FIRE-RES

Innovative technologies & socio-ecological-economic solutions for fire resilient territories in Europe

D1.13 RECOMMENDATIONS AND NOVEL ADAPTIVE MANAGEMENT SCENARIOS TO CREATE RESILIENT LANDSCAPES TO EXTREME WILDFIRE EVENTS (Part II)

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Abstract:

Extreme Wildfire Events (EWEs) challenge conventional fire management approaches and call for integrated strategies that reduce vulnerability and foster resilient landscapes. This deliverable provides a set of recommendations to increase resilience, with a focus on stand-level interventions that can be applied across the wildfire cycle: before, during, and after fire. Three management scenarios are considered in detail: **low-productivity forests**, often not managed and prone to fire; **high-productivity forests**, where intensive management interacts with fire risk; and the **wildland–urban interface**, where protecting people and infrastructure is the priority.

The recommendations emphasize the importance of spatially planning stand-level treatments to reduce vulnerability to EWEs and adapting management to changing fire regimes. They highlight the need to tailor treatments to vegetation structure and composition, with defined thresholds for fuel structure, composition, and load to prevent EWEs. The specific management actions provided are structured around the wildfire cycle. In the **prevention phase**, the focus is on reducing fuel loads and designing vegetation structures less vulnerable to EWEs, using mechanical treatments (thinning, understory clearing, and slash management), fire use (prescribed burns and traditional fire use), and grazing. In the **suppression phase**, the focus is on the opportunities that unplanned ignitions burning under controlled conditions offer to achieve management goals and harness fire's ecological benefits. In the **recovery phase**, recommendations include supporting natural regeneration when possible, applying active restoration when necessary, and promoting vegetation and landscape structures adapted to future fire regimes.

Overall, this deliverable provides practical recommendations for creating resilient landscapes across Europe. While the strategies can be applied widely, they should be adapted to local ecological and socio-economic conditions to improve efficiency.

Key words: fire use, grazing, Integrated Fire Management, landscape planning, mechanical treatments, prescribed burning, vegetation restoration, wildfire management

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Table of contents

1. Introduction

The growing threat of Extreme Wildfire Events (EWEs) demands innovative, comprehensive solutions that reduce landscape vulnerability. This deliverable provides recommendations to increase landscape resilience, with a particular focus on stand-level management actions that can be applied **before, during, and after wildfire events**. At the **prevention phase**, actions focus on creating landscape and forest structures that are less vulnerable to EWEs; at the **suppression phase**, actions involve taking advantage of opportunities offered by unplanned ignitions burning under controlled conditions to achieve pre-defined management goals, and at the **recovery phase**, actions are targeted to promote or maintain landscape structures and vegetation adapted to the new conditions.

Among the many approaches to increase landscape resilience to EWEs, **Integrated Fire Management (IFM)** is increasingly recognized as an effective one. IFM is defined as a comprehensive framework that addresses the challenges, opportunities, and impacts of wildfires and prescribed fires by integrating social, economic, cultural, and ecological dimensions. The main goal of IFM is to minimize fire damage while maximizing associated benefits (Myers, 2006). Implementing an IFM approach involves to actively manage fires across the prevention, suppression, and recovery phases; leaving behind the traditional focus on suppression alone.

Thus, IFM requires promoting changes at landscape, policy, and governance levels. At landscape level, fuel management strategies reduce the risk of high-intensity and extreme wildfires occurrence. However, to efficiently implement innovative strategies at both local and landscape level, it is important to influence the decision-making process, engage stakeholders, and develop new legal frameworks that enable the application of an IFM approach (Oliveras-Menor et al., 2025; Stoof & Kettridge, 2022).

Implementing a successful IFM strategy involves understanding the prevalent fire regime of a given ecosystem. However, because **fire regimes are changing** and becoming more extreme, IFM strategies should be consciously monitored, analysed, and revised, and should be framed within an **adaptive management approach** (Myers, 2006).

IFM strategies do not necessarily aim to completely prevent EWEs, but rather to **minimize their impacts**. While fuels can be managed, EWEs are largely driven by atmospheric conditions that lie beyond our control. Therefore, IFM focuses on reducing vulnerability and limiting damage.

This deliverable aims to provide science- and expert-based **recommendations at landscape level through fuel management strategies** to increase landscape resilience to the growing threat of EWEs. Among the various components and dimensions of IFM, this deliverable emphasizes the integration of several management actions, including mechanical treatments, fire use (through prescribed burning, management of unplanned ignitions, and traditional fire use), and grazing, building on the foundations established by the FireParadox project (Silva et al., 2010) and expanded through the FIRE-RES project.

This deliverable provides recommendations for management interventions under different management scenarios that can be adapted and transferred across Europe, both in ecosystems that are already fire-prone and in those increasingly exposed to wildfire risk under changing climate and land-use dynamics. Their application, though, must always be adapted to the local conditions, as increasing resilience in flat versus mountainous terrain, in broadleaved versus conifer-dominated forests, or in patchy versus homogeneous landscapes requires differentiated approaches.

1.1. Resilient landscapes

A fire resilient landscape is "a socio-ecological system that accepts the presence of fire, whilst preventing significant losses through landscape management, community engagement, and effective recovery" (Thacker et al., 2023). The concept of resilient landscapes moves beyond the ecological considerations and encompasses the entire socio-ecological system, including physical, ecological, economic, and social dimensions, as described in Deliverable 1.1 of FIRE-RES Project (Castellnou et al., 2022). In this deliverable, the recommendations focus primarily on the physical and ecological dimensions, but because all dimensions are closely interconnected, changes made here will also influence socio-economic resilience.

Landscape resilience depends on both the type of ecosystem and the dominant fire regime that shapes it. For example, a fire-resilient landscape in the Mediterranean region differs greatly from a fire-resilient landscape in boreal regions or from one in the wildland-urban interface. Therefore, improving landscape resilience cannot be achieved by applying standardized practices everywhere. Instead, it requires strategies tailored to local conditions, ecosystem type, and fire regime.

In ecology, **resilience** is the ability of a system to recover its functions, structure, and services following a disturbance (Holling, 1973), while **resistance** is the ability of the system to persist during the disturbance (Tilman & Downing, 1994). From a forest management perspective, the definition of resistance and resilience depends on the spatial scale being considered (Derose & Long, 2014):

- At **stand level**:
  - **Resistance** is characterised as the influence of forest structure and composition on fire behaviour.
  - **Resilience** is characterised as the influence of fire behaviour on the subsequent forest structure and composition.
- At **landscape level**:
  - **Resistance** is the effect of the spatial configuration and composition of patches (e.g., fuel continuity, land cover diversity) on fire spread.
  - **Resilience** is the effect of the fire on the subsequent age class and species dominance distribution.

Building resilience is therefore a long-term strategy that aims to create a mosaic of land uses and maintain the desired vegetation structure and composition.

1.1.1. The spatial dimension of fuel and fire management

While stand-level treatments are important to manage fuels, they must contribute to the broader mosaic of land uses to build resilient landscapes. In this sense, the location of the treatments is crucial in both increasing landscape resistance and facilitating firefighting operations. Decisions on where, when, and how to apply treatments should be guided by knowledge of the prevalent fire regime and typical fire propagation patterns at a given area.

Strategic **landscape planning** is therefore essential. Even though landscape configuration and composition may have little influence on fire spread under extreme fire weather conditions (Cruz et al., 2022), strategically placing low-fuel areas can still slow fire growth, improve suppression opportunities, and reduce damage (Moreira et al., 2020; Valor et al., 2023b).

Planning should define the typology and schedule of fuel management actions and should cover **actions to be applied before, during, and after the fire**, ensuring that all interventions complement each other.

Fragmented landscapes tend to be more resistant to disturbances than homogeneous ones, where disturbances can propagate more easily (Turner et al., 1989), especially under mild to moderate fire weather conditions, but also under extreme conditions (see Deliverable 1.7, Acácio et al., 2023). However, under extreme fire weather, landscape structure becomes less important on fire spread patterns (Moreira et al., 2020) because the development and behaviour of an EWE is mostly driven by the atmospheric conditions created by the EWE itself rather than the fuel load and arrangement. Experience shows that EWEs can spread in areas with low biomass, as it is the atmospheric instability what propagates the fire (Castellnou, pers. comm.).

However, since fuel is the first element that feeds a wildfire and can cause it to escalate into an EWE, it is essential to manage it beforehand to prevent erratic and unexpected behaviour. **The goal is to keep fire fronts below the threshold that exceeds firefighting capacity**. The design of the landscape mosaic should therefore match the maximum fire front below the threshold that triggers an EWE.

Fire fronts wider than ~800 m (or greater than ~1 ha in surface) often escalate into EWEs, where fire behaviour is no longer governed by fuel availability, wind, and convective heat transfer but by the massive air movements generated by the fire itself. Once a fire front exceeds ~3 ha, its behaviour is mainly driven by compression-related energy from fire–atmosphere interactions (Castellnou, pers. comm.). For this reason, **the scale of the landscape mosaic should be designed relative to the maximum fire front that firefighting teams can reasonably control**.

1.1.2. Building resilience

Resilient landscapes can slow fire spread and intensity, improve suppression opportunities, and reduce ecological, economic, and social impacts. Building resilience entails an active landscape management across the three phases of fire: prevention, suppression, and recovery.

At the **prevention phase**:

- **Promote heterogeneity** in fuel distribution, structure, and arrangement.
- **Avoid large homogeneous landscapes** that allow fires to become extreme and unpredictable.
- Management actions should be **located where they can most strongly influence wildfire development**.
- Promote **long-term strategies**, such as carbon mitigation policies that slow temperature rise and reduce fire risk.

At the **suppression phase**:

- **Provide structural features** (at forest and landscape level) **and infrastructure** that facilitate firefighting.
- Design such forest structures and heterogeneous landscapes **in advance**, since operational flexibility is limited once an EWE develops.
- Allow **let-burn strategies** when conditions are favourable and pre-designed burn polygons are established. The successful experience in Vall d' Aran (see Oliveres et al., 2025) demonstrates that such strategies are feasible when administrations, practitioners, and local communities agree on predefined potential burning areas.
- **Let-burn strategies** may also be applied when suppression capacity is exceeded and prioritization is necessary. In such cases, decisions on which fires to suppress and which to allow to burn should be based primarily on suppression capacity and fire potential impact, but may also consider the ecosystem's value and ability to recover. Therefore, it may be advisable to allow burning in forest ecosystems that are more fire-adapted –those that are fire-resistant and resilient– while prioritizing suppression efforts in areas where fires would cause greater ecological damage or where recovery capacity is lower.

At the **recovery phase**:

- Support ecosystems with the intrinsic **capacity to regenerate after wildfire**.
- Use management actions to foster vegetation that is **adapted to the local fire regime**, such as assisted migration strategies.
- Apply **active restoration** actions through planting or seeding to re-establish vegetation cover and prevent soil erosion when vegetation cannot naturally recover. Restoration efforts should always be guided by a scientifically and

technically sound plan that clearly defines the objectives that justify active restoration, specifies techniques to be applied, and outlines measures for long-term system maintenance. Such a plan must address the fundamental questions of why, where, and how restoration will take place.

- Take advantage of the new conditions created by the fire and promote new, more resistant and resilient landscapes.

1.1.3. Adapting management to changing fire regimes

In the context of climate change and increasing disturbance intensity, adaptation is fundamental. Just as vegetation must adapt to the prevailing fire regime to resist and recover from a wildfire, **management practices and decision-making must adapt to local, changing conditions**.

When a particular management intervention is implemented, its impacts on the ecosystem should be **monitored** and **evaluated** over time. When vegetation development is aligned with the disturbance regime of the region, follow-up interventions can continue as planned. If not, alternative management practices or different timings should be considered.

Adaptation also requires acknowledging that ecosystems vary in recovery pace, which largely depends on the structure and dynamics of their vegetation communities. For example, highly productive forests (e.g., Atlantic temperate) recover faster than less productive ones (e.g., Mediterranean).

Finally, as global change shapes fire regimes, landscapes that are resilient today may not remain so in the future (Cochrane & Bowman, 2021). Therefore, **management interventions must be continuously reassessed and adapted to ensure that resilience is sustained under new changing conditions**.

1.2. Management scenarios

Management scenarios to create and promote resilient landscapes may vary depending on the ecological and socio-economic context. In Europe, with its broad and diverse contexts, management approaches to increase landscapes resilience must be tailored to local conditions and realities, making broad generalizations difficult.

In this deliverable, when we refer to management scenarios, we focus on three contexts:

- **Low-productivity forest areas**: Typically associated with Mediterranean climates and forest types. These are generally fire-prone areas where active forest management often lacks.
- **High-productivity forests areas**: Typically associated with more humid climates, including Atlantic regions, Central Europe, and boreal zones. While management is usually more intensive here and these areas tend to be more humid, wildfires can still occur, particularly in the Atlantic zone.

- **Wildland-urban interface areas**: Management actions are primarily designed to protect people, settlements, and infrastructure.

Despite the clear differences between these three contexts (see following sections), there is broad consensus that increasing landscape resilience requires the implementation of **fuel management strategies at both the stand and landscape levels**.

Within the main **stand-level fuel management strategies**, we find:

- **Mechanical treatments**: Thinning, clearing, and other mechanical interventions that reduce fuel load and rearrange fuels into structures less vulnerable to EWEs. Treatments can target both the overstory and understory vegetation, creating conditions that lower fire intensity and improve suppression opportunities.

- **Fire use**: Fire can be integrated into management through prescribed burning, managing unplanned ignitions, or supporting traditional fire practices. Fire reduces fuel accumulation and maintains landscape heterogeneity. Within FIRE-RES project, the fire use concept builds on the foundations established by the FireParadox project (Silva et al., 2010).

- **Grazing**: Promoting grazing and silvopastoral systems can contribute to maintain open landscape structures. At the stand-level, forest grazing after mechanical treatments, prescribed fire, or wildfires can be used to control the regrowth and abundance of fine fuels. In addition, wild and domestic grazing reduces treatment costs over time.

As previously mentioned, in practice, the **optimal fuel management strategy depends on regional ecological, physiographic, and socio-economic conditions**. For example, in low-productivity Mediterranean forests, where income from forest management in terms of wood products is low and traditional practices such as fire and grazing persist, a combination of fuel management methods can be a suitable option. However, in more productive and easily accessible Atlantic or boreal forests, where timber harvesting is economically viable and silvicultural treatments are more common, periodic mechanical fuel treatments may be more appropriate.

1.2.1. Low-productivity forest areas

Low-productivity forest areas are characterized by relatively slow tree growth due to factors such as poor soil fertility, unfavourable climatic conditions, or limited water availability. As a result, timber yields are low compared with areas with better ecological conditions. Because of their lower economic value in terms of timber production and the abandonment of traditional forest uses, these areas suffer a generalized abandonment and are **often not actively managed**. Despite this, they provide valuable ecological and ecosystem services –such as habitat, biodiversity conservation, water regulation, soil conservation, ecotourism, and non-wood forest products– and play a critical role in wildfire dynamics.

Due to the lack of forest management, these ecosystems tend to have **continuous canopy layers combined with dense understory vegetation**. The vertical continuity of fuels in such ecosystems often acts as a ladder, enabling surface fires to quickly transition into crown fires under suitable fire weather conditions. Similarly, the horizontal continuity of fuels allows fires to spread quickly, both through the surface or the canopy layers. An example of such areas are Mediterranean forests, where water availability is often the main factor limiting growth. In such regions, periodic droughts increase fuel availability, increasing the likelihood of large forest fires.

Because of this generalized lack of management, fuels accumulate over time and, under the right fire weather conditions, they can easily ignite, intensify wildfire behaviour, and contribute to its development into a high-intensity or extreme wildfire event.

Management in these areas should therefore focus on reducing fuel loads and creating vegetation structures that are less prone to high-intensity fires, alongside the restoration of agroforestry systems. However, the high costs of management and the limited economic return from harvested biomass often make large-scale active management unviable. In such cases, adopting an integrated approach that combines mechanical treatments, fire use, and grazing can be a good option, depending on the forest stand conditions and main management objectives. **Silvicultural treatments** (e.g., thinning, understory clearing) that provide forest structures more resistant to EWEs, should be incorporated into forest management guidelines (Piqué et al., 2017). Also, adopting a **let-burn strategy** under appropriate conditions may be an effective and cost-efficient way to reduce fuel load and continuity (Oliveres et al., 2025). Such approaches can contribute to long-term resilience, provided that fire weather conditions and fire propagation potential are carefully monitored. **Targeted grazing**, if possible with mixed herds (e.g, sheep and goats; sheep and cows), may also help reducing fuel load and continuity.

1.2.2. High-productivity forest areas

High-productivity forest areas are ecosystems with favourable climatic and ecological conditions that support significant vegetation growth, making them economically profitable. Because of their potential economic return, these areas are generally **subject to active management**, which influences their fuel structure and wildfire dynamics.

Examples of productive areas include temperate forests with Atlantic influence, which exhibit high growth rates, and boreal forests, which grow more slowly but are widely managed due to their extent and commercial value. In these systems, management interventions reduce understory and ladder fuels density.

In productive forests, **canopy layers are usually continuous, but understory vegetation tends to be sparse**, and relative humidity is often higher than in drier, low-productivity systems. These conditions have made them historically less fire prone. However, prolonged droughts and higher temperatures due to climate change are increasing the likelihood of fire ignition and spread. Once a fire is ignited, the accumulation of forest litter can lead to prolonged burning combustion, negatively impacting soil health and girdling trees.

Also, one of the main fire risks in productive forests stems from their forest **structural and species homogeneity** and continuous canopy cover. Although the distance between canopy and understory layer may be higher and surface fires may not easily transition to crown fires, once a crown fire has initiated, it can spread quickly across the continuous canopy layer.

Management in these areas should therefore serve multiple objectives, making emphasis on the integration of **productivity, wildfire prevention**, and **biodiversity conservation**. Strategies may include (i) diversifying forest structure and composition to break up continuous canopy layer and increase horizontal heterogeneity, through the implementation of silvicultural treatments and forest management guidelines, as well as (ii) designing landscape mosaics in a strategic way to disrupt fire spread and facilitate suppression. Unlike low-productivity areas, the use of let-burn strategies is more controversial in productive forests due to the potential loss of economically valuable resources. However, carefully planned fire use in specific, strategic zones may still be beneficial for improving resilience.

1.2.3. Wildland-urban interface

The wildland-urban interface (WUI) is the area where vegetation and human infrastructure meet. These zones occur across both low-productivity and high-productivity regions in Europe, but they are distinct because the close proximity of vegetation to human settlements makes wildfire management particularly critical.

With ongoing rural abandonment and demographic shifts towards more urban areas, WUI are expanding (Guo et al., 2024). Houses are increasingly located near or within forested areas, often without adequate fire safety planning. This type of expansion increases wildfire risk to people, making the WUI one of the most pressing challenges in integrated fire management (Jenerette et al., 2022).

Vegetation in the WUI is diverse in structure and composition, from dense forests to open shrublands, but the common characteristic is the close **exposure of human lives and assets to wildfire**. Management here should prioritize safety and risk reduction over economic or ecological objectives. There are several guidelines for fire-prevention in the wildland-urban interface across Europe, since most of the fire-prone regions have developed them (DGPEIS, 2024). In general terms, best practices include:

- Ensuring a minimum distance (25 to 30 m) between houses and the forest edge. The established distance depends on the legal framework in force in each country or region.
- Reduce vertical and horizontal vegetation continuity at the forest edge.
- Promote urban planning that minimizes vulnerability to wildfires.
- Promote the establishment of green areas and low flammability and combustibility gardens (i.e., using plant species less prone to ignition and creating vegetation structures that reduce fire spread). An example of a technical guide on pyrogardening, available in Spanish, can be found at:

https://interior.gencat.cat/web/.content/home/030_arees_dactuacio/bombers/foc_forestal/publicacions_tecniques_i_normativa/guies_tecniques/prevencio_i_extincio/2020_Guia_de_pirojardineria_es.pdf

- Promote construction solutions that provide fire-resistant building and materials.

When such measures are not implemented, wildfires in WUI areas may easily translate directly into human fatalities and property loss. For this reason, the WUI requires strict guidelines and continuous monitoring, with fuel management strategies adapted to local conditions but always prioritizing human safety.

1.3. Barriers for increasing resilience to EWE at the different scenarios

Increasing landscape resilience to EWEs faces a series of barriers that differ depending on the type of ecosystem and local context. These barriers include technical, economic, social, and legal dimensions, and may vary across low-productivity areas, high-productive areas, and the wildland–urban interface (WUI) (Table 1).

Although barriers are context-specific, a few general obstacles exist:

- **Resistance to change:** Shifting from traditional practices or business-as-usual approaches is often difficult and requires coordination across multiple levels.
- **Economic and technical constraints:** Some management interventions, such as fuel reduction through mechanical tools or prescribed burning, may not be economically viable without sustained funding or technically feasible in specific areas.
- **Climate change:** It increases drought pressure, extends growth period in some areas while constraints growth in others, shortens the prescribed burning window, and creates extreme fire weather conditions, limiting opportunities for planned interventions. Additionally, fire regimes may change faster than current management can adapt.
- **Novel disturbance regimes:** New or compounded disturbances (e.g., insect outbreaks or drought followed by wildfire) can produce unprecedented vegetation responses, complicating recovery after the disturbance.
- **Social barriers:** Public risk perception and limited experience with fire use can hinder the adoption of prescribed burning or let-burn strategies, especially in areas historically not exposed to active fire management.
- **Legal limitations:** Lack of clear regulatory legal frameworks for integrated fire management limit its implementation.

Table 1. Specific barriers for increasing resilience to EWEs. Based on McWethy et al., 2019, Nebot et al., 2024, and Oliveras-Menor et al., 2025.

Barrier	Low-productivity areas	High-productivity areas	Wildland-urban interface
Economic	High costs of management with limited economic return; fuel treatments may not be economically viable, need of added value forest products.	Must balance economic objectives (timber, biomass) with wildfire prevention; wildfire prevention interventions may reduce revenue.	Costs of protective measures (fuel breaks, defensible space) can be high; property protection prioritized.
Technical	Dense canopy and understory; difficult access	Homogeneous canopy structures; high productivity may require more frequent interventions.	Complex landscape with mixed vegetation and settlements.
Climate change	Increased droughts and extreme weather can exacerbate fire risk.	Rising temperatures and droughts increase historical ignition risk.	Increased droughts and extreme weather can exacerbate fire risk.
Social	Public acceptance of let-burn or prescribed fires may be low.	Stakeholder conflicts between economic use and fire prevention.	Public safety concerns dominate; coordination with residents and authorities is critical but complex.
Legal	Lack of legal frameworks for implementing proactive IFM strategies; let-burn or controlled fires may face restrictions.	Lack of legal frameworks for implementing proactive IFM strategies; let-burn or controlled fires may face restrictions.	Strict safety regulations; prescribed burning near settlements is heavily restricted.

2. Recommendations to increase resilience

Fuel management is the basis to increase landscape resilience to EWEs. Fuel reduction is often the main objective of wildfire prevention treatments, which include both mechanical and fire treatments as well as silvopastoralism with the introduction of livestock or improving conditions for wildlife grazing. To evaluate how different management treatments affect landscape resilience to EWEs, two main aspects need to be considered: (i) fuel characteristics and (ii) vegetation traits, including adaptation and regeneration strategies.

Moreover, to increase forest and landscape resilience to EWEs, it is necessary to plan interventions considering two fundamental factors:

- **Location of treatment**: Finding the optimal location of the treatment is crucial to increase treatment efficiency. Treatment location is planned at **landscape level**, based on the heterogeneity of the landscape as well as the prevalent fire type and its main spread pattern.
- **Type of treatment** to reduce vulnerability and fire severity. The choice of treatment is planned at **stand level**, based on the structure and composition of the stand.

Management treatments to reduce fuel load and prevent the spread of EWEs are determined according to their **location in a strategic area** that will either facilitate firefighting operations or will contribute to reduce the fire intensity because of its structure.

The decision on where to locate the treatment must be based on landscape planning objectives and the fire regime of the region, i.e., the potential spread pattern and intensity of the wildfire based on the Fire Type concept (Costa et al., 2011).

Both location and type of treatment are highly influenced by the prevalent wildfire spread pattern of the region. Wildfires are classified according to their main spread pattern and the dominant factors that influence fire behaviour (Piqué et al., 2011):

- **Topographic wildfires**: Wildfires driven by local topographic winds, fuel heating, and slope.
- **Wind-driven wildfires**: Wildfires driven by wind speed and direction.
- **Convective wildfires**: Wildfires driven by the high accumulation of available fuel.

For all wildfires, the amount of fuel available is an important factor, but it is those areas where a potential wildfire will be a convective fire, where fuel management matters the most.

The spread of non-extreme wildfires is usually determined by fuel availability, weather conditions, and topography, and the fire front typically advances in a relatively steady manner. In contrast, in EWEs, the **fire couples with the atmosphere**, creating a fire-atmosphere system that drives the fire front forward in intermittent bursts or pulses, rather than as a continuous front.

2.1. Landscape planning

Landscape planning is a cornerstone of wildfire prevention and resilience building. While it is based on several factors that vary locally, a common element across regions is the identification and maintenance of **Strategic Management Points (SMPs)**.

SMPs are placed where fuel modification or infrastructure development significantly improves the safety and efficiency of suppression operations. SMPs are identified by doing an in-depth analysis of both the terrain and the main wildfire spread patterns (Fire Potential Polygons, see Deliverable 1.3, Arilla et al., 2023), which describe the expected movement of fire in a given area. Importantly, SMPs must be established and maintained before the wildfire takes place.

The main objectives of identifying and maintaining SMPs are (Costa et al., 2011):

- **Reduce wildfire activity** by limiting wildfire intensity and spread and preventing crown fires.
- **Confine ignitions** and **protect vulnerable areas**.
- **Facilitate access** by providing anchor points for technical operations.

Although SMPs cover only a relatively small fraction of the landscape, enhancing overall landscape resilience requires management planning at the scale of the entire landscape.

Management options depend on local conditions such as land-use type, property, legal frameworks, accessibility, labour costs, etc. To guide decisions, it may be useful to carry out a **suitability analysis** to find the most appropriate management approaches for a given region. Such an analysis considers multiple factors, including pasture quality, domestic or wild herbivores presence, accessibility, slope, forest biomass, proximity to biomass facilities, and length of prescribed fire season. Together, these factors help determine whether **mechanical treatments, prescribed fire, grazing, or a combination of these approaches** are the most effective and feasible option (Neidermeier et al., 2023).

Simulation models may also be useful for planning treatments at landscape level because they allow managers to predict and evaluate potential outcomes beforehand. For example, potential fire behaviour can be assessed under different scenarios using simulation models where the effect of different combinations of treatments can be evaluated (Vilà-Vilardell et al., 2023).

Landscape planning is structured across three interconnected levels:

- **Strategic planning** (long-term, >20 years): High level planning that sets the overall vision, strategies, and objectives for a landscape area over the long term.
- **Tactical planning** (mid-term, 5-20 years): It translates the strategic goals into practical actions, i.e., sets a roadmap for where, when, and how strategic goals are obtained in the mid-term (5-20 years). It is based on priorities, available resources, and site conditions.

- **Operational planning** (short-term, <5 years): Detailed plans with concrete instructions that guide specific management interventions in the short-term.

2.2. Fuel parameters and thresholds

Fuel structure, composition, and **load** are the **stand-level characteristics** that determine wildfire behaviour (i.e., the intensity and severity of the wildfire). Together with topography and weather, they influence whether an ignition remains a surface fire or develops into a high-intensity or extreme wildfire. At the **landscape scale, fuel connectivity** and **land-use type** further regulate fire spread and severity (Figure 1, from Deliverable 1.11, Valor et al., 2023b).

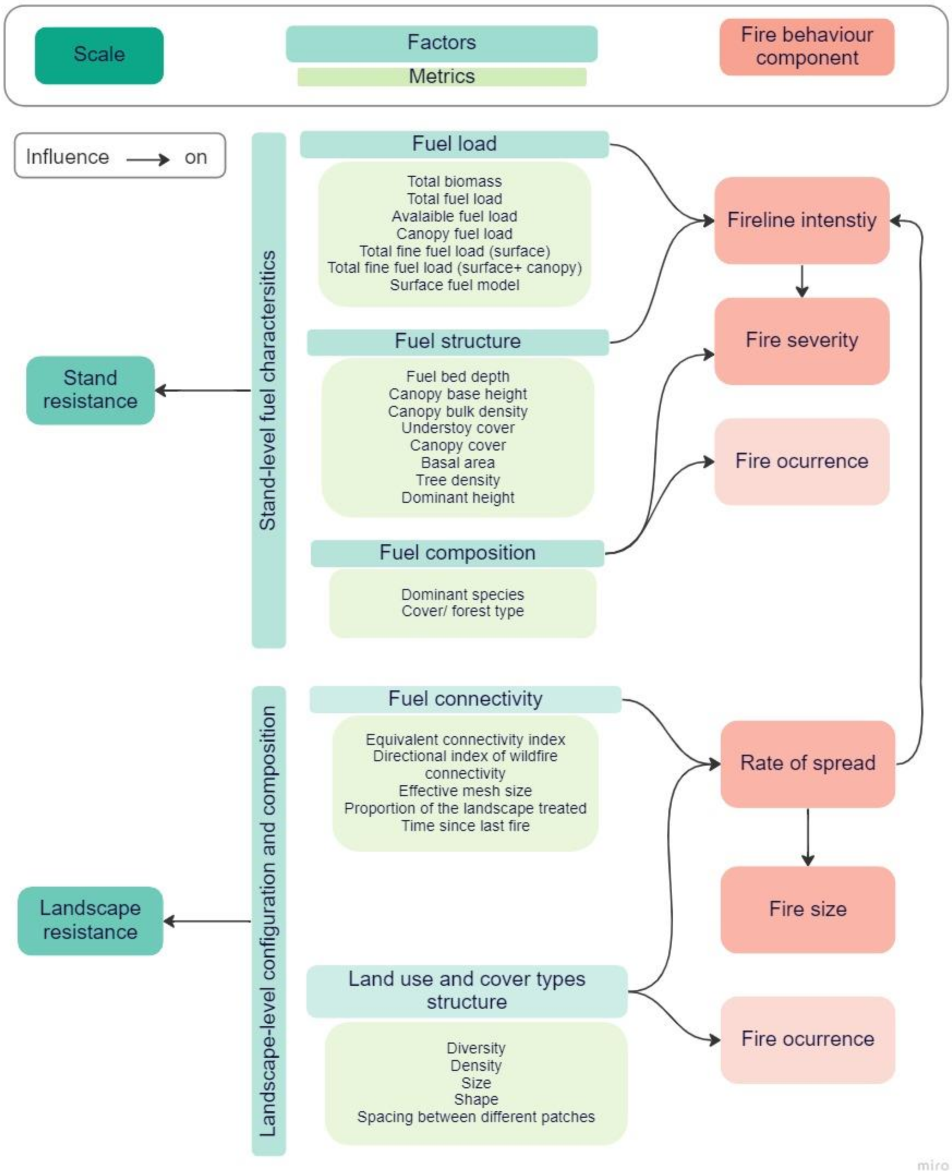

Figure 1. Schematic representation of the factors and metrics that influence stand and landscape resistance to wildfires, and the components of fire behaviour that are influenced by these factors. From Deliverable 1.11 (Valor et al., 2023b).

2.2.1. Fuel structure and composition

Fuel structure and composition characterise the fuel type, including species identity, the vertical and horizontal arrangement of fuels, and fuel size, height, and compactness. Fuel structure and composition, along with topography and climate conditions, determine fire behaviour and the potential for crown fire initiation or EWE development. Key attributes include:

- **Fuel size**: Fine fuels (< 6 mm) dry rapidly, ignite quickly, and drive fire spread. In contrast, coarse fuels (> 7.5 cm) burn more slowly but sustain combustion and may have greater impact on soil or trees.
- **Fuel arrangement**:
    - *Vertical continuity*: It determines the likelihood of crown fire initiation. Ladder fuels and low canopy base heights promote transition from surface to crown fires.
    - *Horizontal continuity*: It determines fire spread, both for surface and crown fire. Dense, continuous canopies promote crown fire spread, while open canopies reduce lateral spread but dry understory fuels faster.
- **Developmental stage**: Forest age (regeneration, young, or adult) influences forest structure and thus, fire behaviour. Mature stands often have higher crowns and thicker bark, making them less susceptible to crown fire initiation and tree mortality.
- **Vegetation composition**: Species with high resin content ignite more readily and are more flammable.

In forests, several structural thresholds are associated with the likelihood of crown fire initiation and spread (see Deliverable 1.11 for details, Valor et al., 2023b):

- **Canopy bulk density (CBD)**: It is a measure of how dense the canopy layer is. Above **0.08 kg m^{-3}**, active crown fire spread becomes likely (Botequim et al., 2019; Gómez-Vázquez et al., 2014).
- **Canopy base height (CBH)**: Stands with tall trees and high canopies are less prone to initiate a crown fire. A minimum **4 m** distance between surface and canopy layer is recommended to reduce crown fire initiation (Piqué et al., 2011).
- **Basal area**: *Pinus radiata* and *P. pinaster* stands with basal area above **14.7 m^2 ha^{-1}** (extreme conditions) or **32.5 m^2 ha^{-1}** (moderate conditions) can sustain active crown fires (Fernández-Alonso et al., 2013).
- **Density and canopy cover**: Stands with **< 500 trees ha^{-1}** and low horizontal continuity of the canopy layer are less likely to sustain active crown fires (Alvarez et al., 2012) but allow faster drying of surface fuels. In contrast, maintaining a moderately closed canopy cover (**~70%**) prevents a fast recovery of the understory vegetation and maintains higher humidity, reducing ignition potential.

To build such structures, characterise the stand vulnerability to high-intensity or extreme wildfires, and select the optimal treatment for a given area, these are the specific parameters at stand level that should be measured (Piqué et al., 2011):

- **Fuel type**: Identification of the primary carrier of surface fire (grass, shrubs, litter, slash)
- **Surface fuel cover**: Percent cover of the surface fuels.
- **Surface fuel height**: Mean height of understory vegetation. It should not exceed 1.3 m.
- **Ladder fuel cover**: Percent cover of ladder fuels.
- **Canopy cover**: Percent cover of the canopy layer.
- **Distance between surface and ladder fuels**: Distance from the upper surface fuels to lower ladder fuels.
- **Distance between ladder and canopy fuels**: Distance from the upper ladder fuels to lower canopy layer.

Based on these metrics, stands can be classified into three crown fire vulnerability types (Table 2, Figure 2, see Piqué et al., 2011 for details).

Table 2. Crown fire vulnerability classification and related fire behaviour.

Vulnerability	Characteristics	Fire behaviour
High	Continuous vertical fuel continuity, variable ladder fuel cover.	Active crown fires are likely; surface fire generates enough heat to sustain canopy spread even under mild conditions.
Moderate	Variable ladder and canopy cover; vertical continuity inconsistent.	Torching and secondary ignition points occur; some crowns burn passively but spread is not continuous.
Low	Vertical discontinuity between fuel layers; variable ladder fuel cover.	Fire remains at surface level; crowns are generally unaffected under moderate conditions.

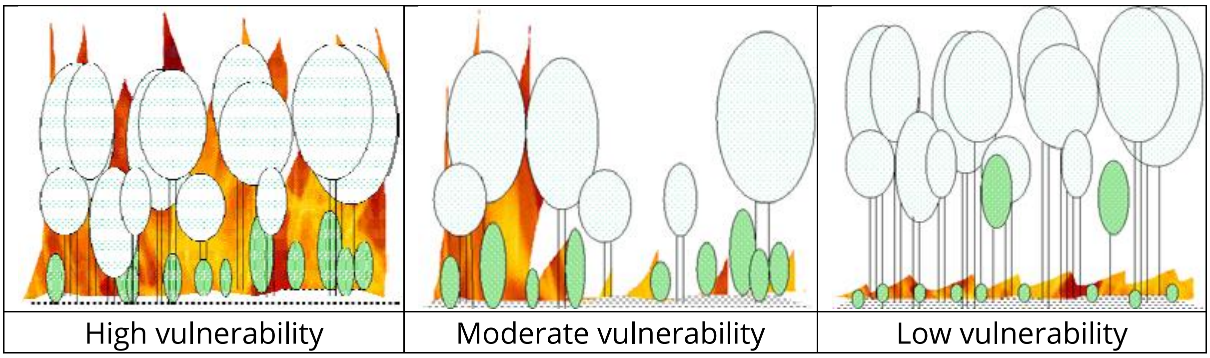

Figure 2. Crown fire vulnerability classification as a function of forest structure.

This classification helps determine the optimal type of prevention measures. However, it is important to note that under extreme fire weather, **the vertical distance between fuel layers is not the main driver** of crown fires and fire spread; instead, **fire-atmosphere energy dominates**.

Particularities of extreme wildfire events:

During an EWE, **dense or closed canopies tend to slow the advance of the fire more than open canopies**. Unlike non-extreme fires that spread steadily, EWEs couple with the atmosphere, producing bursts or pulses of rapid fire spread driven by compression-related energy release. **Closed canopies** may dampen these pulses, slowing fire spread (Castellnou, pers. comm.).

Although precise thresholds of resistance to EWEs are not fully established, the thresholds to prevent high-intensity wildfires are increasingly well documented. Table 3 shows the thresholds for the main factors at stand and landscape level in order of importance (most to least important) (see Deliverable 1.11, Valor et al., 2023b).

Table 3. Summary of the main factors, metrics and thresholds influencing resistance to high intense wildfires and extreme wildfire events. From Deliverable 1.11 (Valor et al., 2023b)

Scale	Resistant factors	Metrics	High intensity wildfires threshold	Fire behaviour component influenced
Stand	Fuel load	Fine fuel load ($t\ ha^{-1}$)	10	Fire intensity and severity
Stand	Horizontal continuity	Canopy bulk density ($kg\ m^{-3}$)	0.05-0.1	
		Canopy cover (%)	70-80	
		Basal area (m^2 ha)	20	
		Understory cover (%)	30	
Stand	Vertical continuity	Canopy base height (m)	7	
Landscape	Fuel connectivity	Time since last fire (years)	9	Fire spread
		Landscape treated in strategic locations (%)	20	
		Effective mesh size[1] (ha)	*Not available*	Fire spread
Stand	Fuel composition	Dominant species	Conifers and shrublands > broadleaves	Fire severity

[1]Average size of the area that a randomly located fire will burn in a fuel type without encountering a barrier or other fuel type (see Fernandes et al., 2016).

2.2.2. Fuel load

Fuel load refers to the amount of live and dead fuel per unit area that can potentially burn. It is classified by size class, layer (ground, surface, ladder, canopy), and condition (live or dead). The size class of the fuel particle determines its readiness to burn and contribution to propagate the fire:

- The main parameter that determines fire spread and intensity is the **fine fuel load**, as fine fuels are the easiest to catch fire and propagate it.
- In forested areas, fuel loads interact with stand structure: even moderate loads can lead to EWEs if canopy connectivity is high.

When **fine fuel load exceeds 10 t ha^{-1}**, under extreme weather conditions, ignitions may escalate into EWEs (Burrows et al., 2000; Fernandes et al., 2016).

2.2.3. Management implications

Considering the abovementioned parameters and thresholds, to limit the potential for EWEs, management treatments should:

- **Reduce ladder fuels** and **increase the distance between canopy and surface fuels** to prevent crown fire initiation.
- **Manage stand density** and **canopy cover** to balance moisture retention with reduced horizontal continuity.
- **Promote structural heterogeneity** at stand and landscape level to create mosaics that slow fire spread and reduce fire-column stability.
- **Prioritize reducing fine fuel loads** in all layers of the system and especially in areas of high fire risk.
- **Tailor interventions to the local management scenario**:
    - *Low-productivity areas*: costly to treat mechanically; grazing and let-burn strategies may be combined.
    - *High-productivity areas*: periodic treatments (thinning + prescribed fire) are justified due to higher fuel accumulation rates.
    - *Wildland–urban interface (WUI)*: fuel load reduction should be strict and continuous, particularly within the first 30–100 m of settlements.

Finally, it is important to consider that the parameters discussed above describe the **resistance** of the system to EWEs. That is, these are factors that reduce the likelihood of EWE occurrence or that slow its development, creating opportunities for suppression. Yet, because these parameters also influence fire severity –the above and belowground organic matter consumed from fire (Keeley, 2009)–, they provide indirect insights into **resilience**. While resilience cannot be fully characterized through these parameters alone, to obtain the full picture, it is also necessary to consider the traits that allow plants to survive or recover after a wildfire.

2.3. Recommendations for fuel management

The main management goals to increase landscape resilience to EWEs are the following:

- **Prevent ignitions**: Maintain canopy cover (~70%) to keep understory humid.
- **Limit fire intensity**: Reduce total fuel loads, particularly fine fuels.
- **Break vertical continuity**: Remove ladder fuels and raise canopy base height.
- **Break horizontal continuity**: Thin dense stands and create landscape mosaics (Figure 3).
- **Determine mosaic patch size**: Mosaic patch size and arrangement affect fire column stability and fire spread, but how exactly they influence fire is not well understood; further research is needed to determine the optimal patch size to prevent EWEs (Castellnou, pers. comm.).

Figure 3. Landscape mosaic with patches of forest, pastures, and houses (Catalan Pre-Pyrenees, Spain).

These structures should be created before the fire event; however, opportunities to establish or maintain such structures also exist during and after the fire. In the following sections, detailed management recommendations are given, organized according to their implementation phase relative to wildfire: prevention, suppression, and recovery (Table 4).

The specific management actions required to achieve these structures depend on factors such as dominant vegetation, terrain, accessibility, tools available, and other management objectives targeted.

Table 4. Recommended management actions according to their implementation phase relative to wildfires.

Fire prevention phase	Fire suppression phase	Post-fire recovery phase
Mechanical treatments	Wildfire management	Natural recovery
Fire use		Active restoration
Grazing		

2.3.1. Prevention phase

The primary objective of wildfire prevention is not to eliminate fire from the ecosystem, but rather to create forest and landscape structures that are less vulnerable to high-intensity and extreme wildfires. By reducing fire spread and severity, these structures also prevent fire behaviour from exceeding the suppression capacity of firefighting teams. For example, in Catalonia, **suppression capacity is surpassed when flame lengths are higher than 3 m or fire spread exceeds 2 km h^{-1}** (Costa et al., 2011).

When planning treatments to avoid EWEs, it is important to consider that EWEs differ from other wildfires in several ways. First, **they do not require continuous fuel cover to spread**, as they can start independent fires by long-distance spotting or the collapse of the fire column under extreme conditions –driven by the compression energy of the fire-atmosphere system. Second, under extreme fire weather conditions, **vertical continuity of the fuels plays a minor role**, as the transition from surface to canopy is driven by fire-atmosphere coupling rather than by ladder fuels (Castellnou, pers. comm.).

Although EWEs are less sensitive to fuel load than other wildfires, managing forest stands remains crucial to reduce the likelihood of extreme events. In forests, crown fires are more likely to develop into EWE than surface fires; therefore, treatments that prevent crown fires also contribute to prevent EWEs.

Key management actions to reduce forest vulnerability to high-intensity wildfires are (Agee & Skinner, 2005):

- **Reduce surface fuel load**: It reduces fire intensity and flame length.
- **Reduce ladder fuels** and increase distance between surface and canopy layer: It prevents fire from jumping to the canopy layer.
- **Reduce canopy cover**: It reduces the likelihood of active crown fires. However, it increases light and wind penetration so surface fuels dry faster.
- **Keep large mature trees**: Their canopies are higher and they have thicker bark.

In the following sections, detailed recommendations for different treatment types including mechanical treatments, fire use, and grazing are provided, tailored to local conditions and prevention goals.

2.3.1.1. Mechanical treatments

Recommendations for mechanical treatments are presented separately by type of treatment. These approaches can be applied individually or in combination, depending on management objectives. In areas of high fire risk, integrating all three treatments (or two in shrubland systems) is strongly recommended.

Thinning

The main purpose of thinning is to remove overstory trees to improve growing conditions for the remaining ones, allowing them to reach more mature stages, while also reducing vertical and horizontal vegetation continuity.

- **Reduce stand density**: Apply light or moderate thinning that maintains a rather closed **canopy cover (~70%)** while still reducing competition among trees. Such canopy structures slow understory growth while keeping relative humidity below canopy high. Importantly, **close canopies dampen the pulses that drive rapid fire spread during an EWE** (Castellnou, pers. comm.). In plantations, establishing a lower-density strip as a buffer may be desirable to reduce fire intensity and prevent the spread of flames into the plantation (CONAF, 2022).
- **Increase canopy base height**: Stands with higher crowns and a greater distance between surface and canopy layer (**~4 m**) are less likely to initiate crown fires (Piqué et al., 2011).
- **Retain the largest, most vigorous trees**: They have higher crown base height and thicker bark, which reduces crown fire initiation and increases the likelihood of surviving.

It is important to note that more light and wind through the canopy can dry surface fuels and increase spread rates under certain conditions –especially during extreme wind events– so thinning must be paired with surface and ladder fuel removal. In addition, thinning increases light availability at the forest floor, promoting vegetation regeneration. While this supports sustainable, natural forest dynamics, it can also accelerate fuel accumulation, potentially counteracting the benefits of reduced fuel load.

Understory clearing

The main purpose of understory clearing is to reduce potential fire intensity and, in forested areas, increase distance between canopy and surface layers to prevent crown fire initiation. In forests, it refers to clearing both surface and ladder fuels, while in shrublands, it only refers to surface fuels.

- **Reduce understory cover**: Remove ladder and surface fuels selectively, to preserve ecosystem functions and biodiversity. Patchy treatments are preferred. The final understory cover can go **from 15-20% to 100% cover**, depending on the stand development and distance between understory and canopy base height (Piqué et al., 2011).
- **Increase distance between canopy and surface layer**: Target a minimum distance of **4 m to minimize torching** (Piqué et al., 2011).

- **Retain or favour species** that increase forest resilience (e.g., fire-adapted, lower flammability, ability to resprout) and promote biodiversity.

Note that in shrublands, the same recommendations apply except for the reduction of the vertical continuity.

Slash management

The main purpose of slash management is to reduce the fine dead fuels following a mechanical treatment (thinning or clearing). The slash generated after treatments increases dramatically the risk of high and extreme wildfire events, both in forests and shrublands. When managed properly, it can improve soil microclimate or serve as a refuge for fauna and regeneration (Bunnell & Houde, 2010).

- **Lop and scatter**: Fuel particles thicker than 5 cm should be cut in smaller pieces to a **maximum of 1 m** to improve soil contact and decomposition (Figure 4; Beltrán et al., 2018).
- **Build piles**: Slash piles **should not be higher than 50 cm**. However, in some cases where fire risk is particularly high, it may be more convenient to set a maximum height of 30 cm, as is the case for *Pinus halepensis* (Beltrán et al., 2011). Slash piles should not be placed nearby streams or areas that are easily waterlogged but on logging tracks to protect soil and avoid compaction (Figure 4; Thompson et al., 2009). Avoid leaving debris or cut logs at the base of remaining trees that would be girdled by prolonged combustion in a surface fire.
- **Mastication**: Mastication might be appropriate when smaller particles are wanted to speed up their decomposition and incorporation into the soil (Figure 4). Masticated fuels create a densely compact fuelbed that often reduces intensity and spread, but it can sustain long-lasting smouldering combustion with severe impacts on soil health (Kreye et al., 2014).Figure 4

Figure 4. From left to right, lop and scatter, slash piles, and masticated fuels (Catalonia, Spain).

2.3.1.2. Fire use

Fire use is increasingly recognized as an essential tool for reducing wildfire hazard and restoring fire-adapted ecosystems. While legal frameworks and planning instruments differ across countries, there is broad agreement that fire management must be integrated across sectors (forestry, agriculture, civil protection) and scales (stand to landscape).

At the **landscape level**, research shows that to effectively limit wildfire extents, managers should **treat >5% of the landscape annually**, considering the spatial pattern and strategical location of prescribed burning treatments (Fernandes, 2015). In Catalonia, for example, strategically applying prescribed burning or managed wildfires over **15,000 ha yr^{-1}**, with a treatment frequency of **8-10 years** would provide an effective baseline for wildfire prevention (Alcasena et al., 2018; Duane et al., 2019).

Prescribed burning

Prescribed burning generally aims to reduce wildfire hazard, but it can also serve to enhance biodiversity conservation or improve pasture quality in rangelands.

Prescribed burning is generally a **low- to- moderate intensity fire** (Figure 5) that is carried out under specific weather and fuel conditions to attain clearly-defined management objectives, known as the burning window (air temperature, relative humidity, wind speed, live and dead fuel moisture). In forests, prescribed underburn is usually implemented in fall or spring.

- **Fall burns**: They may be more intense, since fuels tend to be drier after summer drought; understory recover is slower (Casals et al., 2018).
- **Spring burns**: They are less intense than fall fires, but are related with higher tree mortality because they are conducted during periods of active growth (Valor et al., 2017).

The burning window defines the weather conditions under which prescribed burning can take place, which depends on the type of burning applied (Table 5).

Table 5. Burning window conditions for different types of prescribed burning treatments. Adapted from Fernandes & Loureiro (2010).

Type of burning	Windspeed	Relative air humidity	Air temperature	Remarks
Slash burning	5-25 km h^{-1}	40-80%	Under trees, <22 °C No trees, indifferent	High litter moisture content to prevent soil damage
Direct underburning	5-25 km h^{-1}	30-65%	<22 °C	Preferably in fall to reduce undesired tree mortality

with abundant understory				
Direct underburning with scattered understory	< 5 km h^{-1}	30-90%	<22 °C	When litter layer is thick
	5-15 km h^{-1}	25-55%	<22 °C	When main fine fuel are herbs
Shrublands, grasslands	< 20 km h^{-1}	35-90%	Indifferent	When main fine fuel are herbs
		30-70%	Indifferent	In other cases

To **minimize soil heating** and protect regeneration, burns should be conducted when **duff moisture >30%** (Mäkipää et al., 2023), as moisture prevents soil temperatures from exceeding 95 ºC (Certini, 2005).

Figure 5. Direct prescribed burning in a Pinus nigra forest (left) and slash burning in a Pinus uncinata forest (right) (Catalonia, Spain).

To conduct prescribed burns, a few operational requirements need to be considered:

- **Preparing the burn**: Removal of vegetation to prevent controlled fire to spread across a defence line.
- **Determining ignition pattern**: Should be selected according to objectives and safety of the burn (weather conditions, topography, and fuel load) (Table 6).

Table 6. Common ignition pattern types and their characteristics.

Ignition pattern	Description	Advantage
Backing fire	Ignited on the downwind side or upper slope, usually as a single line of fire.	Uses gravity; fire moves downslope in a controlled manner; increases safety and control.

Strip-head fire	Ignited as a series of lines spaced out from one another, perpendicular to the direction of the wind or slope.	It allows for a high degree of control over the fire's intensity; commonly used on forested burn units.
Point source	Ignited as individual dots of fire spaced out from one another.	It consumes less drip torch fuel and can reduce the overall intensity of fire behaviour.

Traditional fire use

Traditional socio-cultural burning serves as a key tool for management in various regions. Historically, in Europe, fire use shaped landscapes by maintaining grazing lands, reducing agroforestry residues, and supporting game management (Rego et al., 2010). Traditional burning must be conducted under legal regulations and best practices based on **historical know-how**.

Although traditional fire management remains common in some European regions (e.g. northern Britain, Nordic countries, Western Pyrenees), in many areas its use has reduced due to stricter regulation and land-use change (Oliveras-Menor et al., 2025).

Integrating traditional fire use into the Integrated Fire Management (IFM) strategy is essential, as excluding it would neglect the important ecological impacts these fires have on ecosystems. **Regulated** and **knowledge-based use** should be promoted under legal frameworks and best-practice guidelines.

2.3.1.3. Grazing

By consuming herbs, leaves, and twigs, wild and domestic grazers and browsers play a valuable role in reducing fine fuel within agricultural and forest landscapes. However, to effectively contribute to building fire-resilient landscapes, **grazing must be strategically targeted**.

The effectiveness of grazing to maintain fuel biomass below critical thresholds for fire prevention **has been widely demonstrated across the Mediterranean Basin** (e,g., Etienne et al., 1990; Pardini et al., 1993; Rigolot et al., 2002; Ruiz-Mirazo et al., 2009; Figure 6), although an increase of fire risk has occasionally been reported after cattle grazing due to the proliferation of unpalatable species (e.g., Williamson et al., 2014). Large herbivores influence both composition and structure of vegetation, and their impact depends on several factors: species type and behaviour, diet preferences, grazing intensity, and timing. Using mixed herds with different dietary requirements can help manage less palatable species. However, grazing is generally more effective when preceded by forest management interventions –such as shrub clearing or prescribed burning– to improve accessibility, ensure the availability of fine forage, and control vegetation that animals would otherwise reject.

Pastoralism is a **cost-efficient tool** for reducing wildfire risk and conserving biodiversity (Casals et al., 2009) especially when embedded in **a multipurpose agrosilvopastoral**

landscape. However, costs rise when pastoral activity must be reintroduced into areas where it has disappeared. In both scenarios, implementing agri-environmental measures that recognize the ecosystem services provided by silvopastoralism is essential for facilitating its adoption and long-term success (Casals et al., 2009). Although not always easy to implement, forest grazing is a valuable tool for managing Wildland-Urban Interface (WUI) areas and showcasing the multifunctional benefits of silvopasture.

Figure 6. Strategic Management Points (SMPs) grazed by sheep in Andalucia and cows in Catalonia (Spain).

Key points to consider when using grazing as a fire prevention tool are:

- **Integrate existing farms** into regional fire management strategy whenever possible.
- While all domestic herbivores can contribute to reducing fuels, **mixed herds**, –used either simultaneously or in seasonal rotations– are recommended for greater effectiveness in the control of plant fuels.
- Ensure the **availability of water points** and provide **additional forage** resources, such as forage fields or supplemental feed
- Plan for a **regular mechanical treatment or prescribed burning** every few years to manage unpalatable plants.
- Use **rotational grazing** with **short-duration, high-intensity stocking rates.** Ideal stocking levels depend on animal species and breed, and the available grazing resources.
- Schedule grazing **just before summer**, when wildfire risk is highest. Avoid winter or early spring grazing, as late rains can lead the regrowth of herbs.
- **Annually assess** the effectiveness of grazing on fuel reduction just before summer, and **adjust the strategy** as needed.

2.3.2. Suppression phase

Sometimes an unplanned ignition occurs in an area that has already been subject to landscape planning. When weather conditions and fire behaviour are favourable, such **wildfires can provide an opportunity to advance pre-defined management goals**. When such conditions are met, suppression teams can capitalize on the fire's presence by guiding it toward planned management boundaries, allowing it to perform functions that would otherwise require mechanical treatments, prescribed burning, or grazing.

2.3.2.1. Wildfire management

Managed wildfire (commonly referred to as the **let-burn strategy**) is the intentional decision to allow naturally ignited wildfires (typically by lightning) to burn within pre-defined areas and conditions. Rather than fully suppressing the fire, managers guide its spread to meet ecological or fuel reduction objectives, while protecting people, infrastructure, and high-value resources.

This approach recognizes that complete fire exclusion increases fuel accumulation, often leading to more destructive fires in the long term. Allowing certain wildfires to burn under controlled circumstances reintroduces the ecological role of fires while reducing the likelihood of extreme fire events.

Managed wildfire is only feasible under favourable circumstances, requiring:

- **Weather**: Mild or moderate fire-weather conditions that keep fire behaviour within controllable limits.
- **Spatial planning**: Designated management zones identified in advance, where ecological benefits outweigh risks.
- **Operational capacity**: Sufficient resources and contingency plans to prevent escape and protect nearby assets.
- **Protocols**: Strict adherence to legal, technical, and safety guidelines.

Decisions about whether to allow a wildfire to burn must weigh risks vs. benefits in the context of broader management goals. In practice, a single wildfire may be managed differently across its flanks: one sector allowed to burn for ecological purposes, another actively suppressed to defend critical assets. Such decisions require a detailed understanding of the effects of fires across diverse habitats and their key components, as well as the thresholds at which fire shifts from beneficial to harmful. These thresholds are closely tied to fire intensity, which is influenced by both pre- and during-burn weather conditions.

The first planned experience in managed wildfire in the European Union occurred in 2023 in Canejan (Catalonia, Spain), where a naturally ignited fire was allowed to burn within an area designated in advance for wildfire management under the *Strategic Plan for the Sustainable Management of the Fire Regime in Val d'Aran* (more details in https://interior.gencat.cat/web/.content/home/030_arees_dactuacio/bombers/foc_fores tal/consulta_incendis_forestals/informes_incendis_forestals/2020-2029/2023/20230316_VA_Canejan-Managed-Fire-report.pdf and Oliveres et al., 2025).

Benefits of wildfire management are multiple, including:

- **Fuel reduction**: Burning reduces surface and ladder fuels, limiting future fire intensity and spread.
- **Ecosystem function**: Restores fire as a natural process, supporting regeneration, biodiversity, and nutrient cycling.
- **Mosaic creation**: Increases heterogeneity across landscapes, enhancing resilience to future extreme wildfires.
- **Cost-effectiveness**: Reduces long-term prevention and suppression costs by lowering fuel loads and fire intensity.

However, managed wildfire is often controversial and legal frameworks in many countries prioritize suppression rather than operational fire use.

In sum, to effectively introduce wildfire management into an IFM strategy as a complement to prevention, suppression, and recovery, the following aspects need to be considered:

- **Establish pre-defined boundaries**: Identify and map areas where managed wildfire can be safely applied (e.g., remote forests, protected areas, or zones with low exposure).
- **Develop legal frameworks**: Develop frameworks that evaluate risks vs. benefits, including ecological outcomes and asset protection. Wildfire management is inherently complex and dynamic, reflecting the interconnected ecological, economic, and social factors involved. As such, it must be supported by adaptive planning and robust monitoring to inform and adjust strategies over time.
- **Consider public perception**: Communicate that not all wildfires are destructive and that managed wildfire can reduce the probability of catastrophic events. Indeed, the current debate over managed wildfire is political rather than technical or scientific.
- **Engage researchers**: Monitor and evaluate ecological outcomes, fuel reduction effectiveness, socio-economic trade-offs, and established thresholds for fuel load and fire intensity and spread.

2.3.3. Recovery phase

Effective wildfire management does not end with prevention and suppression. Equally important is ensuring successful post-fire recovery, which increases long-term resilience to EWEs. The need or not for **active restoration** depends on fire intensity and severity, topography, and the fire-response traits of the pre-fire vegetation community. In some cases, vegetation recovers naturally while in others, intervention is essential to secure recovery.

2.3.3.1. Assessing the need for restoration

A crucial step after a wildfire is to **evaluate the need for restoration** and to **prioritize areas most at risk of soil loss or ecological degradation**. Key factors include:

- **Soil erodibility**: The higher erodibility the higher erosion risk.
- **Slope**: Erosion risk increases up to **40% slope** (Kapolka & Dollhopf, 2001), above which becomes extreme.
- **Aspect**: The influence of slope orientation varies with climate. For example, in Mediterranean areas, south-facing slopes are more prone to soil erosion due to limited plant establishment (Paneghel et al., 2025).
- **Fire severity**: Areas where fire severity is low present little erosion risk; under moderate severity, risk increases steadily, and under high severity, soil erosion risk is very high.
- **Vegetation resprouting ability**: Plant communities with **less than 40% of resprouting species** before fires are vulnerable to soil erosion (Alloza et al., 2014).

It is important to note that **topography generally outweighs vegetation traits** in determining post-fire erosion risk (see Deliverable 2.7, de Frutos et al., 2025).

Additionally, in certain landscapes, **proximity to human settlements or infrastructure** should also guide prioritization due to direct social and economic consequences.

2.3.3.2. Designing a restoration plan

Once priority areas for restoration are identified, a **restoration action plan** defining the specific post-fire management strategies should be designed. These interventions are the first line of defence and are classified into **hillslope measures** and **channel measures** (see Deliverable 2.7, de Frutos et al., 2025). These measures aim to:

- Protect soil and minimize erosion
- Reduce surface runoff
- Ensure successful vegetation recovery

Since restoration is at times urgent, it is crucial to provide managers with accessible cartographic tools that identify vulnerable areas and prioritize those requiring intervention (de Frutos et al., 2025). One such tool is POSTFIRE, an expert-based system to assist in the management of burned forest areas (https://postfire.es, Alloza et al., 2021).

2.3.3.3. Considering fire-related plant traits

Successful recovery depends on how well plant communities are adapted to local fire regimes. Because plants are adapted to specific fire regimes, an increase in the occurrence of EWEs aligned with an increase in the severity of other climatic stresses may threaten the capacity of vegetation to regenerate. To increase landscape resilience, managers must evaluate which regeneration strategies dominate the community (Table 7)

Table 7. Post-fire regeneration strategies and related management recommendations. See Deliverable 1.12 Part I (Valor et al., 2023a) for details.

Strategy	Post-fire regeneration mechanism	Suitable fire regime	Management recommendations
Resprouters	Resprout from below/above-ground structures	Wide range of frequencies and severities	Promote structures with low fuel loads.
Seeders	Germinate from seeds	High-intensity, infrequent fires	Promote mature stands, low fuel loads, and age-class diversity.
Post-fire colonizers	Recolonize from unburned patches	Low-intensity, frequent fires	Promote large, mature trees with thick bark, low fuel loads, and vertical discontinuity.
No fire-related traits	None	None	Promote large, mature trees with thick bark, low fuel loads, and vertical discontinuity.

When the fire regime does not align with the plant community traits, shifts in species dominance may occur, altering ecosystem resilience. Table 8 presents examples of dominant overstory species on the main forest types in Europe.

Table 8. Post-fire strategies of selected dominant overstory species in a range of European forest types. From Deliverable 1.12, Part I (Valor et al., 2023a).

Resprouters	Seeders		Post-fire colonizer	No fire-related traits
	Soil or canopy seed bank	No seed bank		
Pinus canariensis	*Pinus pinaster*	*Pinus pinea*	*Pinus pinea*	*Abies alba*
Quercus suber	*Pinus halepensis*	*Pinus nigra*	*Pinus nigra*	*Picea abies*
Quercus ilex	*Calluna vulgaris*	*Pinus sylvestris*	*Pinus sylvestris*	
Quercus robur		*Pinus mugo*	*Pinus mugo*	
Quercus pubescens		*Pinus cembra*	*Pinus cembra*	
Fraxinus angustifolia		*Larix decidua*	*Larix decidua*	

Fagus sylvatica				
Castanea sativa				
Populus tremula				
Betula pendula				
Quercus coccifera				
Calluna vulgaris				

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