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

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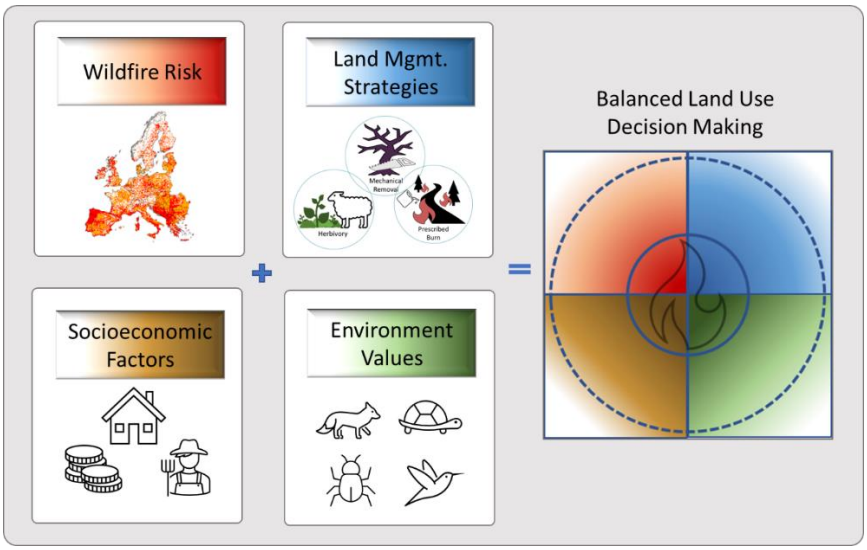
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Executive Summary

Overview

This document provides policy-relevant guidelines to support landscape-level decision making aimed at managing the fuel component of fire risk in Europe via application of land management strategies (LMS). Our results are organized around the biophysical aspects which can dictate LMS applicability and efficacy, the socioeconomic conditions and policy environments that support their uptake, and the environmental considerations which sculpt their legacy on the landscape. We focus on three common LMS targeting fuel compositions in Europe with historical precedence and current relevance as identified in a literature review (full review results can be found here): (1) herbivory, specifically browsing and grazing; (2) mechanical removal of fuels; and (3) prescribed burn. Our examination of the socioeconomic barriers to implementing LMS identified potential intervention scenarios which may improve implementation by way of a fuzzy cognitive map (FCM). Finally, we consider the environmental and ecological impacts of LMS which should be considered to balance potential trade-offs with fuel management activities. Below, we summarize the main findings of the analysis, first thematically by the key intervention points for LMS implementation and secondly by LMS type. The results of this analysis will also be used as a basis for Deliverable 2.4, which maps the opportunities for LMS implementation in areas of high suitability. The holistic consideration of these elements creates a framework in which we can attempt to weigh potential trade-offs of management pathways representing a spectrum of goals, constraints, and opportunities.



Graphical Abstract: Wildfire risk, land management strategies, socioeconomic factors, and environmental values must all be considered for balanced land use planning

Summary of findings by intervention point

- *Applicability*—The applicability and efficacy of the LMS can be mediated by many interconnected factors, such as weather conditions, drivers and perceptions of fire risk in the area, current and historic land cover and use, topography, socioeconomic trends, fuel characteristics, economic

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constraints, traditional/cultural practices, radioactivity, and specialized labour availability, which vary spatially across Europe (Section 2.2). Concurrent use of the LMS, such as prescribed burn with herbivory, has the potential to provide additional benefits to people and landscapes. Best management practices need to strike a balance between managing risk from very harmful fires and risks from fuel management itself (further detailed below). Local conditions and priorities, such as biodiversity, habitat rehabilitation, or poverty alleviation, have relevant consequences for land management decisions.

- *Stakeholders*—Stakeholder perceptions of fire risk and management practices vary across Europe with consequences for policy support and uptake. For example, in Section 3, we discuss how southern European stakeholders did not consistently associate land abandonment, a major driver of increased fire risk in the region, with fire risk. Land use policies that promote land management aimed at reducing fire risk may have limited uptake if the importance is not recognised by local stakeholders. Considering the large areas and fragmented ownership over which effective fuel management needs to take place, buy-in from landowners and managers is vital, as management cannot be restricted to public land. Stakeholder support can be improved through interventions such as media campaigns, improvements to managerial knowledge, and development of stronger links between officials and managers.

- *Laws, Policies, and Regulations*—Although often cited as a limitation to management activities, stakeholders in our study did not identify cost-effectiveness as a barrier (Section 3). Thus, in addition to more straightforward policies (e.g., subsidies) aimed at reducing fire risk through land management, policies could also address other aspects of fire risk relevant to stakeholders, such as knowledge and skills gaps or forest management plan development. We found that laws and regulations were perceived to have the highest impact on LMS implementation, indicating that changes to land management will thus likely be more successful where they carefully consider and fit within existing laws and regulations.

- *Trade-offs*—Fuel management treatments must be guided by ecological principles and integrated with other conservation goals. The ecological consequences of land and fuel management strategies are intricate and context-dependent, and thus should be rooted in identifying critical processes and habitats at both the community and landscape levels and establishing strategies to adequately preserve them. Adaptive management approaches that monitor and adjust practices based on ecological responses are best practices to help minimize negative impacts while achieving fire management objectives. Determining the ideal timing and frequency of treatments is crucial to strike a balance between fuel reduction objectives and ecological considerations. Treatment timing should account for sensitive periods of wildlife and plant species, while treatment frequency should align with the natural disturbance regime of the ecosystem (Section 4).

Considerations specific to herbivory as an LMS

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Refers to livestock, wild herbivores, agroforestry activities, and semi-domesticated animals

- Consider the diversity of herbivory species and their grazing intensity. Different herbivores can have specific diet preferences which can lead to the accidental recruitment of shrubs and other fire-prone species. Research indicates that goats and other mixed feeders can thus be a good option for fire mitigation due to their diverse palette. Signs of over-grazing should be carefully monitored to avoid negative consequences for soil health, forest structure, water quality, and biodiversity.
- Review and account for local land use trends. In areas experiencing agricultural abandonment, incentives and/or alternative options to grazing as an LMS should be considered. This could include the use of wild ungulates for fuel management or increased support for high nature-value farmlands.
- Plan livestock management systems carefully to minimize potential negative impacts on wildlife and reduce the risk of emerging infectious diseases.

Considerations specific to mechanical removal as an LMS

Refers to silvicultural activities, forest-based biomass extraction for industry (e.g., wood pellets), pruning, and thinning

- Mechanical removal can be particularly relevant and useful in the wildland-urban interface and for the management of fire-prone shrubland areas.
- Costs of mechanical removal must be considered for labour, equipment, and disposal of culled material, which may impede economic feasibility over large areas. These costs can sometimes be offset by biomass-based industries (e.g., wood pellets used for heating and energy), contingent on the quality of biomass, density of biomass in relation to the location of processing facilities, market trends, subsidies, etc.
- Industry-related mechanical removal should have a clear sustainability plan and must be monitored for environmental impact. Best practices, such as appropriate machinery, ecologically sensitive area avoidance, and minimization of soil disturbance can help mitigate negative environmental impacts.
- Some uncleared patches within the woodland should be preserved to act as refuges for species which may be adversely affected by removal processes.

Considerations specific to prescribed burn as an LMS

- Local legality must be consulted as prescribed burn is currently illegal in some parts of Europe.
- Smoke management is a critical consideration in prescribed fire programs. Smoke emissions can have significant air quality implications, particularly in populated areas. Ensure appropriate weather conditions, plan burn units strategically, and communicate with the public to minimize smoke impacts.
- The frequency and intensity of applications should aim to align with natural disturbance cycles based on an understanding of regional fire regimes.
- Meteorological conditions should be carefully monitored on prescribe burn days, noting that the number of suitable days may be declining due to climate change. Involve local stakeholders who may have used fire for traditional and cultural purposes and may have specialized knowledge of local land management histories and native habitats.

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List of Acronyms	
LMS	Land Management Strategies
LU	Land Use
WUI	Wildland Urban Interface
FCM	Fuzzy Cognitive Mapping
PBD	Prescribed Burn Days

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1 Introduction

1.1 Background

An historically close relationship exists between people, landscapes, and fire in Europe (Camp et al., 1997; Carnicer et al., 2022; Galizia et al., 2021; Pausas and Keeley, 2009). Fire has been used traditionally 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), weather, climate (Carnicer et al., 2022), vegetation type (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., 2011a; 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 (WUI) dynamics (Chuvieco et al., 2010). Here, we use “fire risk” as an umbrella term with the understanding that although risk is composed of several components, such as danger, exposure, and vulnerability (Chuvieco et al., 2023), here, we primarily address the fuel characteristics which modify fire behaviour.

Despite a reduction in burned area over the past three decades, certain regions of Europe are experiencing a worrisome upward trend in both interannual variability and the magnitude of wildfires. Additionally, previously fire-scarce areas, such as central and eastern Europe, are now encountering a greater number of and more severe wildfires (Joint Research Centre European Commission, 2022b). This phenomenon denotes a significant shift in fire patterns throughout the continent (Joint Research Centre European Commission, 2022b). The drivers of such changes in Europe are complex and spatially variable (Azevedo et al., 2018; Sil et al., 2019). Northern Europe faces greater risk as climate change increases the number of days with fire-prone meteorological conditions (Joint Research Centre European Commission 2020; Jones et al., 2020; Lozano et al., 2017; Turco et al., 2018). In southern Europe, fire regime changes have been largely spurred by demographic and socioeconomic changes which have resulted in large areas of land abandonment, often in marginalized lands (Estel et al., 2015; van Vliet et al., 2015). This land abandonment results in an increase in the cover of unmanaged vegetation (e.g., shrubs and forests). This vegetation can contribute to important ecosystem services, such as carbon storage and biodiversity (Fischer et al., 2012; Schulp et al., 2008; van der Zanden et al., 2017). However, in combination with dangerous weather conditions driven by climate change, it can also become a liability with regards to fire risk (Azevedo et al., 2018; Hermoso et al., 2021; Lasanta, 2019; Moreno et al., 2014; Santana et al., 2018).

Land management strategies which can affect fuels, henceforth referred to as LMS, can therefore be an important tool for reducing wildfire risk by incorporating the drivers of fuel accumulation on landscapes, including socioeconomic and environmental aspects, at the landscape-scale. However, public interest and support for LMS cannot be taken for granted. Efforts to reduce wildfire risk must also garner support from

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a diverse group of stakeholders (Bowman et al., 2011b), who likely vary in their management goals (Martins et al., 2021), relationship to fire (Jones et al., 2022), and perceptions of their responsibility (Tedim et al., 2016). Policies to encourage LMS therefore need to be embedded in local context (Tedim et al., 2016), and will be most effective where they target points in the socioeconomic system with the highest potential for change. Such interventions may include provision of funding for management changes (Canadas et al., 2023; Lasanta et al., 2022), local leadership support for wildfire management (Canadas et al., 2023), or professional support for creation of forest management plans (Gan et al., 2015). At the larger scale, the European Green Deal serves as a strategic framework, offering specific measures to develop adaptation strategies and mitigate the risk of extreme wildfires. It advocates for sustainable land management practices, encompassing the restoration and preservation of both natural and cultural landscapes (European Commission, 2019). Achieving successful reductions in wildfire risk from the local to international scale can therefore benefit from understanding how these social and economic interventions will impact implementation and success of LMS. Modelling of the socioeconomic system can help to identify key points where socioeconomic interventions can be targeted to foster the adoption of LMS. Through modelling the current system in which land management changes are embedded, we can explore the outcomes of potential interventions. Participatory approaches can provide one method for capturing this information and have proved valuable in promotion of land management to reduce fire risk (Marques et al., 2020; Marta-Costa et al., 2016; Iago Otero et al., 2018). Fuzzy Cognitive Mapping (FCM) is a participatory modelling approach, which creates semi-quantitative models using dispersed or uncertain data (Jetter and Kok, 2014; Mourhir, 2021).

This document aims to give background information and policy-relevant guidelines to support landscape-level decision making aimed at managing the fuel component of fire risk in Europe via application of LMS from three angles. First, we assessed the current literature to understand the applicability of LMS across Europe. We focus on three common LMS targeting fuel compositions in Europe with historical precedence and current relevance: (1) herbivory, specifically browsing and grazing; (2) mechanical removal of fuels; and (3) prescribed burn. In the second part, we examine the socioeconomic barriers to implementing LMS to reduce fire risk and identify potential socioeconomic intervention scenarios which may improve implementation of LMS by way of an FCM. Finally, we consider the environmental and ecological impacts of LMS which should be considered to balance potential trade-offs with fuel management activities.

2 Literature review of constraints and opportunities for LMS in Europe

2.1 Literature review methods overview

This deliverable centred around a literature review to identify the constraints and opportunities of adopting different LMS in Europe. In this section, we summarize the literature review methods and results which were used as a basis for the review of the LMS applicability, socioeconomic aspects, and environmental considerations in the following sections.

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A key word search addressing dimensions of land management and fire risk in the EU was carried out in Web of Science (http://www.webofknowledge.com) and was complemented by a grey literature search targeting past EU-funded research and project reports 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). The search covered the publishing period between 2015-2021, for English language papers only. 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 LMS for fire risk reduction in Europe.

Relevant records were then subjected to a full text screening in which articles were excluded in cases which: (1) were based outside of Europe; (2) referred to non-vegetation types of fire (e.g., domestic, surgical); (3) related 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; or (6) did not address the use of LMS for fire risk reduction (e.g., focused on wildfire impacts or exploring LMS for post-fire management, without aiming to reduce future fire occurrence). A PRISMA diagram documents the literature review screening process (Fig. 1).

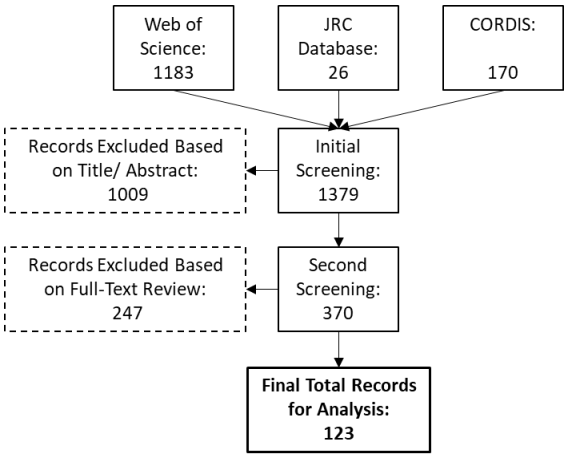


Figure 1: PRISMA diagram of literature review screening results

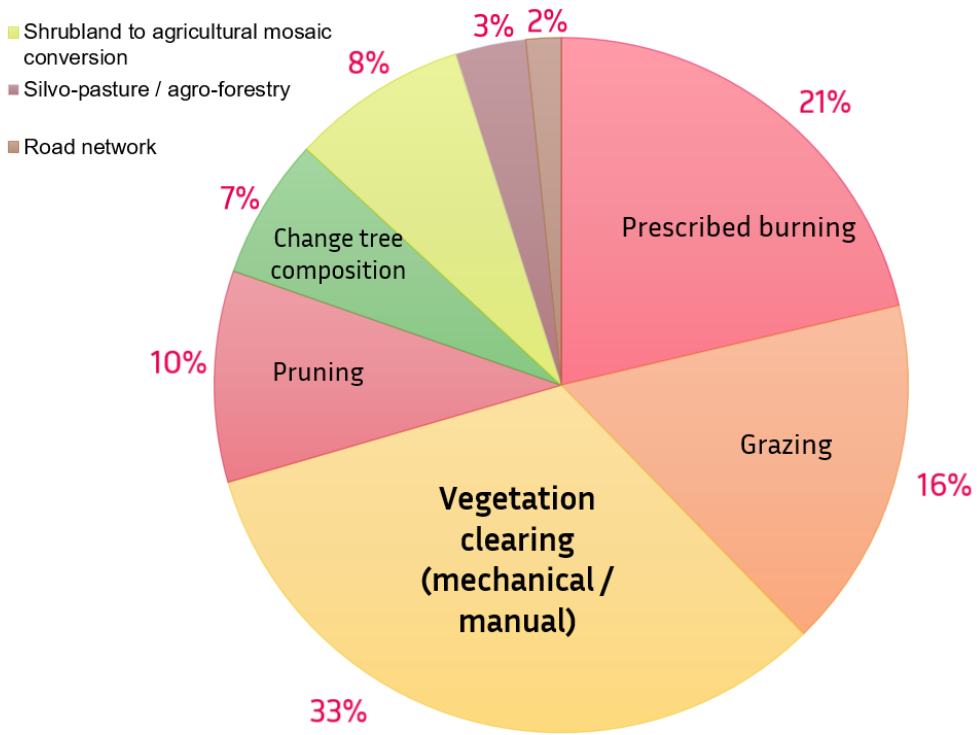
We then conducted a priori coding of the LMS-related themes in the database (Glesne and Peshkin, 1992). As new themes and insights emerged over the course of the review, new codes were developed and applied (Moher et al., 2009). We screened the publications for information regarding details on LMS implementation (i.e., a description of the strategy) and its respective biophysical and socioeconomic drivers, constraints, or impacts. In addition, we coded for actors involved in LMS management and the LMS goal (e.g., whether it aimed to reduce ignition probability vs. burned area, or whether the LMS addressed other social, environmental, or economic objectives beyond fire risk reduction). We primarily

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screened the publications for information regarding details on LMS implementation and its respective drivers, constraints, or impacts. Details addressed technical specifications, actors involved in LMS management, the LMS goal (which dimension of fire risk, which (if any) additional goals beyond fire risk reduction, etc.), whether the LMS involved a change in land use or land management, whether it was introduced in combination with one or more other LMS 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). An Excel spreadsheet with full list of literature, coding scheme and all variables used for multicriteria analysis for each LMS can be found as a supplementary materials file at the following address: https://ars.els-cdn.com/content/image/1-s2.0-S0301479723017292-mmc1.xlsx.

2.2 Literature Review Results Summary

In this section, we present an overview of the literature review results for three focal LMS. These focal LMS were selected as those that had been most extensively studied, and therefore had the necessary data available for analysis (Fig. 2). We therefore do not intend to suggest that these are the only, or even most, suitable LMS in all situations. Further details on the socioeconomic and environmental considerations of each of the LMS can be found in the following sections.



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Figure 2: Percentage of total papers in the literature database which discussed the respective LMS. Note: Multiple LMS codes could be applied to papers as relevant.

2.2.1 Opportunities and constraints for herbivory as an LMS in Europe

Of the 123 articles reviewed, 36 discussed herbivory (here referring to livestock, wild herbivores, agroforestry activities, and semi-domesticated animals, and including both grazers and browsers). Several studies indicated mixed use of grazers and browsers with diverse dietary preferences were most effective for decreasing fire risk. The efficacy of this strategy is dependent on herbivore species (Bartolomé et al., 2020), seasonality (Fetzel et al., 2017), pasture availability and quality, and provision of supplementary feedstock (Álvarez-Martínez et al., 2016; Calleja et al., 2019; Colantoni et al., 2020). Bovine livestock specifically were found recruit shrubs and other woodier biomass (which are associated with higher fire risk than non-woody fuels; e.g., Calleja et al., 2019; Teruel-Coll et al., 2019) due to their preference for grass. Sheep, goats (Álvarez-Martínez et al., 2016; Mena et al., 2016) and wild ungulates (Lecomte et al., 2019) tended more often towards browsing woody vegetation. Especially in areas facing or in the process of agricultural abandonment, wild ungulates were represented as an alternative opportunity for decreasing fire hazard (Lecomte et al., 2019; Linnell et al., 2020; Velamazán et al., 2018). Access to transportation infrastructure, including small and major roads and river networks, was indicated as an enabling factor for herbivory by creating opportunities for pastoralism and the transportation of domesticated and semi-domesticated livestock to areas targeted for fuel reduction (Varela et al., 2018). Transportation networks furthermore allowed for access to markets in which livestock products (meat, cheese, wool, etc.) could be sold, providing an incentive for adoption of grazing activities by rural communities (Varela et al., 2022, 2018).

2.2.2 Opportunities and constraints for Mechanical Removal as an LMS in Europe

Mechanical fuel removal—here referring to silvicultural activities, forest-based biomass extraction for industry (e.g., wood pellets), pruning, and thinning—was discussed in 77 articles. Fire risk reductions were associated with application to specific vegetation types and in combination with prescribed burn (Molina et al., 2018). This practice was specifically mentioned in relation to fuel removal among shrubs, a fuel of interest for fire risk (González-González et al., 2018; Regos et al., 2016), and in certain priority areas, such as the wildland-urban interface (Elia et al., 2016; Pastor et al., 2020). Terrains with slopes above a 30% grade were indicated in the literature as a prohibitive factor due to challenges of equipment transportation and material transport (Madrigal et al., 2017; Santos et al., 2021). However, high implementation costs were identified as a barrier for this LMS. Although indicated as a potential income generating activity through the sale of salvaged harvests in forest and land management activities, the requisite labour, equipment, and transportation in some cases represent prohibitive costs (Abbas et al., 2011; Anderson and Mitchell, 2016; Camia et al., 2021). Feasibility studies have assessed the biomass industry (mostly for electricity production as opposed to heating) as an incentive mechanism for improved forest and land management (Hevia et al., 2017). The economic sustainability, however, is contingent on factors such as the proximity of biomass material to processing facilities (Anderson and Mitchell, 2016); feedstock quality (e.g., hardwoods and softwoods require different

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processing intensities introducing varied cost-benefit ratios); recruitment of skilled labour; and market availability and value (Barrette et al., 2017, 2015). Several studies also evaluated the potential environmental impacts of biomass removal, finding varied consequences for soil and ecosystem health depending on harvesting methods and intensity (Abbas et al., 2011; Curran and Howes, 2011; Lamers et al., 2013; Manolis et al., 2019; Victorsson and Jonsell, 2013).

2.2.3 Opportunities and constraints for Prescribed Burn as an LMS in Europe

Of the 123 articles reviewed, 47 discussed prescribed burning, with a focus on southern Europe. Traditional uses of fire in Europe were discussed, such as for pasture, vegetation clearing for agriculture, or maintenance of culturally valued landscapes, e.g., heathlands (Glikson, 2013; Otero et al., 2018; Varela et al., 2022). Several studies assessed the environmental impacts of prescribed burn, including effects on soils, biodiversity, tree mortality, and water storage, described in more depth in later sections of this document. In terms of biophysical constraints, specific meteorologic conditions were identified as a prerequisite to conduct burns safely (Kupfer et al., 2020; Montiel, 2010). Common conditions cited for prescribed burn days in the literature include cut-offs for maximum daily temperature; average relative humidity; wind speed; and consecutive days without precipitation (Davies et al., 2019). Accessibility to transportation networks was also indicated in the literature as a pre-requisite for the movement of equipment and labour, but also as a fail-safe measure in the event that control is lost when applying a prescribed burn (Alcasena et al., 2018; Castellnou et al., 2019). Several studies analysed perceptions of prescribed burn through surveys and interviews. Aversion to smoke by inhabitants living in the vicinity of prescribed burn applications was qualified in the literature as a barrier to its uptake, with some studies also assessing the potential for the movement of smoke (Ager et al., 2019; Alcasena et al., 2018; Stephens and Moghaddas, 2005).

3 Socioeconomic assessment of the LMS

For the socioeconomic assessment we selected the articles from the aforementioned literature review which identified “Constraints, drivers or impacts (Economic)” or “Constraints, drivers or impacts (Socio-cultural)”. We used this information to feed into the development of a Fuzzy Cognitive Map (FCM) of the socioeconomic barriers to LMS to reduce fire risk. FCM is a participatory modelling approach, which creates semi-quantitative models using dispersed or uncertain data (Jetter and Kok, 2014; Mourhir, 2021). Because FCM uses natural language, the approach can be valuable to bridge the gap between social and biophysical data, capturing both expert and lay person data in a way that allows the modelling of future scenarios (Jetter and Kok, 2014; Mourhir, 2021). FCM does not seek to gather a consensus view, where incorrect or unrelated information may be incorporated, but collects information from a targeted group of stakeholders with knowledge of the system to be modelled. The total number of responses does not need to be high; rather, it is more important that knowledgeable stakeholders with a range of expertise are captured (Jetter and Kok, 2014). The model was refined using surveys of individuals with practical knowledge of LMS to reduce fire risk and by the FirEURisk pilot site leaders. Pilot sites were selected in the initial stages of the project in fire-prone regions experiencing extreme (e.g. central Portugal) or unusual

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events (e.g. Sweden). In these areas, previous work has been conducted and abundant data sources, models, simulations and published knowledge is available, providing firm ground for further scientific work.

From the literature review, we extracted data on the impacts that socioeconomic factors had on the successful implementation of LMS to reduce wildfire risk, and used these to create statements linking socioeconomic factors and LMS. We defined impact as being either related to the likelihood of the strategy being implemented, or the success of the strategy in reducing fire risk once implemented. E.g.,

> Strong leadership has a [*very positive, positive, neutral, negative, very negative*] impact on land management strategies.
> Public support has a [*very positive, positive, neutral, negative, very negative*] impact on strong leadership.

These initial link statements were used to create a draft conceptual model of socioeconomic impacts on LMS to reduce fire risk. This model was refined by the pilot site leaders, including providing suitable definitions, grouping or splitting factors as needed, and adding additional links.

The statements identified by the pilot site leaders were then entered into an online survey, where respondents were asked to link the pairs of factors (e.g., public support and strong leadership) with a judgement on how they impact one another (very positive, positive, neutral, negative, very negative). Stakeholders also provided information on stakeholder type, and types of LMS the respondent was familiar with in their area. Specific LMS were not identified, responses were given to LMS in general.

Surveys were sent to specific individuals identified by case study leaders as individuals who either managed land or were directly impacted by LMS. Because FCM does not seek to find a consensus, but rather to capture knowledge held by stakeholders who are experts in their system this targeted approach is more suitable than a wider distribution with higher numbers of responses, but potentially lower quality data. Survey responses were received from Spain, Portugal and Sweden. One response was received from Central Europe, however this was not enough to carry out analysis, and so was removed from the dataset.

Separate models were created for the Spanish, Portuguese and Swedish pilot sites. Stakeholder answers were assigned scores from 1 (very positive) to −1 (very negative). To assess agreement between stakeholders at each case study consistency in responses for each statement was calculated through response balance:

$$\left(\left(\frac{-P}{T}\right) \times \log_2\left(\frac{P}{T}\right)\right) + \left(\left(\frac{-N}{T}\right) \times \log_2\left(\frac{N}{T}\right)\right)$$

Where P is the number of positive responses, T is the total number of non-neutral responses and N is the number of negative responses (Stirling, 2007).

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Statements with a response balance over 0.8 were considered 'balanced', indicating they had equal positive and negative responses. This suggests that there was not good agreement between stakeholders as to the direction of the relationship, indicating either a variable relationship not suited to the model, or a lack of consensus in understanding between different groups. Balanced responses were therefore removed from the final models. Missing values were assessed for distribution throughout the survey responses, to indicate whether they were true zero values, or were likely to be caused by fatigue or a lack of patience. Where missing values were assessed to be true zeros they were treated as "I don't know" responses. Final models were created using the median value from all retained statements.

In the final part of the analysis, we tested alternative policy or governance scenarios to compare impacts on success of LMS implementation (Jetter and Kok, 2014; Roberts et al., 2021). We developed scenarios iteratively from the final models, identifying coherent groups of policy or governance changes based on the links identified within the models. The 'no-changes' models were run using the median values for each statement as described above. In the 'scenario' models, equilibrium values were artificially set to 1 to increase impact, or 0 to remove impact. The effects of each scenario were represented with the percentage change in equilibrium values (i.e., the final values of each factor after the model had been run) between the 'no-changes' model the 'scenario' model. Scenarios are described in the results section.

3.1 Socioeconomic assessment results

In total 20 responses were received (Table 1) from three pilot sites (Spain, Portugal, Sweden).

Table 1: Survey responses by stakeholder category

Category	Overall	Sweden	Spain	Portugal
Total number of responses	20	5	8	7
Resident	13%	0%	50%	14%
Business owner (local area)	0%	0%	0%	0%
Business owner (reliant on forest)	7%	0%	0%	14%
Small private landowner (one location)	20%	20%	0%	29%
Large private landowner (multiple locations)	0%	0%	0%	0%
Private land manager (for land not owned)	20%	20%	13%	14%
Public land manager	27%	60%	13%	14%
Other	13%	0%	25%	14%

Overall, the most used LMS were grazing, prescribed burning and landscape conversion, identified by over 50% of respondents. Urban design was the only strategy not to be identified by any individual. Differences in LMS can be seen between case studies. Lake construction and peatland restoration were selected only by Swedish respondents, who were also less likely to identify changes to vegetation through clearing, pruning or replacement.

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3.1.1 Models

From the literature, we identified 42 factors with 46 unique statements. Following discussion with pilot site leaders, 34 factors, with 42 statements, were included in the final analysis with stakeholders (Table 2). Missing values were roughly evenly distributed throughout the survey responses, and so were treated as 'I don't know' responses during analysis. Low consistency statements (balance over 0.8) were identified in statements which included the factors: collective action, competing narratives, land abandonment, and contractual obligation. These factors were therefore removed from the final models, along with free riding, depopulation and loss of profit, as these only linked to deleted factors.

Table 2: factors included in the Fuzzy Cognitive Map

Factors identified from the literature	Factors included in full stakeholder models – after study site leader consultation	Factors included in final models – after low consistency statements removed
LMS	LMS	LMS
Public support	Public support	Public support
Strong leadership	Strong leadership	Strong leadership
Shared identity	Shared community identity	Shared community identity
Valued landscape	Valued landscape	Valued landscape
Relationship with officials	Links between officials and managers	Links between officials and managers
Cost	Cost effectiveness	Cost effectiveness
Public knowledge	Public knowledge	Public knowledge
Cost of alternative good	Value of associated good	Value of associated good*
Cultural practise	Cultural practise	Cultural practise
Political knowledge	Political knowledge	Political knowledge*
Shared technical knowledge	Shared technical knowledge	Shared technical knowledge
Loss of property	Risk to property	Risk to property[$]
Media pressure	Media opposition	Media opposition
	Media support	Media support
Laws and regulations	Laws and regulations - Promotion	Laws and regulations – Promotion
	Laws and regulations - restriction	Laws and regulations – restriction
Cost of fire damages	Cost of fire damages	Cost of fire damages
Payment subsidies	Subsidies	Subsidies
Community involvement	Community involvement	Community involvement
Farming benefit	Farming benefit	Farming benefit
Managerial knowledge	Managerial knowledge	Managerial knowledge
Social benefits	Social benefits	Social benefits*
	Low cost of alternatives	Low cost of alternatives*

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	Political support	Political support
	Manager/landowner support	Manager/landowner support
Collective action	Collective action	
Free riding	Free riding	
Competing narratives	Competing narratives	
Land abandonment	Land abandonment	
Depopulation	Depopulation	
Contract for management	Contractual obligation	
Loss of profitability	Loss of profitability	
Effective fire suppression		
Sale of forest good		
Managerial knowledge		
Technical support		
Low-cost fire suppression		
Social knowledge		
Investment in forest management		
Conservation		
Area needed		
Active involvement in management		
Fire suppression focus		
Public participation in decision-making		
Fire risk		
Culture		

* No links to these factors were recorded in the Swedish case study model.

$ No links to these factors were recorded in the Portuguese case study model.

The three models were structurally similar, although Sweden has fewer connections and uses fewer factors than either Spain or Portugal, likely due to a smaller number of LMS employed, and historically fewer fires. Across models, the largest impacts on LMS were seen for manager and landowner support (Figures 3-5).

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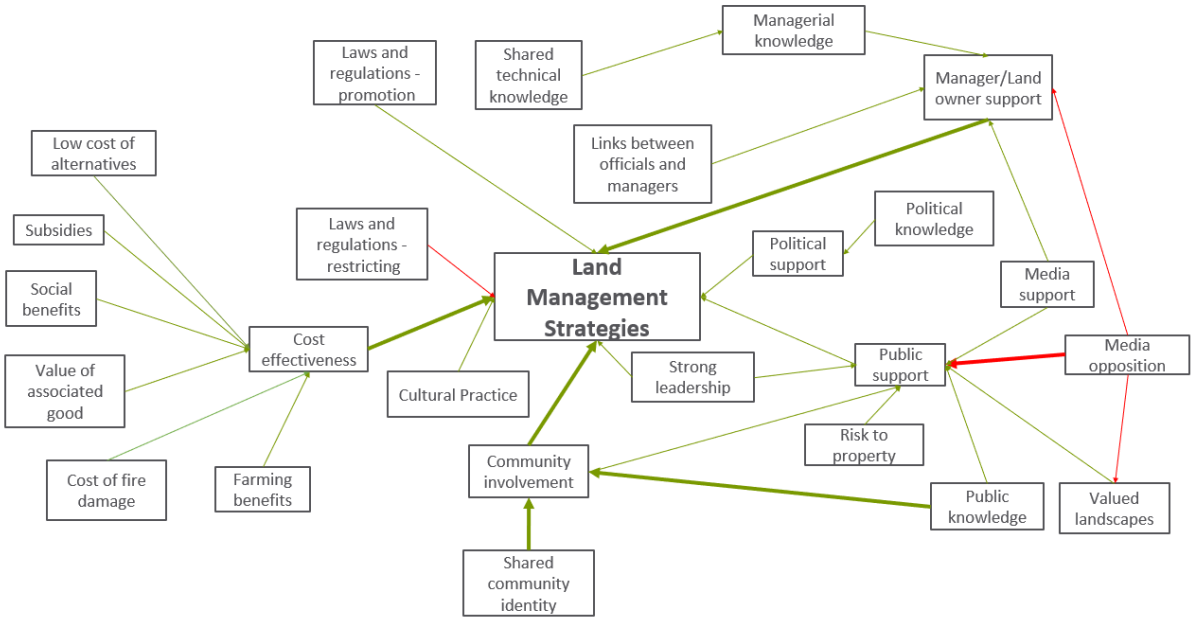


Figure 3: Fuzzy cognitive map for Spanish case study. For full map see Appendix 1
Note: Arrow colours: green = positive relationships, red = negative relationships. Line thickness indicates strength of connections (e.g., thicker line= stronger relationship).

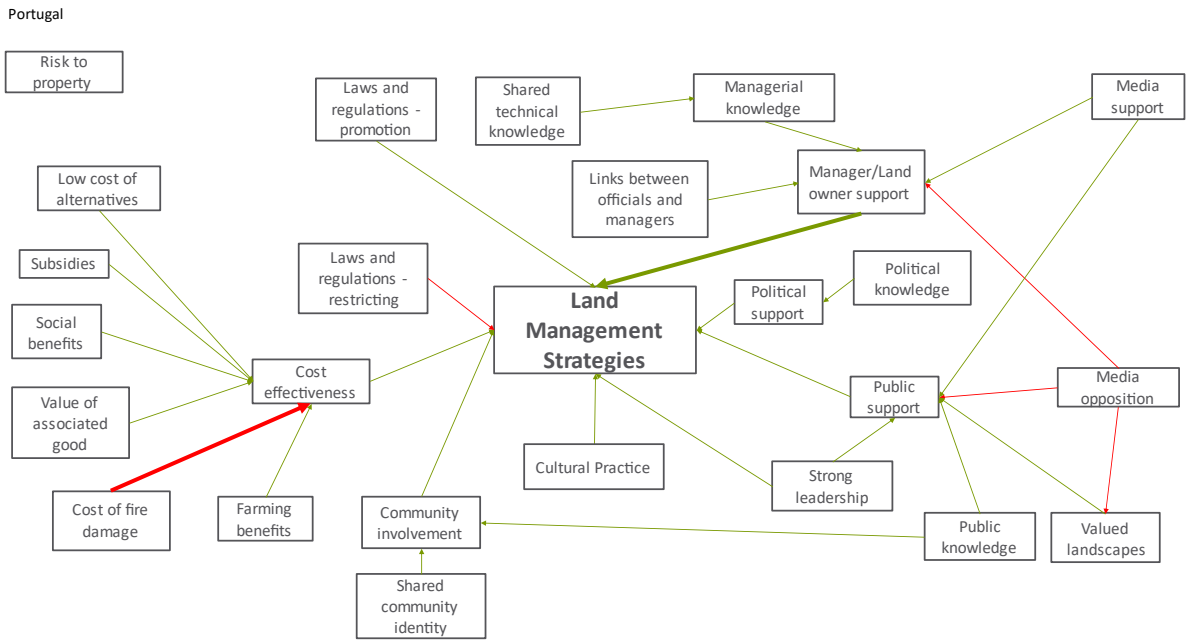


Figure 4: Fuzzy cognitive map for Portuguese case study. For full map see Appendix 1.
Note: Arrow colours: green = positive relationships, red = negative relationships. Line thickness indicates strength of connections (e.g., thicker line= stronger relationship. No links indicates no relationships to any other factors within the system).

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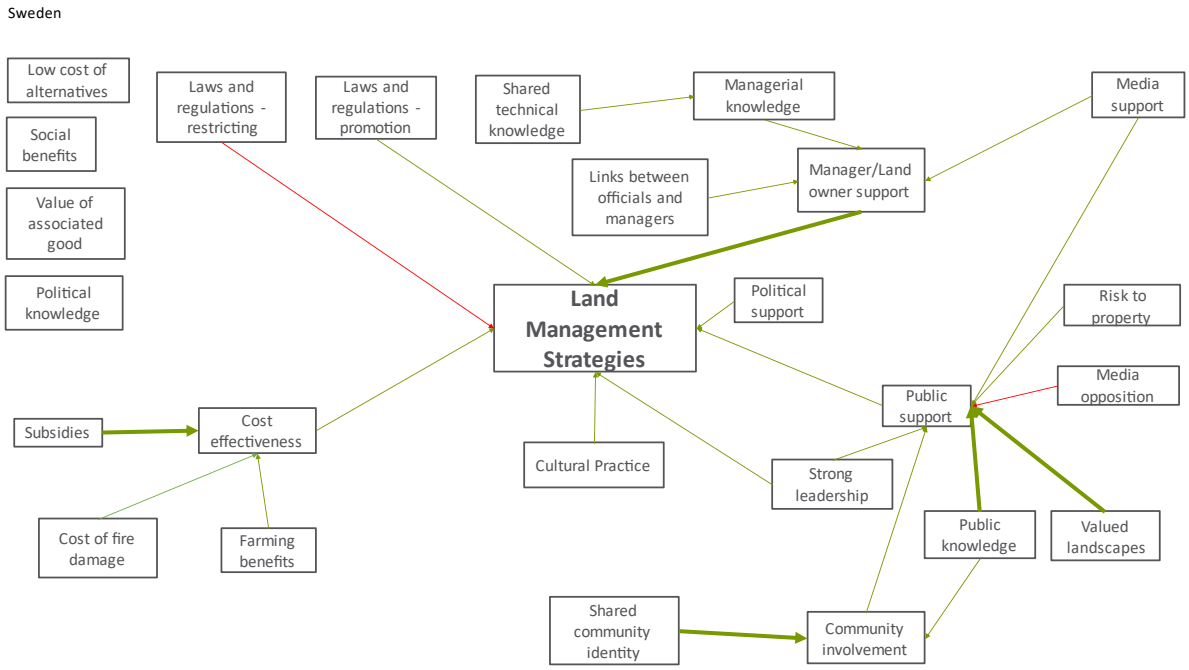


Figure 5: Fuzzy cognitive map for Swedish case study. For full map see Appendix 1.
Note: Arrow colours: green = positive relationships, red = negative relationships. Line thickness indicates strength of connections (e.g., thicker line= stronger relationship. No links indicates no relationships to any other factors within the system).

3.1.2 Scenarios

We tested three scenarios, created from the FCM at each pilot site and intended to be coherent socioeconomic interventions:

a) *Increased manager/landowner support*. In this scenario, we increased media support, managerial knowledge, link between officials and managers and decreased media opposition.
b) *Improved cost-effectiveness.* In this scenario, we increased farming benefits, subsidies, value of associated good, and social benefits.
c) *Effective laws and regulations.* In this scenario, we increased laws and regulations (promotion) and decreased laws and regulations (prevention)

LMS were predicted to be increased in all scenarios for all case studies, with effective laws and regulations having the highest impact on LMS (Table 3). (For detailed results see Appendix 1.)

Table 3: Improvements in LMS implementation for changed policy and governance mechanisms

	Sweden	Spain	Portugal
Increased manager/landowner support	Medium	Medium	Medium
Improved cost effectiveness	Low	Low	Low
Effective laws and regulation	High	High	High

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4 Environmental assessment of the LMS

In this section, we synthesize the current literature and understanding of potential ecological effects of the LMS on vegetation, soils, and fauna which should be considered by policy makers and land managers considering implementation of LMS on the landscapes in which they work. The section also benefits from input and review from experts within the FirEUrisk consortium.

General effects of LMS on vegetation

LMS can influence the composition of the plant community because some plant species may be more resilient and able to regenerate following fuel reduction treatments, while others may be more sensitive or unable to recover. As a result, the composition of the plant community may shift, with certain species becoming more dominant or others declining (Dufour-Dror, 2007; Santana et al., 2011; Valkó et al. 2016; Klich, 2018). Fuel reduction can also affect species diversity because removing or reducing vegetation may create opportunities for some species and promote a more diverse plant community (Pérez-Ramos, et al. 2008; Valkó and Deák, 2021). However, if fuel reduction treatments are too intense or extensive, they may negatively impact biodiversity by removing critical habitat elements or favouring more competitive species (Valkó et al., 2014). Careful consideration of treatment intensity, spatial arrangement, and the specific habitat requirements of target species is necessary to maintain or enhance biodiversity. Balancing treatment frequency and intensity and considering the timing (season) is necessary to maintain plant diversity while reducing fire risk. Fuel reduction treatments can influence successional patterns in vegetation by creating opportunities for early successional species to establish and thrive. These species are often adapted to disturbances and can quickly colonize open areas. Vegetation recovery depends on various factors, including the resilience of different plant species, the availability of seeds or vegetative propagules, and the presence of favourable environmental conditions (Santana et al., 2011; Mancilla-Leytón et al., 2017). Monitoring the recovery of vegetation over time can provide insights into the effectiveness of fuel reduction strategies and their impacts on vegetation.

General effects of LMS on soils

LMS can alter soil physical properties such as soil density, texture, aggregate stability, compaction, water repellence and infiltration. Fuel reduction practices can affect soil erosion risk because without the protective cover of vegetation, the soil becomes more vulnerable to erosion by wind and water. Increased exposure to wind and rain lead to soil erosion, nutrient loss, and degradation of soil structure. The removal of vegetation reduces the amount of plant litter, leaf litter, and woody debris entering the soil, potentially affecting soil chemical properties such as soil organic carbon content and nutrient cycling (Armas-Herrera et al. 2016; San Emeterio et al. 2016). The removal of vegetation and disturbance of the soil impacts the diversity and abundance of soil organisms (soil diversity), including bacteria, fungi, protozoa, and soil invertebrates (Williams et al., 2012; Certini et al., 2021). Changes in soil biodiversity can have cascading effects on nutrient cycling, organic matter decomposition, and overall soil ecosystem functioning (Stark et al., 2003; Piñeiro, 2010). It is important to note that the effects of fuel reduction on soils can be influenced by factors such as the intensity and frequency of management practices, the type of vegetation being cleared, soil type, and climate conditions (Li and Jiang, 2021).

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General effects of LMS on fauna

LMS can potentially lead to changes in habitat for fauna, altering the availability of shelter, nesting sites, and foraging opportunities for different fauna species (Hanane, 2014). Some species may prefer dense, unmanaged vegetation for nesting or foraging, while others may benefit from more open habitats created by fuel reduction activities (de la Montana et al., 2006). Vegetation removal can disturb or remove nesting sites, such as shrubs, trees, or ground cover, potentially affecting breeding success and nest site availability for birds, small mammals, and reptiles. The response of fauna species to fuel reduction can vary depending on their ecological requirements and adaptations (Valkó et al. 2016, Végvári et al 2016). Some species may be negatively impacted due to the loss of vegetation cover. However, fuel reduction can also create favourable conditions for certain species that thrive in open or early successional habitats. Vegetation removal also affects microclimate conditions within the treated areas because openings created by fuel reduction can result in increased light penetration, temperature fluctuations, and changes in moisture levels. These alterations in microclimate can influence the distribution, behaviour, and physiological processes of fauna species depending on their specific environmental conditions. It can impact nesting success, egg incubation, or the thermal suitability of habitat for certain animal species. Fuel reduction treatments may also result in a change or reduction in the availability and quality of food resources for animals by directly impacting plant-associated food sources, such as leaves, fruits, seeds, or nectar. However, fuel reduction can also indirectly affect food resources by altering the structure and composition of the vegetation, which can influence the abundance and diversity of invertebrates, small mammals, or other prey species. Changes in food availability can subsequently impact the foraging behaviour, diet, and population dynamics of fauna. The opening of previously dense vegetation can provide new foraging areas for certain species, while the removal of vegetation cover can expose other species to predation risks or affect their hunting success. Thus, it can also have cascading effects on species interactions within the ecosystem since changes in vegetation structure and composition can alter predator-prey dynamics, or competition for resources (Filazzola et al., 2020).

4.1 Herbivory

Herbivory can lead to changes in vegetation composition in terms of dominance and abundance, as animals selectively consume certain plant species based on palatability-related traits (Archibald et al. 2019). Herbivory can create a more heterogeneous vegetation structure, which can benefit certain plant species that thrive in open or disturbed habitats (e.g., Klich, 2018). However, it may also lead to a decline in plant diversity if herbivory intensity is too high or concentrated on specific plant species (e.g., Mancilla-Leytón, 2013). Moderate grazing can enhance the growth of herbaceous plants, particularly grasses, by reducing competition from shrubs and trees. This may enhance a diverse herbaceous plant community, providing forage for both domestic livestock and native herbivores. However, excessive herbivory and selective removal of preferred plant species, can potentially cause a shift in community composition towards more competitive or unpalatable species. Herbivory may also negatively impact forest structure and functions (Li and Jiang, 2021), hinder the survival and growth of tree seedlings and saplings, decrease

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their abundance (Dufour-Dror, 2007), and affect species regeneration due to reduced reproduction output and viable propagules (Mancilla-Leytón et al., 2017). However, there is currently limited scientific information available on the ecological effects of using herbivory for fuel reduction, particularly in the Mediterranean region (Lovreglio et al., 2014).

Herbivory can influence soil physical properties through trampling and compaction, potentially affecting soil porosity and water infiltration rates and disrupt carbon cycling (Stark et al., 2003). The decrease in soil nutrient levels, specifically nitrogen, resulting from herbivory, has implications for soil carbon cycling and ultimately leads to a reduction in soil carbon stocks (Piñeiro, 2010; Stark et al., 2003). However, controlling herbivory intensity may moderate some of these negative effects (Li and Jiang, 2021).

Herbivory plays a crucial role in shaping global biodiversity patterns as it impacts various trophic levels. It may decrease animal abundance and diversity, particularly among herbivores and pollinators, which are directly influenced by the availability and quality of plants. Moreover, it affects the trophic structure of ecological communities, and these effects can persist after their removal (Filazzola et al., 2020). Livestock herbivory may pose potential threat to population persistence of some bird species by altering the composition and the structure of the nesting habitat (Hanane, 2014).

Last, herbivory may also increase the contact boundaries between livestock, wildlife, and human populations and heighten the risk of pathogen propagation and cross-species transmission (Barasona et al., 2014; Morgan et al., 2006). Consequently, there is a need for a careful planning of livestock management systems in natural areas to minimize the potential impact on wildlife and human health and reduce the risk of emerging infectious diseases.

4.2 Mechanical removal

Mechanical removal can lead to shifts in vegetation composition, particularly if certain plant species are selectively targeted or removed. In mechanical removal treatments, typically shrubs, small trees, and other woody vegetation are targeted for removal. The implementation of fuel reduction programs that involve frequent and extensive removal of the vegetation can result in the elimination of landscape-scale stands characterized by complex, multi-layered plant communities inhabited by large resprouting plants and species with fleshy fruits, while favouring pioneer seeder and dry-fruited shrubs (Santana et al., 2011). Mechanical removal may result in an increase in species richness, encompassing both α-diversity (within-site diversity) and γ-diversity (overall regional diversity), driven by the expansion of open grassland species. However, it can also lead to a decline in β-diversity (between-site diversity) due to a homogenizing effect caused by the expansion or dominance of species that are favoured by this disturbance (Pérez-Ramos et al., 2008).

Mechanical removal can impact soil properties. The use of machinery and equipment can cause soil compaction, disruption of soil structure, and surface disturbance (González-González et al., 2018). These

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disturbances can also affect soil chemical, physical and biological properties (Lamers et al., 2013). Nonetheless, favorable outcomes may also be observed, including heightened carbon and nitrogen content post-harvest, along with a rise in litter volume after clearing activities, attributed to the biomass residue remaining on the ground subsequent to harvesting (González-González et al., 2018). Implementing best management practices, such as using appropriate machinery, avoiding sensitive areas, and not removing logging residues such as woody debris and low stumps, can help mitigate negative impacts on soil properties (Camia et al., 2021; Lamers et al., 2013; Manolis et al., 2019). However, there is a general lack of specific studies addressing the ecological effects of mechanical removal on soil properties.

Mechanical removal of dense Mediterranean woodland may result in improved habitat heterogeneity, making it more suitable for various bird species and contributing to increased species richness. However, it is important to preserve some uncleared patches within the woodland to serve as refuges for a few species that may be adversely affected by the thinning process (De la Montana et al., 2006).

4.3 Prescribed burning

Prescribed burning can have both positive and negative effects on plant diversity (Valkó and Deák, 2021). It can promote the growth and flowering of fire-adapted species and increase plant diversity or lead to changes in vegetation composition in terms of dominance and abundance (Valkó et al., 2016). However, if prescribed fire application is too frequent or intense, it may negatively impact communities (Valkó et al., 2014).

Prescribed fire influences soil physical, chemical and biological properties, including organic matter content, nutrient availability, and soil structure. Fire can reduce the amount of organic material on the soil surface but can also increase nutrient release from burnt vegetation (Pereira et al., 2015). The exposure of bare soil after fire can lead to increased erosion risks and changes in soil hydrology (Shakesby and Doerr, 2006). Overall, the effects of prescribed fire on soil properties can vary depending on fire severity, burn temperature, and post-fire vegetation recovery but there is a general predominance of positive or neutral effects on the different soil properties (Alcañiz et al., 2018; Santín and Doerr, 2016). However, some prescribed fires are performed at higher frequencies, intensities and severities and may have negative impacts (e.g., Armas-Herrera et al., 2016; San Emeterio et al., 2016; Williams et al., 2012).

Prescribed burns can have different impact on fauna, depending on the temporal scale, habitat and species. Different studies show negative, neutral or positive effects (Valkó et al., 2016; Végvári et al., 2016). Prescribed fires are typically smaller in scale, less intense, and slower compared to the majority of wildfires. Soil-dwelling organisms generally experience minimal and temporary harm from this type of fire, and many animals can escape or seek refuge in tree hollows, burrows, or other safe sites (Pausas, 2019). Similarly, smaller organisms can compensate for potential significant losses through the rapid

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reproduction of survivors or by migrating from areas that remain unburned (see a review by Certini et al., 2021).

Prescribed burns generate smoke containing particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOC) and nitrogen oxides (NOx) (Miranda et al., 2010), which impact the quality of the air (Haikerwal et al., 2015, Garcia-Hurtado et al., 2014, 2013). This can have implications for human health (Miranda et al., 2012; O'Keeffe et al., 2016), particularly for individuals with respiratory conditions. Personnel involved in prescribed burning operations can also be affected by the emitted smoke. Miranda et al. (2010) measured the individual exposure to CO, NO_2, VOC and fine particulate matter (PM2.5, with an aerodynamic diameter <2.5 μm) during experimental field burnings for a group of 10 firefighters equipped with portable "in continuum" measuring devices. Monitored data were compared with available Occupational Exposure Standard (OES) limits and several exceedances for CO were observed. Nitrogen dioxide values were within the OES, except for some peak values exceedances. PM2.5 was also within the OES value, but the measured values were very high and could affect human health. Haikerwal et al. (2015) also highlighted the relevance of PM2.5, which concentration levels are found to be consistently elevated during smoke events, because they are particularly harmful to human health due to their fine nature. Notwithstanding the impacts of smoke from prescribed burning, mainly in specific locations on short-term time scales, their potential to reduce community wildfire smoke exposure in relation to smoke from wildfires is needed (Kelp et al., 2023).

Smoke management is a critical consideration in prescribed fire programs and in many parts of the world smoke management programs and guidelines are being introduced to minimize smoke impacts on populations. Informing and preventing the impact of prescribed burning emissions on air quality and human health would be useful for communities living in and around the vicinity of the prescribed burns, especially for at risk people with pre-existing conditions. Effective smoke management strategies, such as choosing appropriate weather conditions, planning burn units strategically, and communicating with the public, are essential to minimize smoke impacts.

A comparative assessment of smoke exposure from prescribed fires and wildfires is needed to better understand the potential net benefits of prescribed burning in relation to wildfires occurrence, and this is particularly relevant in a climate change world.

5 Tackling fire risk from all angles: A discussion of critical considerations for LMS in Europe

For this FirEUrisk deliverable, we examined opportunities to mitigate fire risk through LMS from three angles, highlighting important considerations for landscape managers and policy makers. Our results are organized around the biophysical aspects which can dictate LMS applicability and efficacy, the socioeconomic conditions and policy environments that support their uptake, and the environmental considerations which sculpt their legacy on the landscape. The holistic consideration of these elements

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creates a framework in which we can attempt to weigh potential trade-offs of management pathways representing a spectrum of goals, constraints, and opportunities.

5.1 Opportunities

Our results highlighted several opportunities to manage fire risk though LMS. Europe has a long legacy of land management, including traditional applications of the three LMS covered here, representing a source of knowledge for future management. LMS can be targeted towards areas which meet specialized biophysical conditions, such as appropriate meteorological conditions for prescribed burn, pairing appropriate herbivore species to vegetation types and landscape management goals. LMS can also be used concurrently, such as the use of prescribed burn and grazing in mosaic landscapes, to improve their efficacy and to achieve non-fire related goals, such as increasing biodiversity by selective application of prescribed burn, conserving cultural landscapes such as heathlands, or contributing to local livelihoods.

Insights from the socioeconomic models (Section 3) suggest that opportunities exist within legal and regulatory frameworks to improve LMS uptake and success, having the largest impact of the three scenarios tested. Additional opportunities arise through the building of landowner support for LMS implementation. Given the large areas over which fire management must take place, often with fragmented land ownership, buy-in from landowners and managers is vital, as management often cannot be restricted to public land (Gan et al., 2015; Jetter et al., 2017; Paveglio et al., 2021). Increasing landowner and manager support also requires understanding of individual perceptions of fire risk (Martin et al., 2009) or potential for damage (Paveglio et al., 2021), and management goals, which may not centre on wildfire risk reduction (Gan et al., 2015). Underestimating wildfire risk or damage, more common for absentee landowners, can also reduce support for wildfire risk reduction through land management (Jetter et al., 2017). Policies which address knowledge (Edgeley et al., 2020; Jetter et al., 2017) or skills (Edgeley et al., 2020) gaps in landowners and land managers, or which incorporate the development of forest management plans (Gan et al., 2015) may therefore provide an opportunity to improve landowner or manager support. Policies which improve community engagement have also seen success in improving landowner and land manager support, including in Australia and Sweden (Eckerberg and Buizer, 2017). Engagement with indigenous communities can be particularly informative in building landowner and land manager support, especially regarding current practises and management decisions, as well as recognising the effect of traditional knowledge on effective wildfire management (Sherry et al., 2019; Tedim et al., 2016). Engaging with local experts can also help to shape policies which are more likely to have support, with expert opinion found to vary with distance from the fire management area (Martins et al., 2021).

Funding has been previously recognised as a significant barrier to uptake (Canadas et al., 2023), including due to impacts on landowner support (Edgeley et al., 2020; Jetter et al., 2017). We found, however, that cost effectiveness was the scenario which had the least impact on the LMS, although the impact was still positive. However, unlike changes to laws and regulations, or improving landowner and land manager support, policies focused on cost effectiveness may be more straightforward to enact. Thus, subsidies to

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support shrub clearing, a fuel type of particular concern, for example, may provide an opportunity to address fire risk. Besides direct funding, policies which support increased technical expertise can also improve cost effectiveness (Marey-Perez et al., 2021).

Local ecological dynamics are also pivotal in developing environmental benefits and safeguarding ecological resources. By taking into account vegetation dynamics, biodiversity impacts, soil health, and ecosystem resilience, land managers, policymakers, and researchers can make informed decisions and develop strategies that employ fuel management approaches tailored to the specific characteristics of the ecosystem. This should be based on an understanding of the ecosystem's ecology, considering its historical, current, and desired fire or disturbance regimes. An inclusive approach that considers ecological considerations, involves stakeholders, and applies adaptive management principles could potentially contribute to effective fuel management and reduction of wildfire risk in European landscapes.

5.2 Constraints and knowledge gaps

Despite the many opportunities for fire risk management through LMS in Europe, our results also indicated several constraints, considerations, and gaps in knowledge. Decreasing fire risk by way of land management requires striking a balance between fire risk reduction objectives and ecological considerations, as well as integrating within the socioeconomic and governance system. While measures like herbivory, mechanical removal, or prescribed burn can effectively decrease fuel loads and mitigate fire risk, they can also have ecological repercussions on biodiversity (including flora, fauna, and soil biodiversity), soil properties (such as soil structure, fertility, and nutrient cycling), ecosystem resilience/vulnerability, human health, and ecosystem services. Modifying vegetation structure, decreasing fuel loads, and altering disturbance regimes may have unintended impacts on ecosystem processes and dynamics. Determining the ideal timing and frequency of treatments is crucial to balance fuel reduction objectives and ecological considerations. Treatment timing should account for sensitive periods of wildlife and plant species, while treatment frequency should align with the natural disturbance regime of the ecosystem. Land and fuel management strategies should be rooted in identifying critical processes and habitats at both the community and landscape levels and establish strategies to adequately preserve them. This requires a comprehensive understanding of the underlying mechanisms and leads to diverse solutions for different ecosystems, communities, or species.

To some extent, our findings are constrained by some of the knowledge gaps in the literature. For example, land abandonment was not included in our socioeconomic models due to conflicting information from stakeholders as to the direction of its influence on LMS to reduce fire risk. This conflict was unexpected, particularly in the Spanish and Portuguese case studies, where land abandonment is linked to increased fire risk due to reduced land management (Canadas et al., 2023; Fernández-Manjarrés et al., 2018; García-Ruiz et al., 2020), and the importance of maintaining traditional agriculture has been recognised in previous FCM related to wildfire management (Cleveland, 2022). Land abandonment is thought to be driven by the challenges of rural and agricultural living, including links to restrictive nature

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of the Common Agricultural Policy (Fernández-Manjarrés et al., 2018), and, if unmanaged, can lead to large areas of continuous forest or shrubland, at high risk of wildfire (García-Ruiz et al., 2020). Land use policies which continue to promote land management, either through agriculture or the creation of a mosaic-type landscapes through ecological restoration (García-Ruiz et al., 2020), are expected to reduce wildfire risk, but may have limited uptake if the importance is not recognised by local stakeholders. Further research into understanding whether land abandonment is perceived as less important, or the consequences conceptualised differently, by local stakeholders would be beneficial for design of policies to reduce land abandonment for wildfire risk reduction. Our models suggest that changes to laws and regulations to promote LMS to reduce fire risk would have highest impact. This is not a surprising result, given the mandatory nature of this intervention. However, it is important to note that we did not specify the nature of the changes to the laws and regulations, only that they would change implementation of LMS to reduce wildfire risk. Therefore, although this finding suggests that laws and regulations designed to promote land management would improve management across the EU, it is unlikely that a 'one-size-fits-all' approach across the EU would be successful (Eckerberg and Buizer, 2017), and that actual implementation would need to have local flexibility, particularly with regard to the WUI and more sparsely populated rural areas (Edgeley et al., 2020; Paveglio et al., 2021).

Our results also identify gaps which could have a major impact on LMS us considered 'balanced', indicating they had equal positive e in Europe. Of significance is how the two major drivers of increased fire risk in Europe—climate change and land use change—will evolve over the coming years and the impact they will have not only on fire dynamics but on our ability to use the LMS discussed to mitigate risks. For example, hotter, drier, windier days have already been found to reduce prescribed burn day windows in parts of Europe and North America (Kupfer et al., 2020, Baijnath-Rodino et al., 2022; Duane et al., 2019). It is also not possible to know with certainty how past fire regimes in Europe manifested, with consequences on how prescribed burn intervals, for example, are implemented. We also identified gaps in the literature, noting that a majority of the available scientific data regarding the ecological impacts of LMS has been gathered on a small scale and over a short period. The existing information examining trade-offs between fire risk, biodiversity, ecosystem services, and other landscape management goals primarily relies on localized, short-term studies that often focus on specific aspects of biodiversity. However, the concerns and applications of this data primarily arise on a larger and longer-term scale. A landscape level examination of the cross-section between fire risk, biodiversity, carbon storage, water provision, and other ecosystem services for Europe is currently lacking. Development of such an assessment would contribute to targeted landscape planning to meet multiple goals concurrently. However, given the small scale focus of currently available data, resultant decision-making and actions require extrapolation to different scales and conditions, which must be handled carefully to minimize unintended outcomes.

5.3 Trade-offs

Fire risk management is part of the complex puzzle of land management in Europe. Returning fire to the landscape is a challenging prospect given the accumulation of fuels in some areas, a complex wildland

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urban interface, sensitive areas which need especially careful handling, shrinking natural areas to provide key ecosystem services, and the loss of many traditional management structures. Decisions on land management are unlikely to be able to fulfil all goals from all stakeholders in all areas. However, fire will appear in any management pathway we choose. The question is whether we plan for it or whether it takes us by surprise and devastates something we value, be it homes, ecosystems, or infrastructure. Incentive structures that aim to promote the use of the LMS must thus 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 LMS match the intended goals. 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) 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). Ensuring that LMS promote the long-term ecological value and resilience of ecosystems, while supporting their natural functioning, poses a challenge that requires careful monitoring, adaptive management, and a holistic approach. Consequently, striking the right balance that achieves fire risk reduction goals while minimizing negative ecological effects and gaining and maintaining stakeholder support presents a significant challenge.

6 Conclusion

This report synthesized the current knowledge on fire risk management in Europe through three commonly adopted LMS: herbivory (grazing and browsing); mechanical fuel removal; and prescribed burning. In the context of increased fire risk, our results serve as a basis for conceptualizing a broader fire risk strategy for Europe and prioritizing efforts and resources accordingly. Our study thus has policy implications for consideration at local, regional, and national scales in Europe. The LMS presented here offer no silver bullets, but rather require careful planning, monitoring, and sustained efforts for success.

The decision to use the LMS locally requires a thorough assessment of local factors, including costs and incentive opportunities, interest or opposition to the LMS by local stakeholders, and proper treatment of areas of high conservation value. Potential trade-offs between fire risk, biodiversity, ecosystem services, and unintended effects must also be carefully assessed for balanced decision-making. While LMS can effectively reduce wildfire risk, it is crucial to consider the long-term ecological value and the resilience of ecosystems to recurrent disturbances. Modifying vegetation structure, decreasing fuel loads, and altering disturbance regimes may have unintended impacts on ecosystem processes and dynamics. However, the risk of catastrophic fire to these same areas represents a distinct threat. Ensuring that LMS promote the long-term ecological value and resilience of ecosystems, while supporting their natural functioning, poses

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a challenge that requires careful monitoring, adaptive management, and a holistic approach. With these considerations in mind, LMS implementation can have positive outcomes, reducing the risk of severe fires and increasing biodiversity and other services. Finally, land management occupies only part of the solution of managing fire risk: mitigating climate change and reducing exposure at the wildland urban interface are simultaneously important. Still, our results represent a step towards more targeted and optimized responses to increasing wildfire risk in Europe.

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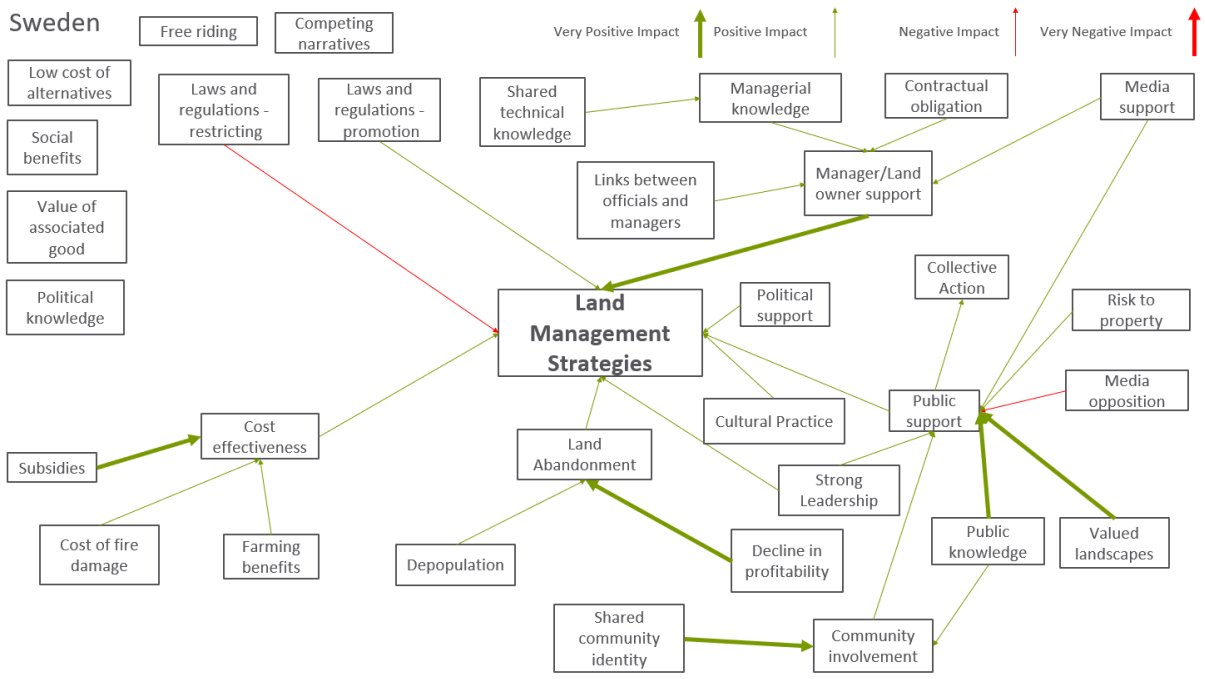
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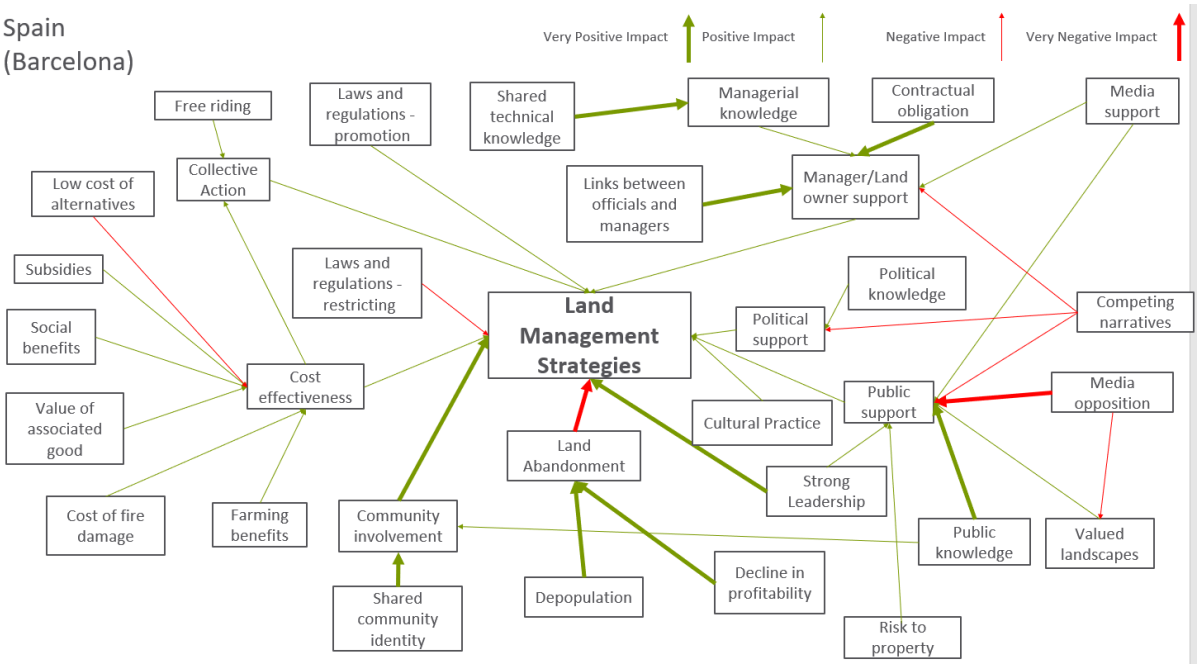
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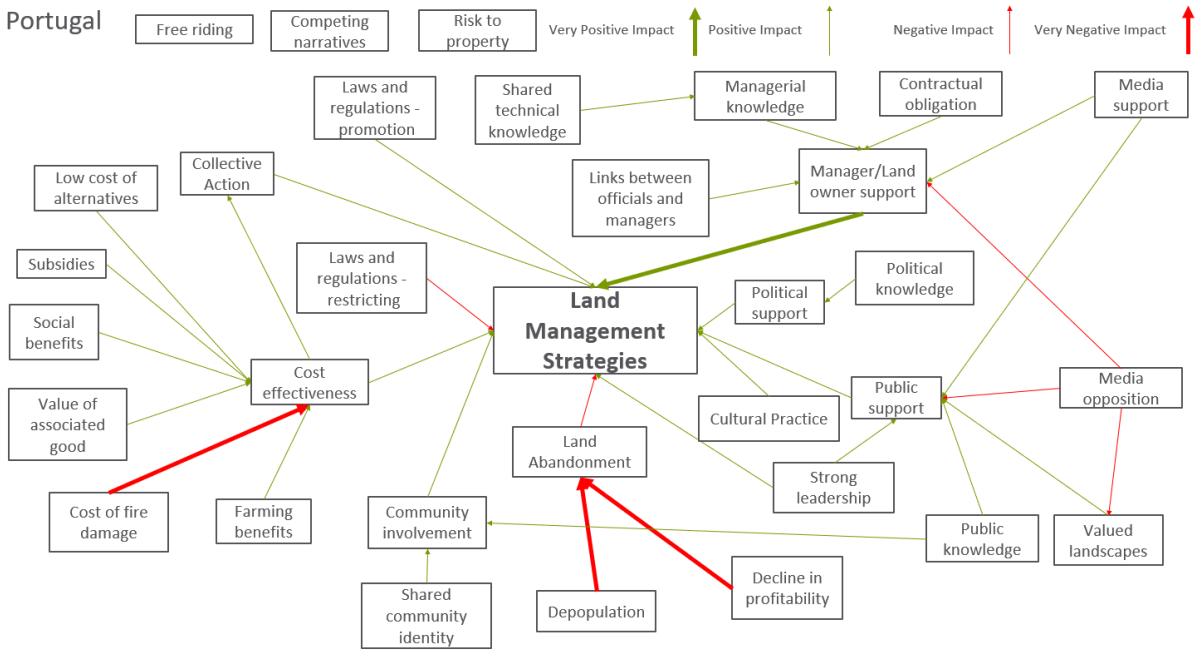
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8 Appendix One – Full FCM models



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