reclassified into low, medium, and high bins based on equal quantiles.

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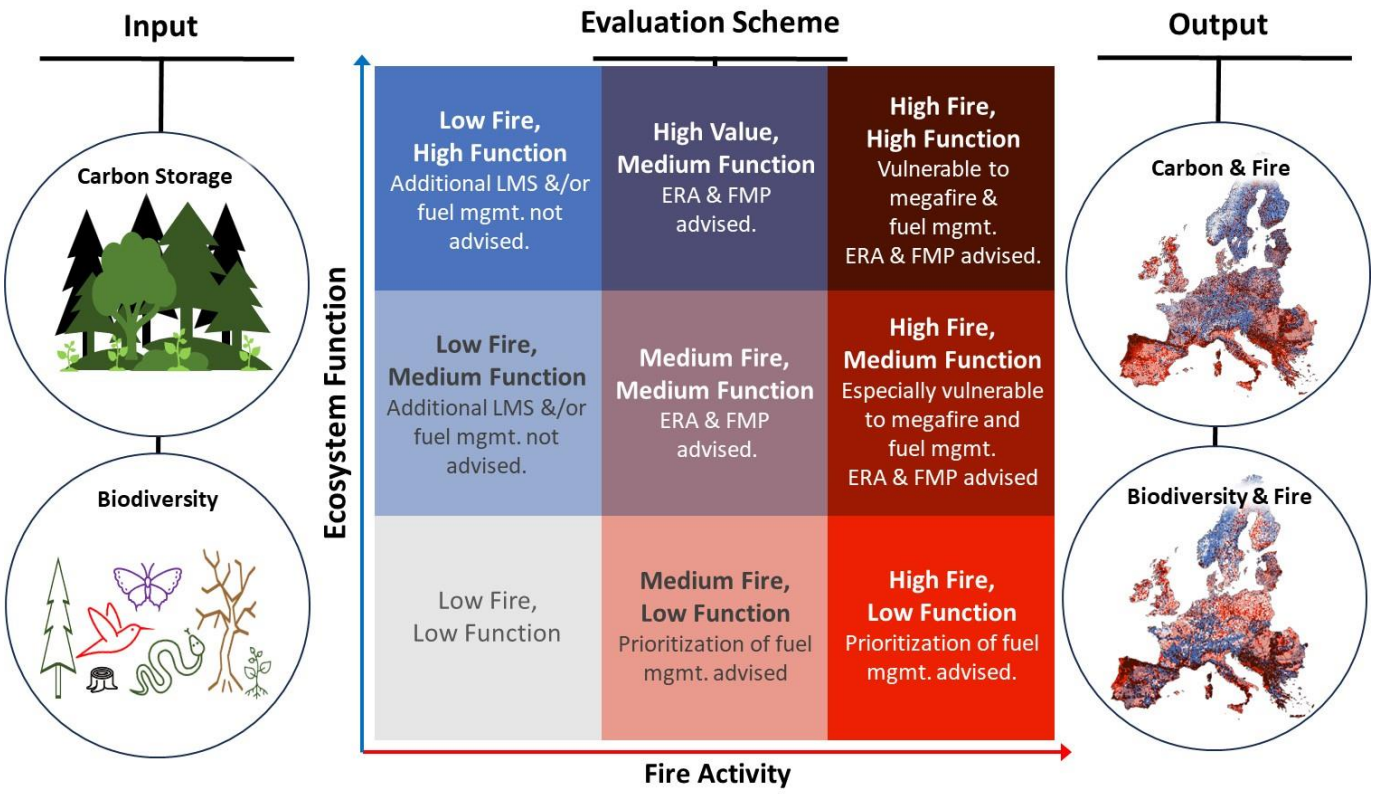


Figure 4: Conceptual framework the relationship between the ecosystem function indices (left). Bivariate choropleth scheme demonstrating trade-off scenarios between ecosystem values (rows) and fire occurrence levels (columns) including potential risk assessments. Neidermeier et al., 2024 (in review).
ERA: Environmental Risk Assessment. FMP: Fuel Management Plan.

3 Results

3.1 Suitability for each FRLMS across Europe

We found that suitability for herbivory was highest in mid-latitude and eastern Europe (Figure 5). Much of Europe, especially France and notably in northern Europe, was found to have high suitability for mechanical fuel removal, with the exception of mountainous areas (Figure 6). Suitability for prescribed burn was found to be quite localized, mostly in southern Europe, especially along the Mediterranean (Figure 7). Limited accessibility in northern Europe impacted the suitability range for all three FRLMS. FRLMS maps by FirEUrisk pilot site can be found in Appendix A.

3.2 Prioritization of FRLMS suitability

We found that much of the high and medium fire occurrence areas in Europe had suitability for all three FRLMS, especially in the Iberian Peninsula and much of central and eastern Europe (Figs. 8 & 9). For some FRLMS, the results were quite localized. For example, in parts of southern Europe, we found that prescribed burn was the only FRLMS with medium to high suitability in areas of high fire occurrence. In much of northern Europe, herbivory was found to be the only suitable FRLMS in high and medium fire occurrence areas. The combination of herbivory

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and prescribed burn dominated in southeastern Europe and had the largest percent cover in both high and medium fire occurrence areas (8.8% and 6.1%, respectively; Table 5).

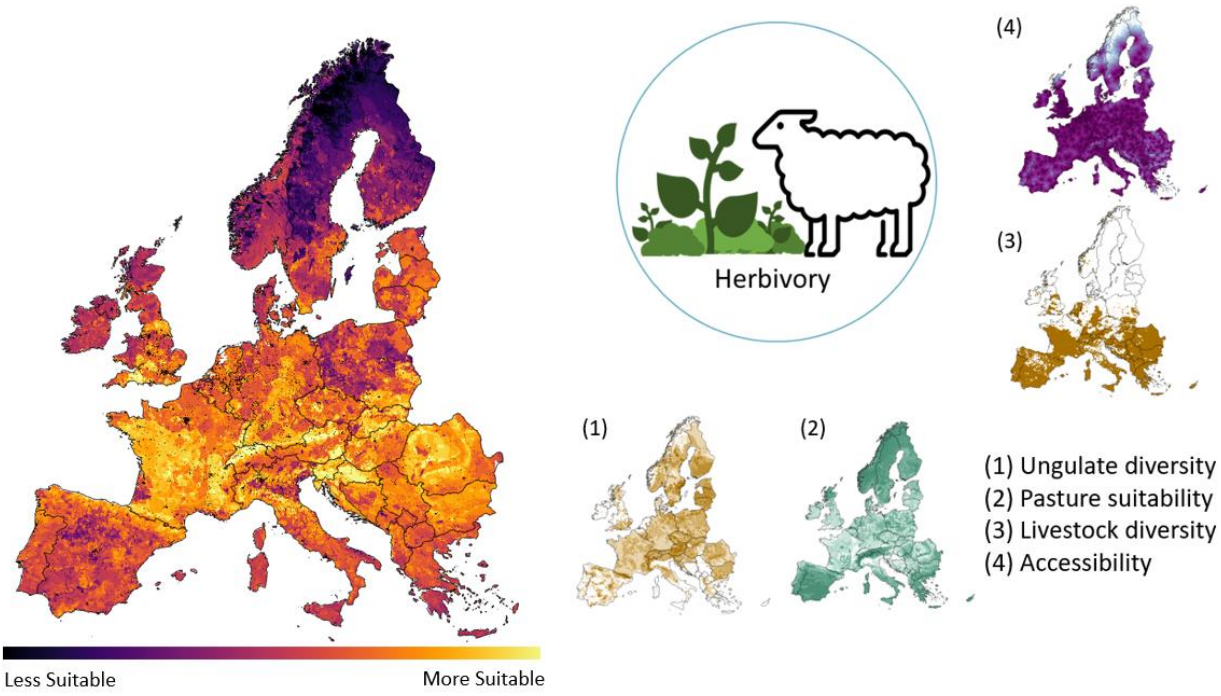


Figure 5: Left: Resulting suitability map for herbivory as an FRLMS. Right: Inset maps of each of the suitability factors used in which darker colors represent higher values for the respective factor.

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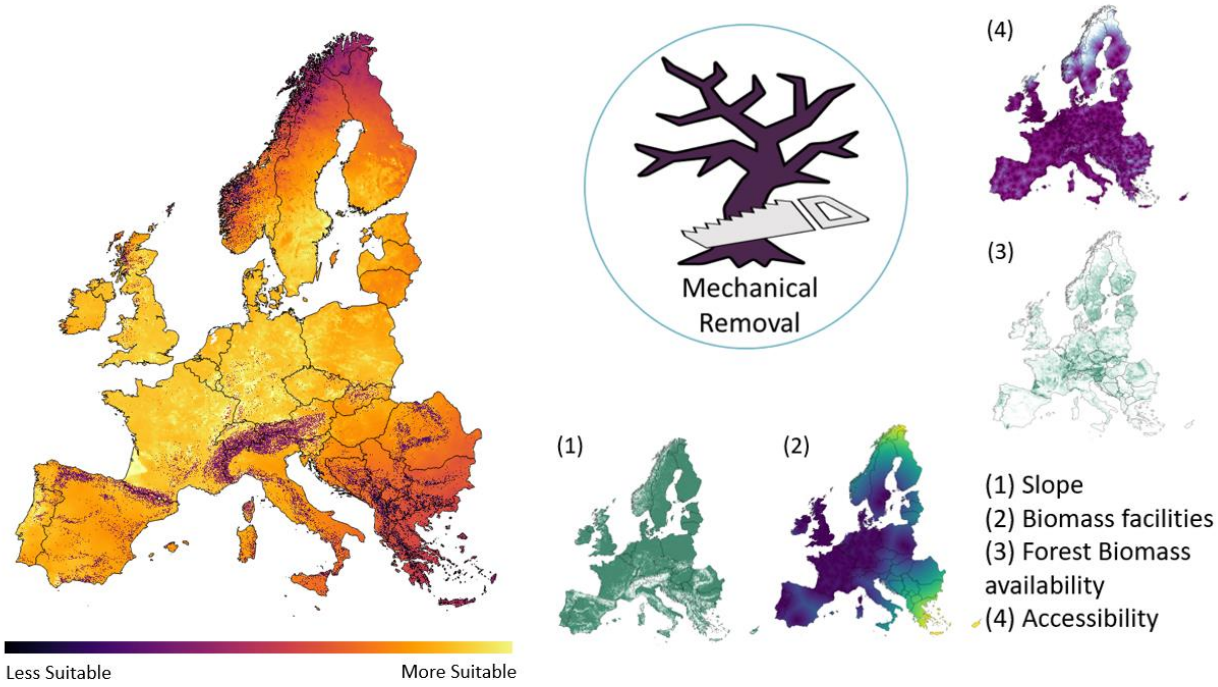


Figure 6: Left: Resulting suitability map for mechanical removal as an FRLMS. Right: Inset maps of each of the suitability factors used in which darker colors represent higher values for the respective factor.

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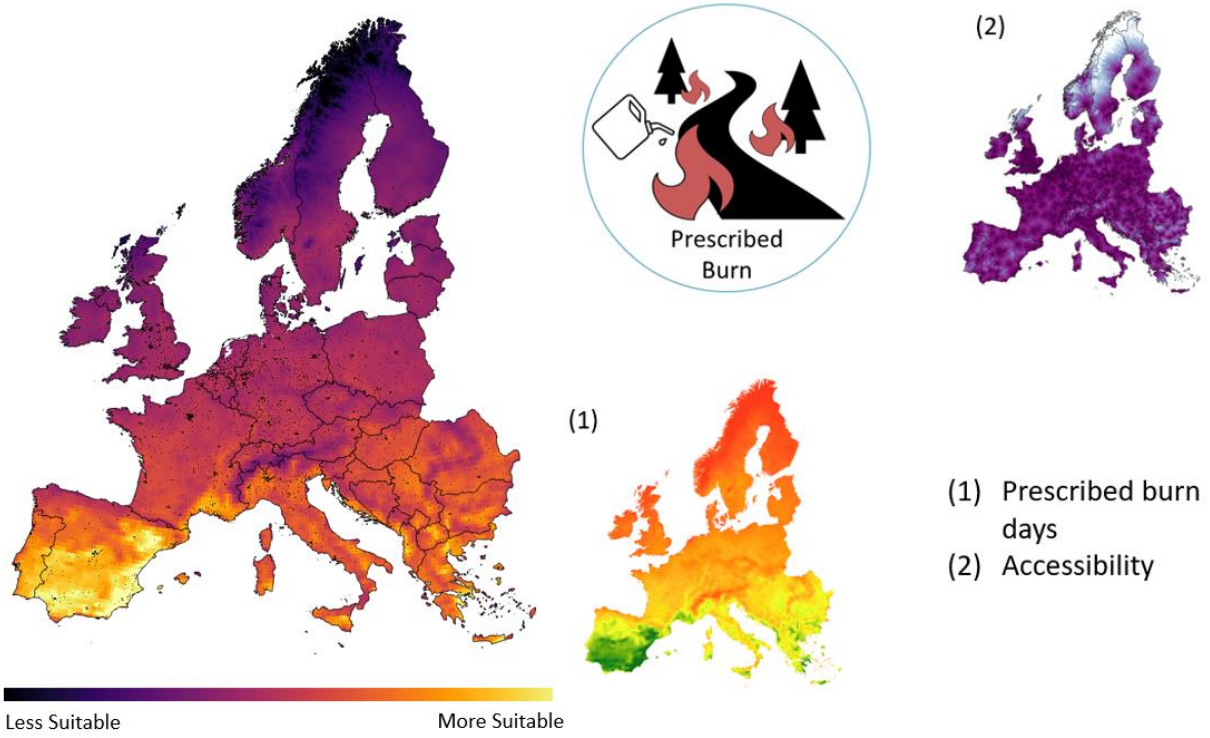


Figure 7: Left: Resulting suitability map for prescribed burn as an FRLMS. Right: Inset maps of each of the suitability factors. For inset figure 1, green means high PBD, red means lower number of PBD; for inset figure 2, darker colors represent higher values.

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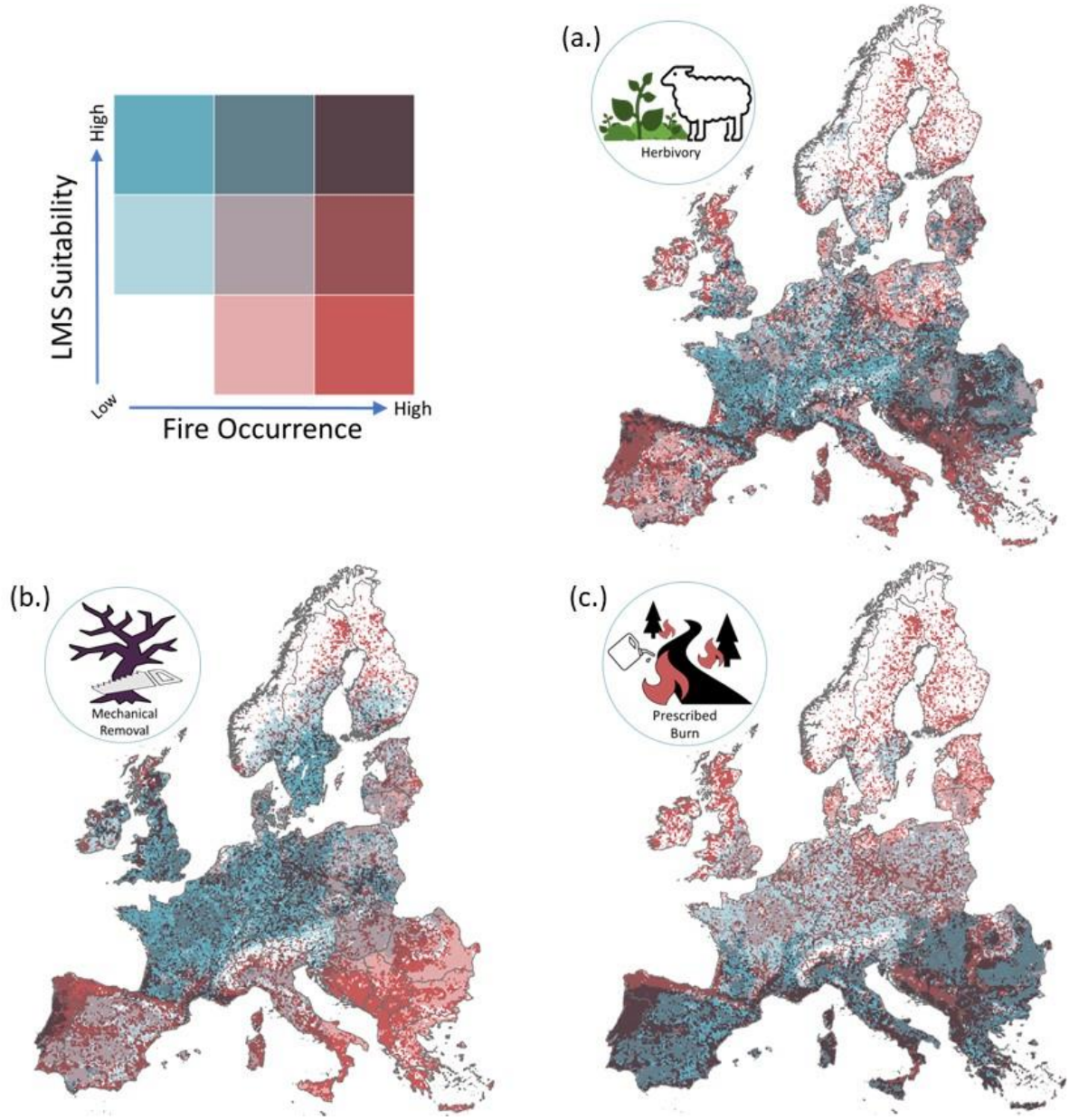


Figure 8: Bivariate choropleth maps of suitability of (a.) herbivory, (b.) mechanical fuel removal, and (c.) prescribed burn which overlap with areas of differing fire occurrence in Europe. Areas in white had low FRLMS suitability and fire occurrence.

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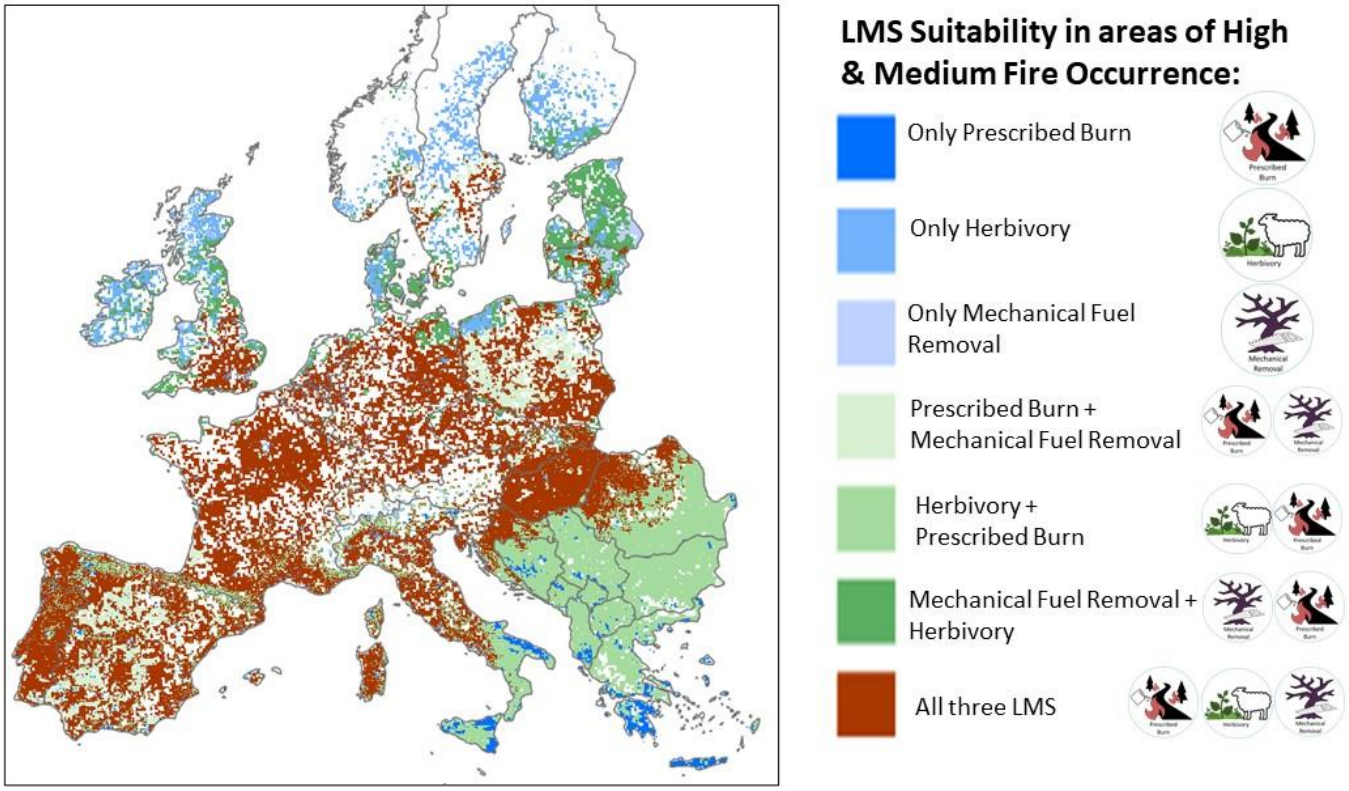


Figure 9: Areas of high and medium (>33%) FRLMS suitability in (masked by) areas of high and medium (>33%) fire occurrence. Areas in white had low FRLMS suitability and/or low fire occurrence.

Table 5: Coverage of highly suitable FRLMS within areas of high & medium occurrence for wildfire in Europe

	Cover (%) of high and medium suitability FRLMS in areas of high & medium fire occurrence
No suitable FRLMS identified (area in white in Fig. 9)	36%
Prescribed burn only	2%
Mechanical fuel removal only	6%
Herbivory only	6%
Prescribed burn & Mechanical fuel removal	1%
Prescribed burn & Herbivory	15%
Mechanical fuel removal & Herbivory	5%
All three FRLMS viable	31%

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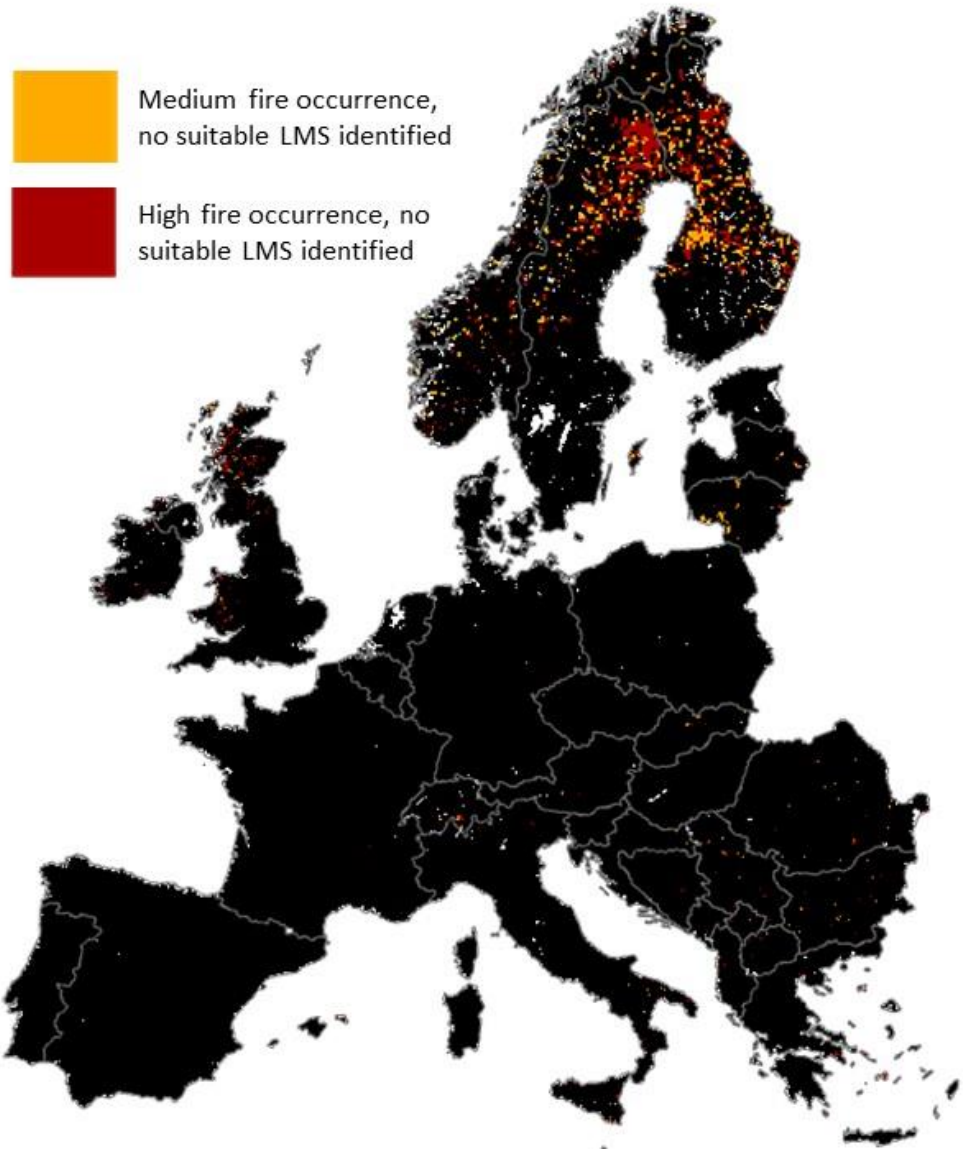


Figure 10: Areas of high and medium fire occurrence in which the suitability of all tested FRLMS had no or low suitability. These areas may face greater challenges in managing fire risk.

3.3 Managing fire and ecosystem function with FRLMS

We identified countries such as Serbia, Croatia, Estonia, and Latvia in eastern Europe as having high mean species diversity but low mean carbon storage. Others, such as Poland and the United Kingdom, had high mean carbon storage but low mean species diversity. A few countries, especially Greece and Andorra, had both high mean species diversity and high mean carbon storage. In terms fuel management opportunities, herbivory and mechanical removal were identified as suitable options for much of southern, western, and eastern Europe (Fig. 10). Herbivory and prescribed burn have good coverage in southern and eastern Europe in high fire occurrence, high species diversity, and high carbon storage areas.

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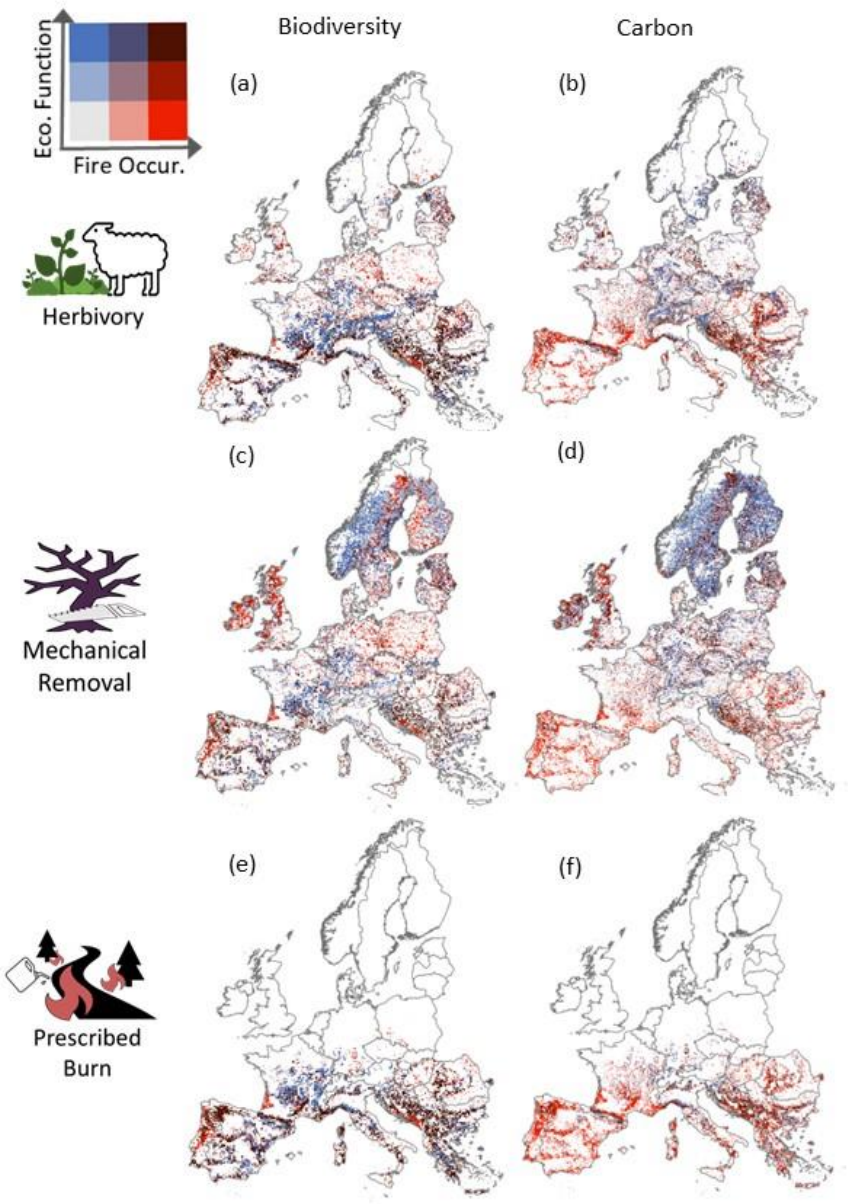


Figure 11: Carbon and species diversity value compared to fire occurrence (see inset legend for relative value by amount of fire occurrence) limited to areas with suitability for each of three FRLMS: herbivory, mechanical removal, and prescribed burn. Areas in white had low suitability for the respective FRLMS.

4 Discussion

Our study synthesized the current knowledge on managing fire risk in Europe through three FRLMS: herbivory, mechanical fuel removal, and prescribed burn. In the context of increased fire risk in many parts of Europe, our results serve as a basis for conceptualizing a broader fire risk strategy and prioritizing efforts and resources accordingly. Our results lend support to the use of FRLMS in some regions which are found to be uniquely suitable in areas of high or medium fire risk with relevant policy-design implications. For example, we found that prescribed burn was uniquely suitable (>33% suitability) in parts of southeastern Europe, including in areas in which it is not

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currently legal, such as Greece and parts of Italy. We also find that the opportunities to concurrently use multiple FRLMS to address fire risk are clear, as over 27% of high fire occurrence areas were suitable for two or more FRLMS (28.9% for medium risk areas). This finding supports the complementarity of the FRLMS, such as the combination of herbivory and prescribed burn (associated with tradition pastoral practices), which covered 8.8% of high occurrence areas and 6.1% of medium occurrence areas. This is promising for the long-term viability and flexibility of the FRLMS. We also identified hot and cold spots in Europe in which wildfire risk and important ecosystem functions overlap. Our maps provide a first prioritization of areas in which to invest in fuel management, such as the Landes de Gascogne and eucalyptus forests in Portugal, which are seen to contribute relatively little to carbon storage or species diversity (Giuditta et al., 2019) but encounter high wildfire occurence. Other areas, such as in much of northern Europe and parts of the Pyrenees, may be better left alone. Such prioritization can to efficiently use limited resources while reducing risks for critical ecosystem functions.

Our results serve as a tool for envisioning broader landscape planning and policy structure. However, local factors play an important role in the success or failure of the FRLMS. For example, the literature highlighted the long history of pastoralism and prescribed burn across some regions of Europe (Scherjon et al., 2015; Trauernicht et al., 2015; Varela et al., 2018) which would likely increase the likelihood of its uptake. However, spatial data on the historic or present use of pastoralism and prescribed burn in Europe is not currently available and would be conflicting to include in the suitability analysis, as fires set locally by pastoralists may escape control, especially under conditions of a changing climate (Alcasena et al., 2018; Castellnou et al., 2019). Therefore, engaging pastoralists is a decision to be made and monitored locally (Varela et al., 2022). Decisions on the number and species of herbivores deployed must also be made locally to match vegetation with herbivore diet preferences and to avoid degradation from overgrazing (Calleja et al., 2019; Colantoni et al., 2020; Lecomte et al., 2019). We opted to use a count of species diversity—including wild ungulate species—as a proxy, which also reflects the reported importance of herbivore diet diversity on fire risk mitigation.

Also mediating the success of the use of the FRLMS, our suitability maps (Fig. 2) are based on factors which are largely in flux. For example, we presented areas suitable for prescribed burn largely based on areas with a greater number of PBD. In addition to omitting the fire adaptedness or dependency of the ecosystems and associated vegetation types, e.g. deciduous versus coniferous (Archibald et al., 2013; Cattau et al., 2022), the impact of climate change on the meteorological parameters considered are not included (European Commission et al., 2020). Hotter, drier, windier days have already been found to reduce PBD windows in parts of Europe and North America (Baijnath-Rodino et al., 2022; Duane et al., 2019; Kupfer et al., 2020). Perceptions of the FRLMS can also shift over time and affect implementation. In some regions of Europe, resistance to the use of prescribed fire can be due to an aversion to the smoke generated, a perception that fire is not a “natural” part of the ecosystem, or fears of consequent damage from prescribed fires which escape control (Ager et al., 2019; Moritz et al., 2014). In order for Europe to move beyond the “fire paradox” paradigm which focuses on eliminating fire from the landscape, perceptions will have to change to ensure stakeholder uptake (Moreira et al., 2020). It is also relevant to note that despite the applicability of the WDTA fire occurrence data used in this study, this data does not account for ignition risk, fuel conditions, climate factors, historical fire regimes (Joint Research Centre European Commission, 2022a), and many other components attributed to fire risk (Chuvieco et al., 2023). However, attempting to establish a universal standard or singular prescription for when and where fires should occur,

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especially in a region of historically intensive land and fire management like Europe, is inherently complex and shaped by landscape management perspectives and priorities (Galizia et al., 2021; Senf and Seidl, 2021). This challenge is further underscored by the uncertainty surrounding future fire regimes (Bowman et al., 2014; European Commission et al., 2017; Fairbrother and Turnley, 2005). Therefore, for this assessment, the results should be interpreted with the understanding that they may not mirror historical trends and that the drivers and magnitude of future fire-proneness are subject to change.

Our study thus has policy implications for consideration at local, regional, and national scales in Europe. The FRLMS presented here offer no silver bullets, but rather require careful planning, monitoring, and sustained efforts for success. Incentive structures that aim to promote the use of the FRLMS must consider trade-offs between fire risk reduction and services provided by land systems, especially biodiversity, ecosystem services and unintended negative effects (Adams, 2013; Celaya et al., 2022; Lecomte et al., 2019; Sacchelli et al., 2013). Careful monitoring is required to ensure that the effects of implementation of the FRLMS match the intended goals and avoid trade-offs. Conversely, policy must also account for potential effects on fire risk. For example, in terms of biodiversity, some conservation schemes aim to increase connectivity across the landscape, such as the EU Natura 2000 sites (based on the Birds and Habitat Directives (European Environment Agency, 2019)) and the EU Strategy on Green Infrastructure (Climate Adapt European Commission, 2023). This, however, can be at odds with mitigating fire risk in cases of creation of continuous or homogenous fuel types and compositions (Moreira et al., 2011). Similarly, forest-based biomass for energy schemes, if not carefully monitored, can contribute to forest degradation, clear-cutting, or understory ecological impacts (Abbas et al., 2011; Lamers et al., 2013; Manolis et al., 2019), especially given unclear guidelines on carbon emission standards and short-fuse for climate action (Norton et al., 2019).

5 Outlook for the use of Fuel-relevant land management strategies to reduce fire risk in Europe

Building on evaluations of the biophysical, socioeconomic, and environmental considerations of fuel-relevant land management strategies (FRLMS) to reduce fire risk in Europe (per FirEUrisk deliverable 2.3), we found considerable spatial variability in the suitability of the evaluated FRLMS across Europe. Our results support integrated landscape planning in response to changing fire regimes by mapping areas in which the FRLMS are most suitable in order to more efficiently utilize resources and proactively address fire risk. However, FRLMS decision making requires a thorough assessment of local factors, including costs and incentive opportunities, interest or opposition by local stakeholders, and socioeconomic trends. Potential trade-offs between fire risk, biodiversity, ecosystem services, and unintended effects must also be carefully assessed at local scale for balanced decision-making. With these considerations in mind, FRLMS implementation has potential to reduce the risk of severe fires and safeguard ecological function and services, particularly in non-fire-adapted ecosystems. FRLMS such as those studied here are, however, only part of the solution: mitigating climate change and reducing exposure at and urbanization into the wildland urban interface are simultaneously important. Still, our results represent a step towards more targeted and optimized responses to wildfire risk in Europe.

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7 Appendix A: Full mapping methodology

Literature review methods

A *Locating & screening the literature*

We carried out a systematic literature review to identify the constraints and opportunities of adopting different land management strategies which may reduce wildfire risk in Europe. A key word search (Table S1-2.1) was carried out in Web of Science which was complemented by grey literature from the publication list of the European Union's Joint Research Centre (JRC) (https://ec.europa.eu/jrc/en/publications-list), as well as reports published by previous EU-funded projects addressing fire-risk reduction in the region (through the CORDIS database https://cordis.europa.eu/projects/en). This resulted in a total of 1183 articles.

Table SI-2.1: Search terms used in land management strategy literature review

Land management		Fire risk		Geography
(land* SAME management) OR (fuel SAME management) OR (vegetation SAME management) OR (fuel SAME treatment) OR (rangeland SAME management) OR (livestock SAME management) OR (graz* SAME management) OR (forest SAME management) OR "land use planning" OR "land-use planning" OR "zoning"	AND	(*fire SAME risk) OR (*fire SAME prevent*)	AND	"Europe*" OR "Russia" OR "Ukraine" OR "France" OR "Spain" OR "Sweden" OR "Norway" OR "Germany" OR "Finland" OR "Poland" OR "Italy" OR "United Kingdom" OR "England" OR "Scotland" OR "Wales" OR "Romania" OR "Belarus" or "Kazakhstan" OR "Greece" OR "Bulgaria" OR "Iceland" OR "Hungary" OR "Portugal" OR "Austria" OR "Czech*" OR "Serbia" OR "Ireland" OR "Lithuania" OR "Latvia" OR "Croatia" OR "Bosnia and Herzegovina" OR "Slovakia" OR "Estonia" OR "Denmark" OR "Switzerland" OR "Moldova" OR "Belgium" OR "Armenia" OR "Albania" OR "Macedonia" OR "Turkey" OR "Slovenia" OR "Montenegro" OR "Kosovo" OR "Azerbaijan" OR "Cyprus" OR "Luxembourg" OR "Georgia" OR "Andorra" OR "Malta" OR "Liechtenstein" OR "San Marino" OR "Monaco" OR "Vatican" OR "Netherlands" OR "Mediterranean" OR "Atlantic" OR "Boreal" OR "Continental" OR "Macaronesia*" OR "Black Sea" OR "Arctic" OR "Anatolian" OR "Alpine" OR "Pannonian" OR "Steppic"

- The titles and abstracts of these articles were subjected to a first screening based on whether the publications addressed the current, past, or hypothetical implementation of one or more Fuel-relevant land management strategies for fire risk reduction in Europe, and shed insight on the drivers, constraints or impacts of FRLMS (Fig. SI-2.2). Articles were excluded which addressed the influence of a certain type of land use or land management on fire risk if the land use / land management practice was not specifically introduced with the (partial) aim of reducing fire risk. Abstracts which merely stated that the study's findings have implications for the development of fuel-relevant land management strategies, while suggesting these were not deliberately the topic of investigation, were not included. This brought the number of papers to a total of 370.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

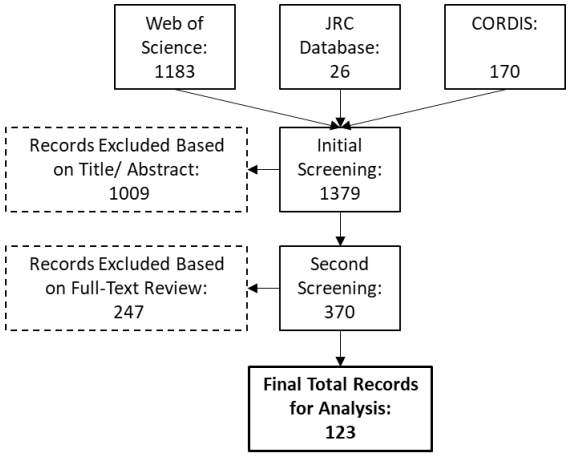


Fig. SI-2.2: PRISMA diagram of literature review screening results

These were subjected to a full text screening in which articles were excluded in cases which: referred to cases which: (1) were based outside of Europe, (2) referred to non-vegetation types of fire (e.g., domestic, surgical) or (3) to non-land-based interventions for fire risk reduction (e.g., use of insurance, information campaigns), (4) had no explicit link to fire risk reduction and land management, and were retrieved through the search string because of homonyms, (5) represented methodological studies solely aiming to improve fire risk reduction methods / models with no specific reference to land management interventions, and (6) studies which did not address the use of FRLMS for fire risk reduction (focusing instead, e.g., on wildfire impacts, exploring drivers/predictors of fire risk without explicitly addressing respective implications for FRLMS implementation, exploring FRLMS for post-fire management without aiming to reduce future fire occurrence). This screening resulted in a final database of 123 articles.

B *Coding the literature*

Excel[1] was used to carry out a priori coding on the resulting 123 papers. As new themes and insights emerged over the course of the review, new codes were developed and applied (Glesne and Peshkin, 1992; Moher et al., 2009; Pickering and Byrne, 2014; Pullin and Stewart, 2006). We primarily screened the publications for information regarding details on FRLMS implementation and its respective drivers, constraints, or impacts (comprehensive coding scheme illustrated in Table 1) per the specifications below:

1 = driver,
-1 = soft constraint,
-2 = hard constraint,

[1] Excel sheet with full list of literature, coding scheme and all variables used for multicriteria analysis for each land management strategy can be found in publication.

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100 = mixed / unclear influence (i.e., acting as both driver and barrier OR only known to be "influencing", but direction is unspecified),
2 = positive impact,
3 = negative impact,
4 = mixed / no impact

- Details addressed technical specifications, actors involved in FRLMS management, the FRLMS goal (which dimension of fire risk, which (if any) additional goals beyond fire risk reduction, etc.), whether the FRLMS involved a change in land use or land management, whether it was introduced in combination with one or more other FRLMSs and whether it has been implemented as part of a broader, multifunctional initiative. The categorization of constraints, drivers and impacts followed the one implemented in the review of underlying drivers of agricultural land use change in Europe conducted by van Vliet et al. (2015).

Table SI-2.2: Coding scheme for reviewed literature

Category	Sub-category	Description
Primary land use	Agriculture	Primary land use class within which the FRLMS is implemented
	Forest	
	Pasture	
	WUI	
	Other	
Goal of FRLMS	Reduce burned area	Stated goal(s) of FRLMS [specify if successful / unsuccessful]
	Reduce burn probability (ignition)	
	Facilitate suppression efforts	
	Prevent crown fires	
	Other socio-econ-env goal	
	[*Other – TBD]	
Actors	Farmers	Actors involved in the implementation and management of the FRLMS
	Pastoralists	
	Forest landowners	
	Gamekeepers	
	Forestry service	
	Civil protection	
	Municipality	
	Research institute	
	[*Other – TBD]	
Constraints, drivers, or impacts (DEMOGRAPHIC)	Rural depopulation	Demographic factors (changing population densities, migration patterns, ageing of land managers, etc.)
	Increased population density at WUI	
	[*Other – TBD]	
	[Comments]	
Constraints, drivers, or impacts (ECONOMIC)	Cost of FRLMS implementation	Market factors such as costs and by-product incentives.
	Demand for FRLMS by-products	
	Revenue from FRLMS by-products	
	[*Other – TBD]	
	[Comments]	
	Availability of technical assistance for FRLMS implementation	Technological variables refer to regional-level infrastructure for FRLMS

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Constraints, drivers, or impacts (TECHNOLOGICAL)	Availability of infrastructure for FRLMS implementation	implementation, as well as technical know-how (technical assistance, capacity building projects, demonstration areas)
	Firefighting capacity	
	[*Other – TBD]	
	[Comments]	
Constraints, drivers, or impacts (INSTITUTIONAL)	Policy	Political variables include existence of subsidies, tax incentives, etc.
	Administrative demands	
	Collaboration demands	
	[*Other – TBD]	
	[Comments]	
Constraints, drivers, or impacts (SOCIO-CULTURAL)	Cultural landscape (sense of place)	Includes societal demands for ecosystem services (e.g., tourism), cultural values
	[*Other – TBD]	
	[Comments]	
Constraints, drivers, or impacts (LOCATION FACTORS)	Land use / land cover	Biophysical variables
	Elevation	
	Slope	
	Climate	
	Soil	
	Fire history	
	Accessibility (water / land)	
	Biodiversity	
	Water resources	
	[*Other – TBD]	
	[Comments]	
Constraints, drivers, or impacts (LAND MANAGER CHARACTERISTICS)	Land ownership	Characteristics of land managers (including details on plot characteristics)
	Land size	
	Distance to plots	
	Hired / family labor	
	Degree of enterprise commercialization	
	A-priori knowledge base for FRLMS implementation	
	A-priori access to equipment for FRLMS implementation	
	Land manager education	
*TBD= To Be Determined		

Mapping spatial suitability for herbivory

Data processing:

C Create a snap raster = **SNAP** from Dou et al. (2021) results.
Cell size= 1000m X 1000m.
Projected coordinate system = ETRS 1989 LAEA,
Projection = Lambert Azimuthal Equal Area

D Herbivory suitability factors data preparation

1. Sheep and goat livestock presence and diversity **(Livestock)**
-Acquire livestock data from FAO (Gilbert et al., 2018). This dataset contains the global distribution of livestock (goats and sheep) in 2010 expressed in total number of cattle per pixel (5 min of arc) according to the Gridded Livestock of the World database (GLW 3). Used the DA GLW model (5_Ct_2010_Da.tif): This layer contains the DA animal numbers per pixel, with weight

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estimated by the Random Forest model.
-Use “Extract by mask” tool to clip raster to the EU territory and simultaneously reproject using SNAP as the mask, output coordinate system, cell size reference, and snap raster reference.
- Normalize using the raster calculator as follows:
("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)

2. Wild ungulate presence and diversity **(UngDiv)**
   -Acquire shapefiles of 18 ungulate species distribution maps (presence/ absence) from Linnell et al. (2020)
   -Use the “Polygon to raster” tool in ArcGIS for each of the 18 ungulate shapefiles. Cell assignment type=Cell Center, Priority Field=NONE, Cell size=1000, YES Build Raster Attribute table. Environment: Match all to SNAP (Output coordinate system, Cell Size, Snap Raster. Default Extent).
   -Reclassify all 18 rasterized files to change all “No data” pixels to 0.
   -Use the raster calculator to add all 18 reclassified, rasterized files.
   -Use “Extract by mask” tool to clip raster to the EU territory and simultaneously reproject using SNAP as the mask, output coordinate system, cell size reference, and snap raster reference.
   - Normalize using the raster calculator as follows:
   ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)
3. Pasture quality/ suitability **(PSI)**
   -Acquire Pasture Suitability Index (Velthuizen and FAO, 2007).
   -Use “Extract by mask” tool to clip raster to the EU territory and simultaneously reproject using **SNAP** as the mask, output coordinate system, cell size reference, and snap raster reference.
   -Normalize using the raster calculator as follows:
   ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)
4. Market access and livestock mobility **(Access)**
   -Acquire Accessibility data from Weiss et al. (2018). This data is a map of every 1km-square grid cell of the globe. It represents a relative measure of how “hard” it is to cross that grid cell, based on whether the cell contains good roads, worse roads, railroads, rivers, various water bodies, or terrain with some slope.
5. Avoid large city centers **(SettlementMask)**
   -Acquire Settlement data from Dou et al. (2021).
   -Reclassify all values to 1 other than high intensity settlements which gets reclassified to 0.

E Create the Herbivory Suitability map

1. Use the raster calculator tool.
   -Calculate as follows:
   (("Livestock"+ "UngDiv"+"PSI"+"Access")/4) * ("SettlementMask")
2. Create three categories of suitability: High, Medium, Low.

- -Use the Reclassify tool in ArcGIS Pro.
  -Choose “Field”->”Value”, “Method” -> “Quantile Breaks”, “Break”->3.
  -Lowest values: 1; Mid-values: 2; High Values: 3.

Mapping spatial suitability for mechanical fuel removal

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Data processing:

F Create a snap raster = **SNAP** (see Step A for herbivory map).

G Mechanical fuel removal suitability factors data preparation

1. Transportation accessibility (**Access)**
   -See description in Herbivory map, Step B.4.
2. Steep slope limitation (**Slope)**
   -Acquire Slope derived from EU-DEM version 1.0 (European Commission, J.R.C., 2016)
   -Use "Extract by mask" tool to clip raster to the EU territory and simultaneously reproject using **SNAP** as the mask, output coordinate system, cell size reference, and snap raster reference.
   -Create a cut-off of slopes greater than 30%.
   The raster values are initially 0 to 250. This represents a conversion from degrees off the horizontal of the surface tangent to a numerical value. The conversion table can be found here as provided by the JRC: here. A value of 240 is equal to a 29% slope as given in the conversion table.
   -Filter all values greater than or equal to 240 DN using the raster calculator.

- -Normalize using the raster calculator as follows:
  ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)

3. Available forest biomass in Europe **(Biomass)**
   -Acquire forest biomass availability in Europe data from Verkerk et al. (2019).
   - Use "Extract by mask" tool to clip raster to the EU territory and simultaneously reproject using **SNAP** as the mask, output coordinate system, cell size reference, and snap raster reference.
   -Normalize using the raster calculator as follows:
   ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)
4. Proximity to known biomass powerplant facilities **(Plants)**
   -Acquire database of power plants from Byers et al. (2021)
   -Filter excel database for countries in the EU, primary fuel source: Biomass. 462 records remaining. Save as CSV file.
   -Import coordinates to ArcGIS Pro using the XY TableToPoint tool.
   -Calculate the Euclidean distance to the biomass plants using the Euclidean distance tool in ArcGIS pro based on the important plant coordinates. Distance Method: Geodesic. Output cell size: 1000. Environment: Output coordinate system=**SNAP**

- -Use "Extract by mask" tool to clip raster to the EU territory and simultaneously reproject using **SNAP** as the mask, output coordinate system, cell size reference, and snap raster reference.
  -Normalize using the raster calculator as follows:
  ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)
  -Invert raster so that areas closer to facilities receive a greater value
  (("Rasterlayer" - Max_value) * -1) + Min_value
-

H Mechanical fuel removal suitability index (**Remove_Suit)**

1. Use the raster calculator in ArcGIS Pro.
   -Calculate as follows:
   (("Access"+"Slope"+"Biomass"+"Plants")/4)
2. Create three categories of suitability: High, Medium, Low

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3. -Use the Reclassify tool in ArcGIS Pro
   -Choose “Field”->”Value”, “Method” -> “Quantile Breaks”, “Break”->3
   -Lowest values: 1; Mid-values: 2; High Values: 3

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Mapping spatial suitability for prescribed burning

Data processing:

I Create a snap raster = **SNAP** (see Step A for herbivory map).

J Prescribed burn suitability factors data preparation

1. Days with favorable weather conditions for prescribed burn **(PBD)**
   -Acquire high resolution historical weather data (2011-2022)
   -Using Google Earth Engine, filter out any days which, between the hours of 8:00AM and 4:00PM, have conditions which fall outside the intervals laid out in Table SI-2.1. Export as .TIFF file.
   -Import to ArcGIS Pro. Normalize using the raster calculator as follows:
   ("raster" - "raster".minimum) / ("raster".maximum - "raster".minimum)
2. Avoid high and medium settlements **(SettlementMask)**
   -Acquire Settlement data from Dou et al. (2021)
   -Reclassify all values to 1 other than high intensity settlements which gets reclassified to 0
3. Transportation of labor force and equipment **(Access)**
   -See description in Herbivory map, Step B.4.

Table SI-2.6: Limiting conditions used to calculate prescribed burn days (2011-2022)

Variable	Unit	PBD Conditions
Maximum temperature	°C	5-25
Relative Humidity	%	30-70
Wind speed	Km/h	0-20
Min. days with no precipitation	Days	4

K Compute Prescribed Burn Suitability Index **(PBD_Suit)**

1. Use the raster calculator in ArcGIS Pro:
   (("PBD"+"Access")*"SettlementMask")/2

L Mechanical Fuel Removal suitability index (**Remove_Suit)**

1. Use the raster calculator in ArcGIS Pro.
   -Calculate as follows:
   (("PBD"+"Access"+"Slope"")/2)*"SettlementMask")
2. Create three categories of suitability: High, Medium, Low.

M -Use the Reclassify tool in ArcGIS Pro.
-Choose "Field"->"Value", "Method" -> "Quantile Breaks", "Break"->3.
-Lowest values: 1; Mid-values: 2; High Values: 3.

Map of Wildfire Occurence

A Acquire the "wildfire danger by thermal anomalies" developed by the European Wildfire Risk Assessment (European Commission et al., 2022) from the EFFIS Wildfire Risk Viewer at https://effis.jrc.ec.europa.eu/apps/fire.risk.viewer/. In brief, this data was developed using satellite imagery from MODIS/VIIRS between the years of 2018 and 2021 of observed thermal anomaly frequency. Because not all thermal anomalies are necessarily wildfires, the developers developed a method to rank the anomalies against areas of known wildfires. A mask of potentially burnable areas was first created which filtered out areas with an NDVI of >0.2, presence of settlements, and presence of water. The authors then used an algorithm to rank (using Pareto ranking) the anomaly data based on

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two criteria: 1) matching thermal anomalies with known historic fires; and 2) identifying the percentage of overlap with burnable wildland fuels. The adoption of this method was taken under the advisement of an expert group leveraged by the consortium of which the authors were a part.

B Extract and reproject data

-Create a snap raster = SNAP (see Step A for herbivory map).

-Use "Extract by mask" tool to clip raster to the EU territory and simultaneously reproject using **SNAP** as the mask, output coordinate system, cell size reference, and snap raster reference.

C Create three categories of suitability: High, Medium, Low

-Use the Reclassify tool in ArcGIS Pro

-Choose "Field"->"Value", "Method" -> "Quantile Breaks", "Break"->3

-Lowest values: 100; Mid-values: 200; High Values: 300

Prioritizing FRLMS suitability maps by Fire Risk

N Import Fire_Risk, Herb_Suit, Remove_Suit, Burn_Suit

O Create bivariate choropleth map for each

1. Assign all values found to be high suitability and high risk to 1, 10, and 100, respectively for each FRLMS suitability map. Assign all other values in the rasters to 0.
2. Use the raster calculator to add the reclassified FRLMS suitability raster's together.

   Key:

   0: No FRLMS found viable
   1: Prescribed Burn Only
   100: Herbivory Only
   10: Mechanical Fuel Removal only
   11: Prescribed Burn and Mechanical Fuel Remove
   101: Prescribed Burn and Herbivory
   110: Mechanical Fuel Removal and Herbivory
   111: All three FRLMS Viable

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8 Appendix B: Land Management Strategy Suitability by FirEURisk Pilot Site Area

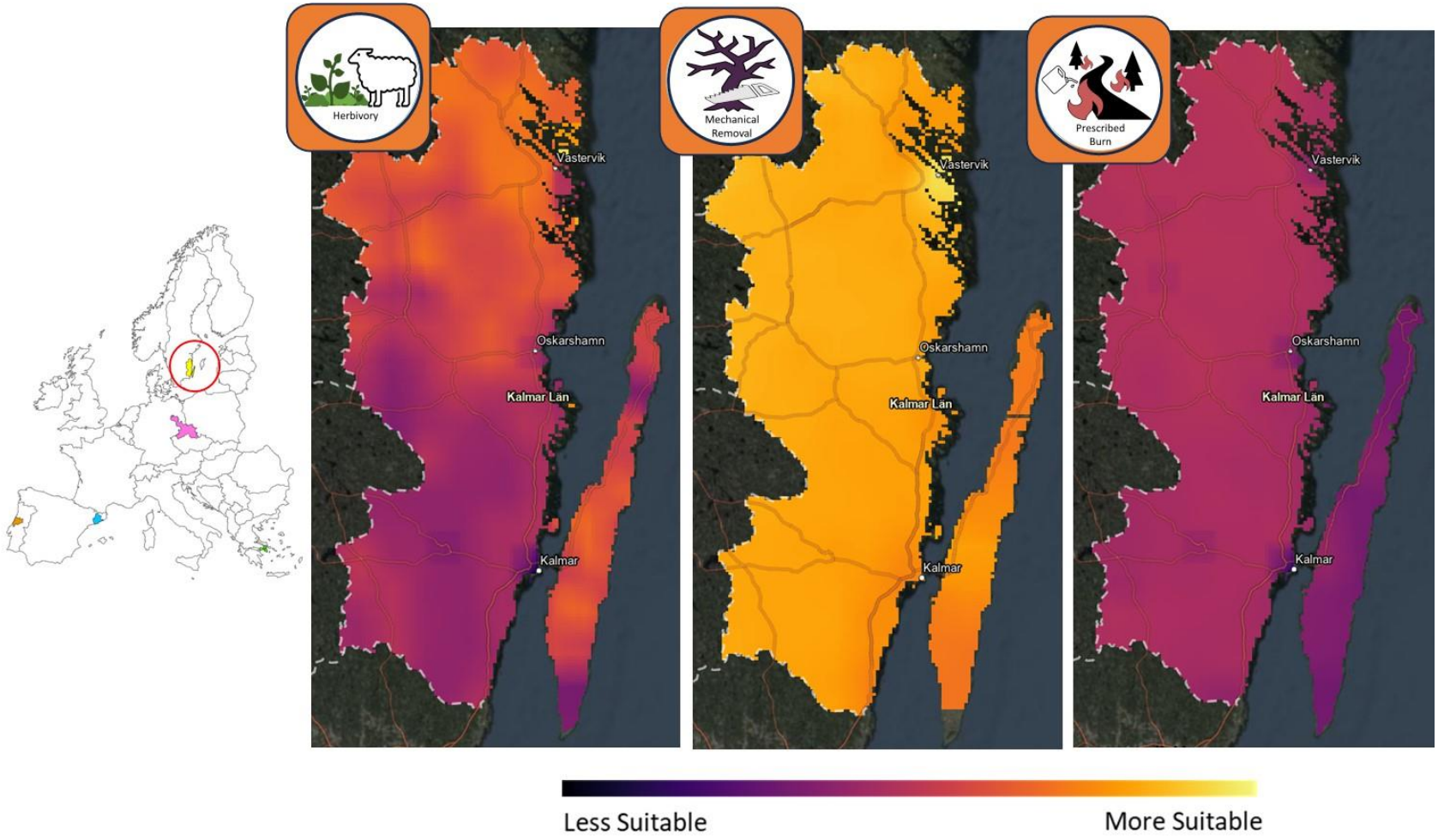


Figure 12: Pilot Site 1 (Sweden) FRLMS Suitability

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101003890.

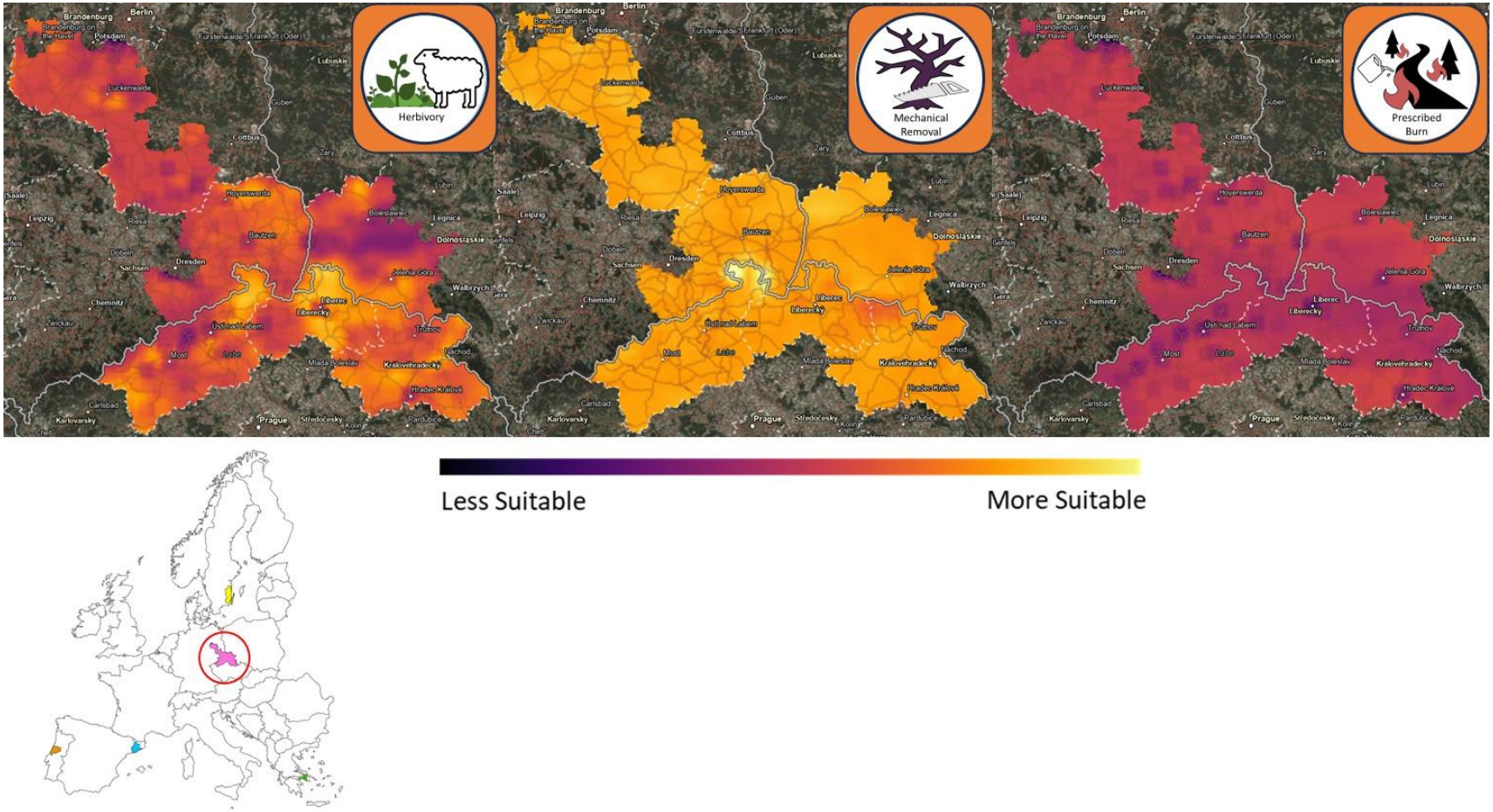


Figure 13: Pilot Site 2 (Germany, Czechia, Poland) FRLMS Suitability

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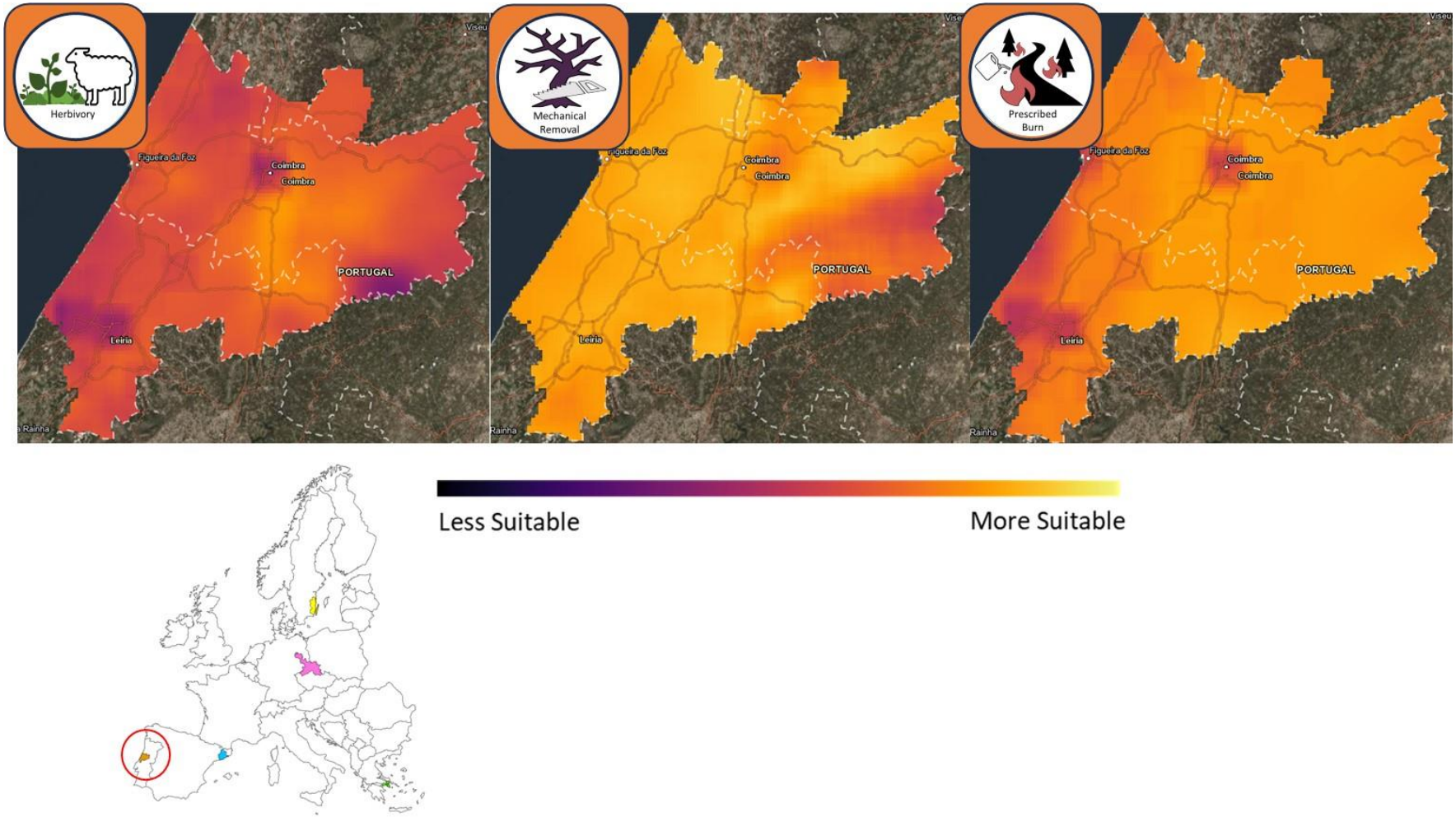


Figure 14: Pilot Site 3 (Portugal) FRLMS Suitability

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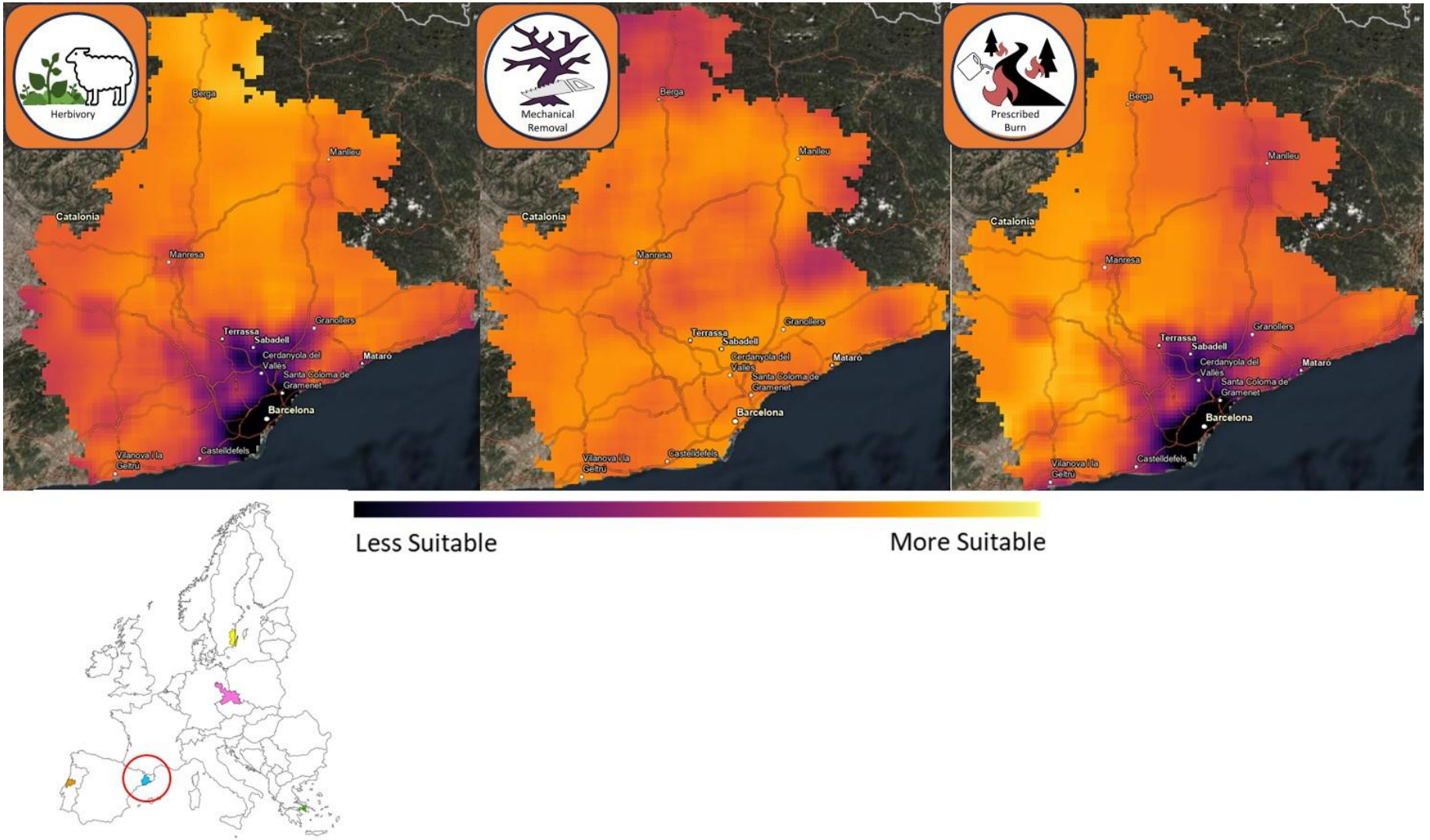


Figure 15: Pilot Site 4 (Spain) FRLMS Suitability

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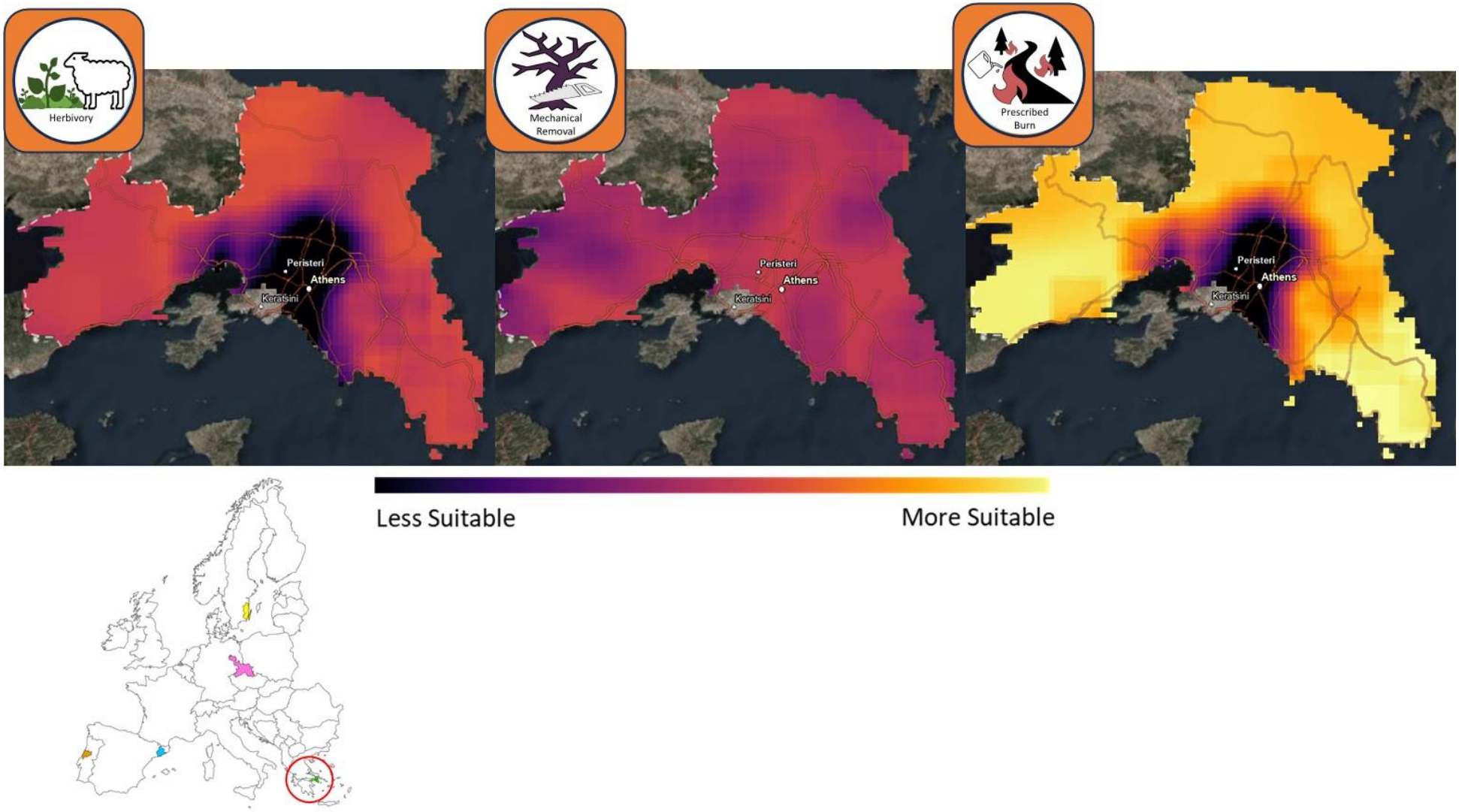


Figure 16: Pilot Site 5 (Greece) FRLMS Suitability

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