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SIMULATION MODEL**

Work package 2

Pilot actions to evaluate fuel treatments using a fire behaviour model

Deliverable 2.1.1

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List of abbreviations and terms

Abbreviation	Definition
AGB	Above Ground Biomass
AI	Artificial Intelligence
ALOS	Advanced Land Observing Satellite
BEHAVE	Fire Behaviour Prediction and Fuel Modelling System
BTU	British Thermal Units
C3S	Copernicus Climate Change Service
CA	Cellular Automata
CDS	Climate Data Store
CLI	Command Line Interface
FARSITE	Fire Area Simulator
FBAT	Fire Behaviour Assessment Tool
FBFM	Fire Behaviour Fuel Models
FBP	Fire Behaviour Prediction
FL	Flame Length
FLI	Fire Line Intensity
FMC	Fuel Moisture Content
FSPro	Fire Spread Probability
GIS	Geographic Information System
IFTDSS	Interagency Fuel Treatment Decision Support System
ISHMP	Forest Inspectorate (Albania)
LiDAR	Light Detection and Ranging
MODIS	Moderate-Resolution Imaging Spectroradiometer
MNZSH	Fire Protection and Rescue Police (Albania)
MTT	Minimum Travel Time
NFDRS	National Fire Danger Rating System
NP	National Park
NUTS	Nomenclature of territorial units for statistics

RAPA	Regional Administration of Protected Areas
ROS	Rate of Spread
RSP	Random Spread Process
SJNP	Shebenik-Jabllanicë National Park
TOM	Treatment Optimization Model
USDA	United States Department of Agriculture
WFAT	Wildland Fire Assessment Tool
WFDS	Wildland-Urban Interface Fire Dynamics Simulator
WFDSS	Wildland Fire Decision Support System
WUI	Wildland-Urban Interface

1. Introduction

Wildfires represent an increasing global threat to ecosystems, human infrastructure, and air quality. Climate change is increasing the frequency and severity of wildfire outbreaks, while demographic changes in high-risk regions are increasing the potential impacts of wildfires.

The “fire behaviour triangle” (Figure 1) outlines key variables influencing wildfire behaviour. Fuel, primarily live and dead vegetation, is the primary fuel. Weather, including wind, air temperature, precipitation, and humidity, influences fires. Topography directly affects fire speed and fuel type. These factors determine the fire's behaviour and intensity.

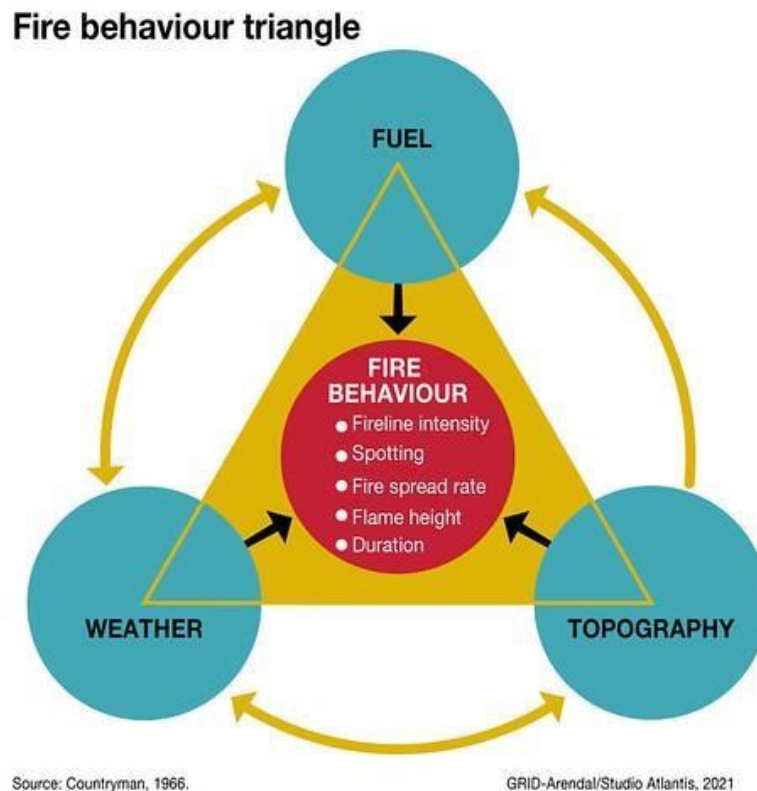


Figure 1 – Fire Behaviour triangle

“**Fire behaviour**” is a term used to describe the general characteristics of a fire, such as its rate of forward spread in the direction of the wind, its fireline intensity, flame geometry, rate of perimeter growth, etc. (Sullivan, 2010).

The complex and dynamic nature of wildfire behaviour, influenced by the complex interaction of weather patterns, fuel characteristics, and

topographic features, necessitates the use of sophisticated tools for effective mitigation and management.

Therefore, fire behaviour models are essential tools for forest management and wildfire prevention, providing insight into how fires might spread under different conditions and how different interventions might reduce fire risk. These models vary in their approach, capabilities and specific applications, each addressing specific management needs. These models enable fire management agencies and land managers to develop proactive strategies, optimize resource allocation during fire events, and assess the effectiveness of various fuel management practices.

The Activity 2.1 “Customizing a Fire Behavior simulation model and developing advanced fire spread visualization techniques” of RES2FIRE consist in identifying the fire behaviour model capable of efficiently expressing the characteristics of the fire (Rate of Spread - ROS, energy emitted, flame height, etc.). The model will be customised to make it adaptable to the study areas and implementable within the webGIS decision support tool. A crucial step in this activity is the identification, selection and collection of input data for the wildfire model. To achieve this, it is necessary to harmonise the input data, including the fuel models.

This report aims to provide a comprehensive overview of wildfire models, including their basic classifications, areas of application, key input parameters and the predominant model used in fire management planning. It also looks at the methods used to model the effects of common silvicultural treatments on fire behaviour and the approaches used to evaluate their effectiveness in altering wildfire dynamics.

The main objective of this document is to identify the most appropriate fire behaviour model for simulating landscape management scenarios to improve wildfire resistance and resilience in natural protected areas and wildland-urban interfaces.

The present report is organised as follows. After a review of fire behaviour simulation models based on an extensive literature search on the state of the art, the selected model is introduced describing its prerequisites, main features and how to organise the model input data preliminary for the assessment of the effectiveness of fuel treatments in pilot areas (Activity 2.2).

2. Review of fire behaviour models

2.1. Introduction

A quantitative basis for fire hazard assessment and fire behaviour prediction became possible with the development of mathematical fire behaviour models (Rothermel, 1972).

Fire behaviour models are essential tools for predicting and understanding the dynamics of wildfires. These models are critical to understanding and managing wildfires by helping to predict fire spread, intensity and behaviour under different conditions. They are used by fire managers, researchers and emergency responders to plan and implement effective fire management strategies, reduce risks and protect communities and ecosystems.

Before examining these types of models in detail, it is necessary to clearly define the context in which they are placed. According to Gomaa et al. (2019), the more general term '**wildfire model**' can refer to:

- a mathematical expression describing the speed at which the fire moves in one direction,
- the area affected by the wildfire in two dimensions and the spread of fire over time, or
- a “software” or a “programme” that provides both the speed of the fire in a straight line and the spread of fire over time in all directions.

As a result, there are three main types of wildfire modelling: fire behaviour models, fire spread models, and fire simulation software/tools. In particular, **fire behaviour models** focus on fire spread in one static direction, while **fire growth/spread models** predict the shape of the affected area. Finally, **fire simulation software/tools** are computer programs that incorporate the above-mentioned models and provide relevant outputs, such as maps of fire spread over space and time.

2.2. Classification of fire behaviour models

Fire behaviour models can be broadly categorized according to their underlying scientific principles and the way they represent the complex processes of combustion and heat transfer. These categories include empirical models, semi-empirical models and physics-based models, in reference to their dependence on experimental data or fundamental laws of physics and chemistry that govern combustion, heat transfer, and fluid dynamics.

2.2.1. Empirical Models

Empirical models rely on statistical relationships derived from the observation and measurement of historical wildfires or controlled experimental fires. These models establish correlations between fire behaviour characteristics, such as the rate of spread, flame height, and fireline intensity, and key environmental factors like fuel type and distribution, topographic features, wind speed, and fuel moisture content. The strength of empirical models lies in their straightforward application and their ability to reflect real-world fire behaviour under conditions similar to those from which they were developed. For instance, widely used empirical models in specific regions, such as the Australian and Canadian fire behaviour models, are tailored to the unique fuel complexes and environmental conditions prevalent in those areas. However, a significant limitation of empirical models is their applicability, which is constrained to the range of data used in their development, making them less reliable for predicting fire behaviour in significantly different environmental conditions.

Two examples of empirical models are: the **Canadian Forest Fire Behavior Prediction (FBP) System** (Hirsch, 1996) and the **McArthur's fire-danger meters for grasslands (Mark 3) and forests (Mark 5)** from Australia (Noble et al., 1980).

2.2.2. Semi-Empirical Models

Semi-empirical models bridge the gap between purely statistical approaches and fundamental physical principles. These models are grounded in the fundamental principles of energy balance, considering the heat generated by burning fuel and the heat required to ignite adjacent fuels. However, they incorporate empirically derived factors and relationships to account for the complexities of heat transfer mechanisms (conduction, convection, and radiation) and fuel combustion processes. A prime example of a widely adopted semi-empirical model is the **Rothermel Fire Spread Model** (Rothermel, 1972), which is based on experimentally determined parameters and stylized fuel descriptions known as fuel models to predict fire behaviour. Semi-empirical models offer a valuable balance between physical realism and computational feasibility, making them suitable for a wide range of operational applications. These models generally provide better accuracy and a broader scope of application compared to purely statistical models.

2.2.3. Physics-Based Models

Physics-based models represent the most detailed and mechanistic approach to simulating fire behaviour. These models are formulated on the fundamental laws of physics and chemistry that govern combustion, heat transfer, and fluid dynamics. They aim to simulate the complex physical and chemical processes involved in fire ignition and propagation, including heat conduction through fuels, convective heat transfer by air movement, and radiative heat transfer from flames. Physics-based models have the potential to simulate fire behaviour in complex and heterogeneous environments, such as the wildland-urban interface (WUI), where structures and vegetation coexist, and to assess the effectiveness of fuel treatments by explicitly modelling the underlying physical processes. Examples of such models include **FIRETEC** and the **Wildland-Urban Interface Fire Dynamics Simulator (WFDS)**. However, the high level of detail and complexity in physics-based models often necessitates significant computational resources and detailed input data, which can limit their widespread operational use in routine fire management planning.

Table 1 - Classification of Fire Behaviour Models

Model Type	Underlying Principles	Key Features	Advantages	Disadvantages	Examples
Empirical	Statistical relationships from observed or experimental fires	Focus on rate of spread, flame height, fireline width based on environmental factors	Straightforward to use, reflects real-life fire behaviour under similar conditions	Limited applicability beyond the data range used for development	Australian and Canadian fire behaviour models
Semi-Empirical	Energy balance principles with empirical factors for heat transfer and combustion	Incorporates experimental data within a physics-based framework, balances realism and computational efficiency	Good balance of accuracy and computational feasibility, wider applicability than empirical models	Relies on empirical parameterization, may not fully capture complex physical processes	Rothermel Fire Spread Model
Physics-Based	Fundamental laws of combustion, heat transfer, and fluid dynamics	Simulates detailed physical and chemical processes, potential for complex scenarios (e.g., WUI, heterogeneous fuels)	Most detailed and potentially accurate simulations	High computational cost, requires detailed input data, limited widespread operational use	FIRETEC, WFDS

2.3. Classification of fire spread models

Fire spread models can be classified according to the spatial methodology they adopt, that is, how the landscape is represented and how fire spread across it is simulated. Two primary approaches dominate the field: raster-based and vector-based methods, with hybrid approaches combining their strengths.

2.3.1. Raster-based models

Raster-based models divide the landscape into a grid of uniform cells, each representing a specific area with unique attributes such as fuel type, topography, and moisture content. Fuel and terrain conditions are usually assumed to be uniform within each cell to simplify basic fire spread rate calculations (Pais et al., 2021). Fire spread is simulated by calculating the likelihood of ignition or fire intensity for each cell based on its characteristics and those of its neighbours.

Key Features:

- Cellular Automata (CA): Fire spread is modelled as a series of transitions between burning and non-burning cells. The probability of spread depends on factors like wind direction, fuel availability, and slope.
- Random spread processes: These probabilistic models use spatial point processes to simulate fire spread based on historical patterns or environmental covariates (Díaz-Avalos and Juan, 2022).
- Implementation: Raster grids can be square or hexagonal, with hexagons offering better spatial accuracy by reducing directional bias (Voltolina et al., 2024).

Advantages:

- Simple to implement and computationally efficient for large-scale simulations.
- Suitable for heterogeneous landscapes where conditions vary significantly across small areas.
- Can integrate GIS data for high-resolution modelling.

Limitations:

- Limited precision in modelling fire perimeters due to the grid's resolution.

- Computational load increases with finer grids.

Examples:

- **Cell2Fire:** A cell-based model designed for strategic management, using CA principles to simulate fire spread across landscapes (Pais et al., 2021).
- **Pyros:** Combines raster grids with vector-based principles for more accurate simulations (Voltolina et al., 2024).
- **PROPAGATOR:** a stochastic CA model for forest fire spread simulation, designed as a quick way for fire risk assessment (Trucchia et al., 2020).

2.3.2. Vector-Based Models

Vector-based models represent fire perimeters as continuous lines or polygons that expand over time. They use geometric principles to simulate the wave-like propagation of fire fronts.

Key Features:

- **Huygens' Wavelet Principle:** Each point along the fire perimeter acts as a source of new ignitions, creating an elliptical shape influenced by wind and slope.
- Fire growth is modelled as a dynamic expansion of these perimeters, allowing for precise tracking of fire edges.

Advantages:

- High accuracy in modelling fire perimeters and dynamic growth patterns.
- Better suited for simulating fires in homogeneous environments or when precision is critical.

Limitations:

- Computationally intensive, especially for large-scale simulations.
- Requires detailed input data (e.g., wind speed/direction, fuel properties).

Examples:

- **FARSITE:** A widely used tool that integrates Rothermel's equations with vector-based perimeter growth (Finney, 1998).

- **PROMETHEUS:** Simulates fire spread using elliptical wavelets to predict growth under Canadian fuel conditions.

2.3.3. Hybrid Approaches

Hybrid models combine raster and vector methodologies to leverage their respective strengths. For example:

- Pyros integrates raster grids for environmental data with vector-based perimeter modelling to simulate complex fire behaviours efficiently (Voltolina et al., 2024).
- These models often use agent-based systems to replicate dynamic interactions between individual cells and the broader fire front.

The choice between raster-based, vector-based, or hybrid approaches depends on the scale of the simulation, the required precision, and computational resources. Raster models excel in large-scale applications with heterogeneous landscapes, while vector models provide higher precision for localized studies. Hybrid methods offer a balance between these approaches, making them increasingly popular in operational settings.

Table 2 - Classification of Fire Spread Models according to the spatial methodology

Model Type	Underlying Principles	Key Features	Advantages	Disadvantages	Examples
Raster-based	divide the landscape into a grid of uniform cells with unique attributes (e.g. fuel type, topography, and moisture content)	Cellular automata; fire spread based on cell attributes and neighbours; large-scale simulations, strategic planning	Computationally efficient, suitable for heterogeneous landscapes, integrates GIS data	Limited precision in fire perimeter modelling, grid resolution affects accuracy	Cell2Fire, Pyros (in part) PROPAGATOR
Vector-based	Fire perimeter represented as continuous lines or polygons	Huygens' wavelet principle; dynamic expansion of perimeters	High accuracy in modelling fire perimeters, precise tracking of fire edges	Computationally intensive, requires detailed input data	FARSITE, PROMETHEUS
Hybrid approach	Combines grid cells with vector perimeters	Integrates CA with vector-based perimeter growth	Balances computational efficiency with precision, leverages strengths of both methods	Can be complex to implement, requires integration of different data types	Pyros (combines raster and vector), agent-based systems

2.4. The Rothermel Fire Spread Model

The Rothermel Fire Spread Model (Rothermel, 1972) is the most widely used wildfire behaviour model for fire management planning, not only in the United States but around the world. This model is the cornerstone of numerous computerised fire behaviour systems used for a wide range of applications including fire management planning, firefighter training and real-time operational forecasting, such as BehavePlus (Andrews, 2007), FARSITE (Finney, 1998), FlamMap (Finney, 2006) and NEXUS (Scott and Reinhardt, 2001).

Its continued success can be attributed to its practical input requirements and the reasonable predictions it provides, which are generally robust to uncertainties in the input data. The Rothermel model has been integrated into the US National Fire Danger Rating System (NFDRS) since its inception in 1972 and continues to be used to determine indices of potential fire activity and behaviour. It has also been used to predict local fire behaviour, simulate large-scale wildfires, and plan fuel treatments and prescribed burns. The fundamental role of the model in fire behaviour research and its widespread use in various fire management tools underline its importance and robustness in the field.

The Rothermel Fire Spread Model is a quasi-empirical model designed to predict the rate of spread (ROS) and intensity of wildland surface fires under steady-state conditions. It is based on a heat balance equation and calculates the rate of spread by considering the heat flux from the burning fuel to the unburned fuel ahead of the fire front, taking into account factors such as fuel properties, fuel moisture content, wind and slope. The model uses experimentally derived parameters that represent the inherent physical and chemical properties of different fuel types as defined by the fuel models. It assumes a stationary surface fire spreading through a continuous and relatively uniform fuel layer. The effects of wind and slope are incorporated as multiplicative factors that modify the base rate of spread calculated for windless, level terrain conditions. The quasi-empirical nature of the model, combining physical principles with experimental data, contributes to its computational efficiency and wide applicability in fire management planning.

2.4.1. Required input parameters

The Rothermel model requires a comprehensive set of input parameters categorised into fuel, weather and topography.

- **Fuel:** The model uses Fire Behaviour Fuel Models (FBFMs) to represent the complex characteristics of wildland fuels. These fuel models provide standardised values for fuel load, size distribution, surface area to volume ratio, heat content and other essential fuel properties for different vegetation types. In addition, the models require information on fuel moisture content, specifically 1 hour, 10 hour, 100 hour, live herbaceous and live woody fuel moisture content.
- **Weather:** Wind speed and direction at mid-flame height are critical weather inputs for the Rothermel model, as wind significantly influences the rate and direction of fire spread.
- **Topography:** The model incorporates the effects of slope on fire spread, with steeper slopes leading to faster rates of spread. Aspect can also be considered as it influences fuel moisture, although it is not a direct input into the core Rothermel equation.

2.4.2. Types of outputs generated

The Rothermel model produces several key outputs that are critical to fire management planning and operations. These include:

- **Rate of spread (ROS):** The model predicts the forward rate of fire spread, typically expressed in units of distance per unit of time.
- **Fire line intensity (FLI):** This output represents the heat energy released per unit time per unit length of the fire front, providing a measure of the intensity of the fire and its potential to cause damage and resist control.
- **Flame Length (FL):** The model estimates the average length of the flames at the head of the fire, which is an indicator of fire intensity and can be used to assess the safety of firefighting operations.
- **Heat per unit area:** This output quantifies the amount of heat released by the combustion of fuel within a defined area.
- **Spread direction:** The model can also provide information on the direction of maximum fire spread.
- **Fire crown activity:** While the core Rothermel model focuses on surface fire, it serves as the basis for models that predict crown fire initiation and spread, often using surface fire intensity as a key input.

These outputs are typically presented as tabular data or can be spatially visualised using Geographic Information Systems (GIS) to map fire behaviour characteristics across a landscape.

2.5. Classification of fire simulation applications

Fire simulation applications can be classified based on their basic approach to predicting fire dynamics and the specific management questions they are intended to address. Understanding these classifications helps forest managers select the most appropriate tool for their specific needs, whether that is predicting fire spread, assessing potential intensity, or evaluating the likelihood of fire occurring in a given area.

Fire simulation systems can be categorized into three primary types based on their functionality and application:

1. **static fire behaviour tools**, such as Landscape Fire Behaviour in the IFTDSS web-based application or simply "FlamMap" in the standalone application, both provided by USDA Forest Service, which calculate potential fire behaviour characteristics for each point on a landscape under constant environmental conditions.
2. **fire spread tools**, represented by Minimum Travel Time (MTT) Fire Spread in IFTDSS or "Short-Term Fire Behaviour" in the Wildland Fire Decision Support System (WFDSS), which simulate the progression of fire across a landscape over time under dynamic environmental conditions.
3. **burn probability tools**, such as Landscape Burn Probability in IFTDSS, which estimate the likelihood of fire occurrence and spread based on multiple simulations with varying ignition points.

Each application type serves different needs, from understanding potential fire intensity at specific locations to assessing likely fire spread patterns or evaluating overall landscape fire risk.

The naming conventions for these tools often differ across applications, which can create confusion for users working with multiple systems. For instance, what is called "FlamMap" in the standalone FlamMap application is referred to as "Landscape Fire Behaviour" in IFTDSS and "Basic" in WFDSS, though all three implement essentially the same fire behaviour calculations. Similarly, the Minimum Travel Time algorithm is variously implemented as "MTT" in FlamMap, "MTT Fire Spread" in IFTDSS, and "Short-Term Fire Behaviour" in WFDSS.

Here's a comparative analysis of key fire behaviour modelling systems, organized by their technical specifications, capabilities, and applications.

Table 2 - Comparative analysis of key fire behaviour modelling systems

Model	Strengths	Weaknesses	Input Requirements	Key Outputs
FlamMap	<ul style="list-style-type: none"> • Landscape-scale fire behavior mapping • Identifies hazardous fuel-topography combinations • MTT algorithm for probabilistic analysis 	<ul style="list-style-type: none"> • Static weather conditions • No temporal variability 	<ul style="list-style-type: none"> • Fuelscape GeoTIFF • Topography (slope, aspect) • Constant weather inputs • Canopy characteristics 	<ul style="list-style-type: none"> • Fire spread rate maps • Flame length distribution • Burn probability • Crown fire potential
BehavePlus	<ul style="list-style-type: none"> • Detailed point-based analysis • Integrated mortality/safety modules • Educational applications 	<ul style="list-style-type: none"> • No spatial capabilities • Limited to single fuel model analysis • No fire growth simulation 	<ul style="list-style-type: none"> • Fuel model parameters • Moisture content • Wind speed/direction • Slope 	<ul style="list-style-type: none"> • Rate of spread • Flame length • Fireline intensity • Scorch height
FARSITE	<ul style="list-style-type: none"> • Temporal fire growth simulation • Dynamic weather integration • Realistic spread patterns 	<ul style="list-style-type: none"> • Complex input preparation • Computationally intensive • Requires detailed weather streams 	<ul style="list-style-type: none"> • Time-varying weather data • Hourly fuel moisture • Multi-layer wind fields • Detailed fuel maps 	<ul style="list-style-type: none"> • Fire progression maps • Perimeter growth • Intensity timelines
FSPro	<ul style="list-style-type: none"> • Probabilistic long-term forecasts • Ensemble weather modeling • Suppression effectiveness analysis 	<ul style="list-style-type: none"> • Requires extensive computing resources • Limited spatial resolution • Complex interpretation 	<ul style="list-style-type: none"> • Historical weather patterns • Ignition density maps • Suppression resources 	<ul style="list-style-type: none"> • Burn probability • Containment likelihood • Fire size distributions

MTT	<ul style="list-style-type: none"> • Landscape-scale spread patterns • Random ignition capability • Treatment effectiveness evaluation 	<ul style="list-style-type: none"> • Fixed burn periods • Simplified spotting • No diurnal weather variation 	<ul style="list-style-type: none"> • Landscape characteristic file • Wind grids • Fuel moisture scenarios 	<ul style="list-style-type: none"> • Fire travel time • Arrival time maps • Spread vectors
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2.5.1. Scopes of Fire Behaviour Models

Fire behaviour models operate across a range of spatial scales and predict various fire characteristics, reflecting their diverse applications in fire management.

2.5.1.1. Spatial Scale

The spatial scale at which a fire behaviour model operates is a crucial aspect of its scope. **Stand-level models** are designed to analyse fire behaviour within relatively small, homogeneous areas, focusing on detailed calculations of fire characteristics like rate of spread and flame length under specific fuel and weather conditions. Tools like BehavePlus are often used for these localized assessments. Conversely, **landscape-level models** simulate fire behaviour and spread across larger, often heterogeneous terrains, considering the spatial variability of fuels, topography, and weather. Examples of landscape-level models include FlamMap and FARSITE (Fire Area Simulator). These models are essential for strategic fire management planning, risk assessment, and simulating the potential impacts of large wildfires or prescribed burns across extensive areas. The choice of spatial scale depends directly on the management objectives, with stand-level models being useful for detailed fuel treatment planning and landscape models for broad-scale risk management and resource allocation.

2.5.1.2. Predicted fire behaviour characteristics

Fire behaviour models are capable of predicting a wide array of fire characteristics, providing critical information for fire managers and incident commanders. These predicted characteristics include:

- the **rate of spread**, indicating how quickly a fire is moving across the landscape;

- the **flame length**, which is a measure of the vertical extent of the flames and an indicator of fire intensity;
- the **fireline intensity**, representing the heat energy released per unit length of the fire front;
- the **potential for spotting**, where embers are carried by wind to ignite new fires ahead of the main fire;
- the **crown fire activity**, describing the involvement of tree canopies in the fire;
- and the **overall fire intensity**, a measure of the energy released by the fire.

Some models also provide probabilistic outputs, such as a map indicating the probability of each cell within a defined area being affected by fire. The specific fire characteristics predicted by a model determine its suitability for different applications, such as assessing the potential for extreme fire behaviour or evaluating the effectiveness of suppression tactics.

2.5.2. Common input parameters

The accuracy and reliability of fire behaviour model predictions are highly dependent on the quality and comprehensiveness of the input parameters provided. Several key categories of input parameters are commonly required by various fire behaviour models.

2.5.2.1. Topography

Topographical factors play an important role in influencing fire behaviour. Elevation, slope and aspect are critical inputs to many fire behaviour models:

- **Elevation** can indirectly influence fire behaviour through its effects on temperature, humidity and vegetation type.
- **Slope** directly affects the rate of fire spread, with fires typically spreading faster uphill due to the preheating of fuels by advancing flames.
- **Aspect**, the direction a slope faces, affects fuel moisture content by influencing solar radiation and consequently the drying of vegetation.

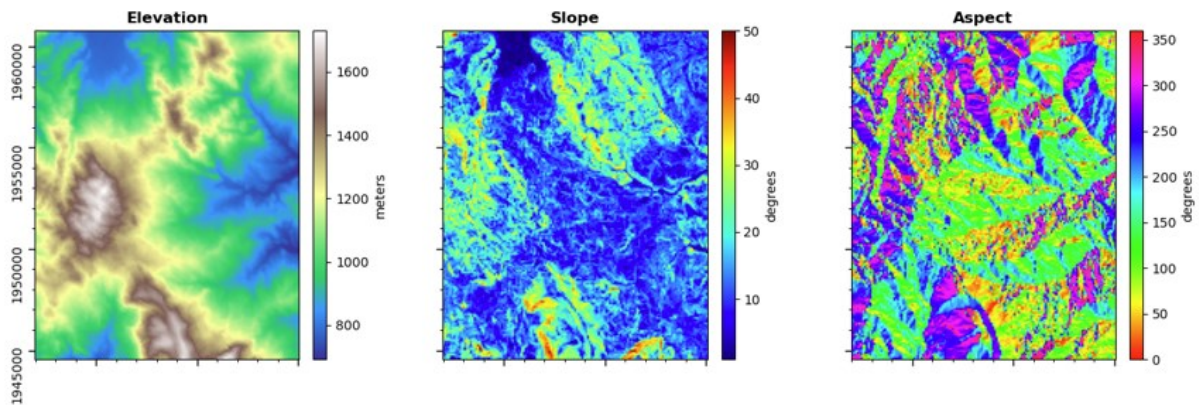


Figure 2 – Example of topographic factors (elevation, slope and aspect)

Landscape level models such as FARSITE often require raster map layers for elevation, slope and aspect to represent the spatial variability of the terrain. Accurate topographic data are therefore essential for spatially explicit fire behaviour modelling, as they directly influence both fire spread and fuel conditions across a landscape.

2.5.2.2. Fuel Characteristics

Fuel characteristics are the primary drivers of fire behaviour. Models require detailed information on the type, amount and condition of fuels present, such as:

- **Fuel type** classifications such as grass, shrubs, timber and slash are essential as they determine the inherent flammability and burning characteristics of the vegetation.
- **Fuel load**, the amount of fuel available for combustion per unit area, directly influences fire intensity.
- **Fuel moisture content**, in both live and dead vegetation, is a critical factor affecting ignition probability and rate of spread.
- **The depth of the fuel bed**, the vertical thickness of the fuel layer and the surface to volume ratio of the fuel particles also play an important role in determining fire behaviour.

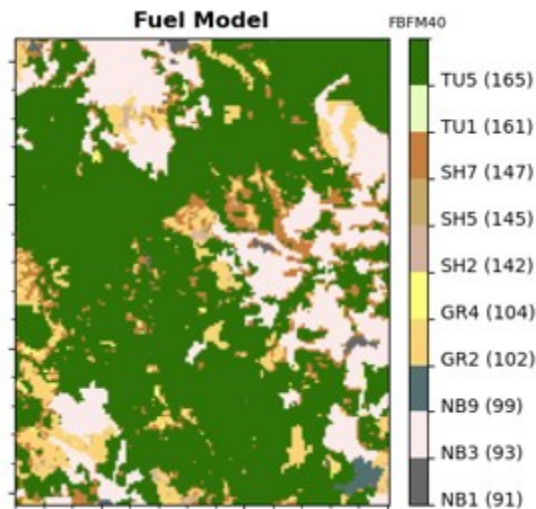


Figure 3 – Example of fuel model according to Scott and Burgan (FBFM40)

Because there are numerous potential combinations of vegetation types, characteristics and successional stages in a landscape, and it is almost impossible to characterise all possible combinations, the most common approach to fire behaviour modelling is to generalise and characterise fuels into a finite number of fuel models (Salis et al., 2016).

A **fuel model** is an identifiable set of forest fuel components of characteristic type, shape, size, arrangement and continuity that exhibit characteristic fire behaviour under defined burning conditions (Anderson 1982).

The correct selection of a fuel model is a crucial step in the mathematical modelling of fire behaviour and fire hazard assessment, where descriptions of fuel properties are required as inputs to the calculation of fire hazard indices or fire behaviour potential. The collections of fuel properties (fuel models) can be organised into four groups: grass, shrub, timber and slash. The differences in fire behaviour between these categories are basically related to the fuel load and its distribution among the fuel particle size classes. Fuel models are simply tools to assist the user in realistically estimating fire behaviour (Anderson, 1982).

To simplify the representation of complex fuel beds, standardised sets of fuel properties known as **Fire Behaviour Fuel Models (FBFMs)** are widely used as inputs in many models. These fuel models, such as the Anderson 13 and Scott & Burgan 40 sets, provide predefined values for various fuel properties based on common vegetation types and conditions. Accurate and detailed fuel data, often represented by these fuel models, is critical for

reliable fire behaviour predictions. The dynamic nature of live fuels, with seasonal changes in moisture content, adds to the complexity and requires models to account for these variations.

2.5.2.3. *Weather conditions*

Weather conditions have a significant influence on all aspects of fire behaviour. **Wind speed and direction** are of paramount importance, affecting the rate and direction of fire spread. Wind can also influence the potential for ignition by carrying embers downwind. **Temperature** and **humidity** play a critical role in determining fuel moisture content and atmospheric stability, both of which affect fire behaviour. Wildfire models require specific weather data as inputs, such as wind speed and direction, temperature and humidity. Dynamic weather conditions are a primary driver of fire behaviour, requiring the use of accurate and timely weather forecasts for effective modelling and forecasting.

3. Selection of the fire simulation application

3.1. Introduction

The selection of an appropriate fire behaviour application depends critically on the specific management question being addressed and the planning timeframe under consideration.

Static fire behaviour applications such as FlamMap excel at identifying areas of potentially high fire intensity across a landscape, making them valuable for prioritising fuel treatment locations or understanding potential fire behaviour under specific weather scenarios.

Instead, fire spread tools such as MTT are better at assessing potential fire growth patterns from specific ignition points, which is useful for planning suppression or evaluating the effectiveness of proposed fuel breaks in modifying fire spread.

Finally, burn probability applications address questions of fire probability over time, helping managers to identify areas with the highest probability of fire and potentially prioritise these for treatment.

Additional specialised models, not available in all systems, such as FARSITE or FSPro may be required for needs such as detailed fire growth prediction or long-term probabilistic assessment.

The temporal focus of management decisions also influences model selection, with immediate tactical decisions requiring different modelling approaches than long-term strategic planning. For example, suppression planning during an active fire may use fire spread models to predict growth over the next few days, whereas long-term fuel treatment planning may rely more heavily on static fire behaviour or burn probability models to identify persistent high-risk areas across a landscape.

The availability of required inputs should also be considered, as more complex models typically require more detailed data on fuels, weather and topography, which may not always be readily available or may introduce additional uncertainty into model outputs. Balancing model complexity with data quality and decision needs remains an important consideration for effective model selection.

RES2FIRE aims at identifying the most appropriate fire behaviour model for simulating landscape management scenarios to improve wildfire resistance and resilience in natural protected areas and wildland-urban interfaces. Consequently, the choice will fall on a static fire behaviour model such as

FlamMap, one of the most widely used fire behaviour modelling applications, as its capabilities are perfectly aligned with the project specific objectives, it is well documented and can be used in both standalone and command line mode. Another strength that supports this choice is the availability of the required inputs of reasonably good quality, thanks to EU-funded projects (e.g. FIRE-RES).

The main differences among the applications examined are related to:

- **The spatial scale of the application.** For instance, FlamMap provides landscape-scale outputs while BehavePlus focuses on single-point analysis (stand level).
- **The temporal dynamics.** FARSITE incorporates time-varying weather while FlamMap considers only static conditions.
- **The probabilistic modelling.** For example, FSPro (Fire Spread Probability) and MTT handle stochastic elements, while other applications such as the Basic FlamMap follow a deterministic approach.
- **The operational complexity.** FARSITE requires detailed hourly inputs vs FlamMap's constant environmental parameters.
- **The treatment planning.** FlamMap's MTT algorithm enables scenario testing of fuel treatments unavailable in FARSITE.

For time-sensitive operations (<72 hrs), FARSITE's dynamic modelling is preferred, while FlamMap excels in strategic fuel management planning. BehavePlus remains valuable for educational purposes and quick point calculations.

3.2. FlamMap

3.2.1. Introduction

FlamMap is one of the most widely utilized fire behaviour modelling systems, providing sophisticated analysis capabilities while maintaining accessibility for practical application. Its design allows for detailed assessment of potential fire behaviour across landscapes under consistent environmental conditions, offering insights that guide strategic planning and intervention design.

At the time of writing, FlamMap is available as:

- **standalone desktop application**¹, version 6.2 (Release Date: 30/08/2024), developed by the Missoula Fire Lab and running on 64-bit Windows operating systems;
- **command line application**² (MS Windows 64 Bit, Release Date: 19/11/2024), developed by the Missoula Fire Lab, although this does not include all the functionalities of the desktop version,
- **command line interface (CLI) module**³, a Python interface for running fire modelling simulations using the Missoula Fire Lab command line application reported above;
- some **ArcGIS tools**, such as ArcFuels⁴, Fire Behavior Assessment Tool (FBAT)⁵ and Wildland Fire Assessment Tool (WFAT)⁶, which allow to run FlamMap in the background and to manage its outputs in ArcMap;
- and some **web-based fire management decision support systems** used in various countries (American and otherwise).

3.2.2. Basic FlamMap

FlamMap's primary function is to calculate essential fire behaviour characteristics such as rate of spread (ROS), flame length (FL), fireline intensity (FLI) and crown fire activity over an entire landscape, using constant weather and fuel moisture conditions for a single point in time. It incorporates several established fire behaviour models, including

¹ <https://research.fs.usda.gov/firelab/products/dataandtools/flammap>

² https://www.alturassolutions.com/FB/FB_API.htm

³ https://github.com/gagreene/US_FireModelling_Automation

⁴ <https://www.firelab.org/project/arcfuels>

⁵ <https://www.frames.gov/fbat/home>

⁶ <https://www.wfas.net/>

Rothermel's 1972 surface fire model, Van Wagner's 1977 crown fire initiation model, Rothermel's 1991 crown fire spread model and Nelson's 2000 dead fuel moisture model. Unlike temporal fire growth models, Basic FlamMap provides fire behaviour outputs for every cell in a landscape simultaneously, essentially modelling what would happen if the entire landscape burned at once under specific conditions. This approach makes FlamMap particularly useful for examining the spatial variability of fire behaviour across a landscape and identifying hazardous combinations of fuel and topography.

Basic FlamMap outputs include raster maps showing fire behaviour characteristics and environmental conditions that can be viewed directly in FlamMap or exported for use in GIS software or other applications. These outputs allow land managers to visualise potential fire behaviour across the landscape, providing valuable insights for planning and decision support. For example, FlamMap can show where crown fire activity is likely to occur during the peak burning season based on predicted weather and winds, helping managers to identify high-risk areas that may require special attention or treatment.

3.2.3. Minimum Travel Time (MTT)

Beyond the basic functionality of FlamMap, the software includes the Minimum Travel Time (MTT) fire growth algorithm, which calculates the minimum fire travel time between adjacent nodes over a gridded landscape. The MTT feature allows FlamMap to simulate fire growth, but with important limitations compared to dedicated fire growth models. MTT simulations use the spatial variability of fuels and topography to drive fire growth, but maintain constant weather conditions throughout the simulation period.

FlamMap's Landscape Burn Probability (LBP) feature uses the MTT algorithm to simulate thousands of randomly placed ignitions, spreading the fire until most of the burnable landscape has been affected. This approach allows the calculation of burn probabilities across the landscape, providing insight into areas of increased fire risk. The MTT algorithm is particularly valuable for analysing how spatial patterns of fuels and topography influence fire spread, independent of changing weather conditions.

3.2.4. Treatment Optimization Model (TOM)

The Treatment Optimisation Model (TOM) module in FlamMap is designed to help evaluate and optimise fuel treatment strategies across a landscape.

TOM focuses on identifying areas where fuel treatments would be most effective in modifying fire behaviour or reducing fire risk. It helps to prioritise treatment sites based on their impact on fire spread and intensity. The module uses geospatial data to simulate fire behaviour under different treatment scenarios. It evaluates the effectiveness of treatments by analysing changes in fire spread patterns, flame length and fire line intensity.

TOM works in conjunction with the other FlamMap modules, such as Basic FlamMap and Minimum Travel Time (MTT), to provide a comprehensive analysis of fire behaviour. It incorporates spatial patterns of fuel and topography into its simulations.

Applications include:

- Planning fuel treatments for wildfire mitigation.
- Evaluate pre- and post-treatment effectiveness.
- Decision support for prescribed fire management and wildland fire use planning.

3.2.5. FlamMap compared to other fire applications

FlamMap differs significantly from other common fire behaviour modelling tools, with each tool designed to address specific aspects of fire behaviour or support particular management needs.

3.2.5.1. FlamMap vs. BehavePlus

FlamMap and BehavePlus have fundamental similarities but differ in important ways:

- Both use the same basic fire spread equations and are non-temporal, using one set of wind and fuel moisture conditions for their calculations.
- The key difference is that FlamMap is spatial, calculating fire behaviour outputs across an entire landscape, while BehavePlus operates at a single point.
- FlamMap can perform millions of runs simultaneously (similar to performing numerous BehavePlus calculations) to produce spatially explicit outputs in map format, while BehavePlus provides tabular and graphical outputs for each calculation.
- FlamMap has been described as 'spatial Behave', extending the point-based calculations of BehavePlus across a landscape to provide a more comprehensive view of potential fire behaviour.

These differences make FlamMap more suitable for landscape-scale analysis and visualisation, while BehavePlus remains valuable for detailed point-based assessments and educational applications.

3.2.5.2. *FlamMap vs. FARSITE*

The distinctions between FlamMap (particularly its MTT component) and FARSITE are particularly important:

- FARSITE is a complete fire growth simulation model that accounts for variability in fuel moisture, wind speed, and wind direction over time and space, making it ideal for simulating realistic fire spread across a landscape.
- Basic FlamMap is not a fire growth simulation model but instead provides fire behavior characteristics for the entire landscape at one instance in time, as if everything was burning simultaneously.
- FlamMap MTT simulates fire spread but only under constant weather conditions, while FARSITE can incorporate changing weather patterns throughout a simulation.
- A critical limitation of FlamMap compared to FARSITE is the static nature of the wind variable, which can lead to unrealistic results when simulating fires that experience significant changes in wind conditions.

This comparison reveals that while FlamMap (with MTT) can simulate fire growth, it lacks the temporal sophistication of FARSITE, particularly regarding changing environmental conditions.

3.2.6. *Input variables*

FlamMap calculations rely on a comprehensive set of input data layers that describe the physical environment and fuel conditions. Required topographic inputs include **slope, elevation, and aspect**, typically extracted from a digital terrain model (DTM) and processed at an appropriate resolution. Weather variables, particularly **wind conditions**, represent another crucial input category, with FlamMap offering specialized tools like "Wind Ninja" that utilize basic weather parameters along with geographical information to generate spatially explicit wind direction and speed rasters across the study area. Forest structural parameters form the third major input category, incorporating **tree height, crown base height, and tree cover density**, which can be derived from field measurements, forest management plans, or remote sensing data like LiDAR.

The FlamMap model, like the FARSITE model, requires a set of input raster dataset in a single **landscape file** (*.lcp or *.tif), a multi-band raster format, containing a minimum of five layers (bands), namely elevation, slope, aspect, fuel model and canopy cover. The landscape file (Figure 4) may also include optional layers such as canopy height (CH), canopy base height (CBH) and canopy bulk density (CBD). In particular, the fuel model layer can be referred to the Anderson 13 (Anderson, 1982) or the Scott and Burgan 40 (Scott and Burgan, 2005) fire behaviour fuel models.

All layers in a landscape file must:

- be co-registered (e.g. have the same reference point and units);
- have the same spatial resolution (cell size);
- have the same spatial extent;
- have the same projection and datum.

Landscape file can be created directly in the FlamMap desktop standalone application or in a GIS environment (e.g., QGIS, GDAL, etc.). An example of layers included in a landscape file is depicted in Figure 5.

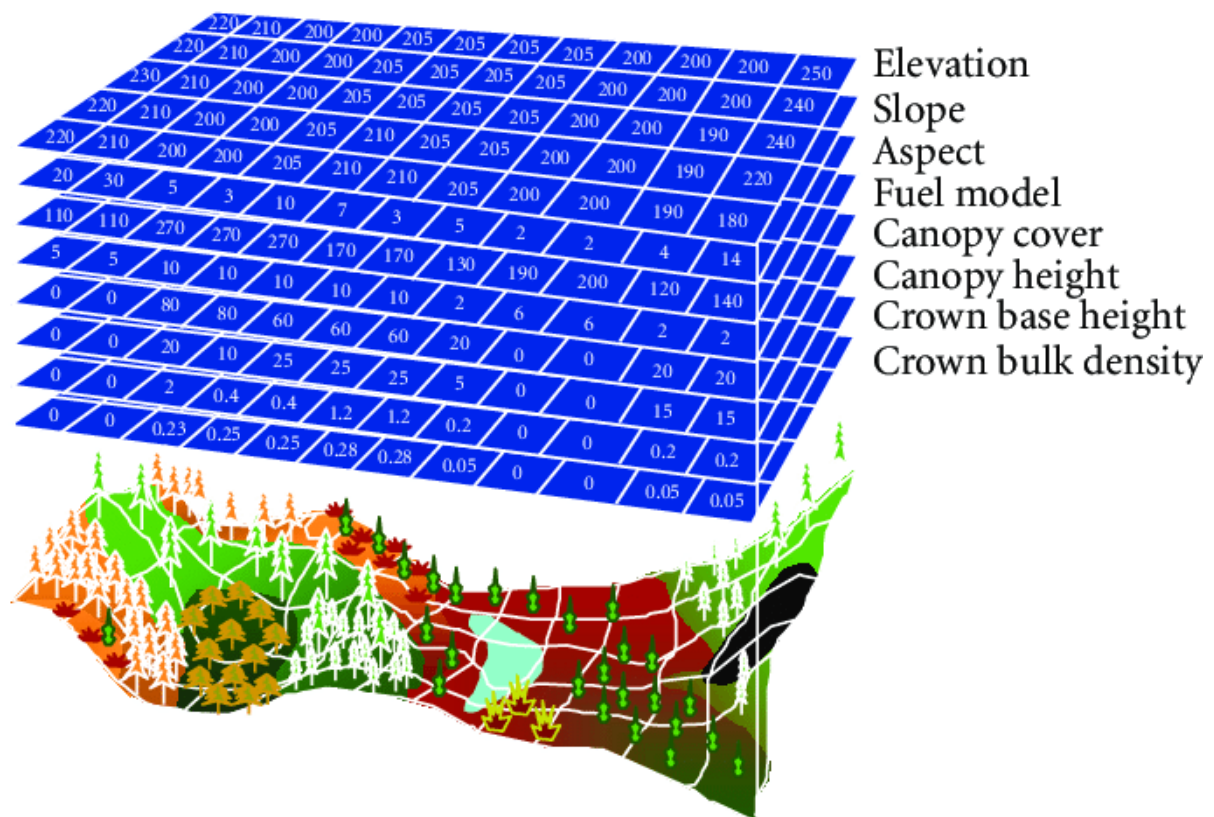


Figure 4 - Input data layers contained in the "landscape file" required to run FlamMap (from Finney, 2006)

The units of each layer included in a FlamMap landscape file are reported in Table 3.

Table 3 – Landscape layer data units (from FlamMap Help)

File Theme	Required	Default Units	Alternate Units
elevation	yes	meters	feet
slope	yes	degrees	percent
aspect	yes	degrees	
fuel model	yes	integer (0-255)	
canopy cover	yes	percent	
stand height	no	meters*10	meters, feet, feet*10
crown base height	no	meters*10	meters, feet, feet*10
crown bulk density	no	kg/m ³ *100	kg/m ³ , lbs/ft ³ , lbs/ft ³ *100

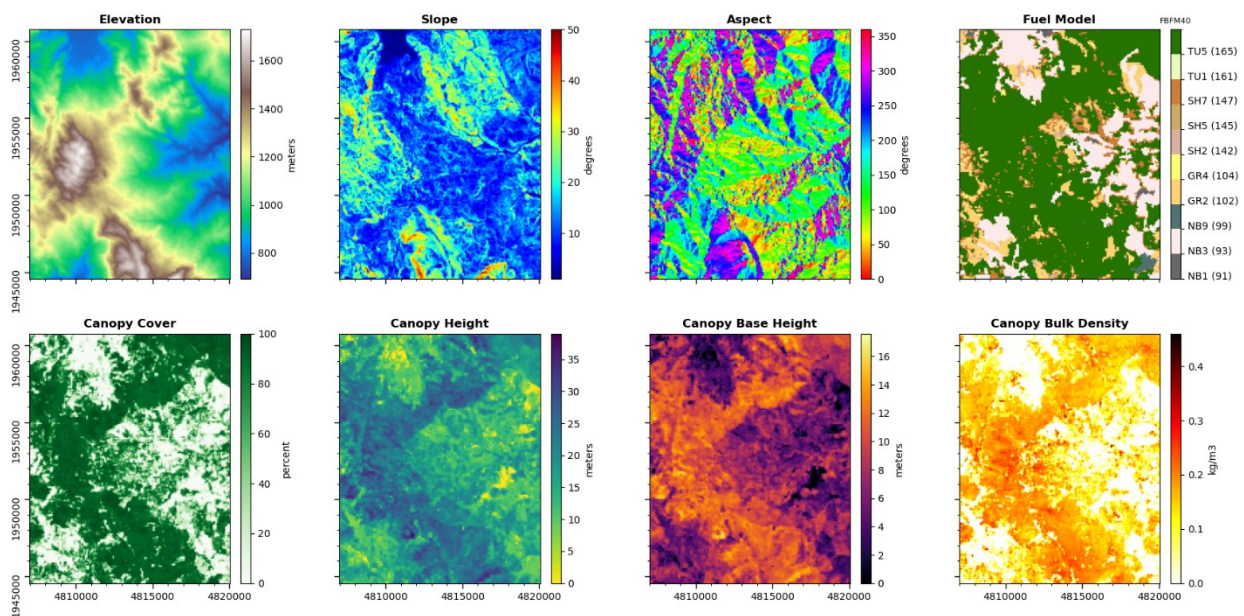


Figure 5 – Example of layers included in a landscape file

3.2.7. Output variables

FlamMap provides a variety of outputs to analyse and predict potential wildfire behaviour across landscapes. Below is a detailed list of its main outputs, along with their definitions and units of measure:

- **Fireline Intensity:** The amount of heat released per unit length of the fire front. Units: Kilowatts per meter (kW/m) or British Thermal Units per foot per second (BTU/ft/s).
- **Flame Length:** The average length of flames in the fire front, which correlates with fire intensity. Units: Meters or feet.

- **Rate of Spread:** The speed at which the fire spreads horizontally across the landscape. Units: Meters per minute (m/min), feet per minute (ft/min), or chains per hour (ch/hr).
- **Heat Per Unit Area:** The amount of heat released per unit area of the burning surface. Units: Kilowatts per square meter (kW/m²) or British Thermal Units per square foot per second (BTU/ft²/s).
- **Horizontal Movement Rate:** The rate at which the fire moves horizontally, considering wind and slope effects. Units: Meters per minute (m/min), feet per minute (ft/min), or chains per hour (ch/hr).
- **Mid-Flame Windspeed:** The wind speed at mid-flame height, which influences fire spread. Units: Miles per hour (mph) or kilometers per hour (km/h).
- **Crown Fire Activity:** Indicates the type of crown fire behaviour (surface fire = 0, passive crown fire = 1, active crown fire = 2). Units: Index (0, 1, 2).
- **Solar Radiation:** The amount of solar energy received by the landscape, affecting fuel moisture levels. Units: Watts per square meter (W/m²).
- **Dead Fuel Moisture (1-hour and 10-hour categories):** Fractional moisture content in dead fuels categorized by drying time (1-hour and 10-hour). Units: Fraction (0.0–1.0).
- **Spread Vectors:** Direction and speed of fire spread. Units: Meters per minute (m/min) and degrees azimuth.

Minimum Travel Time (MTT) Outputs

These outputs are specific to simulations using the MTT algorithm for fire growth:

- **Arrival Time Grid:** Time taken for the fire to reach each cell from ignition. Units: Minutes.
- **Influence Grid:** Measures the prominence of nodes based on how many other nodes burn due to them. Units: Index (logarithm of nodes burned).
- **Burn Probabilities:** Likelihood that a wildfire will burn a specific point or area during simulation. Units: Fraction (0.0–1.0).
- **Flow Paths and Major Paths:** Vector paths showing minimum travel time for fire spread across the landscape. Units: Meters and degrees azimuth.

- **Arrival Time Contours:** Contour lines representing intervals of fire arrival times across the landscape. Units: Interval (e.g., 10-minute increments).

These outputs (Table 4) help model wildfire behaviour under varying conditions, aiding in risk assessment, suppression planning, and fuel treatment optimization.

Table 4 -Summary table of FlamMap outputs

Output	Definition	Units
Fireline Intensity	Heat released per unit length	kW/m , $BTU/ft/s$
Flame Length	Average flame length	Meters, Feet
Rate of Spread	Horizontal spread rate	m/min , ft/min , ch/hr
Heat Per Unit Area	Heat released per unit area	kW/m^2 , $BTU/ft^2/s$
Horizontal Movement Rate	Horizontal movement rate	m/min , ft/min , ch/hr
Mid-Flame Windspeed	Wind speed at mid-flame height	mph , km/h
Crown Fire Activity	Type of crown fire behavior	Index (0-3)
Solar Radiation	Solar energy received	W/m^2
Dead Fuel Moisture	Fractional moisture content	Fraction (0-1)
Spread Vectors	Direction and speed of spread	m/min , Degrees Azimuth
Arrival Time Grid	Fire arrival time	Minutes
Burn Probabilities	Likelihood of burning	Fraction (0-1)

The precision of FlamMap outputs depends significantly on the quality and detail of input data, with field validation playing an important role in ensuring model reliability. Researchers typically collect validation data by establishing sampling plots distributed across different forest types within the study area, measuring parameters such as diameter at breast height (DBH), tree height, crown base height (CBH), and fuel loads. These measurements can be used to develop site-specific relationships, such as height-diameter models, that improve the accuracy of forest structural inputs across the landscape. Additional specialized measurements may include fuel load assessments following standardized protocols that quantify variables like shrub height, herbaceous layer height, litter thickness, and coarse deadwood density. The integration of these detailed field measurements with spatial data layers enables FlamMap to produce realistic simulations of potential fire behaviour that account for landscape-scale variations in topography, fuels, and forest structure.

The FlamMap simulation process involves several configurable parameters that affect the resulting outputs and their interpretation. Users typically define the number and distribution of ignition points, which can be placed

strategically or generated randomly across the landscape, along with maximum simulation time to constrain the extent of fire spread. The model then calculates fire behaviour characteristics for each cell in the landscape under the specified weather and fuel moisture conditions, producing spatial outputs that can be analysed to identify patterns and areas of concern.

Burn probability outputs represent a particularly valuable result, indicating the likelihood that a given location will experience fire under the specified conditions based on multiple simulations with varying ignition points. These probability maps can be further analysed to identify the most important drivers of fire hazard, with regression tree analyses often revealing factors like forest type (coniferous versus broadleaf), aspect, crown cover, slope inclination, and elevation as significant predictors of burn probability.

Interpreting FlamMap outputs requires careful consideration of the model's assumptions and limitations. The model assumes constant weather conditions throughout the simulation period, which may not accurately represent real-world fire events that often occur under changing weather patterns. Similarly, FlamMap does not account for fire suppression actions or the effects of previous fires on fuel conditions, factors that could significantly influence actual fire behaviour. Despite these limitations, FlamMap outputs provide valuable insights for planning purposes, especially when interpreted alongside other information sources and expert knowledge. By identifying areas with high potential fire intensity or elevated burn probability, FlamMap analyses can guide the strategic allocation of resources for fire prevention and mitigation efforts, informing decisions about where and how to implement fuel treatments or other interventions.

4. Modelling vegetation types

4.1. Introduction

The classification of vegetation adds a new dimension to the survey and assists in the understanding of the fuel origin. There are various characteristics that help organize and group the plant species. The more details are added, the most fine the plant scale is becoming.

Vegetation is a crucial factor in wildfires and the various types of trees and grassland change the fire behaviour. The existence of trees can interact with fire totally differently than grassland. Additionally, the type of trees and their leaves can give more burnable surface, or others are non-burnable due to large amounts of moisture. The above traits are referred to as physical and chemical properties of vegetation.

4.2. Physical properties of vegetation

These are the physical characteristics that affect fire behaviour, the ignition points, the fire spread and the intensity.

1. **Fuel Load** is the total amount of flammable material (vegetation) per unit area (tons/acre or kg/m²). When the load is high, it contributes to higher degrees of fire intensity and spread.
2. **Fuel Moisture Content (FMC)** is a physical property that refers to the percentage of water in vegetation relative to its dry weight. This value is different when the plants are alive (leaves and stems with high amounts of moisture) and when they are dead (which is also affected by weather and other conditions). A high degree of moisture leads to slower fire spread and fewer ignition points.
3. The **type of fuel** is different for each plant species. It depends on the type of vegetation, e.g. grass or tree, as each type burns in a different way.
4. The **size and the shape of the vegetation** is another factor which determines the characteristics of fire. The thickness or the dimension of the plant is crucial for fire spread, as larger fuels tend to burn longer than smaller.
5. **Surface to Volume Ratio** refers to the amount of the exposed surface of the plant, directly to the environment, relatively to its size. It is known that smaller and thinner plants (e.g. needles, small leaves of grass) burn quickly and lead to rapid spread of fire. Additionally, they allow the air flow and as a result the burning rate is increasing. In

contrast with small S/V ratio, vegetation with large ratio tend to burn with lower rates, but they sustain the fire for longer period of time.

6. **Bulk Density** stands for the mass amount of vegetation per unit volume. Less bulk density materials (e.g. needles or dry leaves) tend to have more ignition points and a rapid burning rate, in contrast with bulkier materials (e.g. trunks or branches) that burn slowly, have slow ignition, but they burn for a longer period of time.
7. The **height of vegetation** is important to a fire event, as higher trees have more burning surface. The result is the longer period of burning.
8. **Mass of vegetation** has a direct relation on fuel load. Plants with larger mass are burning for a longer period than plants with small mass.
9. **Climate** affects the type of vegetation that grows in an area. For example, in a tropical climate, growing vegetation have larger amounts of moisture, and tend to slow the burning rate.
10. **Weather** is crucial for the development of wildfire. Wind, extreme temperatures and dryness are factors that contribute to fast spread rates, high intensity and large fires.
11. **Location** of an area also contributes to the type of vegetation, such as climate. In areas in the Mediterranean region, vegetation is usually more flammable (resinous conifer trees, dry grasses), but forests in tropical zones rarely burn (high moisture).

4.3. Chemical properties of vegetation

1. **Lignin content** of vegetation is a factor that can act as a fire-retardant, but it can lead to longer burning duration. Lignin is found in larger amounts in wood tree parts.
2. **Cellulose and Hemicellulose** are substances that affect the burning rate. Cellulose is mostly found in wood, and hemicellulose is mostly found in leaves than in wood parts of a tree. They act as fire-retardants.
3. **Oils and resins** that exist in specific types of vegetation (e.g. pine trees) are highly flammable and contribute to rapid and intensive fires. They are responsible for fast ignition and produce high and intense flames.
4. **Volatile Organic Compounds (VOCs)** are found in some vegetation species, and they act as flammable factors. They tend to speed up ignition and increase fire height.
5. **Ash production and Mineral content** of a type of vegetation are highly connected. Mineral content refers to the inorganic

components that cannot be burned when a plant is burning. The high amount of mineral content produces more ash and increases the thermal characteristics of the fire.

6. **Heating value or calorific value** refers to the total energy release of a fully combusted fuel. Vegetation with high moisture levels tend to have lower heating value.

A vegetation classification system is necessary because it not only reveals the diversity and variability of vegetation in a region but also provides insights into the natural environment, climate characteristics, and even the cultural choices related to vegetation in that area. Regarding the above physical and chemical characteristics of vegetation, we organized and grouped various common types of vegetation and their descriptions, in comparison with their categorization by Scott and Burgan. Except from European or international classification systems, we also included Greek classification systems, as they can enhance our research, providing a direct connection to Greek landscapes and presenting their unique characteristics, from the methodological perspective of local experts.

The most common classification systems that are created by Greek scientists for various regions in Greece are organized and presented on the following table:

Table 5 - Classification systems for vegetation by Greek scientists

Dimitrakopoulos et al (2001)		Giakoumakis et al. (2002)		Xanthopoulos et al. (2009)		Mantzavelas et al. (2012)		Sismanis et al. (2023)	
Model I	Evergreen and broad-leaved shrubs (up to 1.5m high).	Model (1)	Areas with grassland or herbaceous crops. The fuel is thin and dry in the summer period, so the speed of spread is high.	Model (31)	Low density shrubs in a pine forest Cover: ≤40% Height: ≤0.4m	F0	Absence of fuel (man-made infrastructure, land covered with water)/ Orchards or vineyards with cleared grassland	7	Non-Fuel
Model II	Evergreen and broad-leaved shrubs (1.5-3m high).	Model (2)	Grassland, with low shrubs (30-60cm) and herbaceous vegetation cover 30-40%.	Model (32)	Dense shrubs in a pine forest Cover: ≤40% Height: ≤0.6m	F1	Riparian herbaceous, bushy, woody vegetation	Shrubland	
								21	Low [0-0.5m)
								22	Medium [0.5-1.5m)
Model III	Oak shrubs (up to 2m high).	Model (3)	Shrubs with medium to large size (0.6-2m) and more than 50% cover.	Model (33)	Low, dense shrubs Cover: ~60% Height: ≤0.4m	F2.1	Sparse and/or low grassland/ Irrigated or non-irrigated crops/ Olive groves	Grassland	
								31	Low [0-0.3m)
								32	Medium [0.3-0.7 m)
Model IV	Phrygana vegetation (Salvia hierosolymitana).	Model (4)	Tall shrubs (>2m) and areas with young saplings (reforestation).	Model (34)	Dense shrubs Cover: ≤90% Height: ≤0.7m	F2.2	Tall or dense grassland	Cropland	
								41	Herbaceous
Model V		Model (5)		Model (35)		F3		Urban	

	Sarcopoterium spinosum.		Forests/woodlands without understorey, due to clearing of the understorey vegetation. Fires are characterized by low spreading.		Medium height, dense shrubs Cover: ≤90% Height: ~1m		Grassland with shrubs	61	Continuous fabric: urban fabric (≥80%)
								62	Discontinuous fabric: vegetation and urban fabric [15-80%)
Model VI	Mediterranean grasslands (low-altitude grasses and forbs).	Model (6)	Forests/woodlands with understorey, mainly low shrubs and trees with crowns starting above the understorey.			F4	Evergreen hardwood bushes	Forest Broadleaved Deciduous	
								1121	Open [15-70%)
								1122	Closed [70-100%)
		Model (7)	Forests/woodlands with a high and dense understorey and trees with crowns starting from a low height.			F5	Phrygana vegetation	Forest Needle leaved Evergreen	
								1211	Open [15-70%)
								1212	Closed [70-100%)
						F6	Coniferous forests dominated by <i>Pinus halepensis</i> or other broad-leaved species		
						F7	Abandoned or fallow crops		

Table 6 presents ten categories of vegetation. These categories are more general than Scott's and Burgan's classification. The categorization of Scott and Burgan is a more detailed system that adds a finer plant scale. Table 6 also presents various vegetation categories and their classification by Scott and Burgan, EUNIS and Corine. Also, these types were matched with the categories from the Greek bibliographies. The development of the new table can combine the related data and present an opportunity for comparison.

Table 6 - Description of vegetation types and various classification systems.

Vegetation Type	Description	Scott & Burgan	EUNIS	CORINE	Dimitrakopoulos	Giakoumakis	Xanthopoulos	Mantzavelas	Sismanis
HERBACEOUS VEGETATION	<p>In dry climate: a. Low and discontinuous b. High and continuous (>0.3m)</p> <p>In humid climate: Usually from 0.3-0.6m dense height.</p>	GR1, GR2, GR5, GR6	E1.1, E1.3, E1.7, E1.9, E2.1, E2.2., E2.3, E3.4	2.3.1, 3.2.1, 3.3.1	Model VI (GR1, GR2)	Model (1) (GR1, GR2) Model (2) (GR1) Model (4) (GR1)		F0 (GR2) F1 (GR2) F2.1 (GR1, GR2) F2.2 (GR5) F7 (GR2, GR6)	31 32 (GR2, GR3, GR5, GR6) 41
	<p>Continuous vegetation: In dry climate: 0-0.9m height In humid climate: height>0.6m, but usually from 0.9-2.4m.</p>	GR3, GR4, GR7, GR8, GR9	E1.1, E1.3, E1.4, E1.7, E1.8, E1.9, E1.A, E1.C, E2.1-E2.5, E3.1-E3.5	2.3.1, 3.2.1				F1 (GR3) F2.2 (GR4, GR5, GR6, GR7, GR8) F7 (GR4)	32 (GR3, GR4) 33 (GR7, GR8, GR9)

	<p>Mixed grassland with shrubs: In dry climate: 0-0.9m and 50% coverage. In humid climate: 0-0.6m height and usually height>0.6m.</p>	GS1, GS2, GS3, GS4	E1.4, E1.6, E1.A, E1.C, E3.3, E3.4, E5.4	2.3.1, 3.2.1, 3.2.4				<p>F2.2 (GR4) F3 F5 (GS1, GS2) F7 (GS1, GS2)</p>	
SHRUB VEGETATION	<p>Shrubs with at least 50% coverage and almost non-existent grassland: In dry climate: height>0.3m, but usually from 1.2-1.8m. In humid climate: a. With coniferous understorey: 0.6-0.9m height. b. With other types of understorey: height up to 1.8m.</p>	SH1, SH2, SH3, SH4, SH5, SH6, SH7, SH8, SH9	F3.1, F3.2, F4.1, F4.2, F5.1, F5.2, F5.3, F5.5, F6.1, F6.1-F6.8, F7.1, F7.4, F8.1, G3.2, G3.2, G3.4,	3.1.2, 3.2.2, 3.2.3	<p>Model I (SH1, SH2, SH3) Model II (SH4, SH5, SH6) Model III (SH1, SH2, SH3) Model IV (SH1, SH2) Model V (SH1, SH2)</p>	<p>Model (2) (SH1) Model (3) (SH2, SH3) Model (4) (SH3, SH4)</p>	<p>MODELS (31)-(35) SH1 - (31) SH2 - (32) SH3 - (33) SH4 - (31) or (33) SH5 - (34) SH6 - (31) SH7 - (35) SH8 - (34) SH9 - (35)</p>	<p>F1 (SH2, SH5) F4 F5 (SH1, SH2) F7 (SH1, SH2)</p>	<p>21 22 23 42</p>
	<p>Mixed grassland with shrubs with 50% coverage and in dry</p>	GS1	F3.1, F3.2, F4.2, F5.2, F5.5,	3.2.1, 3.2.4				<p>F3 F5 (GS1) F7 (GS1)</p>	

	climates up to 0.3m high.		F6.7, F6.8, F7.3, F7.4						
PHRYGANA VEGETATION	Shrubs with at least 50% cover, with or without grass in dry climate, and up to 0.3m high.	SH1, SH2	F7.1- F7.4, F6.7, F6.8	3.2.2, 3.2.3	Model I Model III Model IV Model V	Model (2) (SH1) Model (3) (SH2)		F1 (SH2) F5 (SH1, SH2) F7 (SH1, SH2)	21 42
	Herbaceous or bushy vegetation with a layer of dead organic matter. In dry or humid climates with various types of understoreys.	TU1, TU2, TU3, TU4, TU5	E1.3, E1.4, F5.3, F5.5, F7.1- F7.4, F6 .7, F6.8	3.2.2, 3.2.3, 3.2.4		Model (6) (TU1, TU2, TU3, TU4, TU5) Model (7) (TU1, TU2, TU3, TU4, TU5)		F1 (TU1, TU5) F5 (TU1, TU2, TU3, TU4, TU5) F6 (TU1, TU2, TU3, TU5)	1121 1211
FORESTS AND WOODLAND WITH CONIFEROUS FOREST	Dead woody material - coniferous forest logging material	TL1, TL3, TL5, TL8	G3.1, G3.3, G3.5, G3.7	3.1.2		Model (5) (TL1, TL3, TL5) Model (7) (TL8)		F6 (TL1, TL3, TL5)	1122 1222
	Herbaceous or bushy vegetation with a layer of dead organic matter. In dry or humid climates with various types of understoreys.	TU1, TU2, TU3, TU5	E1-E7, G3.1- G3.7, G3.9, G5.6	3.1.2		Model (6) Model (7)		F1 (TU1, TU5) F5 (TU1, TU2, TU3, TU5) F6 (TU1, TU2, TU3, TU5)	1121 1211
FORESTS AND WOODED AREAS WITH BROADLEAF TREES	Dead woody material - material from the felling of broadleaf forests.	TL2, TL6, TL9	G1.4, G1.5, G1.6, G1.9	3.1.1		Model (5) (TL2, TL6)		F6 (TL2)	1122 1222

AREAS COVERED IN WATER	Areas covered with water	NB8	C1, C2, C3, D2, D4,	4.1.1, 5.1.1, 5.1.2					7 61 62
	Areas bare of vegetation and areas with snow-ice.	NB9, NB2	H4, H5.1, H5.2, X05	3.3.5				F0 (NB2) F2.1 (NB2)	
AREAS BARE OF VEGETATION	Cultivated areas with non-fuel crops.	NB3	I1.1, I1.2, I1.3, I1.5	2.1.1, 2.1.2				F0	
ANNUAL CROPS	Continuous herbaceous vegetation in humid climate, up to 0.3m or between 0.3-0.6m, or > 0.6m high.	GR3, GR5, GR6, GR7, GR8, GR9	I1.1-I1.3, I1.5, E2.1, E2.2, E3.4, E3.5	2.3.1				F1 (GR3) F2.2 (GR5, GR6, GR7, GR8) F7 (GR6)	32
	Cultivated areas with non-fuel crops.	NB3	G1.D, G2.4, G2.9, G4.8	1.4.1				F0	7 61 62
TREE CROPS	Non-fuel cropland (without grass).	NB3	GD.1, G2.9, FB.1-FB.4	2.2.2				F0	
	Cultivated areas with grassland.	GR1, GR2, GR5, GR6 GR3, GR4, GR7, GR8, GR9, GS1, GS2, GS3, GS4, SH1, SH2, SH3, SH4, SH5, SH6,	E7.1-E7.3, X06, X09, X10	2.2.3	Model I (SH1, SH2, SH3) Model II (SH4, SH5, SH6) Model III (SH1, SH2, SH3) Model IV (SH1, SH2) Model V (SH1, SH2)	Model (1) (GR1, GR2) Model (2) (GR1, SH1) Model (3) (SH2, SH3) Model (4) (GR1, SH3, SH4) Model (6) (TU1, TU2, TU3, TU4, TU5)	F0 (GR2) F1 F2.1 (GR1, GR2) F2.2 F3 F4 F5 F6 (TU1, TU2, TU3, TU5) F7	21 22 23 31 32 33 41 42	

		SH7, SH8, SH9, TU1, TU2, TU3, TU4, TU5			Model VI (GR1, GR2)	Model (7)			
AREAS WITH HUMAN INFRASTRUCTURE	Areas with infrastructures such as buildings etc.	NB1	J1, J2, J4, J5	1.1.1, 1.2.1				F0	7 61 62

From the data above and by the concentrated bibliography, a new classification system, more suitable for our research was performed. This system is a customizable model, which is more flexible and related to our project.

4.4. Overview of Forest Fuel

A comprehensive classification of fuel material according to their location within the ecosystem includes three primary types: aerial, surface, and ground combustible material. Aerial combustible material consists of the foliage and the trees' needles, along with the smaller branches of the tree, which are commonly found above ground level and are prone to ignition due to their exposure to atmospheric conditions. Surface combustible material includes the ground cover, such as fallen leaves, dried grass, and shrubs, as well as larger branches and twigs. This category also encompasses small trees and shrubs up to a height of approximately 3 meters. These materials, when dry, contribute significantly to the spread of surface fires. Ground combustible material pertains to the organic matter within the soil, including humus and the root systems of the trees. Each of these categories contributes to the overall fire dynamics within a forest, influencing the behavior and intensity of wildfires.

4.4.1. Physical & Chemical Properties of Forest Fuel Types

The physical and the chemical characteristics of forest fuel types play a vital role in determining how a fire behaves when ignited, spread, and how it is sustained across a landscape. These characteristics are presented in the tables below.

Table 7 - Physical Properties of Fuel Types within an ecosystem

Fuel Type Traits	Introductory Information
Weight per unit area (fuel load)	Typically measured in kg/m ² or t/ha. It refers to the amount of combustible material present in a given area.
Fuel Dimension (Diameter)	Includes the foliage and sub-classifications of the branches' diameter varying between 0.0 cm. up to 7.5 cm.
Surface to volume ratio (S/V)	Smaller volume along with a larger surface area indicates increased flammability due to the easier and enhanced moisture removal from larger surface areas. The highest ratio is found in pine needles, followed by the leaves of broadleaf trees, and then branches. The larger the diameter of the combustible material, the smaller the ratio.
Porosity	Refers to the available fuel load per unit volume. The rate of fire spread is inversely proportional to the fuel's porosity. If the porosity is below an optimal value (0.4), an increase in porosity leads to a corresponding increase in the rate of spread (if <0.2, too much air and too little fuel). If the porosity exceeds the optimal value, its increase results in a decrease in the rate of fire spread (if >0.7, too much fuel and too little air).

Horizontal and Vertical Continuity	Critical in understanding fire behavior. A landscape with both strong horizontal and vertical continuity is more likely to have fast-paced, intense fires that spread rapidly. In contrast, areas with disrupted continuity may slow down or limit fire spread, offering better opportunities for fire management and containment.
Moisture Content	The amount of water (vapor) contained in the combustible material, expressed as a percentage of the dry weight of the flammable substances. It slows down the ignition and combustion process due to the heat losses required to raise the temperature of the fuel's moisture to its boiling point, as well as the heat needed for the evaporation of the water. The variation in moisture content in dry combustible material ranges from 5% to 500%, and this amount depends on the prevailing meteorological conditions. In green fuel, the variation ranges from 60% to 300%, and this amount is mainly influenced by the physiological condition of the plant and the root system's ability to absorb water from the soil.

Table 8 - Chemical Properties of Forest Fuel Types within an ecosystem

Fuel Type Traits	Introductory Information
Essential Oils	These include: a) Substances that act as a chemical accelerant for the foliage's ignition, which is why green foliage can be ignited at moisture levels well above the safety moisture content of the fuel. b) Substances which simply contribute to the thermal value. They evaporate and enter the soil, where they create a hydrophobic zone.
Inorganic Ash	Includes inorganic material that remains after burning. It is divided into metallic ash (which affects combustion inversely) and silicate ash (which does not affect combustion). An increase in the ash percentage reduces the burning intensity.
Thermal Value (Energy Content)	The amount of heat released from the complete oxidation of 1 gram of flammable material (joules/gram). Forest fuels have a consistent or minimal thermal value of approximately 20 KJ/kg. Wood has higher thermal value than bark and leaves.

4.4.2. Fundamental Terms in relation to Forest Fuel Types

Before a formal, concrete classification of forest fuel types in categories is completed, based on the parameters that affect their combustibility, a critical step entails clear understanding of fundamental terminology in relation to those fuel types.

Fuel Particles

A fuel particle is the smallest unit analyzed to understand the structure and characteristics of the fuel. It refers to parts or components of living or dead plant material, such as leaves, needles, thorns, branches of varying sizes, etc. The physical, chemical, and thermal (combustion) properties of these fuel particles are evaluated either at the level of an individual particle or across the entire group of particles belonging to the same biological entity,

for example, the combination of leaves and small branches from a particular type of shrub. These properties significantly influence the heat transfer, ignition, and combustion processes of the particles.

Fuel Particle Complex

The entire forest can be considered as fuel, as all its components (litter, grasses, herbs, small and large shrubs, trees) are flammable materials. However, the ignition process and the influence of these materials on fire behavior differ depending on whether they are alive or dead, as well as their spatial arrangement (horizontal or vertical), their quantity, distinct characteristics, temperature, and moisture content.

Fuel model

A Fuel Model is a complex of fuel particles, whose physical, chemical, and combustion properties represent the average (typical) condition of a specific type of vegetation.

Combustibility

Combustibility refers to how much fuel is available and how well a material sustains burning. A high combustibility rating means the material burns for a long time and provides significant energy output. This is influenced by fuel load, density, and moisture content.

Flammability

Flammability refers to the level of maximum possible heat intensity of a wildfire in a specific type of vegetation, under weather and topographical conditions that promote fire propagation. Greater flammability indicates increased difficulty in controlling the fire, requiring more effort to prevent it from growing into larger fires, as well as a stronger need for the prompt deployment of well-coordinated ground and aerial firefighting resources. Coniferous trees along with scrubland and grassland vegetation are more prone to combustion. In terms of diameter, thin twigs, pine needles, leaves, bark, peeling bark, dry branches, and dead trunks contribute to a quicker start of the combustion process. In addition, humidity plays a vital role in flammability due to elevation. Lower elevation presents decreased possibilities of fire spread since relative humidity begins increasing in higher altitudes.

4.5. Customizing fuel models

Customizing fuel modeling in simulation models such as FARSITE (Fire Area Simulator) or FlamMap, is crucial for the improvement of the accuracy and

reliability of fire behavior predictions. Fuel models represent the physical characteristics of the vegetation, soil, and other materials in a specific landscape that can influence fire dynamics, such as rate of spread (ROS), fireline intensity, along with the emitted energy as well. Customizing these fuel models allows us to more accurately represent the specific characteristics of a landscape, especially when the default fuel models (based on the National Fire Danger Rating System or NFFL fuel models) do not adequately reflect the local conditions.

4.5.1. Why is Customizing Fuel Modeling Important?

Customizing the various fuel models becomes a major element because it contributes to more accurate fire Behavior predictions. The default fuel models tend to present inadequacy in terms of what is demanded, as they may not always match the vegetation and topography of a region, leading to inaccurate predictions of fire behavior. Custom fuel models can provide more realistic results, which is vital for effective fire management decisions. Secondly, different regions may have unique vegetation types, moisture levels, soil conditions, and climate conditions that are not reflected in the generalized fuel models. Customization allows users to account for these local variations, improving fire simulation accuracy. Thirdly, by customizing the fuel models, fire managers can obtain more precise risk assessments, which are vital for allocating resources, planning fire suppression strategies, and understanding the potential spread of fires in specific areas. Moreover, customized fuel models provide valuable information for long-term fire management strategies which include prescribed burn planning, wildfire risk reduction, and post-fire landscape recovery. Accurate fuel modeling, at last, is not only important for fire behavior prediction but also for ecological research, habitat modeling, and vegetation management.

4.5.2. How is the customization process of the fuel models executed?

To achieve a proper customization of the fuel models we are interested in, a necessary first step includes the identification of the purpose behind customization. This can contain the accuracy of a fire behavior simulation, as it helps for better predictions on how fire will spread, its intensity, and its effects on the environment. Others include fire risk assessment so we are able to estimate wildfire risk or understand how fuel changes affect fire behavior over time, fire management planning for use in prescribed burn planning, as well as creating defensible spaces, or prioritizing wildfire suppression effort and ecological modeling for the assessment of how different fire regimes impact vegetation and wildlife habitats. The second

step incorporates a clear understanding of the fuel model's framework, as each fuel model represents specific fuel characteristics that will influence fire behavior.

Common fuel model categories include grass which represents grasses and herbaceous plants, which burn quickly and intensely, s mixed vegetation types such as shrubs and low-growing woody plants, timber that represents forested areas, which may be further divided based on tree species, canopy cover, and understory vegetation and non-vegetative fuels, such as bare soil, rock, and other non-burnable areas that don't contribute directly to fire spread.

The third step in the customization process is to gather local data on fuel types that reflect the fuel conditions of our area of interest. The quality and granularity of this data will directly impact the accuracy of the model. Key data includes vegetation types in terms of what species of plants, grasses, shrubs, and trees exist in the area and how do these plants interact with fire (e.g., some species burn hotter or faster than others). Fuel Loading is the amount of available fuel, measured in tons per acre (or kg per hectare), that contributes to fire spread. Canopy Characteristics include the density, height, and coverage of tree canopies, which influence the vertical spread of fire (e.g., crown fires in forests). As far as fuel moisture is concerned, both live and dead fuel moisture content are dynamic and vary by season, weather, and soil conditions. Topography entails slope, aspect, and elevation which influence how fire spreads (e.g., fire spreads faster uphill). Climate and Weather Data are also essential due to the historical and current weather patterns that affect fire behavior (e.g., wind speed, humidity, temperature, precipitation).

As a general principle, customizing fuel models involves modifying parameters to accurately represent local fuel conditions. We begin the process with modifying fuel load, which is the amount of fuel available for combustion and can vary widely depending on the vegetation type (e.g., dense grasslands, sparse forests). It's necessary to make adjustments based on the fuel type because if our area has dense grass or brush, fuel loading values should be higher to reflect the greater amount of material that can burn. Another parameter is fuel depth, as it represents the vertical thickness of the fuels that influence flame height and fire intensity. This is critical in areas with significant shrub cover or forest understories. moisture content, the percentage of water present in live and dead fuels (as stated above), is crucial because, for instance, live grass has a different moisture content than dry timber litter. Adjusting canopy and tree cover information for the

density of tree canopies (canopy closure) and their vertical continuity is strongly taken into account as well, since in forested areas, crown fires are highly influenced by the type and continuity of canopy fuels. fire behavior parameters shouldn't be dismissed either, as we need to set values for rate of spread, flame length, and intensity for the given fuel type. After collecting the aforementioned data, we can advance to using remote sensing and GIS Tools (e.g., satellite imagery, aerial photos, LiDAR) that are incredibly useful for customizing fuel models over large areas or regions. Remote sensing allows users to map fuel types (identify vegetation types, canopy cover, and fuel loads across large landscapes), to map topography (use Digital Elevation Models (DEMs) to evaluate slope, aspect, and other terrain features), to track seasonal changes: (satellite imagery can track seasonal changes in vegetation and fuel moisture over time) and create spatially explicit fuel models, since GIS software is capable to generate maps that assign specific fuel models to different landscape units based on data collected.

4.6. Classification of fuel models

The following table represents a more thorough dive in Scott and Burgan's method of classification, as it includes the average ratings and percentages of additional variables, such as combustibility and flammability, which play a vital role in fuel model behavior. The incorporation of those two parameters, along with additional insights into density and understory conditions, enhances the model's predictive power and provides a better reflection of the variability in fuel behavior across different environments.

Table 9 - Additional Parameters in Scott & Burgan's Fuel Model Classification (2005).

Fuel Type	Model code & brief Summary	Density (%)	Altitude (m)	Understory
Non-Burnable Models	NB1: Urban/Developed (91)	Any	0-200m	None
	NB2: Snow/Ice (92)	Any	<1200m	None
	NB3: Agricultural (93)	Any	0-400m	None
	NB8: Open Water (98)	0%	Any	None
	NB9: Bare Ground (99)	0%	Any	None
Grass Models	GR1: Short, sparse dry climate grass (101)	15-25%	100-500m	Sparse
	GR2: Low-load, dry climate grass (102)	20-30%	100-500m	Sparse

Fuel Type	Model code & brief Summary	Density (%)	Altitude (m)	Understory
	GR3: Low-load, very coarse grass (103)	25-35%	0-400m	Light Shrubs
	GR4: Moderate-load, dry climate grass (104)	45-55%	100-500m	Grass
	GR5: Low-load, humid climate grass (105)	30-40%	200-600m	Sparse Bushes
	GR6: Moderate-load, humid climate grass (106)	50-60%	200-600m	Grass
	GR7: High-load, dry climate grass (107)	55-65%	0-300m	Grass
	GR8: High-load, very coarse grass (108)	60-70%	0-300m	Coarse Grass
	GR9: Very high-load, humid climate grass (109)	65-75%	0-300m	Dense Grass
Grass/Shrub Models	GS1: Low-load, dry climate grass-shrub (dynamic) (121)	35-45%	200-600m	Sparse Bushes
	GS2: Moderate-load, dry climate grass-shrub (dynamic) (122)	40-45%	300-700m	Bushes
	GS3: Moderate-load, humid climate grass-shrub (dynamic) (123)	45-55%	300-700m	Bushes
	GS4: High-load, humid climate grass-shrub (124)	50-60%	400-800m	Dense Shrubs
Shrub Models	SH1: Low-load, dry climate shrub (141)	50-60%	400-800m	Dry Shrubs
	SH2: Moderate-load, dry climate shrub (142)	55-65%	400-800m	Dry Shrubs
	SH3: Moderate-load, humid climate shrub (143)	60-70%	500-900m	Moist Shrubs
	SH4: Low-load, humid climate shrub (144)	65-75%	500-900m	Moist Shrubs
	SH5: High-load, dry climate shrub (145)	70-80%	700-1000m	Shrubs
	SH6: Low-load, humid climate shrub with pine overstory (146)	70-80%	600-1000m	None
	SH7: Very high-load, dry climate shrub (147)	75-85%	800-1100m	Thick Shrubs
	SH8: High-load, humid climate shrub (148)	80-90%	500-900m	Moist Shrubs
	SH9: Very high-load, humid climate shrub (149)	85-95%	500-900m	Thick Moist Shrubs
Timber-Understory Models	TU1: Low-load, dry climate timber grass-shrub (161)	75-85%	800-1100m	Grass-Shrub
	TU2: Moderate-load, humid-climate timber-shrub (162)	80-90%	800-1100m	Shrub-Litter

Fuel Type	Model code & brief Summary	Density (%)	Altitude (m)	Understory
	TU3: Moderate-load, humid climate timber-grass-shrub (163)	85-95%	900-1200m	Grass-Shrub
	TU4: Dwarf conifer with understory (164)	85-95%	900-1200m	Conifer Understory
	TU5: Very high-load, dry climate timber-shrub (165)	90-100%	900-1200m	Dense Shrubs
Timber Models	TL1: Low-load, compact conifer litter (181)	40-50%	500-900m	Pine Litter
	TL2: Low-load, broadleaf litter (182)	45-55%	500-900m	Broadleaf Litter
	TL3: Moderate-load conifer litter (183)	50-60%	600-1000m	Conifer Litter
	TL4: Small downed logs (184)	55-65%	600-1000m	Fallen Logs
	TL5: High-load conifer litter (185)	60-70%	700-1100m	Thick Litter
	TL6: Moderate-load broadleaf litter (186)	65-75%	700-1100m	Broadleaf Litter
	TL7: Large, downed logs (187)	70-80%	800-1200m	Heavy Fallen Logs
	TL8: Long-needle litter (188)	75-85%	800-1200m	Pine Needle Litter
	TL9: Very high-load broadleaf litter (189)	85-95%	900-1200m	Dense Leaf Litter
Slash/Blowdown Models	SB1: Low-load, activity fuel (201)	Any	Any	None
	SB2: Moderate-load activity fuel (202)	Any	Any	None
	SB3: High-load, activity fuel (203)	Any	Any	None
	SB4: High-load blowdown (204)	Any	Any	None

These classifications of fuel models into detailed categories such as Grass Models, Grass/Shrub Models, Scrub Models, Timber-Understory Models, Timber Models, Slash/Blowdown Models and Non-Burnable Models follow an organized system and are more adaptable to specific environmental conditions, vegetation structures, along with fire behavior patterns that help in predicting its propagation effectively.

Grass Models (GR) are classified separately because grass has a rapid ignition time and high surface area-to-volume ratio, leading to fast-spreading fires. They vary in combustibility and flammability, as they depend on their load and whether they grow in dry or humid climates. The separation of different grass models allows fire behavior analysts to predict

fire spread rates more accurately in regions dominated by grassland fuels. For instance, short and sparse grass in arid conditions burns differently from dense, humid-climate grass, necessitating their distinct classifications.

Grass/Shrub Models (GS) and **Scrub Models (SH)** incorporate shrubs and mixed vegetation, where the additional fuel complexity alters fire behavior. Shrubs introduce increased fuel load and vertical continuity, allowing fires to transition from surface to crown fires with much greater ease. The differentiation between dry and humid climate shrub models recognizes that humidity influences fuel moisture, which directly impacts fire intensity and spread. Additionally, models with pine overstories are categorized separately due to their ability to create different fire dynamics by providing ladder fuels that aid fire transition into the canopy.

Timber-Understory Models (TU) and **Timber Models (TL)** are categorized distinctly due to their high structural fuel complexity. Timbered landscapes contain substantial amounts of fuel in the form of litter, understory vegetation, and downed woody material. The presence of coniferous or broadleaf litter affects combustion rates and fire spread, warranting separate models. The classification of timber fuel models aids in forest management and helps in determining prescribed burn strategies or suppression tactics based on the expected fire intensity and spread under various conditions.

Slash/Blowdown Models (SB) are treated as a distinct category because they represent areas with heavy concentrations of dead and downed fuels, typically resulting from logging operations or natural disturbances, such as storms. These fuel types tend to have extreme fire behavior, including high-intensity burning and prolonged heat release.

Finally, **Non-Burnable Models (NB)** classify areas where fire propagation is minimal or nonexistent, such as urban zones, snow-covered areas, or open water. This classification provides crucial data for fire managers to identify barriers to fire spread and improve fire prediction modeling. The structured classification system enhances wildfire risk assessment, allowing for efficient resource allocation and improved fire suppression strategies.

4.7. Final Customization model

Table 10 is based both on international and Greek scientific systems and it presents six main levels. Each one is segmented to sub-levels (usually 2-3). These table presents the following characteristics for each category:

- (a) Type, (b) Height, (c) Coverage, (d) Combustibility, (e) Flammability, (f) Altitude, and (g) Understory. More specifically:
- (a) Type - refers to the type of vegetation (e.g. forest).
- (b) Height - refers to the height of vegetation (e.g. low, medium or high).
- (c) Coverage - refers to the percentage of a region that is covered by vegetation (e.g. low, medium or high).
- (d) Combustibility - refers to the ignition properties of vegetation (average values - scale from 1 to 10).
- (e) Flammability - refers to the sustainability of combustion and support of burning (average values - scale from 1 to 10).
- (f) Altitude - refers to the altitude (m) where a type of vegetation usually is found.
- (g) Understory - refers to the layer of vegetation found under the forest canopy (e.g. Sparse, Dense etc.).

Continuously, we proceed to the next categories, where the distinct vegetation characteristics are presented in detail. Beginning with Level 1, it refers to herbaceous/ shrub or tree lands. For this level there are three sub-levels - L.1.1 (Grasses), L.1.2 (Shrubs) and L.1.3 (Trees). Level 2 refers to more extensive regions and specifically grasslands, shrublands and forested areas. These are the sub-levels L.2.1 (Grasslands), L.2.2 (Shrublands), and L.2.3 (Forested Areas). Level 3 refers to agricultural areas, and it is segmented into L.3.1 (Irrigated Cropland) and L.3.2 (non-irrigated). Continuously, Level 4 is about Hydric Landscapes and is segmented into five sub-categories - L.4.1 (Riparian Vegetation), L.4.2 (Coastal Vegetation), L.4.3 (Wetland vegetation), L.4.4 (Areas covered with water) and L.4.5 (Areas with Snow/ Ice). Additionally, Level 5 refers to non-Hydric areas and is split into L.5.1 (Natural terrestrial areas) and L.5.2 (Semi-Natural terrestrial areas). Finally, Level 6 refers to bare areas and it has two sub-levels - L.6.1 (Lack of vegetation) and L.6.2 (Areas with man-made infrastructure). Continuing on, Table 10 follows:

Table 10 - Customized Classification System of Fuel Parameters.

Levels		Type	Height	Coverage	Altitude	Understory	Scott & Burgan	FARSITE code
Units			(m)		(m)			
Level 1 (Herbaceous/ Shrub/ Trees)	L. 1.1	Grasses	≥1m	Low/ Medium	100-700m	Sparse/Coarse Grass/Dense Grass	GR1	101
							GR2	102
							GR3	103
							GR4	104
							GR5	105
	L.1.2	Shrubs	1-5m	Low/ Medium	200-800m	Sparse/Dense Shrubs	SH1	141
							SH2	142
							SH3	143
							SH5	145
							GS1	121
	L.1.3	Trees	≤5m	Low/ Medium	200-1200m	Conifer Understory	GS2	122
							TU1	161
							TU2	162
							TU4	164
							TL1	181
Level 2 (Grasslands/ Shrublands/ Forested Areas)	L.2.1	Grasslands	0.5-2m	Medium/ High	200-800m	Coarse/Dense Grass	TL2	182
							TL3	183
							TL4	184
							GR4	104
							GR6	106
	L.2.2	Shrublands	1-5m	Medium/ High	500-900m	Dry/Moist/Thick Moist Shrubs	GR7	107
							GR8	108
							GR9	109
							SH4	144
							SH6	146
						SH7	147	
						SH8	148	
						SH9	149	
						GS3	123	
						GS4	124	

	L.2.3	Forested Areas	≤5m	Medium/ High	700-1200m	Pine Litter/ Pine Needle Litter/ Broadleaf Litter/ Dense Leaf Litter/ Conifer Litter/ Thick Litter/ Fallen Logs/ Heavy Fallen Logs	TU3	163
							TU4	164
							TU5	165
							TL3	183
							TL4	184
							TL5	185
							TL6	186
							TL7	187
							TL8	188
							TL9	189
Level 3 (Agricultural areas)	L.3.1	Irrigated Cropland	Grains: 0.5-3m	High	0-600m	Sparse to None. Some fields might have weeds or organic mulch	GR5	105
			Vegetables: (0.3-1.5m)				GR6	106
			Fruit orchards: 3-6m				GR8	108
			Plantations: 2-30m				GR9	109
	L.3.2	Non-Irrigated Cropland	Drought-resistant crops: 0.5-1.5m	Low/ Medium/ High	100-1000m	Light to Moderate Vegetation (e.g. weeds, stubble, organic residue)	GR1	101
			Row crops: 1-3m				GR2	102
							GR4	104
							GR7	107
Level 4 (Hydric Landscapes)	L.4.1	Riparian Vegetation (Rivers, Streams)	1-30m	High	0-1500m	Dense Shrubs & Moist Leaf Litter	GS3	123
							GS4	124
							SH3	143
							SH4	144
							SH6	146
							SH8	148
							TU2	162
							TU3	163
TL6	186							

	L.4.2	Coastal Vegetation (Beaches, Dunes, Cliffs)	0.3-5m	Low/ Medium/ High	0-500m	Sparse to Dense Shrubs, Salt-Tolerant Plants. Can include a mix of grasses, low shrubs and organic debris	GR1	101
							GR2	102
							GR3	103
							SH1	141
							SH2	142
	L.4.3	Wetland vegetation (Swamps, Marshes, Bogs)	0.3-15m	High	0-500m	Dense Aquatic Plants, Peat, Moss, Decaying Organic Matter	GR8	108
							GR9	109
							SH3	143
							SH8	148
							SH9	149
	GS4	124						
	L.4.4	Areas covered with water (Rice Fields, Ponds, Lakes)	0.3-1.5m	Medium/ High	0-600m	Submerged, Floating Vegetation, Organic Debris	NB8	98
L.4.5	Areas with Snow/Ice	-	-	500-2500m	None	NB2	92	
Level 5 (Non-hydric Areas)	L.5.1	Natural terrestrial areas	Grasslands: 0.5-2m	High	0-3000m	Dense Forest Litter, Shrubs, Dry Grass, Deadwood	GR2-GR7	102-107
			Shrublands: 1-5m				GS1-GS3	121-123
			Forested Areas: 5-40+ m				SH2	142
							SH5	145
							SH7-SH8	147-148
							TU1	161
							TU3	163
							TU5	165
							TL3	183
	TL5	185						
	TL8	188						
	L.5.2	Semi-Natural terrestrial areas	Managed Grasslands: 0-1.5m	Medium/ High	0-2500m	Managed Grasslands, Shrubs, Crop Residues	GR1	
							GR3-GR4	

			Wooded Areas: 5-20m					
Level 6 (Bare Areas)	L.6.1	Bare land (lack of vegetation - e.g. from agricultural activities)	0m	Low	Any	None		
	L.6.2	Areas with man- made infrastructure	Roads, pavements etc.: 0m	Low	Any	None		
			Small Buildings: 3-5m					
			High Buildings/ Skyscrapers: 10-300+ m					
		Bridges, tower: variability						

Grasses classified as Level 1.1 exhibit a wide range of combustibility, from 3 to 9, depending on moisture availability and seasonal variations. In humid environments or regions with consistent rainfall, combustibility remains relatively low (3-5), whereas in arid or drought-prone areas, it can increase significantly (8-9), particularly during late summer and early autumn. Fine-textured grasses are more prone to ignition than coarser species, contributing to rapid fire spread under dry conditions. Flammability levels range from 4 to 10, with lower values (4-6) observed in well-maintained or humid grasses and higher values (8-10) in unmanaged areas with substantial accumulations of dry vegetation. Fire spread is often accelerated in open, wind-exposed regions and is particularly intense in dense, continuous grasslands. Various types of grass are found in different altitudes, ranging from 100 to 700 meters, with lower elevations experiencing higher fire risks due to increased temperatures and reduced humidity. In contrast, grasses at higher elevations (500-700 meters) generally retain more moisture, reducing fire severity. The composition of the understory plays a crucial role in fire behavior, as sparse grasses present a lower fire risk, whereas denser or mixed grass-shrub areas contribute to increased fuel loads and greater fire intensity. The primary factors influencing fire risk in

these ecosystems include wind exposure, seasonal desiccation, grazing activity, and land management practices. While grazing can mitigate fire hazards by reducing available fuel, the accumulation of dry, dead grass significantly elevates fire risk, making late summer and early autumn the most hazardous periods for fire outbreaks. Additionally, anthropogenic activities, such as controlled burns and the establishment of firebreaks, can substantially influence fire behavior within these ecosystems.

Shrubs classified as Level 1.2 present moderate combustibility, typically ranging from 5 to 8, based on the vegetation's density, moisture availability, and seasonal conditions. In regions with regular precipitation, combustibility remains on the lower end of this range (5-6), whereas in drier climates or areas experiencing seasonal drought, it increases significantly (7-8).

Flammability varies from 6 to 9, with well-maintained or periodically grazed shrubs displaying lower values (6-7) and unmanaged areas with high amounts of dry biomass reaching higher levels (8-9). Fire spread is typically faster in open landscapes with continuous vegetation and wind exposure, particularly where shrubs form a dense, interconnected fuel source. These shrubs are generally found at altitudes between 200 and 800 meters, with fire risk being higher at lower elevations where temperatures are elevated,

and humidity levels are reduced. In contrast, higher-altitude shrublands (600-800 meters) tend to retain more soil moisture, moderating fire intensity.

The understory structure influences fire dynamics, with sparse shrub cover presenting a relatively lower fire hazard, while denser, continuous stands significantly increase both fire intensity and rate of spread. Key factors affecting fire behavior in these ecosystems include seasonal drying, wind exposure, fuel load accumulation, and fuel reduction methods.

Trees grouped at Level 1.3 exhibit high combustibility, ranging from 8 to 10, depending on vegetation density, tree species, and seasonal moisture availability. In regions with consistent precipitation and a well-maintained understory, combustibility remains at the lower end of this range (8-9), whereas in drier climates or areas with significant fuel accumulation, it reaches its highest levels (10). Flammability varies from 7 to 9, with open-canopy woodlands and managed forests exhibiting lower values (7-8), while dense, unmanaged stands with substantial dry biomass reach higher levels (9). Fire spread in these ecosystems is influenced by tree cover, understory composition, and wind exposure, with greater continuity of fuels contributing to increased fire intensity and duration. They can be found at altitudes between 200 and 1,200 meters, with fire risk being greater at lower elevations where temperatures are higher, and humidity levels are lower. In contrast, trees at higher elevations (900-1,200 meters) often retain more moisture, which can manage fire propagation more effectively. The understory critically affects how fire patterns, as sparse vegetation presents a lower fire hazard, while dense shrubs, grasses, and leaf litter significantly increase fire intensity and spread potential.

Grasslands grouped as Level 2.1 present moderate to high combustibility, ranging from 4 to 7, determined by fluctuations in seasonal moisture variations and vegetation cover. During wetter periods or in well-maintained areas, combustibility remains at the lower end (4-5), while in drier seasons or unmanaged landscapes, it can escalate (6-7), particularly in late summer and early autumn. The flammability of grasslands is relatively high, with values between 6 and 9, increasing significantly in regions with prolonged dry spells or excessive fuel accumulation. They occur at altitudes between 200 and 800 meters, where lower elevations (200-400 meters) are more prone to fire due to higher temperatures and reduced humidity, whereas higher elevations (600-800 meters) generally retain more moisture, limiting fire intensity. The understory, consisting of coarse to dense grasses, is a vital element due to its influence on fire behavior, as

denser vegetation provides continuous fuel, facilitating rapid fire propagation.

Shrublands classified as Level 2.2 exhibit moderate to high combustibility, ranging from 5 to 8, with changes in vegetation density and seasonal moisture affecting fire characteristics. In drier conditions, particularly during late summer and early autumn, combustibility reaches its peak (7-8), as dry shrubs and accumulated organic debris provide ample fuel for ignition. Flammability values range from 6 to 8, with the most intense fire activity occurring in areas dominated by highly volatile shrub species or where thick, dry undergrowth is present. Located at varying altitudes, between 500 and 900 meters, shrublands at lower elevations (500-600m) are generally more fire-prone due to higher temperatures and lower humidity, whereas those at higher elevations (800-900m) tend to maintain their moisture levels longer, tempering fire intensity. The understory also shapes fire dynamics. Dry shrubs fuel fast-moving fires, whereas moist shrubs offer some resistance to ignition, and thick, moisture-rich vegetation acts as a natural fire buffer in well-hydrated regions.

Forested areas categorized as Level 2.3 feature high combustibility, ranging from 7 to 9, with fire behavior largely dictated by the composition and the density of the understory. Flammability is even more extreme, ranging from 8 to 10, making these ecosystems particularly prone to intense and prolonged wildfires. Situated at altitudes between 700 and 1200 meters, these forests experience varying fire risks depending on elevation and moisture retention. Lower elevations (700-900m) tend to dry out more quickly, increasing the likelihood of ignition, while higher elevations (1000-1200m) often retain more humidity, delaying fire spread but not eliminating the risk. The understory demonstrates an immediate effect on fire intensity, as thick accumulations of pine needle litter, broadleaf litter, and conifer debris provide an abundance of highly combustible fuel. In areas with dense leaf litter and fallen logs, fires can smolder for extended periods, re-igniting with shifting winds or rising temperatures. The presence of heavy fallen logs further exacerbates fire severity, as they burn longer and contribute to prolonged heat zones.

Irrigated croplands classified as Level 3.1 present low combustibility, ranging from 2 to 4, as regular watering significantly reduces the likelihood of fire spread. Flammability follows a similar pattern, with values between 2 and 4, making these landscapes among the least fire-prone within vegetated areas. Located at altitudes between 0 and 600 meters, these

croplands are most commonly located in lowland regions where water supply control and managed agricultural practices further mitigate fire risks. The understory is generally sparse to nonexistent, as most fields are maintained to minimize unwanted vegetation. However, in some areas, weeds or organic mulch may be present, which, under prolonged dry conditions, could contribute to localized fire hazards. Fire behavior in irrigated croplands is heavily influenced by land management techniques, crop type, and seasonal agricultural activities. While the presence of irrigation serves as a natural fire deterrent, extended droughts, inefficient water distribution, or abandoned fields with dry crop residues can create isolated ignition points. Additionally, human activities such as mechanized farming, controlled burns for post-harvest clearing, and improper disposal of agricultural waste can influence fire risks. Overall, well-maintained irrigated croplands remain one of the safest land types in terms of fire potential, but vigilance is necessary to prevent fire outbreaks in neglected or poorly managed fields.

Non-irrigated croplands classified as Level 3.2 exhibit moderate to high combustibility, ranging from 4 to 7, with the probability of fire largely driven by seasonal moisture availability and land management practices. Flammability levels range from 5 to 8, increasing significantly during dry spells when vegetation dries out and crop residues accumulate. Found at altitudes between 100 and 1000 meters, these croplands experience varying fire behavior based on elevation, with lower altitudes (100-400m) typically being more fire-prone due to higher temperatures and lower humidity, while higher elevations (800-1000m) may hold moisture for a longer period, slowing fire spread. The understory consists of light to moderate vegetation, including weeds, stubble, and organic residue, which can serve as fine, fast-burning fuel if left unmanaged. Fire risk is highest in fields with excessive post-harvest debris, particularly during late summer and autumn when dry conditions prevail.

Riparian vegetation classified as Level 4.1 present moderate combustibility, ranging from 3 to 7, shaped by seasonal shifts in moisture and the density of vegetation. Flammability follows a similar pattern, ranging from 4 to 7, with fire risk increasing during extended dry periods when leaf litter and woody shrubs dry out. Spotted at altitudes between 0 and 1500 meters, riparian zones typically benefit from higher humidity and water availability, which can hinder fire progression, especially in well-hydrated areas. However, during droughts or in regions with reduced water flow, fire risk escalates as dense shrubs and accumulated moist leaf litter become

receptive to ignition. The understory, characterized by thick shrubbery and decomposing organic material, plays a crucial role in fire behavior, as dry conditions can turn these fuels into a significant fire hazard. Fires in riparian areas can be unpredictable, with slow-burning smoldering fires persisting in damp litter, while fast-moving flames may spread through dense, dry vegetation.

Coastal vegetation grouped as Level 4.2 exhibits moderate combustibility, ranging from 4 to 8, influenced by the density of shrubs, grasses, and organic debris. Flammability varies between 5 and 9, with fire risk increasing during dry and windy conditions when salt-tolerant plants and accumulated debris become more susceptible to ignition. Found at altitudes between 0 and 500 meters, coastal landscapes experience constant exposure to oceanic winds and salt spray, which can either inhibit or accelerate fire spread depending on moisture levels. The understory, consisting of sparse to dense shrubs, salt-tolerant plants, and a mix of grasses and organic material, plays a key role in fire behavior, as dry conditions can turn these fuels into a significant fire hazard. Fires in coastal vegetation can be erratic, with rapid spread in dry, wind-driven environments, while more humid conditions may suppress ignition and slow fire propagation.

Wetland vegetation classified as Level 4.3 displays low to moderate combustibility, ranging from 2 to 6, influenced by the saturation levels of peat, moss, and decaying organic matter. Flammability varies between 2 and 7, with fire risk significantly increasing during prolonged dry periods when water levels drop, exposing dense vegetation and organic debris to ignition. Found at altitudes between 0 and 500 meters, wetland vegetation preserves high moisture content, which suppresses fire spread and promotes slow, smoldering combustion rather than rapid flames. The understory, consisting of dense aquatic plants, peat, moss, and decomposing organic material, significantly influences fire behavior, as dried-out peat can sustain underground fires that persist long after surface flames are extinguished. While wetland fires are less frequent, they can be severe, producing thick smoke and prolonged burning, especially in areas where organic soils have become dry and compacted.

Areas covered with water, classified as Level 4.4, exhibit low to moderate combustibility, ranging from 2 to 6, with fire risk largely dependent on seasonal water levels and vegetation density. Flammability varies between 2 and 7, increasing in periods of drought when submerged and floating vegetation, along with organic debris, become exposed and dry out.

Located at altitudes between 0 and 600 meters, these landscapes—including rice fields, ponds, and lakes—typically maintain high moisture content, which naturally suppresses fire spread. The understory, consisting of submerged and floating vegetation along with organic debris, plays a significant role in shaping fire propagation, as accumulated dry plant matter can ignite under extreme conditions. While fire occurrence in these areas is rare, the presence of decomposing organic material in drained or shallow regions can lead to smoldering fires, producing dense smoke and prolonged burning.

Areas with snow and ice, classified as Level 4.5, present very low combustibility and sustainability, both ranging from 1 to 2, due to the predominance of frozen surfaces and the absence of significant vegetation. Found at altitudes ranging from 500 to 2500 meters, these areas are typically characterized by cold climates where snow or ice covers the ground year-round, preventing the growth of substantial plant life. The nonexistent understory means there is little to no organic material available to sustain a fire, and the frozen environment makes it highly unlikely for fire to spread or take hold. While the low combustibility and sustainability reduce the fire risk, the area's relatively stable, snow-covered condition can pose challenges for fire management in the rare case of unusual weather patterns or human activity introducing fuel sources. However, under typical conditions, snow and ice-covered areas are largely resistant to fire, with limited capacity for combustion or fuel continuity, thus maintaining a low overall fire risk.

Natural terrestrial areas, classified as Level 5.1, exhibit high combustibility, ranging from 5 to 9, and flammability between 6 and 10, making them highly susceptible to fire. Situated at altitudes between 0 and 3000 meters, these landscapes encompass grasslands, shrublands, and forested areas, where dry conditions and fuel accumulation can significantly increase fire risk. The understory, consisting of dense forest litter, shrubs, dry grass, and deadwood, plays a major role in fueling wildfires, as dry and compacted organic material can ignite easily and sustain intense, fast-spreading flames. Fire behavior in these environments varies, with surface fires consuming dry grasses and leaf litter, while crown fires can rapidly spread through dense vegetation in forested regions. Strong winds, prolonged drought, and high temperatures further exacerbate fire danger, making natural terrestrial areas particularly vulnerable to large-scale, destructive wildfires.

Semi-natural terrestrial areas, classified as Level 5.2, display moderate to high combustibility, ranging from 4 to 8, and flammability between 5 and 9, impacted by the vegetation density and meteorological patterns. Found at altitudes between 0 and 2500 meters, these landscapes include managed grasslands, wooded areas, and agricultural zones where human activity influences fire behavior. The understory, consisting of managed grasslands, shrubs, and crop residues, contributes to fire propagation, as dry plant material can ignite easily under hot, dry, and windy conditions. While controlled land management practices, such as grazing and crop rotation, can help reduce fuel accumulation, prolonged droughts or abandoned fields increase the risk of rapid-fire development. Fires at this level can vary from slow-burning ground fires in thick vegetation to fast-moving surface fires in dry grasslands, making proactive fire prevention strategies essential in these regions. Bare land, classified as Level 6.1, exhibits very low combustibility, ranging from 1 to 2, and minimal flammability, between 2 and 3, due to the absence of significant vegetation. Situated at any altitude, these areas typically result from agricultural activities, land clearing, or natural soil erosion, leaving little to no organic material available to sustain a fire. With a nonexistent understory, fire spread is highly unlikely, except in cases where external fuel sources, such as windblown debris or human activity, introduce combustible material. While bare land itself poses minimal fire risk, surrounding vegetation or dry soil conditions may contribute to localized ignition if exposed to extreme heat or prolonged drought. However, overall, the areas of this level remain largely resistant to fire due to the lack of continuous fuel.

Areas with man-made infrastructure, categorized as Level 6.2, present low to moderate combustibility, ranging from 1 to 2, and moderate flammability, between 2 and 3. These areas, which can be found at any altitude, are typically characterized by urban development or industrial zones where buildings, roads, and other human-made structures dominate the landscape. The lack of an understory greatly reduces the availability of organic material to fuel a fire. While the infrastructure itself is not highly combustible, the moderate flammability rating suggests that fire can still pose a risk, particularly in conditions where nearby materials or external sources of ignition, such as discarded debris or human activity, introduce potential fuel. The absence of an understory further limits the spread of fire, making it unlikely to expand rapidly unless affected by extreme heat or dry conditions. Despite these factors, the area remains relatively resistant to widespread fire due to the absence of continuous natural fuel sources, although localized fires can still occur depending on external influences.

5. Modelling fuel treatments

5.1. Fuel treatments

Fuel treatment is any mechanical, silvicultural or burning activity whose primary objective is to reduce fuel loads or modify fuel characteristics to reduce fire behaviour or severity (Reinhardt et al., 2008).

Fuel treatments, such as thinning, pruning, manual or mechanical removal of understory and prescribed burning, are commonly employed to modify forest structure and reduce wildfire risk by altering fuel characteristics. Fire behaviour models can be utilized to simulate and evaluate the effects of these treatments.

Table 11 – Principles of fire resilience (from Agee and Skinner, 2005)

Principle	Effect	Advantage	Concerns
Reduce surface fuels	Reduces potential flame length	Control easier; less torching (initiation of crown fire)	Surface disturbance less with fire than other techniques
Increase height to live crown	Requires longer flame length to begin torching	Less torching	Opens understory; may allow surface wind to increase
Decrease crown density	Makes tree-to-tree crown fire less probable	Reduces crown fire potential	Surface wind may increase and surface fuels may be drier
Keep big trees of resistant species	Less mortality for same fire intensity	Generally, restores historic structure	Less economical; may keep trees at risk of insect attack

A number of simple principles (Table 5) are important to consider in fuel reduction treatments: reducing surface fuels, increasing height to live crown, reducing crown density, and preserving large trees of fire-resistant species (Agee and Skinner, 2005). To control surface fire behaviour in a forest, treatments should either reduce or prevent increased fire behaviour. This can be achieved by reducing surface fuels or reducing the greening of grasses and low shrubs. To reduce the potential for crown fire (torching) initiation, the potential flame length can be compared to a critical flame length, which is a function of canopy base height (CBH). Reducing the surface fire behaviour and increasing the canopy base height can minimise the torching potential. Reducing canopy bulk density (CBD) can also help reduce the spread of active crown fires. In the short term, large trees need to be preserved in the stand as they are the most fire-resistant trees. In the

long term, there should be sufficient spatial variation in age classes to replace larger trees as they die. In the absence of large trees, the largest of the small trees should be maintained. A resilient forest is capable of maintaining substantial live basal area after being burned by a wildfire. Forests treated with these principles will be more resilient to wildfires (Agee and Skinner, 2005).

Fuels come in all shapes, sizes and arrangements. There are live and dead fuels, herbaceous and shrub fuels, litter, branches and twigs, ladder fuels (small trees) and canopy fuels (larger trees). A fuel reduction treatment may address any or all of these fuels. These treatments directly modify the fuel component of the fire behaviour triangle, influencing the amount, arrangement, and flammability of fuels available to burn (Table 6).

Table 12 – Main silvicultural treatment types, their primary changes in fuel characteristics and expected impact on fire behaviour

Treatment type	Primary changes in fuel characteristics	Expected impact on fire behaviour
Thinning	Reduced surface and canopy fuel loads, increased crown base height, altered wind flow	Decreased rate of spread and fire intensity, reduced potential for crown fire
Pruning	Increased crown base height	Reduced likelihood of torching and transition to crown fire
Manual removal of understory and/or midstory vegetation	Reduced surface fuel load, altered fuel structure and composition	Decreased rate of spread and fire intensity, reduced flame lengths, lower probability of ignition and sustained burning
Mechanical understory treatments		
Grazing		
Prescribed Burning		
Firebreak		

The impact of treatments on fuel characteristics is the following:

- **Thinning:** This treatment involves reducing the density of trees in a stand. Thinning primarily decreases surface and canopy fuel loads by removing smaller trees and understory vegetation. It can also increase the crown base height of the remaining trees and alter wind flow patterns within the stand.
- **Pruning:** This treatment consists in the removal of lower branches from trees. This practice significantly increases the crown base height, reducing the likelihood of surface fires torching individual

trees and subsequently spreading into the canopy to become crown fires.

- **Manual removal of understory and/or midstory vegetation:** This treatment can limit wildfire hazards by reducing fuel loads and creating space between ground cover and the tree canopy.
- **Mechanical understory treatments,** such as mastication or mowing: These forest management techniques use heavy equipment to remove trees and shrubs, and alter the structure of the forest floor. Such treatments decrease surface fuel loads.
- **Grazing:** Grazing means using any tract of land to feed or supply farm animals with grass or pasture or other wild vegetations. Grazing decreases surface fuel loads by removing herbaceous vegetation.
- **Prescribed burning:** This involves the controlled application of fire to the forest floor under specific weather conditions. Prescribed burning consumes surface fuels like leaf litter, dead branches, and small understory vegetation, leading to a reduction in overall fuel load and potentially altering the structure and composition of the remaining fuels.
- **Firebreak:** A firebreak is a gap in vegetation or fuel material that slows or stops a wildfire. They can occur naturally in areas lacking vegetation or fuel, such as rivers, lakes or gorges, or they can be man-made, such as logging roads, four-wheel drive tracks, secondary roads or highways.

5.2. Methods for modelling treatment effects

The impacts of silvicultural treatments on fire behaviour can be modelled using various approaches within the framework of fire behaviour models:

- Adjusting fuel model parameters: One common method involves selecting or creating custom Fire Behaviour Fuel Models (FBFMs) that accurately represent the post-treatment fuel conditions. This requires modifying specific parameters within the fuel model, such as fuel load by size class and fuel bed depth, to reflect the changes resulting from the treatment.
- Using spatially explicit fuel data: For landscape-level models like FlamMap or FARSITE and physics-based models such as FIRETEC, the effects of treatments can be represented through detailed spatial datasets of fuel characteristics. These datasets are updated to reflect the changes in fuel load, canopy cover, and crown base height in treated areas.

- **Implementing treatment scenarios in stochastic models:** Stochastic models can simulate different treatment scenarios by directly altering parameters related to vegetation type and fuel load in areas where treatments have been implemented. This allows for the probabilistic assessment of how treatments might influence fire spread under various conditions.

5.3. Evaluating the treatment effectiveness

Fuel treatments can significantly influence forest structure and fuel conditions, thereby affecting potential fire behaviour. Quantitative methods for measuring the effectiveness of these interventions provide essential feedback for adaptive management and continuous improvement of fire hazard reduction strategies.

Fire behaviour modelling tools, such as FlamMap, provide valuable tools for evaluating the effectiveness of fuel treatments in reducing wildfire risk or modifying fire behaviour. This typically involves comparing simulation results under treated and untreated conditions.

By simulating fire behaviour for the same weather and topographic conditions, but with different fuel conditions representing treated and untreated areas, managers can directly compare expected fire characteristics such as rate of spread (ROS), flame length (FL), fireline intensity (FLI) and potential area burned between these scenarios (Figure 6), and quantitatively assess the impact of treatment. These comparative simulation approaches provide spatially explicit information on how treatments modify potential fire behaviour across a landscape, identifying areas where treatments are successfully reducing hazard as well as locations where additional treatments may be needed.

For example, simulations might show a significant reduction in the rate of fire spread and flame lengths in thinned and pruned stands compared to untreated stands under the same weather conditions.

Fire behaviour models can also be used to calculate fire hazard indices, such as crown fire hazard or surface fire intensity potential, for treated and untreated landscapes. By comparing the changes in these indices, a more integrated measure of the overall impact of treatments on wildfire risk can be obtained. A reduction in crown fire hazard index in treated areas would indicate a decreased susceptibility to severe, high-intensity crown fires.

Conducting sensitivity analyses can further enhance the evaluation of treatment effectiveness. This involves running simulations under a range of

different weather conditions, from moderate to extreme fire weather, to understand how the effectiveness of treatments varies depending on environmental factors. For instance, a treatment might be highly effective in reducing fire intensity under moderate weather but offer less benefit during extreme wind and dry conditions.

Where possible, comparing fire behaviour model predictions in treated areas with observations from actual wildfires or prescribed burns is crucial for validating the model's ability to accurately represent the effects of treatments. This involves collecting data on fire behaviour (e.g., rate of spread, flame length, burn severity) in treated areas during actual fire events and comparing these observations with model predictions for the same conditions. Such comparisons help build confidence in the reliability of fire behaviour models for evaluating the effectiveness of silvicultural treatments.

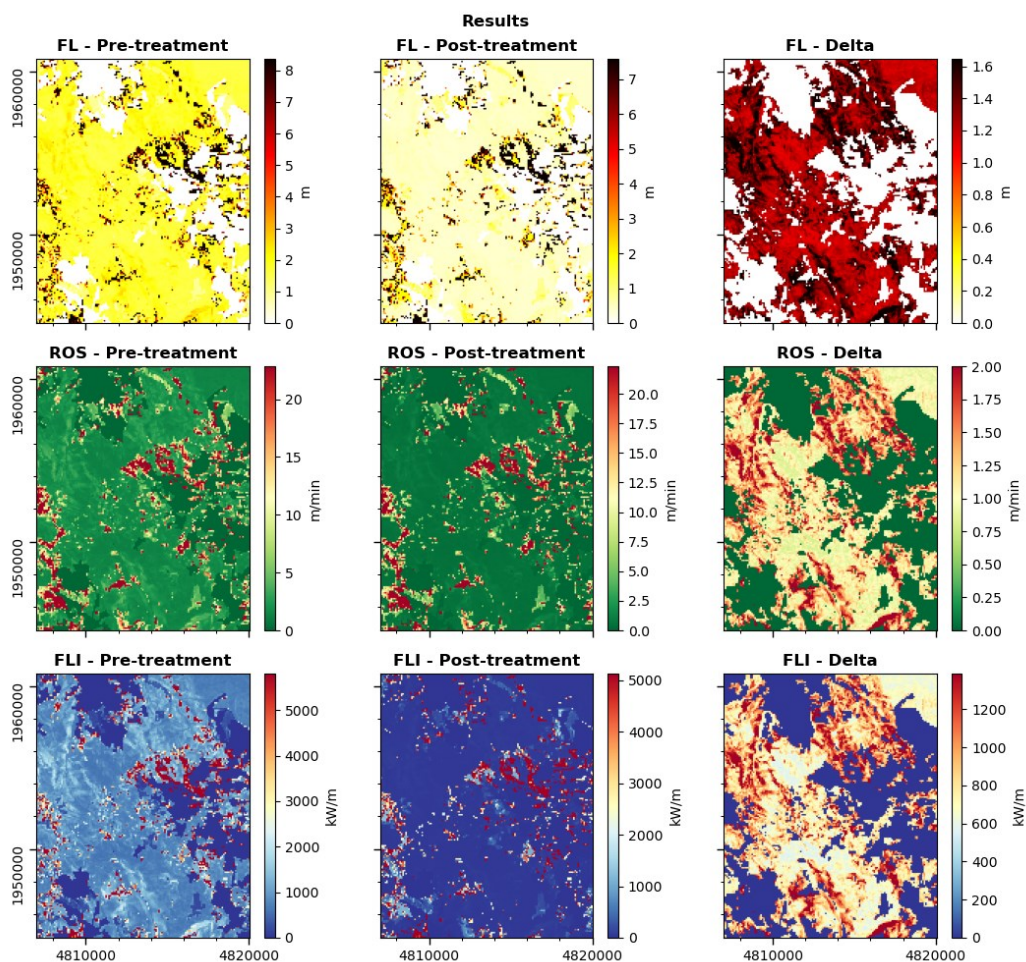


Figure 6 – Example of comparison of fire behaviour characteristics, such as rate of spread (ROS), flame length (FL), fireline intensity (FLI) in pre-treatment and post-treatment conditions.

5.4. Fact sheets about fuel treatments

5.4.1. Study area 1: Appennino Lucano Val d'Agri Lagonegrese NP (Italy)

The Appennino Lucano Val d'Agri Lagonegrese National Park is an extensive protected area, covering about 69,000 hectares in the Basilicata region. It encompasses, in whole or in part, 29 municipalities within its boundaries.

Wildfire management in the Appennino Lucano Val d'Agri Lagonegrese National Park – in all its components (prevention, prevention, and active suppression) – is regulated by a Multi-Year Wildfire Management Plan. This plan is drafted in compliance with Article 8, paragraph 2, of Law No. 353 of November 21, 2000, which requires the preparation of a specific A.I.B. plan for National Parks and Nature Reserves. This planning instrument follows the guidelines of the Scheme for the preparation of wildfire management plans for National Parks, issued by the Ministry of the Environment and Land Protection. From a technical perspective, it also follows the procedures outlined in the *"Manuale per l'applicazione dello SCHEMA DI PIANO A.I.B. NEI PARCHI NAZIONALI-2018"*. The provisions of the multi-year plan are implemented through the preparation of annual operational plans.

Within the plan, based on several factors (fire frequency, vulnerability of areas, environmental quality, etc.), large "Priority Intervention Areas" are identified. Inside these areas, further criteria are applied (most affected forest types, maximum acceptable fire size, presence of forest rangers, etc.) to define priority wildfire prevention and suppression operations during the plan's validity.

The wildfire prevention measures involving vegetation management, as provided for in the Plan, can be classified into the following categories:

a) Silvicultural Treatments

These are interventions aimed at:

- Increasing resistance/resilience of forest stands.
- Supporting renaturalization processes in artificial forest plantations to favour more resilient native vegetation.
- Reducing understory fuel loads in specific high-risk areas.

In general, forest management criteria for fire protection aim to establish stands with tall and dense canopy cover, which reduce understory development and maintain a clean forest floor, also ensuring conditions suitable for regeneration. Silvicultural practices such as thinning, cleaning, lengthening coppice rotations, converting old coppices into high forest,

creating uneven-aged stands, and interventions for the renaturalization of artificial stands improve shading and soil moisture conditions, enhance resistance and resilience, and progressively reduce stand vulnerability to wildfires. However, since interventions are carried out within a protected area, the underlying methodological approach is that of close-to-nature forestry, which considers the complexity of biological systems, the often-delicate interconnections between them, their multifunctionality, and the constant and careful monitoring and evaluation of natural system responses to the implemented interventions.

More specifically, the silvicultural interventions planned are:

a.1) Thinning

These types of interventions are of particular importance because they promote the functionality of forest systems, guiding stands toward more stable structures and therefore less vulnerable to fire. In some conditions and for certain forest types, unthinned stands develop mechanically and biologically unstable structures. As a result, they are particularly vulnerable to wildfires due to the accumulation of necromass caused by excessive stand density and strong competition among individuals, which trigger dangerous processes of self-thinning. In denser stands, thinning operations consist of removing declining and diseased trees, which reduces necromass on the ground and consequently lowers fire risk. Thinning also leads to a significant diameter increment in the remaining trees, indirectly increasing bark thickness and thus improving the resistance of forest stands to fire spread.

This type of intervention will primarily concern black pine afforestation (*Pinus nigra*), often characterized by excessive density, as well as Turkey oak stands (*Quercus cerris*), managed as high forest, or in transitional phases toward high forest.

a.2) Improvement of Degraded Forests

Anthropogenic factors, or more rarely natural ones (such as the low resilience of certain forest stands to Climate Change), can lead to forest formations showing varying degrees of degradation. Human-induced causes are often linked to irrational and intensive logging practices and unsustainable grazing regimes. This mismanagement, persisting over time, has resulted in degraded stands characterized by irregular density, declining trees, and excessive development of the lower layer dominated by invasive shrub vegetation. These formations are extremely vulnerable to various types of disturbances and to wildfires. Improving such forests is

therefore of great importance and can be achieved through targeted interventions to restore both vegetative and generative regeneration processes, combined with grazing exclusion on the treated surfaces. In most degraded forests, it may also be appropriate to carry out sanitary felling to prevent excessive accumulation of necromass, both standing and on the forest floor, which could otherwise act as ignition points or significantly contribute to fire spread.

This type of intervention mainly concerns Turkey oak (*Quercus cerris*) stands, where the most suitable form of intervention is determined case by case, according to site characteristics and the condition of individual stands.

a.3) Pruning

Pruning consists of removing both dead and live branches up to a height of approximately 2–2.5 m from the base of the trees. This intervention will primarily concern black pine (*Pinus nigra*), plantations which often present branches inserted very low on the trunk, many of which are no longer vital due to reduced light penetration. These lower branches are particularly dangerous because they create vertical continuity in forest structure, enabling fire to spread from the herbaceous/shrub layer to the tree crowns. Once fire reaches the crown, it may propagate independently of ground fuels, becoming extremely dangerous in terms of both energies released and suppression difficulty. Where thinning is planned, pruning should be carried out simultaneously, with removal of all resulting material. For fire prevention purposes, it is essential to remove all woody debris generated by silvicultural operations, particularly conifer slash. Harvest residues must either be extracted from the site or, where feasible, chipped and destroyed in place.

a.4) Manual or mechanical removal of understory removal

Where thinning, pruning, or other silvicultural interventions are planned, fire prevention measures must include the extraction of all woody material resulting from such operations, with particular attention to conifer slash. Harvest residues must be removed from the site or, where feasible, chipped and destroyed in place. During removal, the accumulation of residues along skid trails or the formation of biomass piles in the understory must be strictly avoided.

Ground fuel management, consisting of clearing and partial removal of the herbaceous and shrub layer, must be carried out with caution, taking into account floristic diversity, which is a qualifying feature of a National Park.

Biodiversity must be particularly safeguarded where monitoring of SAC/ZSC areas has identified plant species of community interest, and always in compliance with the management tools in force for these areas (Conservation Measures, Management Plans).

In general, understory removal is recommended only in specific cases: to favour the development of regeneration nuclei of higher-value species, where present, by reducing competition from invasive shrubs; to clean and eliminate understory in areas with a recreational function (tourist areas, picnic areas, rest areas, equipped areas, etc.); to clear forest strips of shrubby and herbaceous species; and in the case of artificial conifer plantations.

a.5) Renaturalization of Conifer Afforestations

The afforestations present in the Park area are quite extensive and, as noted previously, can be classified into two major categories: the “Oro-Mediterranean Pine Forests,” which cover an area of just under 1,800 hectares and are mainly composed of Black Pine (*Pinus nigra*) afforestations (about 1,600 ha), and the “Mediterranean Pine Forests” (Mediterranean pines afforestation), which cover almost 1,400 ha and consist primarily of mixed Mediterranean conifer afforestations and, secondarily, Aleppo Pine (*Pinus halepensis*) afforestations. These stands are particularly susceptible to being affected by fire.

In an initial phase of planning, attention in forest management will be focused on conifers, and in particular on the Black Pine and Aleppo Pine afforestations, which are highly vulnerable to fire.

The approach will prioritize silvicultural interventions starting from areas where processes of naturalization are already underway. On several surfaces, natural colonization is occurring beneath the conifer canopy by native species. These species generally belong to the Mediterranean shrub in Mediterranean conifer afforestations and include thermophilic shrubs or oak species in montane afforestations, particularly those of Black Pine.

From these nuclei, it is possible to plan progressive thinning interventions that allow for the introduction or establishment of native species, significantly reducing the time needed for spontaneous recolonization. Gradual replacement of highly flammable species (conifer afforestations) with less flammable ones would make these systems less fire-prone and, should fire occur, more resilient.

a.6) Extension of rotation length or change in forest form

The chestnut groves in the area are all managed as coppices and have been found to be particularly sensitive to fire. For these stands, it is possible to adopt a silvicultural technique known as “coppice with a long rotation length.” Extending the rotation length, together with the application of appropriate silvicultural practices, is the main method to enhance the economic and environmental potential of the species, increase the quantity of products, and improve the quality of timber assortments.

Lengthening the rotation allows for the production of larger assortments, while thinning affects the quality of the stems, biodiversity, stand stability, and reduces vulnerability to fires. Thinnings from below or of mixed type could be repeated in cycles of seven years, impacting approximately 30% of the basal area.

In areas of particular landscape value, thinnings could be carried out following selective thinning principles—i.e., a technique aimed primarily at favouring a limited number of trees capable of producing high-quality timber, while simultaneously creating stands more resistant to fire.

In chestnut groves located in ecologically marginal areas for the species, often characterized by abandoned management, structural anomalies, and lack of stability, the introduction of other species—or, where present, their enhancement—could be an appropriate silvicultural practice to recover both the productivity and environmental value of these stands, making them more resilient to biotic and abiotic stresses and thus less susceptible to fire.

High forest conversion operations—i.e., the transition from coppice to high forest—are planned for those oak stands with predominant Turkey oak (*Quercus cerris*) that correspond to aged coppices, specifically stands older than two rotation cycles, provided that soil and climatic conditions can support the development of high forest. Conversion not only increases the ecological and landscape value of the stands but also makes them less vulnerable to fire and its spread, since coppices are generally more fire-prone than high forests.

b) Firebreaks

Firebreaks are preventive measures that can be highly important under certain conditions, as they allow for the activation of a defence strategy to either stop a fire or, at the very least, slow it down, enabling firefighting teams to operate safely and with a higher chance of success.

In traditional firebreaks, all combustible material is completely removed down to bare soil. These interventions are significant in impact and are

avoided in this context, given the high environmental value of the area. Additionally, traditional firebreaks are costly to maintain.

Instead, “green firebreaks” are proposed. In these, the combustible material is only reduced, focusing mainly on the shrub layer. The forest stand is only marginally affected; interventions such as thinning or crown lifting are applied to the tree layer to break vertical fuel continuity. The maintenance of the tree layer ensures that this type of firebreak is effective in slowing down the fire and reducing key fire behaviour variables, such as energy release, flame height, and rate of spread.

Green firebreaks still require the intervention of firefighting teams if a fire occurs, but they facilitate the operation because the fire is likely to be of low intensity, primarily consuming surface fuel. A major advantage is their low environmental impact compared to traditional firebreaks, since the tree layer is not completely removed—an important factor in a high-value natural, environmental, and landscape area such as a national park.

Active or green firebreaks are designed to slow fire and facilitate team access, not to stop the fire entirely, and therefore always require the presence of firefighting teams. To ensure accessibility, these firebreaks should be created along the edges of forest roads and have a width of approximately 20 meters.

Within the National Park, there are several active and passive firebreaks. The Forest Fire Prevention Plan provides for their maintenance, which is crucial for their continued effectiveness. No new firebreaks are planned at present; however, future revisions of the plan should allow for the creation of new firebreaks based on events, spatial location, and the type of areas affected.

c) Prescribed Burning

Prescribed fire can be defined as the expert and authorized application of fire on planned areas, following specific prescriptions and operational procedures, to achieve specific objectives integrated into territorial planning. Prescribed fire is primarily understood as a forest fire prevention tool, particularly for the management of firebreaks, reduction of litter fuels in coniferous forest areas, or in herbaceous and shrub formations.

In Basilicata, apart from some experimental trials, there has been no operational application of this fuel reduction technique. This is despite the fact that the Basilicata Region, when issuing its regulations implementing the national framework law on forest fires, was among the first Italian regions to regulate prescribed fire, recognizing it as a possible action for fire prevention.

In fact, Regional Law L.R. 13/2005 allows the use of controlled or prescribed fire to prevent fire spread or to manage the herbaceous and shrub vegetation along firebreaks.

The limited use of prescribed fire is fundamentally due to three factors:

- Excessive and often unjustified concern about the negative consequences of fire, even when conducted according to best practices;
- The need for highly qualified professionals and operators with experience in the design and management of prescribed fire;
- Significant ecological impact, especially in areas of particular environmental value (Parks, Nature Reserves, Natura 2000 sites, etc.).

The Park's Forest Fire Prevention Plan (AIB Plan) does not currently include the application of prescribed fire. However, it does not rule out that in the future, if conditions require it (e.g., mountain and Mediterranean conifer afforestation) and if site-specific conditions (topography, climate parameters, etc.) allow, areas may be identified where prescribed fire could be used as part of AIB prevention measures.

d) Reduction of fuel load along regular and forest roads (tracks and trails)

Communication routes often constitute areas vulnerable to the ignition of fire, even accidentally. The presence of a developed road network is, in fact, a double-edged sword: on one hand, roads significantly facilitate surveillance, the deployment of personnel and equipment, faster response times, and lower forest maintenance costs; on the other hand, they can contribute to both negligent and intentional fires.

It is planned to clear vegetation—both herbaceous and shrub layers—along a strip 10–20 meters wide adjacent to regular and forest roads, while respecting, where established, the regeneration of the tree. In areas with conifers, pruning is planned along tracks and trails to 2 meters above ground for a strip of about 10 meters on both sides of the road.

Where human and financial resources allow, these clearing operations should be carried out annually. It is important that this work be completed before the period of highest fire risk for the area in question (summer).

As previously mentioned, the measures outlined in the Multi-Year Forest Fire Prevention Plan are implemented through annual implementation plans, depending on the available financial resources.

The body responsible for carrying out forest fire prevention works is the Consorzio di Bonifica of the Basilicata Region. The Consorzio di Bonifica is

the sole managing authority that consolidates forest sector management, overcoming the excessive fragmentation of responsibilities that existed prior to 2017.

Based on the needs arising from various public bodies, such as Municipalities, Park Authorities, Basin Authorities, ANAS, State Railways, and Water Cycle Authorities, the Consorzio annually carries out forest maintenance works, calibrating operations according to priorities and intervening on different areas each year depending on available funding.

In recent years, several management interventions have been carried out within the Park, including the maintenance and creation of active and passive firebreaks, pruning, reduction of surface fuel through mechanical removal of herbaceous and shrub layers, maintenance of forest roads, sanitary felling for the removal of deadwood, low-intensity thinning from below, and the management of green spaces in urban and peri-urban areas.

It is difficult to quantify the annual extent of these treatments, but in summary, they can be classified into the types shown in Table 7.

Table 13 – Prevalent treatment characteristics in the Appennino Lucano Val d’Agri Lagonegrese National Park

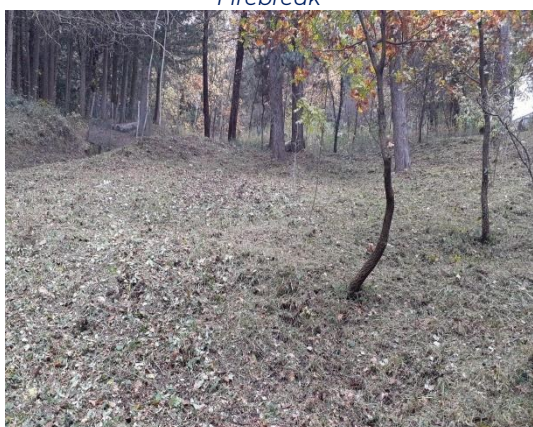
Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	10-15 %	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	CBH = 2.5-3 m	<input checked="" type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Manual removal of understory vegetation		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments		<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Grazing		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Firebreak (maintenance)		<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Other (see description in the text above)		



Firebreak



Green firebreak



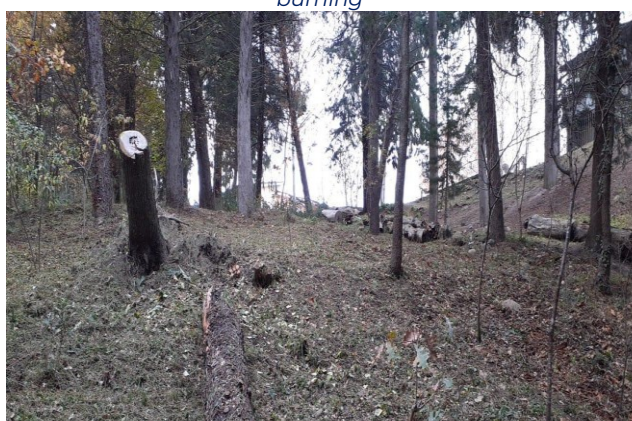
Brush clearing



Mechanical understory treatments and brushwood burning



Clearing of forest trails



Thinning

Figure 7 - Some examples of fuel treatments in the Park area (source: Consorzio di Bonifica della Basilicata)

5.4.2. Study area 2: Sutjeska NP (Bosnia and Herzegovina)

Sutjeska National Park, as a protected and mountainous area, faces significant challenges in fuel management due to difficult terrain and limited accessibility. The most common fuel treatment methods applied in the area include forest thinning (approximately 13%, involving both broadleaved and coniferous forests) and grazing (around 7 hectares annually). These treatments aim to reduce fuel loads and help maintain forest structure, particularly in zones of higher wildfire risk.

Past experience has shown that human activity is the main cause of fire outbreaks. Therefore, considerable efforts are made to raise awareness among tourists and visitors, with a strong focus on responsible behaviour and the cautious use of fire.

Fuel management is further supported through the establishment of forest order, maintenance of fire protection roads, and active lookout stations that enable early detection and rapid response. Regular training and evaluation of staff—especially those involved in fire prevention and intervention (rangers, firewatchers, and gatekeepers)—form a crucial part of the Park's preparedness strategy.

Continuous monitoring and the presence of trained personnel ensure that Sutjeska National Park remains under constant surveillance, with lessons learned from past fire events being regularly integrated into fuel management practices.

Table 14 – Prevalent treatment characteristics in the study area 2

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	13% (10% B, 3% C)	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Pruning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Manual removal of understory vegetation		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Mechanical understory treatments		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	7 ha/yr	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M

The price of forest thinning treatment per hectare is an average of 200 BAM (approximately 100 €), depending on the configuration of the terrain, location, etc.

5.4.3. Study area 3: Shebenik-Jabllanica NP (Albania)

Shebenik-Jabllanicë National Park (SJNP or the Park) includes some of the most beautiful mountainous areas in eastern Albania. Located in the Librazhd District, Elbasan County, the area was declared a national park in 2008, with a total surface area of 33,928 ha. Spread around the sources of the Shkumbin River, the Park is dominated by mountains and valleys. Its altitude above sea level ranges from 300 to 2,200 m and it is characterized by a variety of climatic conditions, geological formations, landscapes, habitats, and plant and animal species.

The Shebenik-Jabllanicë area extends from 300 to 2200 meters above sea level. Being located inland, the area has a continental climate and not a Mediterranean one. The average annual temperature is 13.4°C, while rainfall reaches around 1,360 mm per year.

In this area, three types of land were identified: natural pastures (natural areas), aquatic environments, and artificial habitats. Natural pastures are divided into six components: three types of forests, shrublands and low shrubs, meadows, as well as soils characterized by landslides and unproductive land. The three main types of forests are thermophilic deciduous forests (oak forests, mainly from *Quercus frainetto* and *Quercus cerris* or *Quercus petraea*, and forests dominated by *Carpinus orientalis* or *Platanus orientalis*), coniferous forests (mainly dominated by *Pinus nigra*, *Pinus peuce* and *Abies alba*), and mesophilic deciduous forests (beech forests dominated by *Fagus sylvatica*). Oak forests are located in lower areas, while beech and coniferous forests occupy higher altitudes. Meadows are mainly found at high elevations above the tree line.

Pursuant to Law no. 81 dated 04.05.2017 “On Protected Areas”, Law no. 9385 dated 04.05.2005 “On Forests and the Forest Service” as amended, Law no. 8766 dated 05.04.2001 “On Fire Protection and Rescue”, Law no. 45/2019 “On Civil Protection”, DCM no. 288 dated 27.06.2002 “On determining and taking measures against fire and rescue in objects of economic and state importance”, DCM no. 290 dated 30.04.2004 “On the approval of the national strategy for fire management in forests and pastures”, DCM no. 835 dated 03.12.2004 “On the approval of the national civil emergency plan”, and DCM no. 1080 dated 22.12.2010 “On rules and prevention regarding forest and pasture fire extinguishing”, for the prevention and timely extinguishing of possible fires in forests and pastures and for coping with emergency situations, the following organizational measures have been taken.

The Administration of Shebenik-Jabllanicë National Park is obliged to establish and implement a Forest Fire Protection Plan, which specifies: Fire risk assessment, Fire protection organization, Use of firefighting units, Notification system, Fire emergency procedures, Equipment and technical means for fire extinguishing, Water supply methods, Access roads, Cooperation with other firefighting and rescue units.

In the Elbasan RAPA (Regional Administration of Protected Areas), local headquarters of the Fire Protection and Rescue (MNZSH) have been established and an action plan has been prepared at regional and local level, in cooperation with local government bodies and specialized agencies, such as the prefectures, Civil Emergency Offices, Fire Protection and Rescue Police (MNZSH), regional branches of the former Forest Inspectorate (ISHMP), as well as legal and physical entities, domestic and foreign, that operate in forest and pasture areas.

The Elbasan RAPA has in full readiness all the existing material base (working tools, fire extinguishers, vehicles, etc.) for extinguishing fires in forests and pastures, especially in coniferous forest areas with high fire risk. The occurrence of forest fires is often associated with human activities: the periodic use of fire to clear pastures, lighting fires in unauthorized places, barbecues and abandoned fires, etc. Furthermore, extreme heat and drought increase fire risks.

Risk assessment in protected areas is a procedure that determines the level of risk in relation to damages caused by human or natural factors such as illegal logging, poaching, fires, as well as a series of other interventions in protected areas. The purpose of developing a risk management plan is to ensure that small problems do not evolve into emergencies: to assess the probability of different events occurring and their respective impacts, in order to address problems in time or prevent others as a result of measures taken in advance.

It is the process that determines which types of risks are important and most frequently present in protected areas. Risk assessment identifies the presence and effects of a specific risk, as well as its development, management, or control trend. Each risk must be assessed according to its level of hazard and the necessary measures must be taken to avoid or manage it. This process is carried out once a year, and as a measurement indicator, the entire history of damages observed in all protected areas over the years is taken into account, referring to each case throughout the RAPA. Risks are then classified into low, medium, and high levels.

Based on all the data resulting from this assessment, measures are planned to manage these risks, starting with the timing and method of monitoring, drafting operational plans, as well as cooperation with other law enforcement institutions.

Table 15 – Prevalent treatment characteristics in the Shebenik-Jabllanica NP (Albania)

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	10 %	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Pruning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Manual removal of understory vegetation		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	70 ha/yr	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Fire belt under power lines		<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M

The average costs are as follows:

- thinning: 1 ha = 1000 BAM (about 500 EUR)
- mechanical treatment: 1 ha = 100 BAM (about 50 EUR)

Fire belts under power lines, and fire belts along the main road, are cleared by the relevant companies.

5.4.4. Study area 4: Velvento Forest (Greece)

The Velvento municipal forest borders the settlements of Velvento and Palaioqratsano and lies within 40 km of the urban center of Kozani. While the management plan does not specify a formally designated buffer zone with fixed distance parameters from built-up areas, its proximity to residential zones implies indirect WUI relevance. Instead of pre-defined buffer widths, protection strategies rely on forest structure and microclimatic factors. Preventive silvicultural interventions such as thinning and fuel reduction are implemented at an intensity of approximately 15% of the standing volume across all diameter classes of black and forest pine. These operations are scheduled cyclically, with some compartments designated for treatment every 15–20 years. These activities help reduce fuel accumulation, particularly in compartments adjacent to inhabited areas. Moreover, no major wildfires have been recorded in recent decades in the Velventos forest. This is attributed to high natural humidity levels, relatively low summer temperatures and limited economic exploitation, reducing ignition risk. Additionally, the forest management plan notes that failure to implement fuel treatments from previous cycles has led to overaccumulation of biomass. This underlines the critical importance of consistent intervention, particularly near vulnerable interfaces. Moving forward, timely and systematic thinning is emphasized to preserve ecological balance and reduce fire risk.

Table 16 – Prevalent treatment characteristics in the Velvento Forest (Greece)

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	15 %	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	CBH = 3 m	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	N/A	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	24,2 ha/yr	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	N/A	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Prescribed Burning	N/A	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Firebreak	600-750 m/yr approx.	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M

Key Notes

Based on the Forest Management Plan of the Velvento Municipal Forest (2022–2031)

Silvicultural measures:

- **Thinning:** Implement thinning interventions involving the removal of 15% of the standing timber volume across all diameter classes.
- **Pruning:** Pruning is conducted on trees within Classes I-III up to a height of three meters.
- **Understory Vegetation:** Understory clearance is not included in the plan. However, preventive measures against forest fires are implemented through the '**Antinero**' program, which includes reforestation, maintenance of roads and water tanks, forest cleaning and selective silvicultural logging.

Non-Management Plan Activities:

Although such activities are not explicitly included in the current management plan, concessionaires are required by the Forest Service to execute specific forestry works within the Regional Unit of Kozani due to the presence of multiple renewable energy projects. These include silvicultural operations, forest cleaning, forest road maintenance and creating recreational spaces.

Manual Removal of Understory:

Manual understory clearance is not carried out separately, as all interventions adhere to the ten-year cycle defined by the management plan.

Mechanical Understory Treatments:

Mechanical means are used for transporting timber. In contrast, animal transport, particularly by mules, is used for firewood (typically broadleaf species such as oak) to minimize damage to natural regeneration. While mechanical equipment is efficient, it may cause localized damage to young saplings.

Grazing:

Grazing is strictly prohibited in accordance with the management plan to facilitate and protect natural regeneration processes.

Prescribed Burning:

This practice is not used in Greece, despite being widely discussed internationally as a method of preventing fires.

Firebreak Development (Est.):

Based on the 1:20,000 scale forest map, the proposed forest road/firebreak network within the Velvento Municipal Forest is estimated to cover 6,000–7,500 metres in total. Distributed over the ten-year period of the management plan (2022–2031), this equates to an average of 600–750 metres per year.

Protection of coniferous trees:

Selective logging of individual trees is not recommended, as the aim is to encourage regeneration of the species. However, four to five overmature trees are retained per compartment to support local biodiversity, for example by maintaining nesting habitats and protecting fauna.

5.4.5. Study area 5: Osogovo Mountains (North Macedonia)

Fuel treatment activities in Osogovo Mountains are currently carried out in an ad-hoc manner, rather than through any formal or systematic mechanism. There is no established long-term strategy or coordinated institutional approach.

Most of the interventions (such as grazing, clearing, or pilot prescribed burning) are implemented through individual projects, temporary collaborations with NGOs or forest services, or community-driven initiatives – rather than being part of regular operational plans.

This situation highlights the need for more structured planning and inter-institutional coordination, especially given the increasing fire risk in the region.

Lessons learned: In the past, lack of active fuel treatments led to excessive accumulation of combustible materials. Recent pilot projects involving controlled grazing, selective thinning, and limited prescribed burning have helped restore ecosystem balance and reduce wildfire risk.

Collaborative approaches: Local NGOs and environmental institutions have promoted eco-friendly interventions, often in coordination with EU and GEF-funded projects. These include training in fire ecology, participatory forest planning, and grazing-based vegetation control.

However, systematic fuel management is still lacking due to unclear institutional responsibilities and insufficient long-term funding.

Table 17 – Prevalent treatment characteristics in the Osogovo Forests (North Macedonia)

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	~10-20% of stand density	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	CBH =2-3 m	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	~50 ha/yr	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	~20 ha/yr	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	~150 ha/yr	<input checked="" type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Prescribed Burning	~5 ha/yr (pilot projects)	<input checked="" type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak	~1,000 m/yr	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M

Table 18 – Estimated treatment costs

Treatment type	Cost per treatment unit
Thinning	~350-500 €/ha
Pruning	~250-400 €/ha
Manual understory removal	~300 €/ha
Mechanical treatment	~450 €/ha
Grazing (cooperative model)	~100 €/ha (subsidized)
Prescribed burning (pilot scale)	~200 €/ha
Firebreak construction	~2-4 €/m

5.4.6. Study area 6: Municipality of Potenza (Italy)

Potenza is the main town of the Basilicata region (Southern Italy) with an extension of about 175 sq. km and about 64,000 inhabitants. In the period 2007-2023, the number of fires affecting the municipality of Potenza was equal to 46 for a total covered surface area of 856.3 ha, with an average annual surface covered of over 50 ha, an average fire surface of over 18 ha and a ratio between total surface covered by fire and municipal surface of approximately 5%. Such data highlights how fires in the Municipality of Potenza represent a significant challenge. WUI management is a top priority because fires that start in vegetation can rapidly threaten buildings, infrastructure and people. Municipal planning and AIB plans increasingly include specific measures for *'incendi di interfaccia'*.

The Municipality must map WUI exposure inside their territory (identify built areas adjacent to vegetation, critical infrastructure, evacuation routes) and include wildfire scenarios in the *'Piano Comunale di Protezione Civile'* (municipal emergency plan) or a dedicated *'Piano emergenza incendi di interfaccia'*. These plans set roles, alarm chains, evacuation procedures and places of refuge.

In the Basilicata region, municipalities (often together with the Region, landowners and communities) adopt fuel-reduction measures near settlements: cleaning undergrowth, maintaining buffer/defensible zones around buildings, clearing roadside vegetation to keep access routes safe, creating and maintaining fuel breaks where appropriate, and enforcing rules about burning/practices. Regional AIB plans provide technical guidance and timing for these activities.

The Regional Fire Prevention Plan (*'Piano Antincendio Regionale'* - PAR) 2024-2026 for Basilicata, which includes the municipality of Potenza, provides the most relevant framework for fire and land management related to buffer zones around built-up areas. The PAR is based on regional law for forest fire protection and fire risk reduction (No. 13 of 22 February 2005) in accordance with the national framework law (No. 353 of 2000).

The *'Consorzio di Bonifica della Basilicata'* (Basilicata Land Reclamation Consortium), a public authority that plays a crucial role not only in terms of water resources but also in terms of forestry, is the sole regional operator responsible for environmental and forestry maintenance and improvement, including urban areas, as well as critical hydraulic issues.

The main interventions planned by the Basilicata Land Reclamation Consortium for the Municipality of Potenza in the framework of the Public

Forestry Project 2025, not specifically related only to prevention and defence against forest fires, are as follows:

- Maintenance of urban green areas, school grounds, playgrounds, avenues, cycle paths, etc.
- Maintenance of green areas, equipped areas
- Brush clearing on road embankments.

Furthermore, the Municipality of Potenza has issued Municipal Ordinance No. 36/2025 at the beginning of the fire season for the elimination of risk factors for fire prevention in areas adjacent to railway stations. All owners of lands, cultivated or not, located in areas adjacent to the railway line passing through the municipal territory of Potenza, are required to check and eliminate hazards posed by falling trees and the risk of fire and its spread, keeping the land clear of dry vegetation and any other combustible material, in accordance with Presidential Decree No. 753 of 11 July 1980, up to a limit of 20 metres from the railway boundary, in order to prevent situations that could endanger train traffic. Presidential Decree No. 753 of 11 July 1980 stipulates, among other things, that no plants or hedges that could interfere with the railway line may be allowed to grow along the railway network within a distance of 20 metres, and that adjacent wooded land may not be less than 50 metres from the nearest railway track.

The Municipal civil protection plan for Potenza (Figure 7) considers the urban-rural interface zone as a particularly vulnerable area where vegetation is close to buildings, increasing fire risk. The specific buffer distance defined in this plan with regard to fire risk for built-up areas is commonly around 50 meters. This 50-meter buffer zone is a standard measure used to designate the perimeter around urban or built-up areas to manage fire risk, including fuel reduction and vegetation management, to prevent fire spread and enhance protection. The buffer is implemented to create a defensible space around critical infrastructure and settlements by reducing flammable vegetation and is a part of the vulnerability and hazard assessment in fire prevention planning for municipalities similar to Potenza. This 50-meter distance is a commonly referenced buffer width for urban-rural interface fire risk management in Italian regions and municipalities, supported by guidelines provided by the Italian Department of Civil Protection and fire risk assessment protocols that incorporate GIS and spatial analysis to identify and manage these zones effectively. The buffer aims to reduce vulnerability by isolating buildings from contiguous vegetation that could carry wildfires.

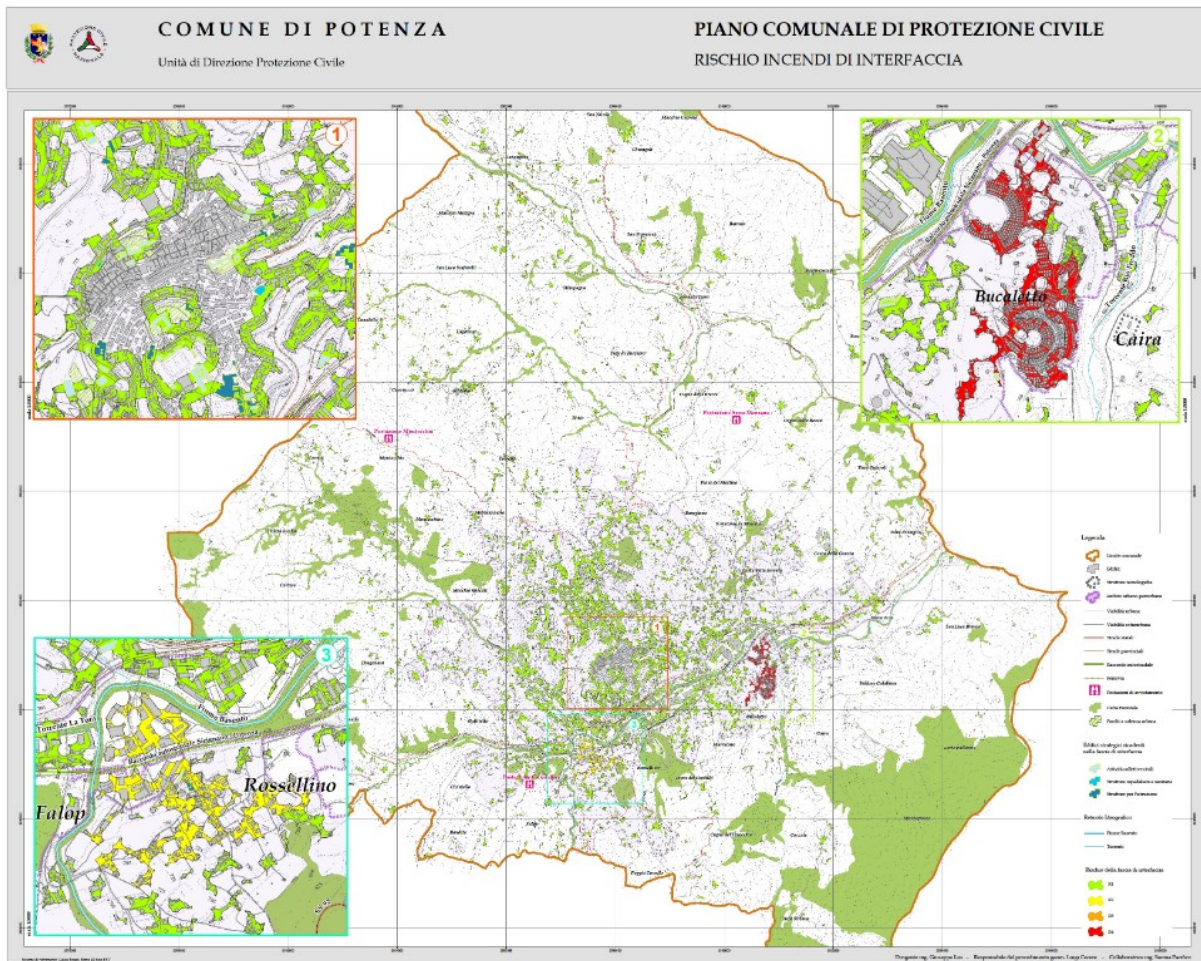


Figure 8 - Municipal civil protection plan for Potenza – WUI fire risk

To assess the risk associated with interface fires, the hazard posed by the area affected by natural disasters and outside the interface zone is evaluated, as well as the vulnerability of exposed buildings and infrastructure within the zone itself. To this end, an additional 200 m zone outside the interface zone is considered for use in assessing both the danger and the alert phases to be implemented during alert procedures.

The plan emphasizes "self-protection" actions by residents to create fire-resistant space around homes, which include vegetation management within buffer zones. Fuel management (removal or modification of inflammable surface and ladder fuels) is part of the strategy to prevent fire spread near built areas. The management also involves periodic monitoring, fuel reduction, and training and drills for fire response.

Fire prevention and management effectiveness in the region are supported by coordinated institutional actions, technological surveillance, active firefighting resources, and volunteer organizations.

Experience suggests that maintaining vegetation-free or low-fuel buffer zones around built-up areas helps reduce fire spread and exposure, but effectiveness depends on regular maintenance and community engagement.

Through local planning instruments the Municipality can regulate new building in high-risk WUI zones, impose setbacks from wild vegetation, require fire-resistant materials and safe access for firefighting vehicles, and limit uses that increase ignition risk. Furthermore, the local Office of Civil Protection joins to awareness campaigns targeted to students and residents, coordinate with local volunteer groups, and cooperate in synergy with the Fire Brigade, the Forestry Carabinieri and the regional Department of Civil Protection, which issues daily fire hazard bulletins during the fire season.

In conclusion, Basilicata's fire management and land plans (including for Potenza) do provide for buffer zones around built-up areas, generally on the order of 50 meters or more, managed through fuel reduction, vegetation control, and community self-protection measures. These zones are part of integrated fire prevention efforts involving monitoring, training, and coordinated institutional action. Their effectiveness relies on continuous maintenance and adaptive management informed by past experience and local conditions.

Table 19 – Prevalent treatment characteristics in the study area 6

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input type="checkbox"/> Thinning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Pruning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Grazing		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M

5.4.7. Study area 7: Municipality of Marathon (Greece)

The Municipality of Marathon, located in the northeastern part of the Attica Region, represents a critical Wildland-Urban Interface (WUI) zone that has repeatedly faced the devastating consequences of wildfires, most notably the 2018 Mati tragedy, which resulted in significant loss of life and property. The area is characterized by complex topography, alternating between coastal plains and forested hills, combined with Mediterranean vegetation types, predominantly coniferous forests (*Pinus halepensis*) and dense shrublands, which are highly flammable during the dry summer season.

Fire Prevention and Management Framework in Greece under the antiNERO Programme

A significant advancement in Greece's approach to wildfire prevention, response, and post-fire ecological restoration is the launch of the antiNERO programme, a flagship national initiative funded by the European Union's Recovery and Resilience Facility (RRF). This programme, officially rolled out in Spring 2022, targets high-risk forested regions, including peri-urban landscapes and areas of cultural importance such as archaeological sites. Its primary objective is to reinforce the country's wildfire resilience through proactive vegetation management and spatially strategic interventions.

The antiNERO programme is a multi-agency initiative coordinated by three principal national entities:

- The Hellenic Forest Service, operating under the Ministry of Environment and Energy,
- The Ministry of Civil Protection,
- The Hellenic Fire Service.

Together, these agencies collaborate on planning, executing, and monitoring fire prevention actions that align with the principles of sustainable land management, ecosystem conservation, and community safety.

Structured Fire Prevention Zoning Approach in WUI Areas

In accordance with guidelines issued by the Hellenic Forest Service (HFS), the programme promotes the systematic creation of buffer zones in Wildland-Urban Interface (WUI) areas. These zones are designed to limit fuel continuity, reduce fire intensity, and facilitate tactical firefighting operations by segmenting forested areas adjacent to human settlements.

The zoning approach consists of three sequential and functionally distinct strips:

1. Central Firebreak Zone

- **Width:** On average, 50 meters, subject to variation depending on vegetation height, slope, and fuel characteristics.
- **Treatment:** Complete removal of all surface vegetation, creating a bare mineral soil strip. This zone acts as a primary physical barrier to slow fire spread.
- **Purpose:** Enables safe space for back-burning operations and acts as a critical access line for fire suppression resources.

2. Sheltered Zones with Broadleaf Trees

- **Structure:** Two 50-meter-wide strips placed adjacent to both sides of the central firebreak.
- **Treatment Measures:**
 - Complete removal of understory shrubs
 - Pruning of coniferous and broadleaf trees up to 2.5 meters from ground level
 - Encouragement or replanting of broadleaf species (e.g., *Quercus* spp.) in conifer-dominated stands to enhance fire resistance.
- **Rationale:** Broadleaf trees typically exhibit higher moisture content and lower flammability than conifers, thereby creating a microclimate that moderates fire intensity and inhibits crown fire initiation.

3. Extended Sheltered Zones

- **Width:** Up to 100 meters on each side of the sheltered zone.
- **Treatment:** Selective thinning, removal of ladder fuels, and pruning of lower branches to limit vertical fire propagation.
- **Effectiveness:** This zone functions as a transitional buffer, minimizing ember spotting and providing extended time for response teams.

Collectively, these zones can total **up to 350 meters in width**, providing a highly stratified defence against wildfire intrusion into urban areas. The structure of these zones reflects international best practices on defensible space design and forest fire mitigation (Agee & Skinner, 2005).

Table 20 – Prevalent treatment characteristics in WUI areas of study area 7

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	CBH = 2.5 m	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Grazing		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Firebreak	width = 50 m	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Planting broadleaves		<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M

Technical Specifications and Regulatory Basis

The antiNERO buffer zone methodology is based on the Hellenic Forest Service's 2020 Technical Guidelines titled: "Update of the Technical Specifications for the preparation of Fire Protection Plans and determination of the cost estimation method" (Ministerial Decision YPEN/DPD/61247/2789).

The guidelines further specify:

- **Firebreak width must be at least twice the height of the dominant vegetation** to be effective for suppression and back-burning under high-risk fire scenarios.
- **Recommended minimum widths for firebreaks under extreme wildfire conditions**, depending on vegetation type and slope:

Vegetation Type	Flat Terrain	70% Slope
Conifer stand with understory	45 meters	60 meters
Dense tall shrubland (1.5-2 m height)	20 meters	25 meters
Medium-height shrubland (1-1.5 m)	12 meters	15 meters

- **Design Principles for Firebreaks:**
 - Should be sinusoidal (non-linear) to prevent wind tunnelling and improve visual integration with natural terrain.
 - Must be maintained free of vegetation through mechanical means (mowing, brushing, mulching).
 - In high-erosion risk zones, firebreaks should be established along ridgelines to prevent soil degradation and sediment transport.

These principles follow ecosystem-based fire management strategies that balance fire hazard reduction with landscape stability and ecological integrity (Xanthopoulos et al., 2023).

Operational Considerations

Vegetation regrowth in Mediterranean ecosystems is rapid, particularly in pine-dominated or maquis shrublands. Empirical observations and national maintenance schedules recommend **re-treating buffer zones every 2–3 years** depending on biomass regeneration rates, fuel accumulation, and climate variability.

Post-treatment monitoring, combined with remote sensing and field inspections, plays an increasingly important role in verifying treatment effectiveness and prioritizing maintenance interventions. Fuel moisture indexes and seasonal fire danger ratings (Giannaros et al., 2024) guide these operational decisions.



Figure 9 - MODIS satellite image depicting smoke plumes over East and North Attica during the August 2024 wildfires, Red hotspots in the image show actively burning fire and copious gray smoke pours from the fire to the southeast. (Source: https://modis.gsfc.nasa.gov/gallery/individual.php?db_date=2024-08-15, Image Credit: MODIS Land Rapid Response Team, NASA GSFC)

Implementation in the Municipality of Marathon

The Municipality of Marathon, located in the northeastern Attica region, is a quintessential example of a Wildland-Urban Interface (WUI) environment—an area where urban development meets or intermingles with flammable natural vegetation. Over the years, Marathon has experienced significant wildfire events, highlighting the pressing need for proactive and strategic risk reduction measures.

In alignment with national fire prevention policies and the broader framework of the antiNERO programme, the Municipality has undertaken extensive planning and implementation of vegetation management strategies.

Buffer zones have been systematically established around the built environment following national technical guidelines set forth by the Hellenic Forest Service. These zones serve as pre-emptive measures to hinder wildfire spread and to protect human lives, property, and critical infrastructure. Specifically, the buffer system implemented in Marathon adopts a multi-zonal structure designed to gradually reduce fuel load and fire intensity with increasing distance from the urban edge. This approach aligns with internationally recognized principles of fire ecology and WUI planning, particularly those proposed by Agee & Skinner (2005).

The buffer structure consists of three tiers:

- **Zone 1 (2–20 meters wide):** *This is the most immediate protection strip adjacent to buildings and critical assets. It involves complete removal of flammable surface vegetation, including grasses, shrubs, and accumulated litter. The aim is to eliminate any fuel that could enable the fire to encroach on structures.*
- **Zone 2 (20–40 meters wide):** *This intermediate zone focuses on selective thinning of overstory trees, removal of ladder fuels (such as small understory trees), and aggressive pruning of remaining vegetation to raise the crown base height to at least 2.5 meters. Where applicable, replanting with broadleaf species is encouraged, especially within dense coniferous stands, to increase landscape fire resistance.*
- **Zone 3 (up to 100 meters wide):** *Functioning as an extended management area, this zone includes further thinning, clearing of residual understory, and maintenance of fuel discontinuity. It also acts as an operational buffer for suppression activities, enabling firefighters to access and control advancing fire fronts safely.*



Figure 10 - Newly established firebreaks in Marathon aimed at enhancing wildfire prevention measures in July 2024 (Source: Protothema News, <https://en.protothema.gr/2024/07/31/new-fire-zones-opened-in-marathon-by-the-civil-protection-see-photos/>)

Combined, these zones can cover a width of **up to 160 meters**, though site-specific adjustments are made based on topography, vegetation composition, and proximity to urban structures. The zoning system implemented in Marathon is a locally adapted version of the broader antiNERO protocol, ensuring both environmental compatibility and operational feasibility.

One critical factor influencing the long-term effectiveness of these interventions is the rapid regrowth of vegetation in Mediterranean ecosystems. Pine species (*Pinus halepensis*), macchia-type shrubs, and phrygana regenerate swiftly, often re-establishing dense fuel beds within two to three years. Thus, regular maintenance—typically through mechanical and manual means—is essential. The Hellenic Forest Service recommends a cyclical management approach, revisiting each treatment area on a 2–3 year rotation, particularly in high-risk zones.

Marathon's experience has demonstrated that wide, traditional firebreaks—while visually effective—may not provide sustainable or ecologically sensitive protection. These linear clearings, if not maintained regularly, often become corridors for fast-spreading grass fires and may contribute to soil erosion on steep slopes. Consequently, the antiNERO model promotes sheltered fuel breaks instead: zones with reduced fuel density but

maintained vegetative cover. These zones act not as fire barriers, but as fire moderators, slowing down fire intensity and offering firefighters better tactical opportunities.

Moreover, a by-product of these interventions—biomass from pruned or felled vegetation—can be repurposed for renewable energy production, offering an economic incentive to complement environmental goals. In this way, fire prevention becomes not only a public safety measure but also a vehicle for local development and green economy integration.

The effectiveness of these practices is strongly supported by comparative evidence from nearby regions such as Mount Parnitha. In areas where similar fuel treatments had been implemented prior to wildfire events, fire intensity was noticeably lower, and fire progression was slower. Ground firefighting teams were able to establish and hold containment lines more effectively, often converting potential crown fires into controllable surface fires. In contrast, untreated zones exhibited rapid fire spread, high flame lengths, and increased difficulty in suppression.

This contrast is particularly visible in roadside fuel breaks in Parnitha, where maintenance operations—especially the clearing of understory and thinning of canopy—resulted in observable decreases in flame height and spread rate. These treated areas often transitioned from crown fire to low-intensity surface fire, thereby offering proof-of-concept for Marathon’s own efforts.

From a financial standpoint, the Municipality of Marathon dedicated a total of €350,765 to wildfire protection measures in 2024, as documented in the national Transparency Portal. A detailed breakdown of these actions is presented in Table 14.

Table 21 – Costs of wildfire protection measures in 2024 for the Municipality of Marathon

Treatment/Measure	Cost
Branch and Large Object Removal for Fire Protection	15,000.00 €
Manual or mechanical removal of understory vegetation	47,625.00 €
Fire break construction	260,000.00 €
Cleaning of roads and public spaces	20,000.00 €
Cleaning of streams and surrounding public space	8,140.00 €
TOTAL	350,765.00 €

These expenditures reflect the Municipality's commitment to operational readiness and long-term risk reduction. The construction of firebreaks is specifically funded under the "Forest Protection and Enhancement 2024" programme, within Priority Axis 6 (P.A.6) of the Green Fund. This

programme aims to enhance perimeter defence around forest-adjacent settlements and strengthen local capacity to respond to wildfires.

Importantly, a portion of the interventions is financed through the Municipality's own resources, showcasing a proactive stance on fire governance. This co-funding mechanism increases programme resilience by reducing dependency on external financing and allowing flexible, locally tailored responses.

Overall, Marathon's implementation of antiNERO principles exemplifies a multi-layered, scientifically informed, and operationally grounded model of WUI fire management. Continued investment in maintenance, public awareness, and data-driven simulation (as supported by RES2FIRE) will be essential for sustaining and scaling these benefits.

5.4.8. Study area 8: Municipality of Kocani (North Macedonia)

Buffer zone management: According to local fire prevention and spatial plans, a buffer zone of 30 to 50 meters is established around urban and peri-urban areas adjacent to forests and dense vegetation.

Management practices: These include periodic manual clearing of undergrowth (every 1–2 years), removal of dry biomass and debris, occasional grazing by local livestock (mainly goats and sheep), and in rare cases, controlled burning.

Effectiveness: Where implemented, these activities have significantly reduced fire risk. However, limited budgets and human resources often prevent consistent coverage of all buffer zones.

Lessons learned: Cooperation with forest authorities and local shepherds is key to sustainable fuel management. Grazing has proven especially effective in controlling understory vegetation.

Table 22 – Prevalent treatment characteristics in the study area 8

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input type="checkbox"/> Thinning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Pruning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	N/A	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Mechanical understory treatments		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	N/A	<input checked="" type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Prescribed Burning	N/A	<input checked="" type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M

Table 23 – Estimated treatment costs

Treatment type	Cost per treatment unit
Thinning	~350–500 €/ha
Pruning	~250–400 €/ha
Manual understory removal	~300 €/ha
Mechanical treatment	~450 €/ha
Grazing (cooperative model)	~100 €/ha (subsidized)
Prescribed burning (pilot scale)	~200 €/ha
Firebreak construction	~2–4 €/m

5.4.9. Study area 9: Municipality of Loznica (Serbia)

Fuel treatment practices in Serbia remain underdeveloped and fragmented, particularly in the context of wildfire prevention. There is currently no strategic or operational framework in place that systematically addresses buffer zones or fuel treatment in municipal or forest management plans. This gap poses a serious challenge to effective wildfire risk reduction. In the case of the Municipality of Loznica, consultations with local stakeholders such as JP Srbija Šume (*Šumsko gazdinstvo Boranja* unit) and KJP "Naš dom" confirmed that no buffer zones are defined in their plans. Furthermore, neither stakeholder maintains structured data on fuel treatment activities. While routine maintenance of urban green areas does occur, such as mowing, tree pruning, and removal of dry branches, these actions are not formally recorded or managed as part of a broader fire prevention strategy. At the national level, Serbia lacks a coherent legal and planning framework for fire protection. A national fire protection strategy has not been adopted, and the Disaster Risk Reduction Strategy is still under development. Mandatory fire protection and disaster risk plans at all levels of government are largely absent or outdated. Additionally, current funding mechanisms—especially at the local level—do not allocate sufficient or efficiently used resources for preventive fire protection (State Audit Institution, 2024). As can be concluded from the previous statements: without formal plans, funding, and coordination, fuel management efforts remain informal and largely ineffective. Preventive maintenance is happening, but it lacks strategic intent and measurable impact.

Table 24 – Prevalent treatment characteristics in the study area 9

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Manual removal of understory vegetation		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Grazing		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M

The Municipality of Loznica does not gather information about the average cost per hectare of fuel treatment.

5.4.10. Study area 10: Kozara NP (Bosnia and Herzegovina)

Forests cover over 90% of the Kozara National Park territory. The largest area of the Park belongs to climatogenic community of beech and fir which covers 60% of the Park area. Forest overview in the National Park area is as follows mixed forests (57%), coniferous forest (39%), and broadleaves forest (4%).

Kozara National Park is in obligation to create and implement a Forest Fire Protection Plan, and the following is determined by the Plan: Fire risk assessment, Fire protection organization, Way of using fire rescue units, System of notification, Procedure in case of fire, Technical equipment and means for extinguishing fires, Way of water supply, Approach roads, Cooperation with other fire rescue units.

Fire protection in the National Park is organized and continuously implemented in all areas of the Park. Permanent duty, observation, notification and supervision of the Park area and construction facilities in the Park are ensured by rangers, guards and other workers who moved around the Park area. The park has formed three mobile intervention teams consisting of workers trained in firefighting.

The Kozara National Park area is at a risk of forest and open-space fires. Wildfire occurrence is often associated with human activities: using fire periodically to clear grazing properties, starting fires in undesignated sites, abandoned barbecues and campfires, etc. Also, extreme heat and droughts lead to increased fire risks.

Fuel treatments in Kozara National Park include thinning, mechanical treatment and grazing with the aim to reduce wildfire risk and making the area more resilient to fires.

Past experience has shown that the main cause of fires in the Park area was human-caused due to uncontrolled use of fire in land-clearing. In order to prevent forest fires the National Park conducts awareness raising activities which is also foreseen by the Forest Fire Protection Plan. At the most visited sites within the Park fire prevention signage has been placed. Signs indicate fire bans, fire restrictions, and educational messages emphasizing awareness.

Table 25 – Prevalent treatment characteristics in the Kozara NP (Bosnia and Herzegovina)

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	10 %	<input type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Pruning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Manual removal of understory vegetation		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Mechanical understory treatments	59 ha/yr	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	30 ha/yr	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Firebreak		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Fire belt under power lines	7.5 ha	<input checked="" type="checkbox"/> B <input checked="" type="checkbox"/> C <input type="checkbox"/> M

The average costs are as follows:

- thinning: 1 ha = 1000 BAM (ab. 500 EUR)
- mechanical treatment: 1 ha = 100 BAM (ab. 50 EUR)

Fire belts under power lines, and fire belts along the main road, are cleared by the relevant companies.

5.4.11. Study area 11: Slovenia

Slovenia is one of the most forested countries in Europe, with more than 60% forest cover. However, the risk of wildfires is rising due to climate change, resulting in longer fire seasons and more intense droughts. The most fire-prone regions are located in the southwestern part of the country, particularly in the Karst, Slovenian Istria, and other thermophilous forest zones. Increasingly, southern-exposed slopes in Alpine areas are becoming vulnerable due to warming trends.

Forest fire occurrence in Slovenia is strongly influenced by climate, vegetation type, fuel structure and moisture, and human activity—particularly negligence, which remains the primary ignition source. The number and extent of wildfires fluctuate significantly from year to year, primarily depending on temperature and humidity conditions.

To support wildfire planning and mitigation, Slovenia classifies its forests into four levels of fire hazard:

- Level 1 – Very high fire risk
- Level 2 – High fire risk
- Level 3 – Moderate fire risk
- Level 4 – Low fire risk

These classifications are used in mapping and prevention strategies coordinated by the Slovenian Forest Service.

Table 26 – Prevalent treatment characteristics in Slovenia

Prevalent treatment type(s)	Treatment intensity	Forest type (B=broadleaves, C=conifers, M=Mediterranean macchia)
<input checked="" type="checkbox"/> Thinning	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Pruning	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Manual removal of understory vegetation	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Mechanical understory treatments		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Grazing	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input type="checkbox"/> Prescribed Burning		<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M
<input checked="" type="checkbox"/> Firebreak	N/A	<input type="checkbox"/> B <input type="checkbox"/> C <input type="checkbox"/> M

In Slovenia, fuel treatment practices (Table 17) are implemented as part of regional forest management and fire protection strategies, particularly in areas prone to wildfires such as the Karst, Brkini, and sub-Mediterranean regions. These measures are defined within forest management plans and

are based on national methodologies outlined in the Rules on Forest Protection.

The most common and effective fuel treatment practices include: firebreaks, clearing of underbrush, small-scale targeted measures (thinning, pruning, and crown lifting), grazing, etc.

Construction and Maintenance of Firebreaks

Firebreaks of the 1st and 2nd category are established to prevent the spread of wildfires and to allow access for firefighting units. The recommended spacing between roads is 400 meters, with passing bays every 200 meters and turning points every 400 meters.

Clearing of Underbrush and Forest Edge Maintenance

Regular removal of dry biomass and dead trees, especially in high-risk zones (fire risk levels 1 and 2), helps reduce available fuel and ignition potential. Forest edge maintenance plays a key role in preventing fire spread from open areas to forest interiors.

Small-scale Targeted Measures

These include selective thinning, pruning, and crown lifting in localized areas to reduce fire-prone vegetation while preserving ecological stability.

Grazing as a Preventive Measure

Controlled grazing is practiced to reduce undergrowth in vulnerable zones, effectively decreasing fine fuel loads and fire continuity.

Infrastructure and Surveillance

Maintenance of forest roads, creation of access to water sources (hydrants), and installation of observation posts (including video surveillance systems) are vital for early detection and rapid response.

Awareness Raising and Signage

Public education campaigns and placement of fire risk and prevention signage are carried out in frequently visited forests and near urban-forest interfaces to reduce human-induced ignition.

These practices are tailored according to terrain conditions, vegetation type, land ownership structure, and accessibility. They contribute to wildfire prevention, biodiversity conservation, and sustainable forest management.

These treatments are funded through public investments in forests of all ownership types, with priority given to forests in very high and high fire risk categories.

Strategic and Legal Framework

Fuel treatment and wildfire prevention are regulated through a coordinated legal and policy framework:

- Forest Management Plans, prepared by the Slovenian Forest Service, include silvicultural prescriptions for fuel reduction.
- The National Protection and Rescue Plan, integrating fire prevention and emergency response at the state level.
- Municipal wildfire protection programs tailored to local forest types and risk levels.
- Regulation on Fire Protection in the Natural Environment, defining conditions for prescribed burning and fire-use restrictions.

The Slovenian Forest Service is responsible for planning, implementation, and monitoring, as well as supporting suppression and maintaining fire-related records.

Slovenia uses GIS and simulation tools to model wildfire risk and support management, as the **Forest Data Viewer – Slovenia**⁷ (*Pregledovalnik podatkov o gozdovih*) developed by the Slovenian Forestry Service (*Zavod za gozdove Slovenije – ZGS*) as part of the SylvaMED project, co-financed by the European Union, and publicly launched in 2015.

This public web-based GIS application provides comprehensive spatial data on Slovenian forests. It serves forest owners, professionals, researchers, and public authorities by enabling access to detailed forestry planning documents, forest functions, and ecological data.

A key functionality of the viewer is its support for forest fire risk assessment and prevention planning. Users can access:

- Data on protection forests and fire-prone areas
- Spatial layers related to forest management, including forest density, tree species composition, and terrain features relevant to wildfire spread
- Integration with Natura 2000 zones and other environmental protections that may influence fire prevention strategies

⁷ Application link: <https://prostor.zgs.gov.si/pregledovalnik/?locale=en>

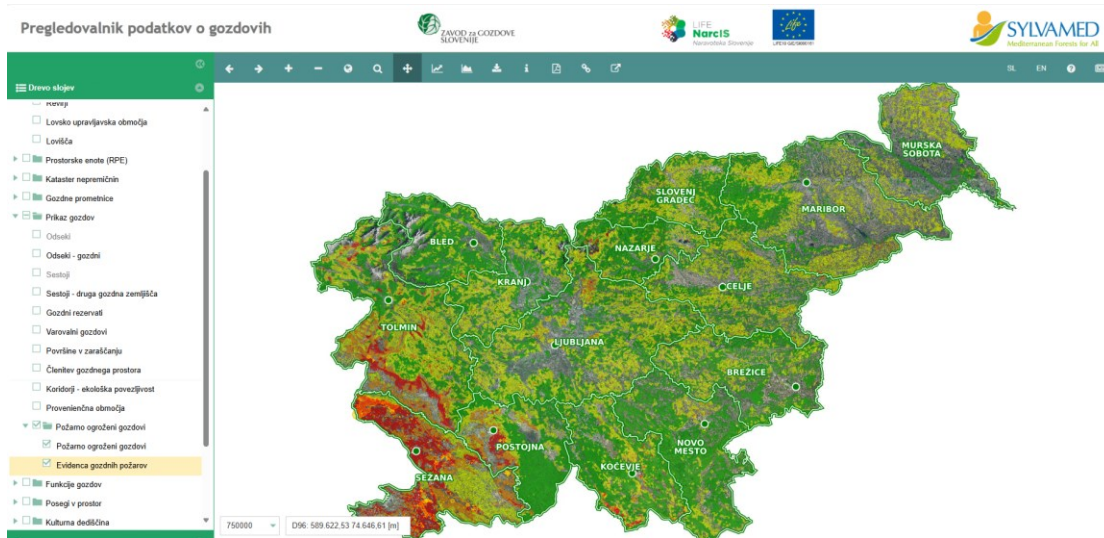


Figure 11 - Forest Data Viewer – Slovenia

Slovenia also uses other GIS and simulation tools to model wildfire risk and support management:

- FARSITE and FIRETEC are applied primarily in research by forestry institutions.
- The Forest Information System (GIS) supports risk analysis and intervention planning.

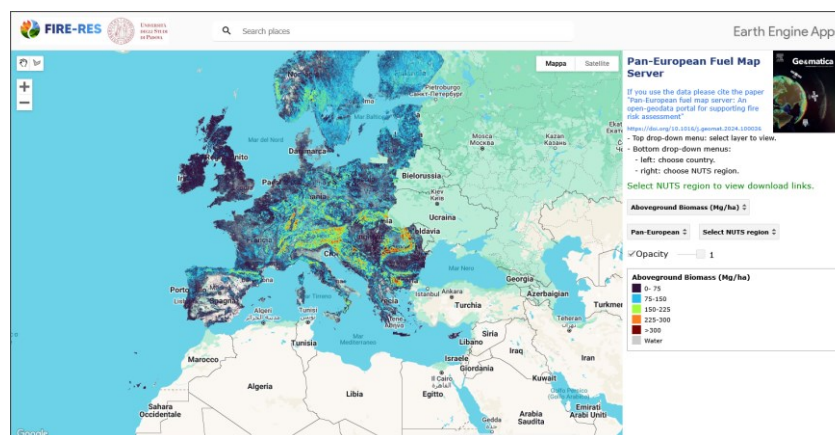
6. Harmonised geospatial data for fire simulation

6.1. Introduction

Having identified a suitable fire simulation application, namely FlamMap, and having defined the approach to be followed in assessing the effectiveness of fuel treatments in the selected pilot areas, we basically need a suitable “landscape file” and weather data (wind speed and direction, fuel moisture content, specifically 1-hour, 10-hour, 100-hour⁸, live herbaceous and live woody fuel moisture content) to run the fire simulations.

6.2. Landscape data (topography and fuel)

Following the data collection carried out in WP1 and the review of available European datasets, a suitable and already harmonised data source was identified in the “Pan-European Fuel Map Server”⁹, an open geoportal for supporting fire risk assessment, provided by the University of Padua in the framework of the EU funded Horizon 2020 “FIRE-RES” project (Kutchartt et al., 2024). Such a geoportal provides all landscape layers individually or in a single ZIP file, in GeoTIFF format and in the same reference system (EPSG:4326 - WGS 84), extent and spatial resolution (100 m) at a pan-European scale. In particular, the geospatial layers are available at all the European NUTS levels from 0 to 3.



⁸ Fuel size classes refer to down dead materials and are determined by how quickly they gain or lose moisture with changes in humidity. Fine fuels, such as grasses and leaves, are 1-hour fuels because they adapt quickly. Small branches are 10-hour fuels, larger branches are 100-hour fuels, and logs are 1000-hour fuels, which take the longest to dry or absorb moisture and are more difficult to ignite.

⁹ <https://www.cirgeo.unipd.it/fire-res/app/>

Figure 12 - "Pan-European Fuel Map Server" geoportal

In reference to landscape layers provided by the geoportal, as described in Kutchartt et al. (2024), **topography layers (elevation, slope and aspect)** were derived from ALOS World 3D originally at 30 m resolution. Tolan et al. (2024) provided high-resolution canopy features like **canopy height** maps using a convolutional network trained on GEDI observations. Hansen et al. (2013) and then Liu et al. (2024) generated **canopy cover** fraction using Landsat data and MODIS observations. Finally, **canopy base height, canopy bulk density and surface fuel models** were produced by the FIRE-RES project through the estimation of aboveground biomass (AGB) using AI and a set of predictors that include bioclimatic variables, vegetation indices from Sentinel-2, and radar backscatter from Sentinel-1 and ALOS following the method provided in Pirotti et al. (2023).

In future research, Kutchartt et al. (2024) intend to downscale the fuel model and canopy fuel rasters to an even more operational scale (30 m or less) and to apply validation methods using LiDAR data and forest inventory plots as ground truth values.

Once we have downloaded the ZIP file for a specific NUTS level from the geoportal, unzipped it and checked the coregistration of layers, spatial extension and resolution, we can easily assemble a landscape file as a multiband GeoTIFF within the FlamMap application or using a whatever dedicated external tool capable of doing so. The landscape file thus obtained can be further cropped according to the extent of the area of interest in order to be usable for fire simulations.

6.3. Weather data

Weather conditions are of crucial importance in assessing fire behaviour. FlamMap requires specific weather data inputs for fire behaviour simulation, mainly constant environmental conditions during the simulation period. The essential weather inputs include:

- **Wind speed and direction**, which strongly influence fire spread and intensity. The wind can be represented as a fixed value or a gridded wind field accounting for terrain effects.
- **Fuel moisture conditions for surface fuels**, often specified as fixed moisture values by fuel model or adjusted through a weather stream file that modifies moisture based on elevation, aspect, and fuel size classes (e.g., 1hr, 10hr dead fuels).
- **Canopy fuel moisture**, including foliar moisture content, which can affect crown fire potential.

- **Temperature and relative humidity**, which influence fuel moisture and fire behaviour but are indirectly accounted for through moisture inputs or weather streams.

In more detail, FlamMap uses a combination of a landscape file plus weather inputs such as:

- An initial fuel moisture (.FMS) file specifying moisture percentages for dead and live fuels, that can be used "as is" or as a starting point for the optional dead fuel moisture model (which also requires a weather stream (.WXS) file).
- A weather stream (WXS) file with hourly weather data over a specific period that can dynamically adjust fuel moisture content.
- Wind inputs as fixed values or generated gridded wind fields.

This allows FlamMap to simulate spatial variability in fire behaviour with weather conditions held constant during the run or conditioned by the weather stream file.

In summary, FlamMap fire behaviour simulation needs:

1. Wind speed and direction (constant or gridded).
2. Fuel moisture data (fixed or weather stream conditioned).
3. Canopy/fuel moisture parameters.
4. Optionally, hourly weather stream files to adjust moisture.

These inputs enable accurate representation of fire potential across a landscape for the modelled period.

6.3.1. *Wind data*

In particular, **wind** significantly impact fire behaviour, influencing fire spread and ignition. Wind characterization for wildfire prevention involves analysing speed, direction, and variability to predict fire behaviour and prioritize mitigation efforts. Since all wildfires burn in the direction of the prevailing wind, scenarios of prevailing wind both in terms of speed and direction occurring during the fire season over the last 15 years (2010-2024), i.e. a sufficiently long period of observation, will be defined in the pilot sites.

Understanding the fire season within the IPA ADRION countries requires considering the diverse climates across the region. This region encompasses a wide geographical area, experiencing a range of climates, from Mediterranean to continental, which significantly influences fire seasons. The general fire season trends include:

- **Mediterranean Climate:** Countries like Greece, coastal Italy, and parts of the Balkan Peninsula with Mediterranean climates typically experience peak fire seasons during the summer months (June to September). This is due to hot, dry conditions that increase the risk of wildfires.
- **Continental Climate:** Inland areas of the Balkan Peninsula, with continental climates, may also experience fire seasons during the summer, but the timing and intensity can vary depending on specific weather patterns.

Without losing significance, we consider a “standard” fire season the months from June to September for all pilot sites. We will derive the main dominant wind scenario based on the hourly wind data from 2010 to 2014 included in the “ERA5-Land hourly data from 1950 to present” dataset¹⁰ available in the Climate Data Store (CDS) provided by the Copernicus Climate Change Service (C3S). In particular, ERA5-Land is a reanalysis dataset that offers a consistent view of land variable evolution over decades, combining model data with global observations, providing an accurate description of past climates using physics laws.

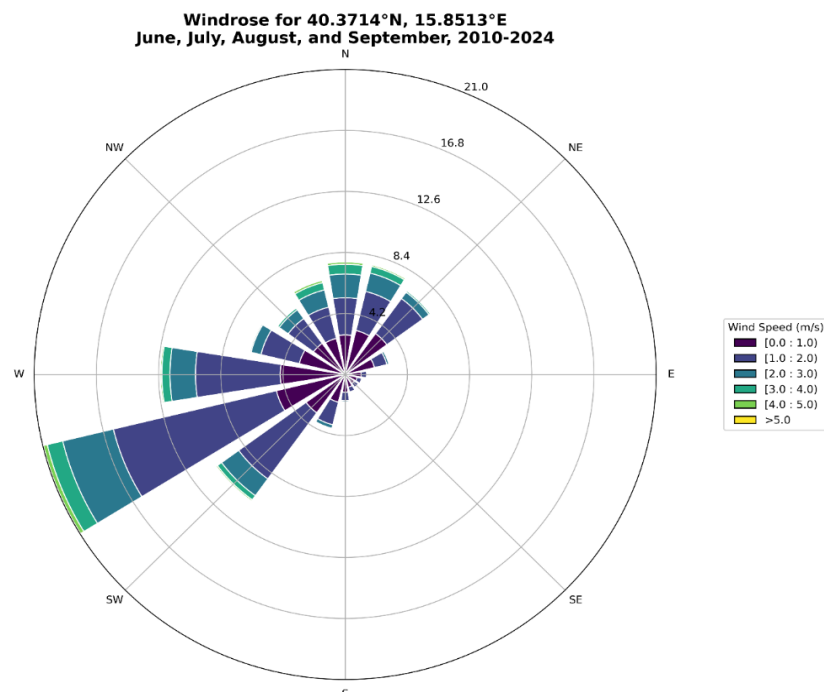


Figure 13 – Example of wind rose during the fire season showing how wind speed and direction are typically distributed at a particular location.

¹⁰ <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land>

7. Conclusion

Fire behaviour models are indispensable tools for understanding, predicting, and managing wildfires. Their classification into empirical, semi-empirical, and physics-based categories reflects varying levels of complexity and reliance on observational data versus fundamental physical principles. The scope of these models encompasses a range of spatial scales and the prediction of numerous critical fire characteristics. Common input parameters include detailed information on topography, fuel characteristics, and weather conditions. The Rothermel Fire Spread Model stands out as the most widely used model globally for fire management planning, providing a robust framework for predicting surface fire behaviour. Fire behaviour models/applications, such as FlamMap, are also essential for evaluating the effectiveness of silvicultural treatments in modifying fuel characteristics and ultimately reducing wildfire risk. By comparing simulation outcomes under different treatment scenarios, assessing changes in fire hazard indices, conducting sensitivity analyses, and validating model predictions against observed fire behaviour, land managers can gain valuable insights into the benefits and limitations of various fuel management practices.

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