



FIRE-RES

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

D2.8 Landscape design strategies, using tactical planning methods

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Abstract: Tactical forest planning for a landscape aims at allocating the best suited management alternatives to the forest stands or management units that conform that landscape. The selection of those alternatives requires the definition of goals and restrictions to be considered. Integrating fire risk either as an indicator to address an objective or to evaluate potential losses requires a linkage between growth and yield and fire spread models. Such integration allows to evaluate how risk evolves across time and space whenever a management plan is applied. Such integration is site specific due to the availability of growth simulators, management objectives and restrictions and due to how fire risk is to be integrated into a planning problem. In this innovation action we required four study areas to integrate fire risk into tactical planning at landscape level to explore which opportunities and limitations are to be found in this process. The results showed that even if including fire mitigation objectives may contribute to minimize losses, including fire risk management in tactical planning is a challenge that requires approaches tailored to the specificity of the problem under analysis.

Key words: Forest growth, yield of ecosystem services, tactical planning, management schedule

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1. Introduction

1.1. Overview of the problem

Incorporating fire risk through simulation at different planning levels presents distinct challenges, depending on each level's objectives and timeframes. At the strategic level, two types of fire spread simulators are typically used: landscape fire succession models—when long-term temporal dynamics are considered—or more detailed fire spread models, when a static landscape is assumed. Landscape fire succession models, such as LANDIS (He and Mladenoff, 1999), DRYADES (Mailly et al., 2000), SELES (Fall and Fall, 2001), and MEDFIRE (Duane et al., 2016), are designed to simulate forest dynamics and disturbance regimes over extended periods. These models often rely on simplified fire spread algorithms and coarse fuel data to reduce computational demands, given the need to simulate numerous fire events across evolving landscapes. Despite differences in methodology and accuracy, their common goal is to understand long-term ecological processes or test hypotheses about how landscapes interact with fire. In this context, management is viewed as a driver of change rather than an element to be optimized (Scheller and Mladenoff, 2007). Conversely, when strategic planning focuses on prioritizing management actions and assessing values at risk in a static landscape, more detailed fire spread models can be used. Tools like FSim or FSPro (Thompson et al., 2013; 2016), FlamMap (Alcasena et al., 2018, 2019), FORSYS (Pudlow et al., 2023) or previously known as Landscape Treatment Designer (USDA Forest Service, 2022) and Wildfire Analyst (Gonzalez-Olabarria et al., 2019) fall into this category. In operational planning, fire spread simulators are similarly used to evaluate fuel management strategies across the landscape, but with a more localized focus. After identifying priority zones, the effectiveness of specific fuel treatments is typically assessed at the stand level using non-spatial fire behaviour models (Waldrop et al., 2010; Piqué and Domènech, 2018)

Tactical forest planning, particularly when addressing fire mitigation or incorporating risk assessments to reduce uncertainty in goods and services yields, presents significant challenges due to its inherent complexity. At the landscape scale, it involves developing a spatial and temporal schedule of management activities aimed at achieving specific objectives. When fire risk is assessed through spatially explicit simulations, tactical planning requires systems capable of modelling multiple fire events across the landscape over the planning horizon. These systems must also account for dynamic landscape changes, driven both by natural forest development and by management actions scheduled for evaluation (González-Olabarria and Pukkala, 2011). Earlier approaches to integrating fire simulations into tactical planning often relied on simplifying assumptions—using overly simplistic forest landscapes (Konoshima et al., 2008), limiting the number of simulated fires (Bettinger, 2009; Kim et al., 2009), or applying rudimentary fire spread models (González-Olabarria and Pukkala, 2011). More recent efforts have introduced greater complexity. For example, Chung et al. (2013) combined the fuel modelling capabilities of the Forest Vegetation Simulator (Reinhardt and Crookston, 2003) with fire probability proxies from FlamMap to optimize fuel treatment allocation in time and space. However, this approach focused solely on fire-related outcomes and did not consider broader forest management goals, falling short of the requirements for tactical planning. Barreiro et al. (2021) advanced the field by using a fire hazard index, generated

from multiple simulations at the beginning of the planning period, to evaluate scenarios and support decisions regarding forest and fuel treatments over an evolving landscape. Although this approach integrates fire risk into their scenarios, it relies on a static initial fire risk map and propagates hazard over time using stand-level growth indicators, rather than dynamic fire simulations. A more comprehensive solution was presented by Ager et al. (2020) with LSim, a fully integrated system linking the Forest Vegetation Simulator with FSim. LSim simulates forest growth, management, and wildfire activity over a 50-year horizon, prioritizing treatment allocation using multiple criteria.

As a resume it can be said that an intermediate planning level brings exceptional complexities and questions, still unresolved. The objective of tactical planning should be the provision of ecosystem services, and the integration of objectives into a dynamic productive process. Evaluating risk overtime, is a challenging task, as there is an immense quantity of potential optimal solutions that will define the evolution of the landscape. Integrating fire risk into tactical forest planning makes sense, as the yield of services depends on the expected losses due to fire, and the impact of forest management should affect the evolution of risk on time and space. Still, it can hardly be said that there is an adequate methodology to integrate fire into landscape planning when a tactical approach is considered and aim at including fire mitigation objectives into the problem is rather an advance.

2. General Methodology

2.1. General framework

Wildfire represents a major ecological and economic challenge, especially in forested regions where ecosystems support biodiversity, carbon storage, and local livelihoods. As climate change increases the frequency and severity of fires, there is an increasing need for advanced tools to assist in strategic forest management.

To address this challenge, recent research has focused on combining forest growth simulation models with fire spread models. This integrated approach makes it possible to evaluate how different management strategies influence both forest development and fire behaviour over time.

The central question guiding this work is: How can the combination of forest growth models and fire spread models support the assessment of forest management strategies in terms of reducing fire risk?

The objective of this work is to develop a general approach to assess the effectiveness of various forest management scenarios by simulating their long-term impacts. This includes evaluating fire behaviour indicators such as burn probability, average flame length, intensity, rate of spread and changes in ecosystem service indicators over time. By comparing these indicators across scenarios, this work provides insights about how to design strategies that best enhance forest resilience and reduce fire vulnerability.

To assess long-term changes in forest ecosystems and the impact of different management strategies, we used an integrated approach combining forest growth and fire spread simulation (Figure 1).

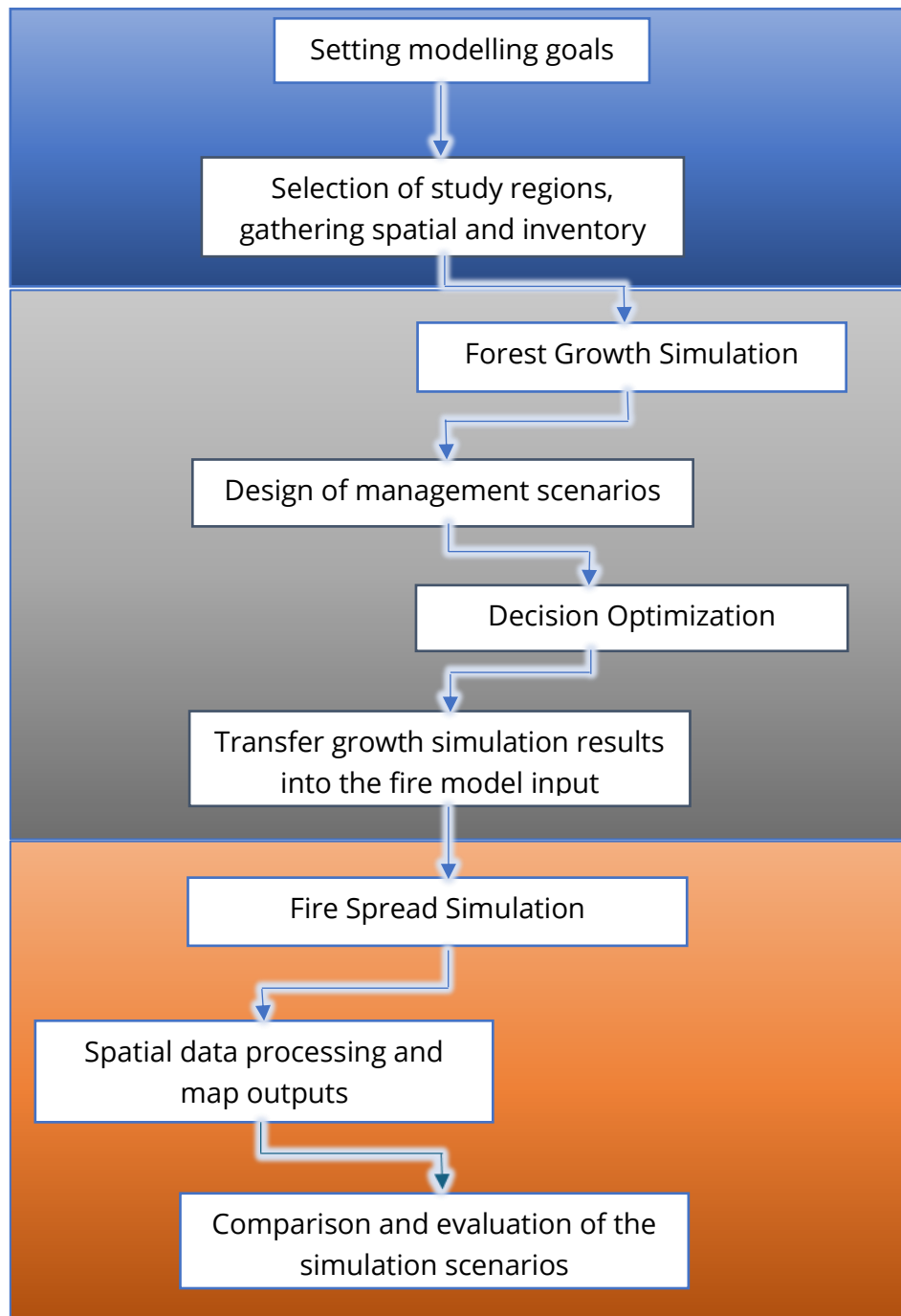


Figure 1: General methodological framework

2.2. Data Collection and Preparation

The initial phase of the study involved the collection and preparation of various datasets necessary to support both simulation models. These datasets comprised:

- ✓ **Spatial data on forested areas and topography**, which were collected to describe the physical and environmental characteristics of the landscape at a specific moment. These included land cover maps, digital elevation models (DEMs), slope and aspect maps, and other geographic layers relevant for forest growth and spatially explicit fire behaviour

simulation systems. This geospatial information enabled accurate representation of terrain heterogeneity, which plays a critical role in both forest development and fire propagation. For forested stands, it will be also necessary detailed information on forest composition, stand structure, tree species distribution, and biomass estimates. This dataset served as the baseline for characterizing the current condition of forest ecosystems and for defining the initial simulation parameters.

✓ ***Weather scenarios describing fire hazard conditions***, which were integrated to reflect varying levels of fire risk. These scenarios were defined based on historic or projected trends in temperature, precipitation, and wind patterns – key drivers of fuel availability and fire behaviour. By incorporating weather variability, the models could assess how fire risk and ecosystem responses may evolve under changing environmental conditions.

2.3. Forest Growth Simulation

This stage aimed to replicate natural processes such as tree growth, mortality, and structural development over time, while also assessing how various management interventions could influence these dynamics.

The forest growth simulation component consisted of the following key elements:

- Implementation of tree growth and associated forest dynamics models, which allow for the estimation of changes in stand composition, canopy structure, and fuel accumulation over the simulation period.
- Calculation of ecosystem services. This may include, aboveground biomass accumulation, timber productivity, carbon sequestration, and the probability of tree mortality due to fire. These indicators provide insight into the ecological performance of each scenario and its contribution to long-term forest resilience.
- Generation of forest management alternatives, which involves designing and testing different silvicultural strategies such as thinning regimes, selective harvesting, and interventions aimed at reducing fire hazard. These alternatives serve as the foundation for scenario analysis in later stages of the study.

The forest growth simulation followed a unified modular structure applied consistently in all the Living Labs regions. This workflow is presented in Figure 2 and integrates ecological processes, ecosystem service modelling, and management decision-making into a flexible simulation framework.

Modular workflow components include:

1. Input Data: Initial forest structure, environmental variables, and site conditions used to initialize the simulation.
2. Forest Growth Models: Simulate dynamic processes of tree growth, mortality, and forest development over time.
3. Ecosystem Services Models: Estimate key indicators such as biomass, carbon sequestration, timber yield, and fire-induced mortality.

4. Management Alternatives Generator: Produces and applies a range of silvicultural strategies tailored to different objectives.

5. Simulation Outputs adjusted to the Planning Decision Space: Evaluates projected forest conditions and ecosystem service performance for each scenario.

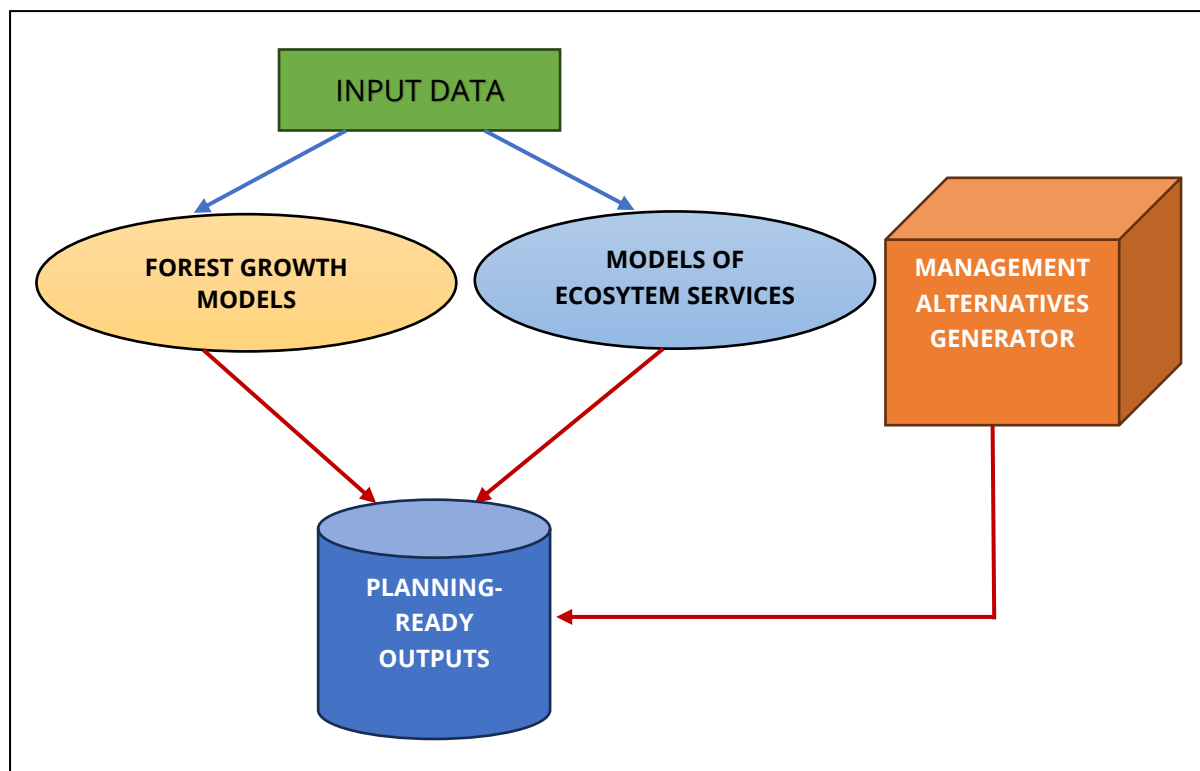


Figure 2: General workflow of the forest growth simulation framework

2.4. Management scenarios

To evaluate the impact of different policies, we established what we called *management scenarios*, that set specific objectives or restrictions to the planning problem.

Within the flexibility provided to each of the Living Labs, the planning challenges are defined by selecting the management scenarios. These changing scenarios will provide different results, and can be defined by a modification of goals, or a change in the simulation parameters (either growth or fire simulation). Other scenario selection can be defined by selecting certain management schedules or land use changes in specific areas or stands. For example, in the Catalan study case, 3 scenarios were defined (see section 3.1.5): one where no specific restrictions were applied before running the optimization process; one where specific areas were selected as fuel breaks at the beginning of the planning period; and a final scenario where, through expert opinion, different management schedules were defined for several of the forest stands.

2.5. Optimization of Forest Management Decisions

This phase aimed to identify the most effective forest management strategies by evaluating their performance against multiple, and often competing, ecological,

economic, and social objectives. The goal was to support informed decision-making by determining which alternatives best balance priorities such as fire risk reduction, biomass productivity, and ecosystem service provision.

The optimization process involves the selection of the most effective forest management alternatives, guided by multiple criteria, including the maximization of timber yield, minimization of fire risk, preservation of biodiversity, enhancement of carbon storage, and maintenance of landscape aesthetics. Each Living Lab selects their own ecosystem services and criteria.

To support this process, various decision-support tools are employed. These can include multi-criteria decision-making (MCDM) methods, mathematical optimization techniques such as linear programming, goal programming, genetic algorithms, or Pareto-based approaches, among others. These tools facilitate the exploration of trade-offs among objectives and support the systematic comparison of alternative management strategies.

This optimization process provided a structured framework for identifying solutions that offer a meaningful balance between ecological resilience and economic feasibility, while remaining flexible across different Living Labs contexts.

2.6. Transfer growth simulation results into the fire model

To assess the impact of forest dynamics on fire behaviour, the results of the growth simulation were translated into input data for the fire spread model. This step ensured consistency between vegetation structure, fuel characteristics, and landscape configuration across models.

The transfer process involves:

- Converting forest growth simulation outputs (e.g., canopy cover, fuel load) into spatial layers compatible with the fire model.
- Aligning temporal and spatial resolution between the growth and fire simulations. All inputs of spatial layers used in the fire spread model (e.g., elevation, fuel load, canopy cover) were standardized to the same spatial resolution. Temporal resolution was also aligned, meaning that fire simulations were based on forest conditions projected for the corresponding simulation years (e.g., year 0, 10, 20, etc.). This alignment allowed for accurate overlay and interaction between layers during simulation.
- Preparing fire behaviour inputs that reflect management-induced changes in vegetation and fuel continuity. Fire behaviour inputs were prepared by compiling fuel-related spatial layers, topographic variables, and weather scenarios. These inputs defined the environmental conditions under which fire spread was simulated, ensuring realistic representation of fire behaviour across different landscape configurations.

2.7. Fire Behaviour Assessment

The fire spread simulation component was used to assess how varying forest conditions – resulting from different management scenarios – affect fire behaviour over time and

space. This phase of the analysis relied on high-resolution spatial inputs, including fuel load and type, canopy cover, topography (elevation, slope, aspect), and weather scenarios, which together define the physical environment for potential fire propagation.

By integrating these variables, the fire model simulated key fire behaviour indicators such as flame length, rate of spread, fire intensity, burned area, and crown fire potential. These simulations were conducted across multiple time steps to reflect forest evolution and changing risk levels throughout the planning horizon.

Each management scenario was tested under identical weather conditions to isolate the effect of vegetation structure and fuel continuity on fire dynamics. The simulations allowed for a comparative assessment of fire risk across alternative landscape configurations, revealing how specific interventions (e.g., thinning, fuel breaks, multifunctional land uses) can alter fire intensity and spread potential.

Moreover, the model outputs provided spatially explicit fire behaviour predictions that could be integrated into further analysis of ecosystem resilience, suppression difficulty, and potential socioeconomic impacts.

2.8. Spatial data processing and map outputs

Simulation outputs were processed and translated into spatially explicit representations of key fire behaviour variables. These included burn probability, flame length, rate of spread, fire intensity, aboveground biomass accumulation, and changes in ecosystem service indicators such as timber production, carbon sequestration, and aesthetic value.

All variables were mapped consistently across scenarios and simulation time steps, enabling side-by-side comparison of spatial patterns. The resulting maps made it possible to identify high-risk fire zones, detect areas of effective fuel reduction, and evaluate how different management strategies influence forest structure, fire vulnerability, and ecosystem function over time.

Spatial analysis allowed for the quantification of changes at both landscape and sub-regional levels, highlighting zones of increased resilience or critical concern. These spatial outputs serve not only as analytical tools, but also as powerful visual aids for communicating complex simulation results to stakeholders, planners, and policy makers.

2.9. Comparison and evaluation of the simulation scenarios

Simulation results were systematically compared across the different management scenarios to assess their relative performance in achieving ecological, fire risk reduction, and economic objectives. This evaluation focused on a set of key indicators, including burn probability, average flame length, biomass accumulation, carbon storage, and ecosystem service provision (e.g., timber yield, mushroom productivity, landscape aesthetics).

Both spatial and temporal dimensions were considered to capture how management interventions influenced forest dynamics and fire behaviour over time and across landscapes. The analysis also included economic indicators such as net present value, profit, and management costs, allowing for a comprehensive assessment of trade-offs between ecological benefits and economic feasibility.

Through this multi-dimensional evaluation, the study identified which scenarios provided the most balanced outcomes, highlighting areas of synergy (e.g., fuel reduction with biodiversity benefits) and potential conflicts (e.g., fire suppression versus economic returns). These insights offer valuable guidance for decision-makers aiming to design adaptive and resilient forest management strategies.

3. Results

3.1. Soriguera (Catalonia)

3.1.1. Input data

Soriguera landscape, located in the province of Lleida within Catalonia, Spain, was selected as the study area for the Catalonia Living Lab. Covering approximately 111 165 hectares, this mountainous landscape spans a broad elevation range from 500 to 2 800 meters above sea level, contributing to its ecological diversity and management complexity. Approximately 60% of the area (65 621 hectares) is covered by forest, divided into 5 261 forest stands for planning and simulation purposes.

A more detailed depiction of the fraction of the area covered by tree vegetation is shown in Figure 3.

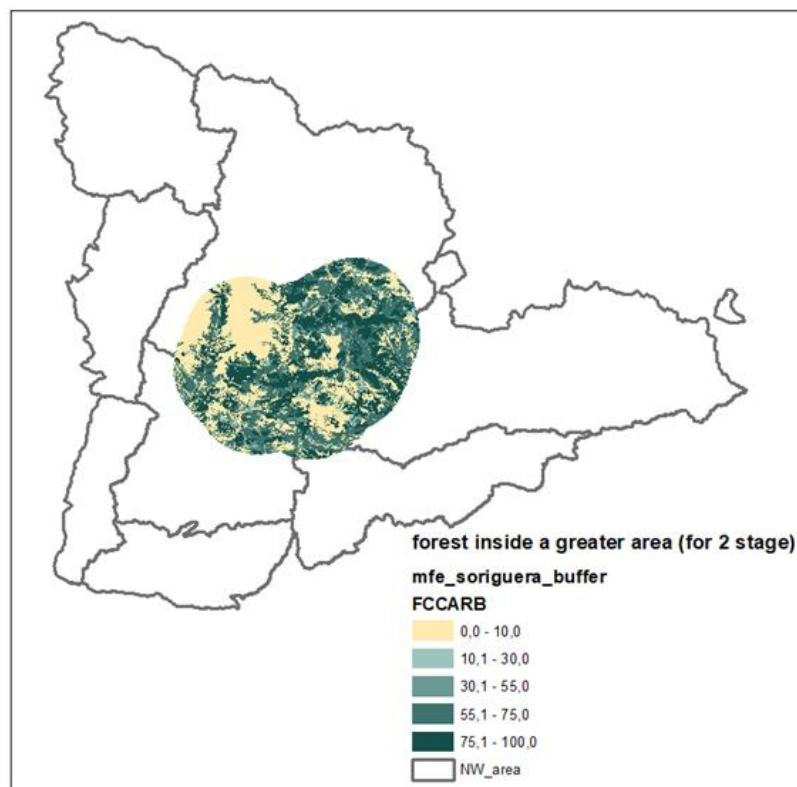


Figure 3: Soriguera landscape Living Lab: Tree canopy cover (FCCARB, %)

The vegetation is characterized by a mosaic of ecosystems shaped by altitude and microclimatic variations. Dominant tree species include pines (*Pinus* spp.), firs (*Abies* spp.), oaks (*Quercus* spp.), beeches (*Fagus* spp.), and chestnuts (*Castanea* spp.), reflecting the transitional nature of the landscape between Mediterranean and montane environments. These forests support a wide range of biodiversity but are also exposed to increasing wildfire risk due to changing climatic conditions, fuel accumulation, and limited accessibility for suppression efforts.

Soriguera's terrain is highly variable, with steep slopes in many areas, particularly in higher altitudes. The climate is typically sub-Mediterranean, with humid, cold winters and dry, warm summers that elevate fire danger during the fire season. Human activity, including traditional land use practices and rural abandonment, has significantly influenced forest structure and fuel continuity, increasing vulnerability to large-scale wildfire events.

The forest canopy is predominantly composed of coniferous and broadleaf species, while the understory varies from sparse grasses in managed stands to dense shrub layers in less accessible zones.

The combination of ecological richness, climatic conditions, and anthropogenic influences makes Soriguera a pertinent case study for assessing wildfire dynamics and developing adaptive forest management strategies in Mediterranean mountain regions.

Data on forest stands provided by the National Forest Inventory

The stand data for Soriguera was derived from the 1:25 000 forest map and the Spanish National Forest Inventory (NFI), and included:

- Tree-level information per sample plot, such as species composition, tree diameters, and number of trees per hectare.
- General plot descriptors, including altitude, average slope, and UTM coordinates.

To spatially assign stand identifiers to the simulation polygons in Soriguera, a data-driven clustering approach was applied using LiDAR-derived structural variables (ICGC 2016_2017). Specifically, the following attributes were calculated for each polygon:

- Mean tree diameter (DBH)
- Standard deviation of tree diameter
- Basal area

These variables reflected the structural complexity of each polygon and guided the clustering-based assignment of plot IDs. Using this data, K-means clustering was performed to group polygons with similar forest structure. Each resulting cluster was then matched to the most representative IFN stand based on structural similarity to the cluster centroid. This method ensured a consistent and ecologically relevant assignment of stand IDs across the landscape, providing robust input data for the growth simulation model.

Weather scenarios describing fire hazard conditions

Weather scenarios were included among the input datasets to support the fire spread simulations. These scenarios define the meteorological conditions under which fire events are modelled and are essential for simulating realistic fire behaviour. For Soriguera, 61 weather scenarios were obtained from the PREVINCAT platform (<https://previncat.ctfc.cat/#home>), representing some of the worst historic conditions in terms of combination of high wind speeds and high temperatures.

Each weather scenario contains a set of key attributes:

- Scenario ID – the identifier of the scenario.
- Date and time – the timestamp associated with the weather conditions.
- Wind speed (WS) – a critical driver of fire spread dynamics.
- Wind direction (WD) – determines the main axis of fire propagation.
- FireScenario code – describes specific fire hazard conditions linked to the scenario (e.g., landscape type or fuel humidity).

These data were used to parameterize fire behaviour across a range of possible weather conditions (but focusing on risky ones, as mentioned), enabling a probabilistic and robust simulation approach.

Each weather scenario was treated as a possible fire weather event. To reflect their relative likelihood, the probability of occurrence for each of the 61 scenarios was calculated based on historical frequency. This probabilistic weighting ensures that simulations are not biased by rare or extreme conditions and instead reflect realistic weather variability.

3.1.2. Forest Growth Simulator

The Forest Growth Simulator is a modular tool developed within the scope of the Soriguera case study to simulate forest dynamics over time, integrating both natural ecological processes and forest management interventions. It supports the assessment of structural changes, ecosystem service provision, and long-term impacts of alternative management scenarios. While designed for Soriguera, the simulator's flexible structure allows for adaptation to other regions and Living Labs using locally relevant data and parameters.

Forest Growth Simulation Models

In the development of this Forest Growth Simulator, the following models were implemented:

- Growth (dynamics) models
- Fuel models
- Ecosystem service models

Table 1 presents all the sub-models that were implemented to predict the future evolution of specific forest stands under different management scenarios.

Table 1: Models used in the Forest Growth Simulator

MODEL CLASS	SUB-MODELS
Growth models	Diameter increase
	Height increase
	Mortality / Survival
	Incorporation
Fuel models	Forest canopy cover (FCC)
	Canopy base height (CBH)
	Canopy bulk density (CBD)

	Understory shrub coverage
	Fuel Models Assignment
Ecosystem service models	<i>Provisioning Services</i> Biomass production Timber production Mushroom production <i>Regulating and Maintenance Services</i> Carbon sequestration Forest fire prevention indicator The proportion of trees that die due to fire <i>Social Services</i> Scenic beauty

The growth sub-models, as described by Trasobares and Pukkala (2007), simulate individual tree growth and mortality, with outputs aggregated to provide stand-level estimates.

Fuel models are assigned to each plot for Fire Spread Simulation, using Scott and Burgan (2005) models due to their regional accuracy. To assign the fuel model, computations were conducted for the following variables:

- Forest Canopy Cover (FCC),
- Canopy Base Height (CBH),
- Canopy Bulk Density (CBD),
- Understory Shrub Cover (CCarb).

In Scott and Burgan's methodology, fuel models were categorized based on humidity as follows: (a) for dry areas experiencing a water deficit during summer months, and (b) for humid areas without a water deficit. In these models, vegetation types were organized into 5 groups according to the fuel load characteristics, as shown in Table 2.

Table 2: Correspondence between basic fuel models and Scott and Burgan's models (2005)

VEGETATION TYPES	FUEL TYPE BY SCOTT AND BURGAN (2005)
Wooded forest area	Slash-Blowdown (SB), Timber Litter (TL), Timber Litter (TL)
Regenerated forest	Shrub (SH)
Scrubland	Grass-Shrub (GS), Shrub (SH)
Grassland	Grass (GR)
Non-burnable	Non-burnable (NB)

Fuel models are differentiated by a unique code and number, defined by the algorithm outlined by Scott and Burgan (2005).

An example of the algorithm applied for *Pinus halepensis* is shown in Figure 4.

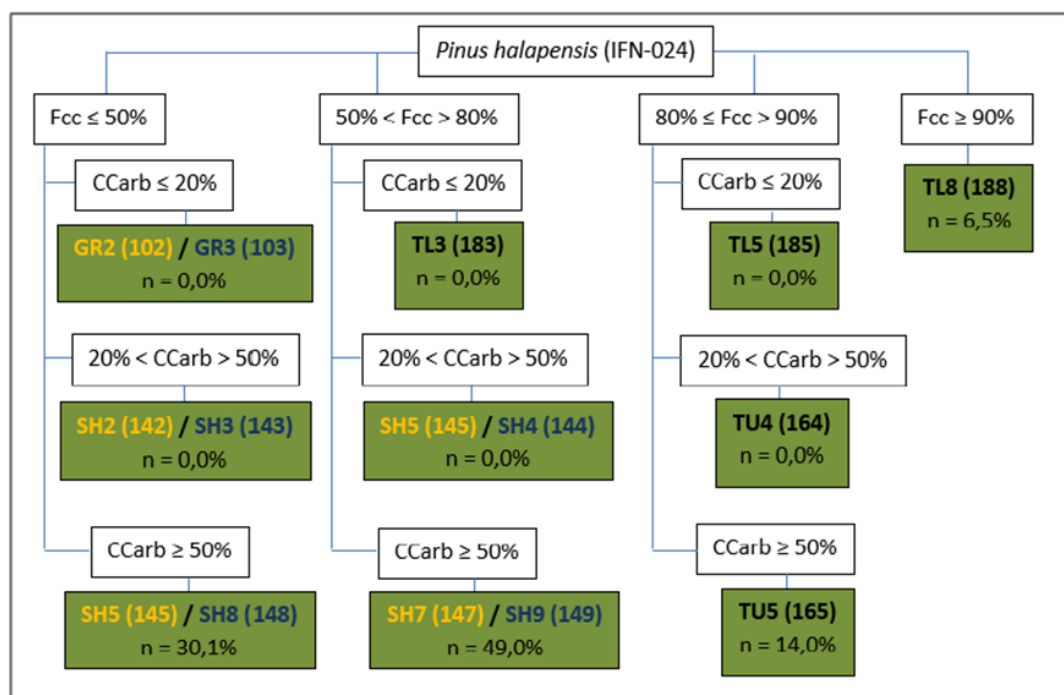


Figure 4: Algorithm used for assignment of the Scott and Burgan model to stand populated by *Pinus halepensis*; Fcc = Forest Canopy Cover; CCarb = Understory Shrub Cover; yellow color = model assigned if the pixel is located within the dry area; blue color = model assigned if the pixel is located within the humid area; black color = model assigned regardless of the area; n = representativeness of the model (% in the total area covered by species).

Among the sub-models of ecosystem service models, the following were considered:

- *Models of the Provisioning Services:*

Biomass Production: Model proposed by Ruiz-Peinado et al., (2011).

Timber Production: Calculated using the formula:

$$VW = FB / density,$$

where *VW* is the volume of cut wood, *FB* is the foliar biomass, and *density* is wood density at 12% humidity (kg/m³).

Harvesting Costs: Divided into felling and transportation costs, estimated based on tree size and stand accessibility.

Net Present Value (NPV): Estimates the profitability of a forest management intervention by discounting future net cash flows over time to their present value.

Mushroom Productivity: Models developed by de-Miguel et al., (2014).

- *Models of Regulating and Maintenance Services:*

Carbon Sequestration: Model to estimate carbon stocks proposed by Ruiz-Peinado et al., (2012).

Tree Mortality due to Fire: Calculated according to the stand-level damage model proposed by Gonzalez et al., (2007).

Forest Fire Prevention: Calculated as burn probability using the Fire Spread Simulator Cell2Fire.

- *Models of Social Services:*

In this services group, the indicator of the amenity of a forest stand, specifically estimating Scenic Beauty preferences at the stand level, is considered. For predicting preference regarding the scenic beauty of stands, models described by Blasco et al., (2009) are implemented.

[Forest Management](#)

Forest management in the growth simulator considers various interventions that shape forest structure and influence the delivery of ecosystem services. In Catalonia, the primary strategies include Land-use change, Thinning, Pre-commercial thinning, Final harvests, Pruning, and Brush clearing, each contributing to forest development and risk reduction in different ways.

Land-use change involves converting forested areas into agricultural land or urban spaces, typically requiring the complete removal of vegetation from a given plot.

Thinning, on the other hand, focuses on the selective removal of trees to enhance the growth conditions for those that remain, improve structural stability, and lower the risk of wildfires.

When this process targets young trees that have not yet reached commercial size, it is referred to as **Pre-commercial thinning**—an approach that helps reduce competition and encourages healthy development of the stand.

Final harvests aim at timber production and may be executed either through *successive thinning* or *clear-cutting*. The *successive thinning* method unfolds in three phases over a specified period, usually a decade for each phase. In the first two phases, approximately half of the basal area is removed—first by targeting smaller trees and then by applying a proportional approach. The third phase focuses on harvesting the remaining large trees, though users can opt to retain some of them. Alternatively, *clear-cutting* entails the complete removal of all trees in a plot, after which replanting is planned based on the number specified in the management configuration.

In addition to these standard silvicultural practices, two preventative fire treatments are applied: **Pruning** and **Brush clearing**. **Pruning** entails cutting lower branches to break the vertical continuity of fuels, which not only limits fire spread but also enhances wood quality. **Brush clearing** targets the understory vegetation, often in conjunction with thinning, to further reduce the fuel load in forest stands.

For **Thinning** operations, users can choose whether to base the intervention on *basal area* or *tree count*. Once the cutting type is defined, the specific trees to be removed can be selected through different strategies. A systematic approach removes a consistent proportion across all diameter classes. Alternatively, trees can be removed preferentially either **from above**—starting with the largest individuals—or **from below**—targeting the

smallest ones first. These methods provide flexibility in designing interventions tailored to specific management goals or stand conditions.

Creating Decision Space

In the Forest Growth Simulator developed for Catalonia, the space of management alternatives is defined according to the specified parameters for Thinning, Pre-commercial thinning, Final harvests, and accompanying management practices such as Pruning and Clearing.

The size of this space (the number of alternatives) depends on the specified bias parameter for Thinning and Final harvests, which sets the options for the management initiation rule, as well as on the management intensity parameters.

For example, in Table 3 are presented parameters defining management alternatives for *Pinus nigra* (with species code 25 according to IFN3).

Table 3: Parameters Defining Management Alternatives for Pinus nigra

Parameter	Value / Description
Species	Pinus nigra
Species code (IFN3)	25
Thinning	
Initiation (G, m ² /ha)	32, 37, 42
Intensity	30%
Strategy	50% smallest trees first, 50% proportionally distributed
Final Harvest	
Initiation (dm, cm)	25, 30, 35
Phase Duration (years)	10
Intensity	Phase 1: 40%, Phase 2: 40%, Phase 3: 0%
Pre-commercial Thinning	
Initiation diameter	11 cm
Trees to leave	1200
Incorporation	
Initiation diameter	7.5 cm
Number of trees	2500
Plantings	3

These alternatives are obtained by combining three different conditions for the initiation of Thinning and Final harvests:

- the initiation of Thinning can vary from a basal area value of 37 ± 5 , with one alternative each for $G = 32$, $G = 37$, and $G = 42$;
- similarly, a bias of 5 for the initiation of Final harvests provides 3 alternatives with mean diameter values of $dm=25$, $dm=30$, and $dm=35$.

In this example, the intensity parameters do not vary, so the same intensity will be applied to all management alternatives: of the 30% of the forest to be cut, 50% of the smallest

trees are initially cut, and then the remaining 50% is proportionally distributed among the other diameter classes.

Figure 5 illustrates the definition of the management space with the 9 alternatives described above, as implemented in the Forest Growth Simulator.

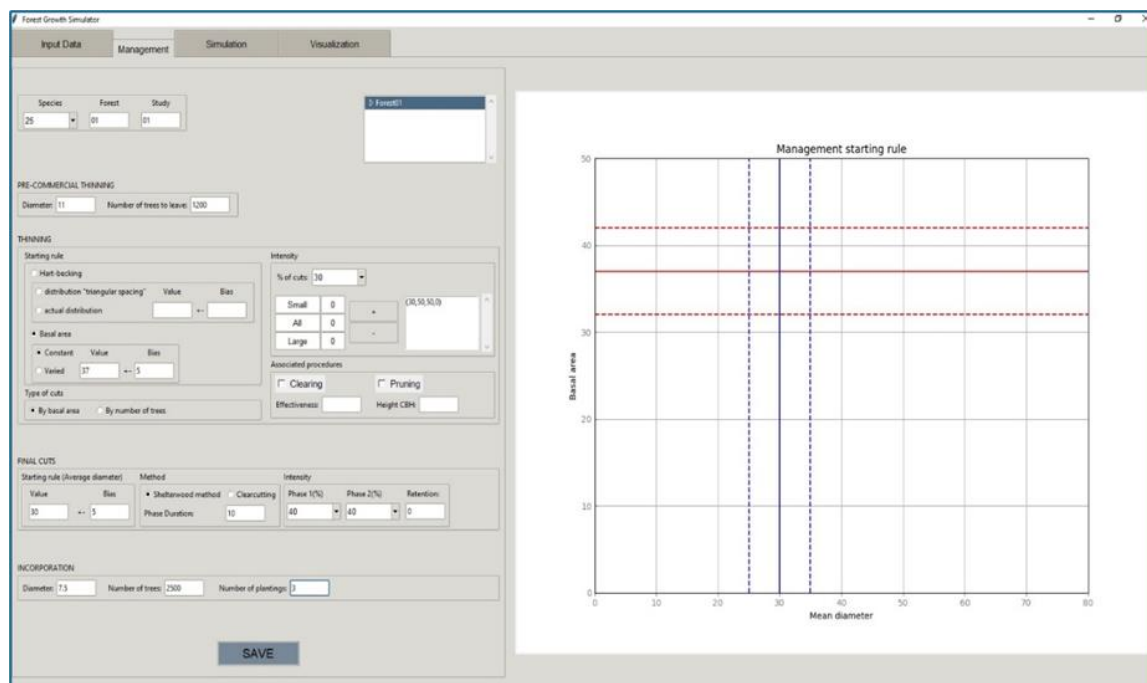


Figure 5: A variant of forest management for the dominant species *Pinus nigra*, which is represented in a space of 9 alternatives

3.1.3. Optimization of Forest management strategies

Within the Forest Growth Simulator, an optimization module was implemented to support decision-making by balancing competing ecological and economic objectives. A multicriteria optimization task was performed using the CBC solver from the PuLP linear programming library in Python.

The optimization aimed to identify the best combination of forest management alternatives across all stands, based on 6 selected ecosystem services. Each ecosystem service was assigned a specific weight in the objective function (see Table 4) and was converted into utilities to enable their comparison and integration into the objective function, ensuring balanced decision-making despite their different units of measurement (see Table 5). The process of selecting weights and converting the value of the indicators related to criteria into a utility function was accomplished through a meeting with a selected number of stakeholders. In general, the utility functions were based on observed ranges of data, receiving the maximum level of satisfaction, those yields reaching the maximum observed. In the case of the weights, or relative importance of the individual objective, a consensus was again by performing a Pairwise comparison of criteria through an analytical hierarchy process (Satty, 1987).

Table 4: Ecosystem service weight coefficients (Soriguera)

ECOSYSTEM SERVICE	WEIGHT COEFFICIENT
Total biomass average	0.1
Edible mushroom production average	0.1
Scenic beauty preferences average	0.1
Proportion of trees that die due to fire	0.24
Total volume of cut wood	0.17
Net present value (NPV)	0.28

Table 5: Conversion of Ecosystem services into utilities

ECOSYSTEM SERVICE	CONVERSION INTO UTILITIES
Total biomass average	min -> 0, max -> 1
Edible mushroom production average	min -> 0, max -> 1
Scenic beauty preferences average	min -> 0, max -> 1
Proportion of trees that die due to fire	min -> 1, max -> 0
Total volume of cut wood	mean -> 1, min -> 0, max -> 0
Net present value (NPV)	until 0 -> 0, max -> 1

The objective function was formulated as a weighted sum of normalized utility values associated with each service:

$$\sum_{i=1}^n \sum_{j=1}^{l_i} \sum_{k=1}^m f_k * w_k * a_{ij} \rightarrow \max$$

where:

- f_k – value of ecosystem service k converted into utility,
- w_k – weight coefficient for ecosystem service k ,
- a_{ij} – binary decision variable selecting alternative j for stand i ,
- n – number of stands,
- l_i – number of alternatives per stand i ,
- $m=6$ – total number of ecosystem services considered.

The utility values f_k lie within the range $[0, 1]$, and the weights w_k were normalized to sum to 1. As the objective function aggregates these weighted utilities across all stands and selected alternatives, its magnitude depends on the number of stands and the specific combination of selected options. The maximum value is reached when all selected alternatives provide the highest utility across all ecosystem services.

To ensure feasible and realistic solutions, the following constraints were introduced:

Management area constraint:

The total area under active forest management must be between 20% and 70% of the entire forested landscape. Providing flexibility to the problem to reach the current management levels or raise them.

$$0.2 * Total_Area \leq \sum_{i=1}^n \sum_{j=1}^{l_i} area_i * a_{ij} \leq 0.7 * Total_Area$$

Decision variable constraints:

- Binary nature of decisions: $a_{ij} \in \{0,1\}$

An alternative a_{ij} can be selected ($a_{ij} = 1$) or not selected ($a_{ij} = 0$).

- One alternative per stand:

$$\forall i: \sum_{j=1}^{l_i} a_{ij} = 1$$

Only one management alternative can be applied to each stand.

3.1.4. Studied scenarios

The identification of simulation scenarios is based on the presence or absence of specific management restrictions for selected stands.

To identify forest management scenarios, a combined approach utilizing both forest growth and fire spread simulations is employed. The process involves the generation of forest management alternatives based on the predominant tree species in each stand, followed by the optimization of these alternatives within the decision space.

For the study area Soriguera, three different simulation schemes are considered:

Scenario 1: Unrestricted Forest Management (see Figure 6)

- All stands are subjected to management and subsequent decision optimization based on the predominant tree species.
- Fire spread simulation is applied to the results of growth simulation, allowing for an evaluation of fire impact under optimized conditions.

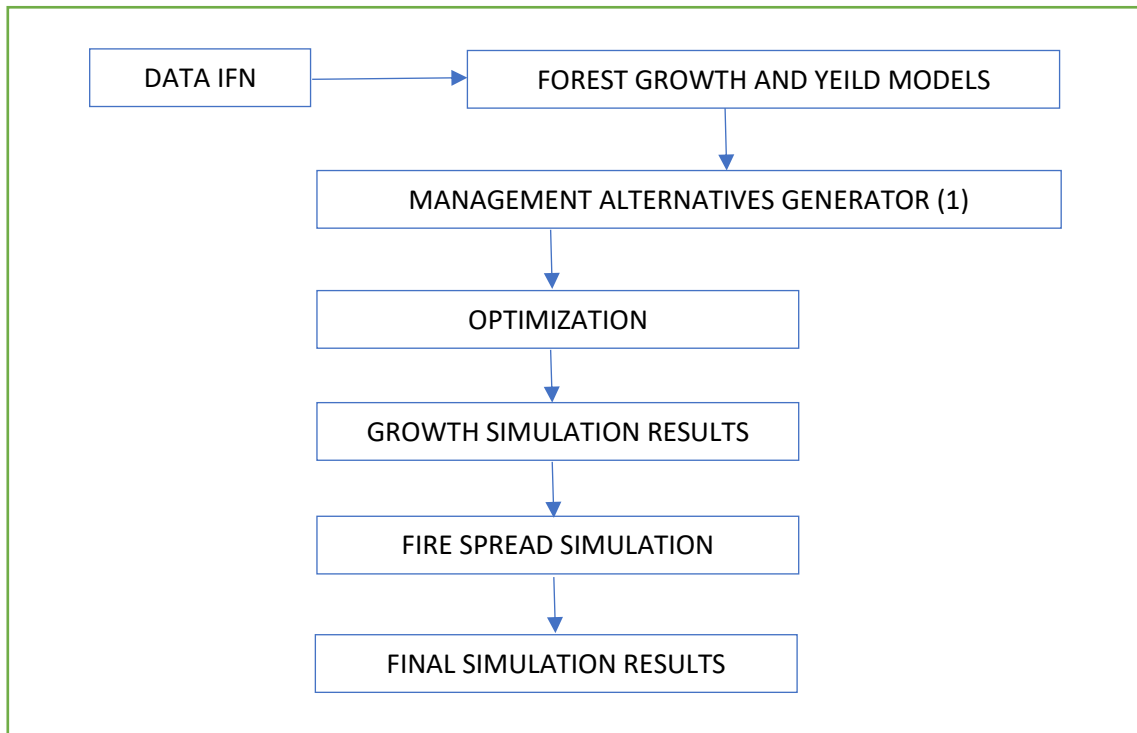


Figure 6: Scenario 1. All stands undergo management according to the predominant tree species. Alternative optimization is performed, followed by fire spread simulation.

Scenario 2: Firebreak Integration (see Figure 7)

- Management alternatives are optimized for all stands except those designated as firebreak areas.
- The "cut all" alternative is applied to stands selected for conversion into firebreaks in the first year of simulation.
- Fire spread simulation is conducted on the resulting forest landscape.

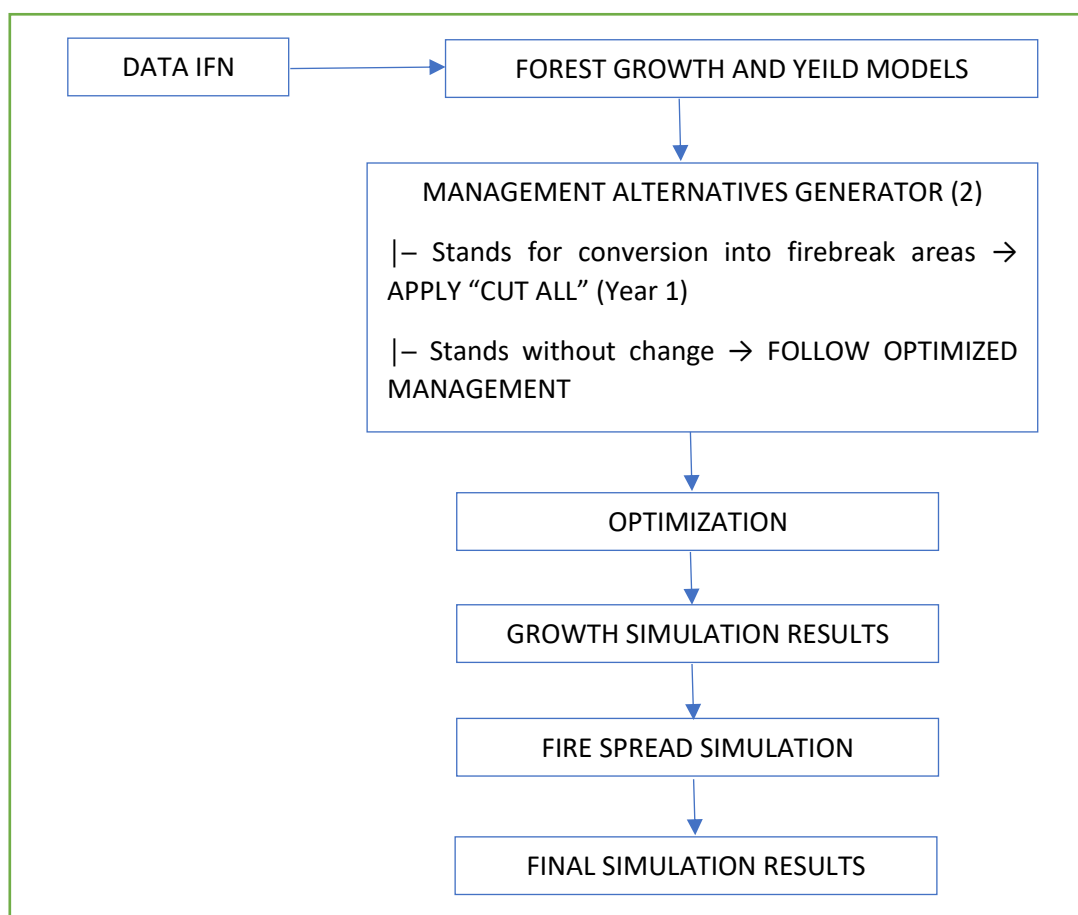


Figure 7: Scenario 2. Some stands are designated as firebreak areas where the "cut all" alternative is applied. Other stands undergo standard management optimization

Scenario 3: Biodiversity and Pasture Recovery Considerations (see Figure 8)

- Specific management alternatives are applied to certain stands to support biodiversity conservation, pasture recovery and *dehesa* management.
 - *Dehesa* management is implemented in selected areas, balancing tree cover with open pastureland to support agro-sylvopastoral systems.
 - Other stands follow optimized management strategies based on predominant tree species.
 - Fire spread simulation is applied to the resulting landscape configuration.

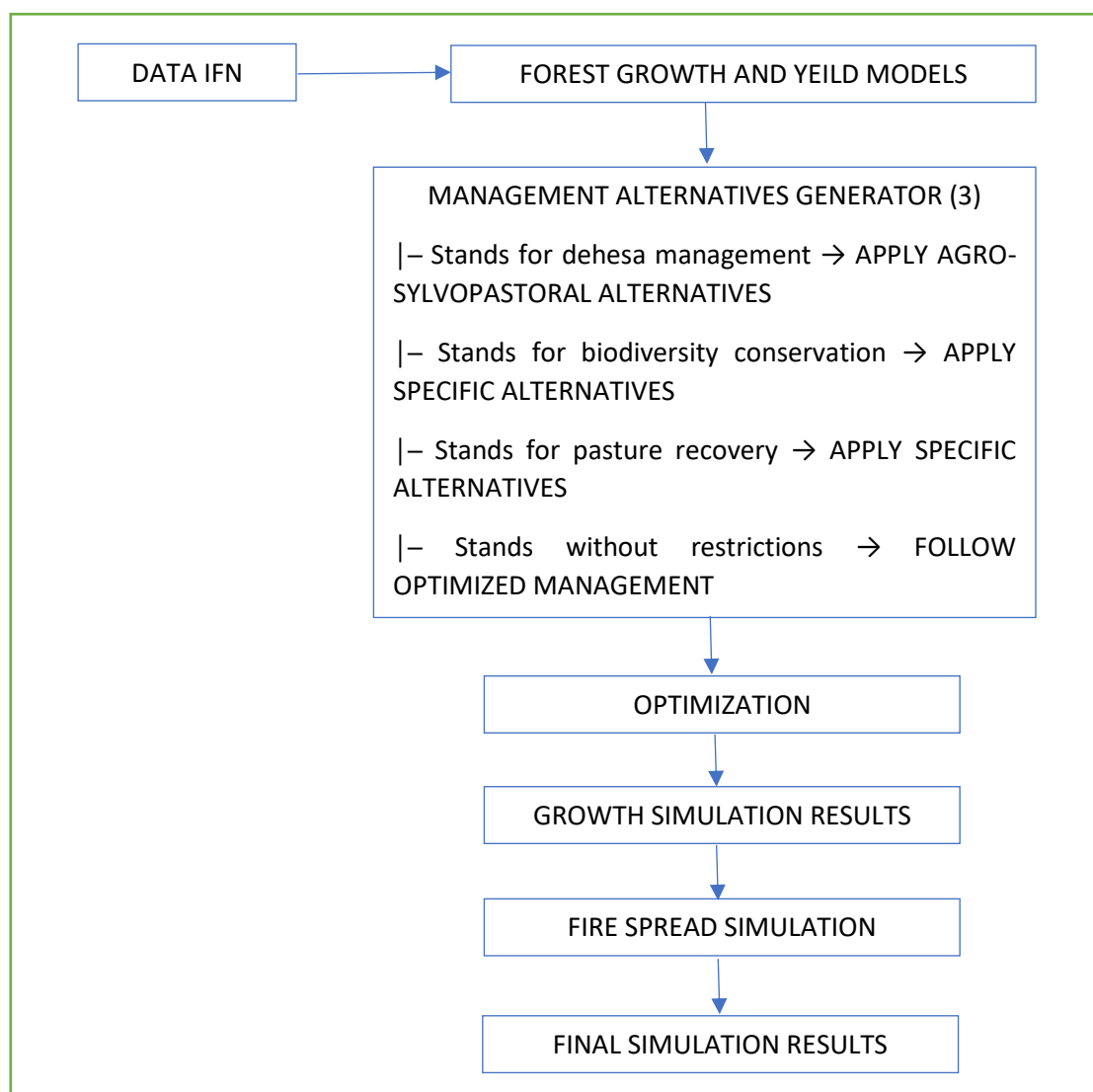


Figure 8: Scenario 3. Specific management alternatives are applied to certain stands to support biodiversity conservation, pasture recovery, and dehesa management. Other stands undergo standard optimization

3.1.5. Fire Behaviour Assessment

As part of this study, the Cell2Fire fire spread simulator was used, specifically the adapted version Cell2Fire_SB (Gonzalez-Olabarria et al., 2023), which is designed to support tactical forest management planning.

Cell2Fire_SB is capable of simulating both surface and crown fires, using fire spread rules and fuel models commonly applied in Europe and the United States. It integrates seamlessly with other modelling components, such as the forest growth simulator and optimization modules, allowing for the evaluation of fuel evolution, spatial allocation of treatments, and the impacts of management decisions over time.

As shown in Figure 9, Cell2Fire_SB operates through a structured simulation workflow that incorporates key spatial inputs such as fuel models, topography, and ignition points.

These inputs are processed through the fire spread engine to generate spatial outputs like flame length, rate of spread and others. This modular workflow facilitates integration into broader forest management planning systems.

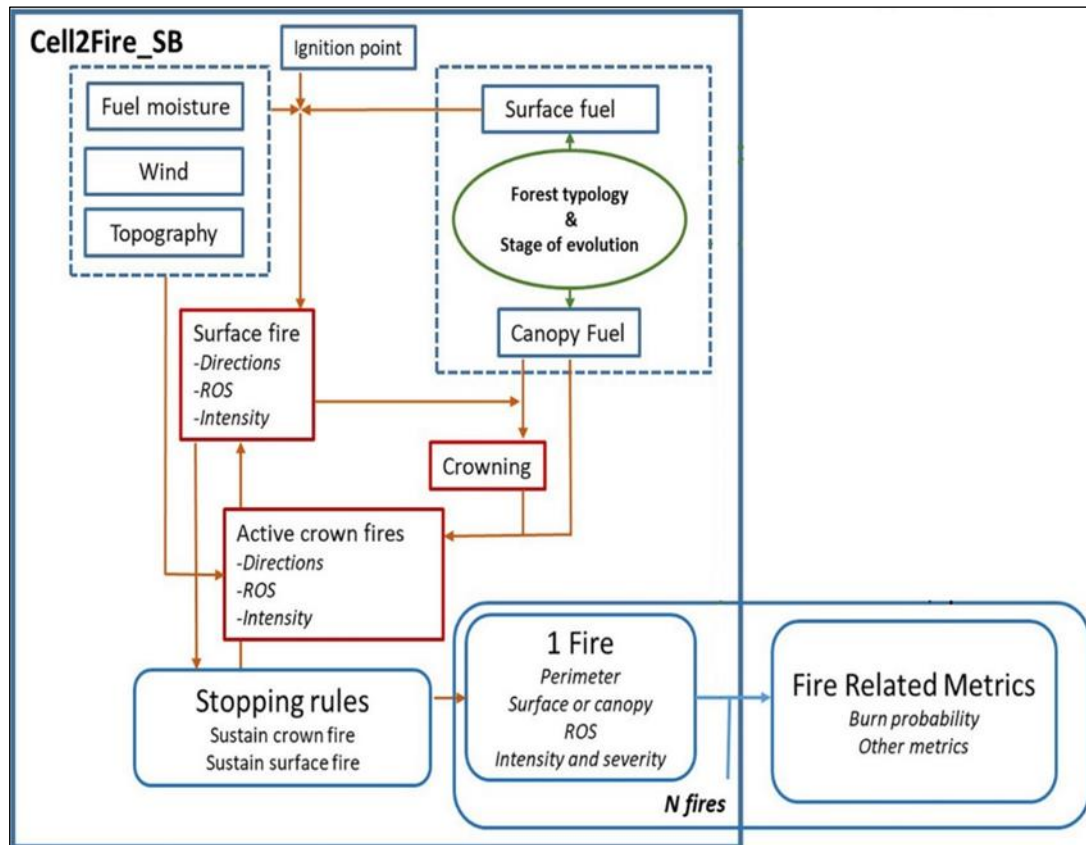


Figure 9: General workflow of the Cell2Fire_SB fire spread simulator

The simulator operates using data on vegetation structure, topography, and weather conditions. For ease of use and integration, Cell2Fire_SB was implemented as a QGIS plugin, facilitating the import of spatial input layers and visualization of simulation outputs directly within the GIS environment (see Figure 10).

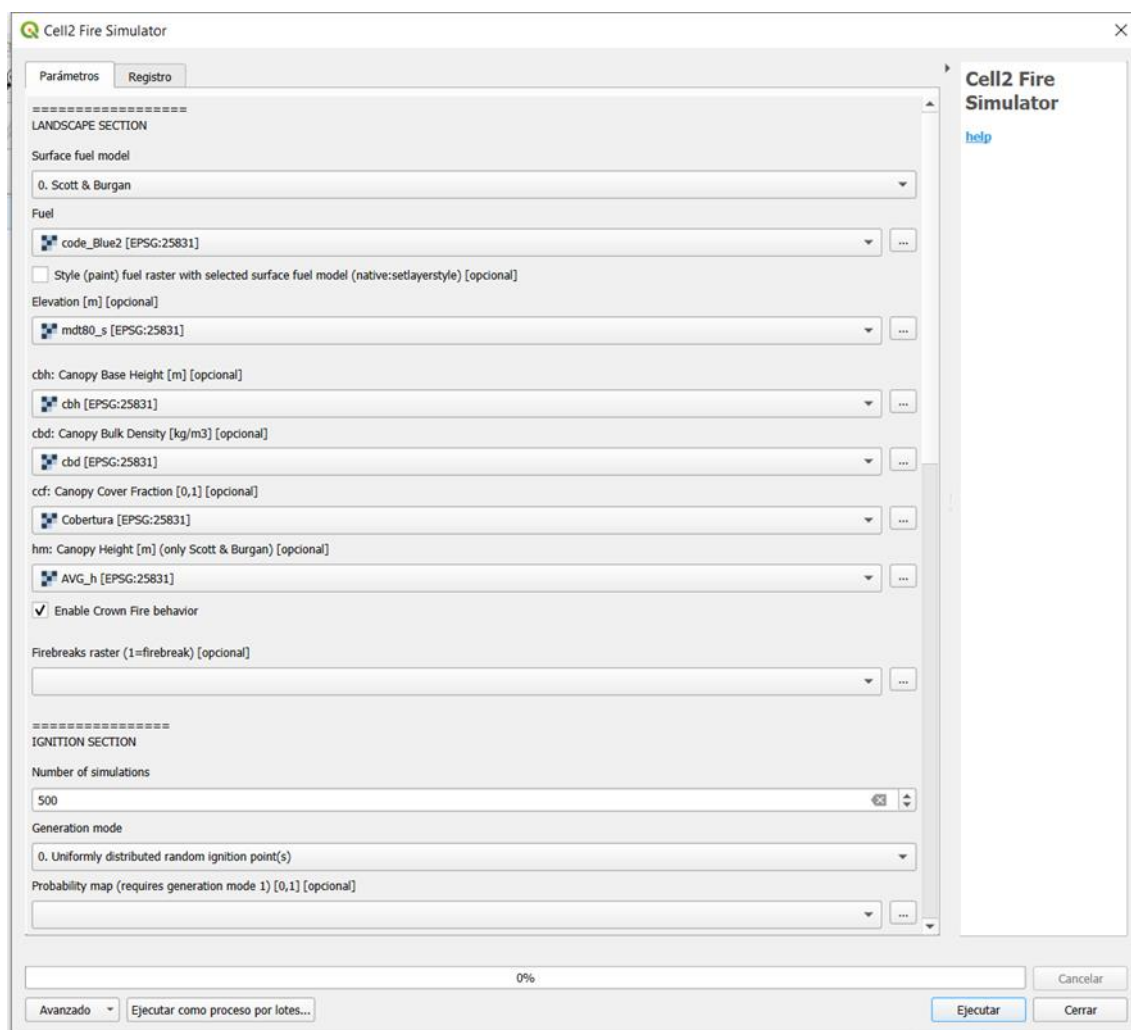


Figure 10: Cell2Fire_SB QGIS plugin interface

A set of weather scenarios is used to drive fire spread simulations. In broader Catalonian fire modelling applications, up to 500 ignition points are commonly simulated, each potentially paired with a distinct weather scenario. In the case of Soriguera, 61 high-resolution weather scenarios from the PREVINCAT platform were sufficient to capture a wide range of fire-conducive weather conditions and realistically represent ignition variability across the landscape. Each scenario was assigned a relative selection frequency to represent its probability, informed by historical data. This approach enabled a more detailed assessment of fire spread under varying, region-specific conditions.

This integration of spatial, structural, and meteorological data enables Cell2Fire_SB to produce spatially and temporally explicit predictions of wildfire behaviour across management scenarios – supporting decision-making under conditions of uncertainty and weather variability.

3.1.6. Integration of Forest Growth and Fire Spread Simulators

To ensure integration between the two simulators applied in the Catalonia Living Lab, the fuel models used in the forest growth simulation generate fuel codes for each stand based on the following parameters:

- **Forest Canopy Cover (FCC):** represents the percentage of the area covered by the forest canopy, which is important for determining the overall availability of fuel for fire spread.
- **Canopy Base Height (CBH):** indicates the height of the lower level of the canopy, influencing the possibility for fire to reach this level and spread through it.
- **Canopy Bulk Density (CBD):** measures the fuel mass per unit volume within the forest canopy, directly affecting the intensity of combustion.
- **Understory Shrub Cover (CCarb):** represents the presence and density of shrubs in the understory, which can serve as an additional fuel source for fire.

These values are converted into spatial layers in the form of rasters, which are then used by the Cell2Fire fire spread simulator to model the process of fire propagation through the forest ecosystem.

The final inputs for the fire propagation simulator include six rasters, four of which are mentioned above, along with a fuel raster and an elevation raster. The elevation raster is essential for considering the terrain, which can significantly alter the trajectory and speed of fire spread.

All spatial input layers for the fire spread model, such as elevation, fuel load, and canopy cover, were adjusted to a consistent spatial resolution. Additionally, the temporal resolution was synchronized, ensuring that fire simulations were conducted based on the forest conditions projected for the specific years of the simulation (e.g., year 0, 10, 20, etc.).

These data enable the creation of more accurate predictions of fire behaviour under various conditions, such as changes in terrain or variations in forest cover.

The general interaction scheme between the simulators is shown in Figure 11.

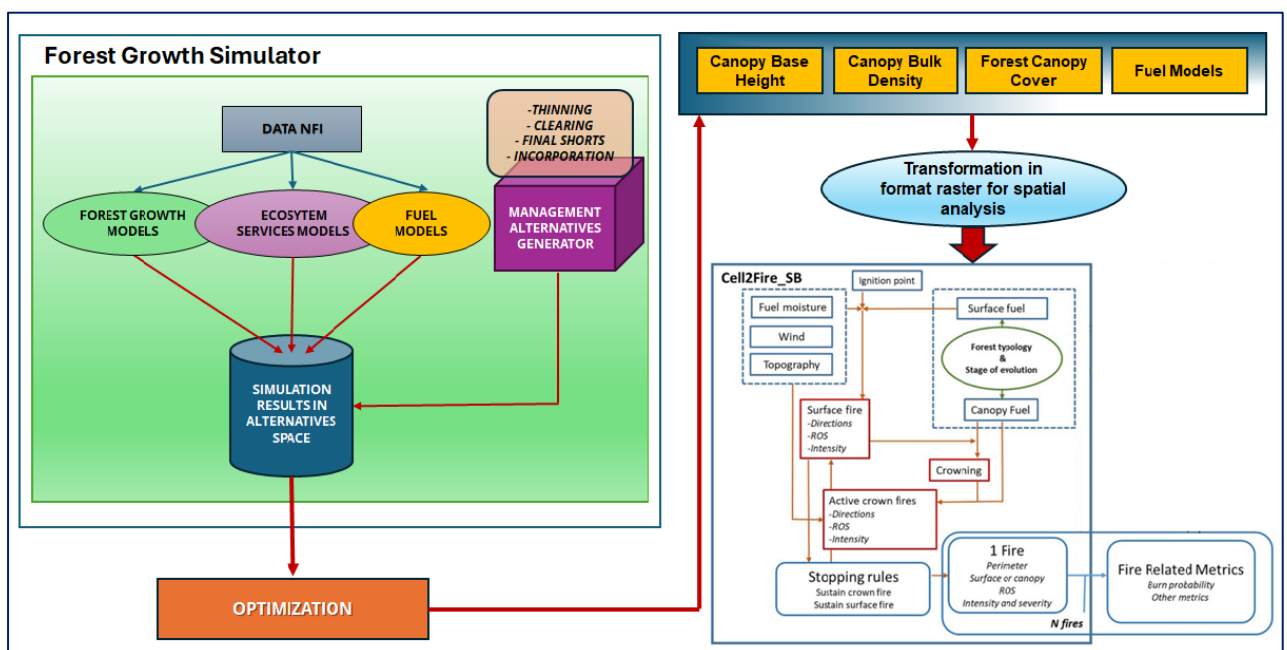


Figure 11: Interaction between Forest Growth Simulator and Fire Spread Simulator Cell2Fire

3.1.7. Analysis of results

Both the forest growth and fire spread simulations were conducted over a 50-year planning horizon with a 5-year time step, resulting in a total of 11 simulation time steps (Year 0 to Year 50). This temporal resolution enabled the assessment of long-term forest dynamics and fire behaviour changes under various management scenarios.

The simulation results for the Soriguera landscape were analyzed both spatially and numerically to evaluate the effectiveness of the three alternative forest management scenarios under fire-prone conditions.

Table 6 summarizes the ecosystem service and economic indicators derived from simulations over a 50-year horizon. In terms of **carbon storage**, **Scenario 1** and **Scenario 3** led to the highest CO₂ accumulation (+2.59 and +2.57 million tons, respectively), while **Scenario 2** showed a much lower gain (+1.70 Mt CO₂), indicating that intensive harvesting practices reduced biomass build-up.

When comparing the per-hectare values, similar trends were observed. **Timber harvesting volumes** were slightly higher in **Scenario 2** (57 212 t) compared to the other scenarios (see Table 6), which is also reflected in the per-hectare values — 44 771 kg/ha including unmanaged polygons. However, when considering only managed areas, **Scenario 1** reached the highest harvesting volume per hectare (63 644 kg/ha), followed closely by **Scenario 3** (63 305 kg/ha), while **Scenario 2** had the lowest value (62 863 kg/ha). As shown in Table 7, this suggests that although total timber output was maximized in **Scenario 2**, its efficiency within managed forests was slightly lower.

Edible mushroom production showed limited variation among scenarios. Per-hectare values were slightly higher in **Scenario 2** (32.01 kg/ha), followed by **Scenario 1** (31.68 kg/ha) and **Scenario 3** (31.54 kg/ha) (see Table 7), indicating a relatively stable provisioning of non-timber forest products.

Table 6: Ecosystem service and economic indicators per landscape (Soriguera)

METRIC	SCENARIO1	SCENARIO2	SCENARIO3
Carbon Storage (BT) Year 0 (t)	13883861.03		
Carbon Storage (BT) Year 50 (t)	16478750.77	15586175.57	16458600.98
CO ₂ Evolution (Δ CO ₂) (t)	+2594889.75	+1702314.54	+2574739.95
Timber Harvesting (t)	56928.61	57212.21	55515.80
Edible Mushrooms Year 0 (t)	2014.48		
Edible Mushrooms Year 50 (t)	2061.19	1996.44	2030.14
Edible Mushrooms Evolution (t)	+46.71	-18.04	+15.66
Profit (€)	1592137724.49	1594587365.54	1548436930.15
Costs (€)	1181306142.45	1212631080.41	1161205001.03
Cash Flow (€)	410831582.71	381956284.50	387231928.02
NPV (€)	-928634.31	-1483981.01	-836176.00

From an economic perspective, **Scenario 2** had the highest average **profit** (2 228 €/ha), but also the highest **costs** (1 695 €/ha), resulting in the lowest **cash flow** (534 €/ha) and the most negative **NPV** (-22.81 €/ha). **Scenario 1** demonstrated a better balance between revenues and expenses, with a higher **cash flow** (574 €/ha) and a less negative **NPV** (-

14.27 €/ha). **Scenario 3** generated the lowest **profit** (2 164 €/ha) but also incurred the lowest **costs** (1 623 €/ha), which led to the least negative **NPV** (-12.85 €/ha), making it the most economically sustainable option in the long term (see Table 7).

Table 7: Ecosystem service and economic indicators per forest hectare (Soriguera)

METRIC	SCENARIO1	SCENARIO2	SCENARIO3
Carbon Storage (t)	253.30	264.21	255.68
Timber Harvesting (kg)			
with unmanaged polygons included	44549.35	44771.28	43443,7618
including only managed polygons	63643.78	62862.63	63304.56
Edible Mushrooms (kg)	31.68	32.01	31.54
Profit (€)	2224.86	2228.27	2163.80
Cost (€)	1650.76	1694.54	1622.68
Cash Flow (€)	574.10	533.75	541.12
NPV (€)	-14.27	-22.81	-12.85

Spatial fire behaviour metrics also revealed important differences. Table 8 summarizes the **Crown Flame Length** statistics across all scenarios and simulation years. **Scenario 2** consistently showed a **smaller area affected by crown fires**, especially by year 50 (only 413 km²), compared to Scenario 1 (505 km²) and Scenario 3 (496 km²). The average flame length in Scenario 2 by year 50 was also the lowest (5.07 m), suggesting effective fire hazard reduction. In contrast, Scenarios 1 and 3 recorded values of 5.41 and 5.42 m, respectively.

Table 8: Summary of Flame Length statistics across simulation years (Soriguera)

	SCENARIO1		SCENARIO2		SCENARIO3	
	Surface affected by fire (km ²)	Flame Length (m)	Surface affected by fire (km ²)	Flame Length (m)	Surface affected by fire (km ²)	Flame Length (m)
Year0	574.61	5.66	574.61	5.66	574.61	5.66
Year10	568.45	5.75	479.64	5.59	562.62	5.75
Year20	551.67	5.84	461.06	5.67	542.89	5.84
Year30	529.02	5.97	437.97	5.77	519.67	5.97
Year40	534.11	5.75	439.65	5.52	525.42	5.75
Year50	505.45	5.41	413	5.07	496.42	5.42

The comparison of **burn probability** revealed clear differences: Scenario 2 yielded the lowest probability (0.0377), while Scenarios 1 and 3 showed similar, higher values (0.0517–0.0521). These results align with spatial trends in flame length and support the effectiveness of Scenario 2 in reducing fire hazard (see Table 9 and Figures 12, 13).

Table 9: Average burn probability and probability of fire-induced tree mortality (P_{dead}) per polygon across management scenarios (Soriguera)

METRIC	SCENARIO1	SCENARIO2	SCENARIO3
Burn Probability	0.0521	0.0377	0.0517
P_{dead}	0.0620	0.0566	0.0612

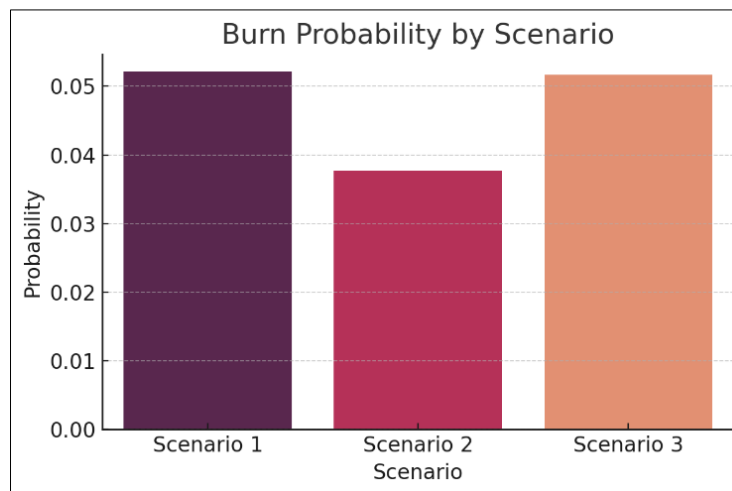


Figure 12: Average burn probability across scenarios (Soriguera)

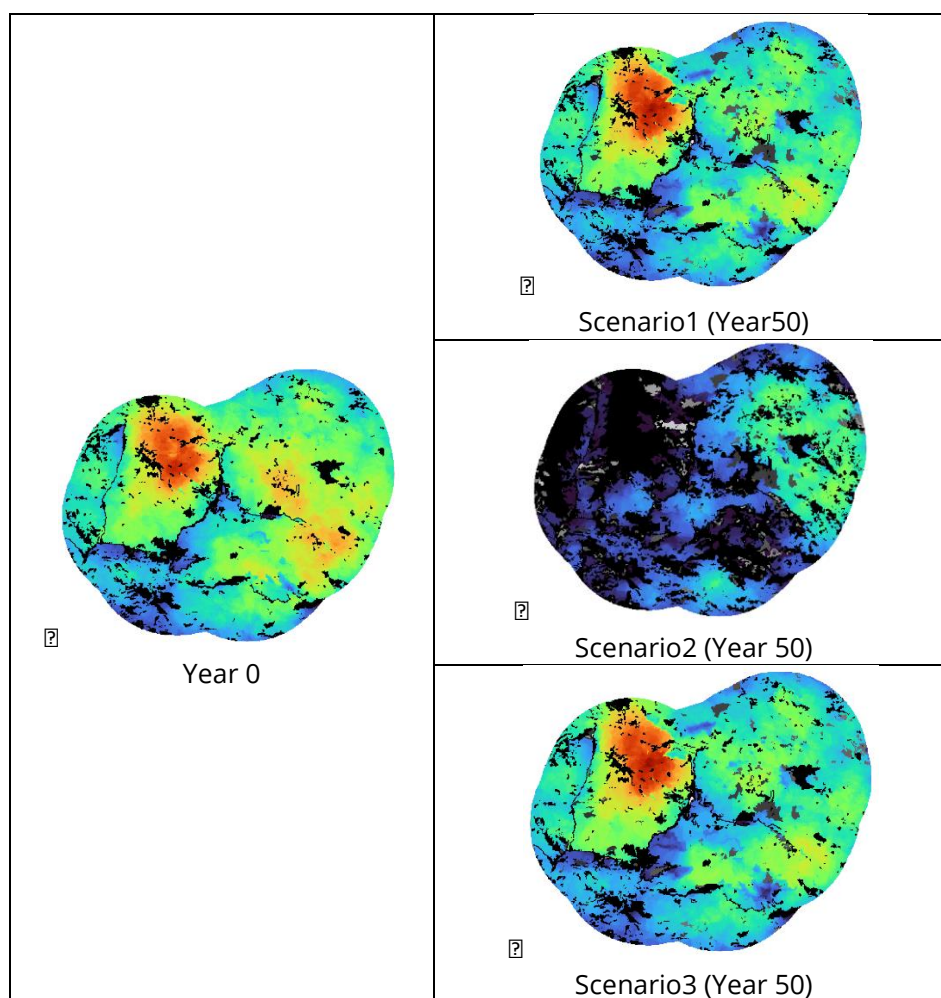


Figure 13: Spatial distribution of burn probability across three management scenarios (Soriguera). Higher values indicate greater likelihood of ignition and fire spread.

In addition to fire behaviour and ecosystem services, the simulation also assessed the **probability of tree mortality due to fire (P_{dead})**, which remained slightly lower in Scenario 2 compared to Scenarios 1 and 3, further supporting its role in enhancing forest resilience under fire-prone conditions (see Table 9).

Overall, the integrated analysis of numerical and spatial outputs revealed trade-offs between ecological performance, fire risk mitigation, and economic returns. **Scenario 1** prioritized carbon accumulation and mushroom production but exhibited higher vulnerability to fire. **Scenario 2** was the most effective at reducing fire risk and maximizing timber output and short-term profitability but at the expense of other ecosystem services and long-term economic viability. **Scenario 3** provided intermediate outcomes, balancing fire hazard control with ecosystem functionality and long-term sustainability.

These results offer valuable insight for strategic forest management planning in Mediterranean fire-prone landscapes, highlighting the importance of considering multiple objectives when designing resilient forest systems.

3.2. Kassandra (LL GREECE)

3.2.1. Input Data

The Kassandra peninsula, located in the Halkidiki region of Northern Greece, was selected as the study area for the Greek Living Lab. This landscape combines forested areas dominated by Aleppo pine (*Pinus halepensis*), agricultural lands, touristic zones, and a complex wildland-urban interface (WUI), making it highly vulnerable to wildfire events. The area has experienced severe fires in the past decades, with large portions of the forest burned and recurrent fire activity posing an ongoing threat to biodiversity, infrastructure, and human safety (see Figure 14).

Kassandra's topography is relatively flat, with steeper slopes typically found in its north-western part, and a maximum altitude of 320 m. The climate is characterized as Intense Mediterranean, with mild winters and dry hot summers lasting from May to September (average annual rainfall is ~580 mm). The most frequent wind directions are NW (17.59%). During the fire season, the prevailing wind directions are the east and southeast with their intensity typically exceeding 50 km/h.

Kassandra belongs to the Mediterranean Vegetation Zone (*Quercetalia ilicis*), with two subzones — Oleo-Ceratonion at lower altitudes and Quercion *ilicis* at higher ones — where diverse sclerophyllous and evergreen species thrive. Due to historical human pressures, deciduous oaks have largely disappeared, allowing *Pinus halepensis* to dominate 44% of the area.

Pine trees dominate the canopy, dense and flammable maquis shrubs fill the understory, streams support rich riparian vegetation, and agricultural land—mostly olive groves—covers about 44.5% of the area.

Stands of evergreen broadleaves mixed with individuals or clusters of *Pinus halepensis* are often affected by forest fires, similarly to pure *Pinus halepensis* stands.

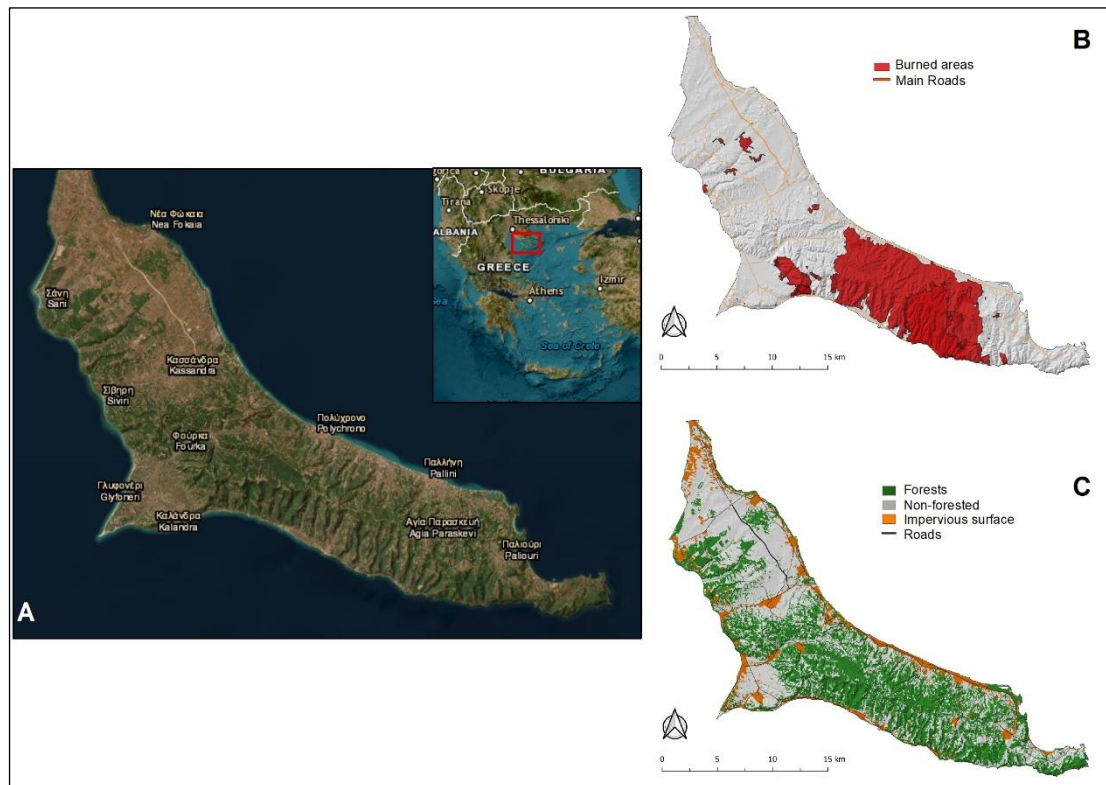


Figure 14: A) satellite image of Kassandra and its locations over Greece (red square); B) Burned areas from wildfire incidents for the period 1980 – 2022; C) Map of the main land characterization types of the study area

Input data preparation followed the same methodological framework applied in other case studies. Forest structure information was based on the Greek National Forest Inventory and further refined using geospatial datasets. The data included forest composition, basal area, mean diameter, canopy cover, and species distribution, used to initialize forest growth simulations. Spatial layers describing topography (elevation, slope, aspect), vegetation, and land cover were also incorporated to support both forest growth modelling and fire behaviour simulations.

All spatial data were harmonized to a consistent resolution and projection system. The integration of these input layers provided a detailed representation of the biophysical characteristics and landscape heterogeneity in the Kassandra region.

In addition, a set of climate scenarios was developed specifically for the fire behaviour simulations in Kassandra. These scenarios were constructed based on the frequency distribution of wind directions, with two fuel moisture conditions for each direction: low (D2 L2) and very low (D1 L1). A total of 16 scenarios were defined, each with a unique combination of wind direction and moisture code (e.g., 1_68_4, where 68° is the wind direction and 4 indicates very low fuel moisture). The selection frequency of each scenario was used to represent realistic ignition conditions. This ensured a probabilistic and regionally grounded modelling of fire behaviour under diverse weather conditions.

As in the case of Soriguera, both forest growth and fire spread simulations for Kassandra were conducted over a 50-year planning horizon with a 5-year time step, allowing for the assessment of long-term changes in forest structure and fire behaviour under different

management scenarios. Due to similarities in the type of forests and commonly used fuel models, for the case of Kassandra, we used the same simulation approach and tools as in Catalonia.

3.2.2. Forest Growth Simulator

The same modular Forest Growth Simulator used in the Soriguera Living Lab was also applied to the Kassandra region in Greece. This simulator replicates key ecological processes such as tree growth, mortality, and structural development over time, while assessing how different forest management interventions affect forest dynamics and ecosystem service provision. In the case of Kassandra, only the growth, management and yield related to *Pinus halepensis* forest was applied, as it was the predominant tree species (Banchantourian, 2024).

The simulator was executed using a unified workflow across both case studies, ensuring methodological consistency and enabling comparative assessment of management outcomes across different Mediterranean landscapes.

Forest Growth Simulation Models

The simulator includes a suite of sub-models grouped into three categories: growth models, fuel models, and ecosystem service models. These sub-models estimate changes in stand structure and composition, calculate fire-related fuel attributes, and quantify multiple provisioning, regulating, and cultural ecosystem services. All models were applied consistently across both case studies to ensure comparability.

A detailed list of sub-models used in the simulator is provided in Section 3.1.2.1 (Table 1), and includes species-specific models for diameter and height growth, mortality, biomass accumulation, timber yield, carbon sequestration, mushroom productivity, and aesthetic value. Fuel models were assigned following the methodology of Scott and Burgan, allowing for accurate simulation of fire-related attributes such as canopy bulk density and base height.

Forest Management

Forest management in the Kassandra case study was simulated using the same structural approach as in Soriguera, while adapting the management alternatives to local forest conditions and planning objectives. The interventions applied in the simulator include:

- Pre-commercial thinning
- Thinning
- Final harvest with successive thinning

The space of alternatives was defined by combining different initiation thresholds and intensity levels for both thinning and final harvest operations. Specifically:

- **Thinning** was initiated when basal area (G) reached one of three threshold values: **G = 20, G = 25, or G = 30**. **Cutting intensity** varied across three levels: **20%, 30%, and 40%** of basal area removed, during those thinnings.

- **Final harvest** was triggered when the mean diameter (dm) reached one of the following values: **dm = 25, 30, or 35**.

This combination of variables allowed for the creation of a flexible and diversified set of management alternatives, enabling the exploration of trade-offs between timber production, fuel reduction, and ecosystem resilience. These alternatives were later evaluated through optimization and scenario-based simulations.

3.2.3. Optimization of Forest Management Strategies

The same multi-criteria optimization approach implemented in Soriguera was also applied to the Cassandra Living Lab to identify the most effective forest management strategies. The objective was to evaluate and select optimal alternatives that balance key priorities, including fire risk reduction, timber production, biodiversity conservation, and the provision of ecosystem services.

In the case of Cassandra, the objective function used in the optimization process focused on four ecosystem service indicators: average edible mushroom production, average scenic beauty preferences, proportion of trees that die due to fire, and total volume of cut wood. This selection was based on the specific characteristics of the region and was guided by feedback from local experts and stakeholders, who emphasized the importance of balancing fire risk reduction with provisioning and cultural services that reflect local priorities.

The optimization was performed using the CBC solver from the PuLP linear programming package in Python. Management alternatives were assessed across multiple planning periods, allowing for the dynamic allocation of interventions over time.

While the methodological framework was identical to that used in Soriguera, the weights assigned to the ecosystem service indicators were adapted to reflect the specific management goals and stakeholder preferences in the Cassandra region (see Table 10). These weights influenced the objective function of the optimization process and guided the selection of scenarios with the highest overall utility under local constraints.

Table 10: Ecosystem service weight coefficients (Cassandra)

ECOSYSTEM SERVICE	WEIGHT COEFFICIENT
Edible mushroom production average	0.05
Scenic beauty preferences average	0.1
Proportion of trees that die due to fire	0.7
Total volume of cut wood	0.15

The resulting management plans served as input to both the forest growth and fire spread simulators, ensuring consistency and integration of decision-making across the modelling framework.

3.2.4. Studied scenarios

For the Cassandra region, only two simulation scenarios were considered. These scenarios involve different forest management strategies and fire behaviour simulations.

Scenario 1: Unrestricted Forest Management (see Figure 6 in Section 3.1.4)

- All stands are subjected to management interventions based on the predominant tree species, followed by the optimization of these management strategies.
- The fire spread simulation is then conducted on the results of the forest growth simulation, allowing an evaluation of fire behaviour under the optimized forest conditions.

Scenario 2: Firebreak Integration (see Figure 7 in Section 3.1.4)

- In this scenario, management alternatives are optimized for all stands, except for those designated as firebreak areas.
- The "cut all" alternative is applied to the stands designated as firebreaks in the first year of the simulation, with the goal of creating clear firebreaks.
- Fire spread simulation is applied to the resulting forest landscape, considering the altered configuration due to firebreak integration.

3.2.5. Fire Behaviour Assessment

The Cell2Fire_SB fire spread simulator (Gonzalez-Olabarria et al., 2023), as used in the Soriguera Living Lab, was also applied in the Cassandra region. This agent-based simulator is specifically designed to model the behaviour of both surface and crown fires across heterogeneous Mediterranean landscapes. It supports the evaluation of fire risk under different forest structures and management strategies.

To simulate realistic fire dynamics, the simulator was fed with spatially explicit inputs describing topography, vegetation structure, and fuel characteristics, all derived from the forest growth simulation and local geospatial datasets. These variables were used to generate fire behaviour attributes such as burn probability, flame length, fire intensity, and rate of spread.

In the case of Cassandra, a specific set of **16 weather scenarios** were developed based on local wind direction frequencies and fuel moisture conditions. For each wind direction, two moisture classes were applied – low and very low – resulting in diverse ignition conditions. Each scenario (e.g., 1_68_4) encoded the scenario number, wind direction (in degrees), and moisture level. The relative **frequency of selection** was assigned to each scenario to reflect its likelihood based on historical weather patterns. This probabilistic representation allowed for a nuanced analysis of fire spread under variable and region-specific conditions.

All spatial inputs used in the fire simulation – elevation, canopy base height (CBH), canopy bulk density (CBD), fuel models, canopy height, and canopy coverage – were processed as raster layers with a spatial resolution of 30×30 meters. This resolution was chosen to

ensure compatibility with the Cell2Fire_SB engine and to balance computational performance with spatial detail.

For Cassandra, fire spread simulations were conducted with **850 runs** per scenario, year, and fuel moisture condition. However, not all runs led to effective fire spread outcomes. Due to the characteristics of the landscape and the fuel types – particularly fuel model "91", which does not ignite – a substantial number of simulations did not result in fire scars.

Additionally, to ensure relevance, simulations where less than 10% of fuel pixels burned were excluded from the analysis. As a result, the number of effective simulations per year and scenario ranged between 250 and 300, ensuring that the analysis was based on realistic and significant fire behaviour events.

As in Soriguera case, the Cell2Fire_SB simulator was run via a QGIS-integrated plugin, allowing for streamlined integration of input layers and visualization of simulation results. The fire outputs were then used to evaluate the effectiveness of the different management scenarios under wildfire-prone conditions.

3.2.6. Integration of Forest Growth and Fire Spread Simulators

In the Cassandra Living Lab, the connection between forest growth and fire spread simulators follows the same approach as in the Soriguera region. The forest growth simulation provides essential fuel information, which is used by the fire spread model to simulate the propagation of fire through the forest (see Figure 12).

The forest growth simulator generates key fuel data that is subsequently used as input for the Cell2Fire fire spread simulator. This is obtained by evaluating the evolution of the different stand state variables, estimated using the growth simulator—either directly through allometric functions (e.g., CBH, CBD, tree height) or, in other cases, via classification trees (Krsnick et al., 2020)—as was done in the Catalan case. However, in this case, the main forested stands were limited to fuel types associated with *Pinus halepensis* forests. This data is converted into rasters representing different aspects of forest structure, such as canopy characteristics and fuel loads. These rasters are then integrated with the elevation raster, which is crucial for considering terrain effects on fire behaviour.

All spatial input layers for the fire spread model, including fuel-related rasters and elevation data, are adjusted to the same spatial resolution. The temporal synchronization ensures that fire simulations reflect the forest conditions projected for different years of the simulation (e.g., year 0, 10, 20, etc.).

This interaction between the simulators allows for accurate fire behaviour predictions based on the forest conditions and terrain for the Casandra region, considering different management and environmental scenarios.

3.2.7. Analysis of results

As in Soriguera, both the forest growth and fire spread simulations in Kassandra were carried out over a 50-year planning horizon with 5-year time steps.

Simulation outputs for the Kassandra region were analyzed to assess the performance of each management scenario in terms of fire risk, forest dynamics, and ecosystem service provision. Two scenarios were evaluated: **Scenario 1** (baseline) and **Scenario 2** (optimized management).

Ecosystem Services and Economic Indicators

A comparative overview of key ecological and economic metrics is provided in Tables 11 and 12. Both scenarios showed an increase in carbon storage over the 50-year simulation period. However, the scale of change differed notably:

- **Scenario 1** resulted in a net increase of **+297 million tons CO₂**, while
- **Scenario 2** achieved only a marginal gain of **+6 million tons CO₂**.

Table 11: Ecosystem service and economic indicators per landscape (Kassandra)

METRIC	SCENARIO 1	SCENARIO 2
Carbon Storage (BT) Year 0 (t)	1851412.95	
Carbon Storage (BT) Year 50 (t)	2148690.62	1857710.93
CO ₂ Evolution (Δ CO ₂) (t)	+297277.67	+6297.98
Timber Harvesting (t)	3017.94	2774.88
Edible Mushrooms Year 0 (t)	471.28	
Edible Mushrooms Year 50 (t)	483.23	427.03
Edible Mushrooms Evolution (t)	11.95	-44.25
Profit (per landscape) (€)	66034491.96	69953960.07
Costs (per landscape) (€)	103833623.73	63163205.33
Cash Flow (per landscape) (€)	-37799131.91	6790754.83

This reflects a substantial difference in biomass accumulation, also seen in the average carbon storage per hectare: **Scenario 1** stored less **carbon per hectare** (105.5 t/ha) compared to **Scenario 2** (112.3 t/ha) (see Table 12), indicating that the optimized management scenario (**Scenario 2**) retained more standing biomass despite fuel reduction efforts.

Timber harvesting volumes were slightly lower in **Scenario 2** (2774.9 t) compared to **Scenario 1** (3017.9 t) (Table 11). However, when considering only managed polygons, the average per-hectare extraction was lower in **Scenario 2** (14.7 t/ha) than in **Scenario 1** (18.0 t/ha), suggesting a more conservative or selective harvesting approach under **Scenario 2** (see Table 12).

Mushroom yields exhibited divergent trends: **Scenario 1** showed a slight increase (+11.95 t) over the simulation period, while **Scenario 2** recorded a significant decline (-44.25 t) (see Table 11), likely reflecting trade-offs between intensive management interventions and the provision of non-timber forest products.

From an economic perspective, **Scenario 2** clearly outperformed **Scenario 1**. It resulted in higher average **profit per hectare** (312 €/ha vs. 295 €/ha), lower average **costs** (282

€/ha vs. 463 €/ha), and a positive **cash flow** (+30 €/ha) compared to the negative **cash flow** in **Scenario 1** (-169 €/ha) (see Table 12). Scenario 2 also yielded a substantially higher **NPV** (+10.98 €/ha) while **Scenario 1** showed near-zero returns (-0.03 €/ha), suggesting that the optimized scenario was more economically sustainable in the long term.

Table 12: Ecosystem service and economic indicators per forest hectare (Kassandra)

METRIC	SCENARIO 1	SCENARIO 2
Carbon Storage (t)	105.48	112.29
Timber Harvesting (kg)		
with unmanaged polygons included	7946.28	7306.29
including only managed polygons	18027.11	14679.47
Edible Mushrooms (kg)	23.72	25.81
Profit (Average)(€)	294.69	312.19
Cost (Average) (€)	463.38	281.88
Cash Flow (Average) (€)	-168.69	30.31
NPV (Average) (€)	-0.03	10.98

Fire Risk Indicators

As shown in Table 13, **Scenario 2** consistently achieved lower **fire behaviour metrics**. The **average burn probability** decreased from 0.05 in **Scenario 1** to 0.04 in **Scenario 2**, and the **average tree mortality probability (P_{dead})** was also slightly lower. These results reflect the success of optimized interventions in reducing landscape-level fire susceptibility.

Table 13: Average burn probability and P_{dead} per polygon across scenarios (Kassandra)

METRIC	SCENARIO 1	SCENARIO 2
Burn Probability	0.05	0.04
P _{dead}	0.04	0.03

Figure 15 provides a spatial comparison of burn probability between the two management scenarios, highlighting differences in fire exposure across the territory.

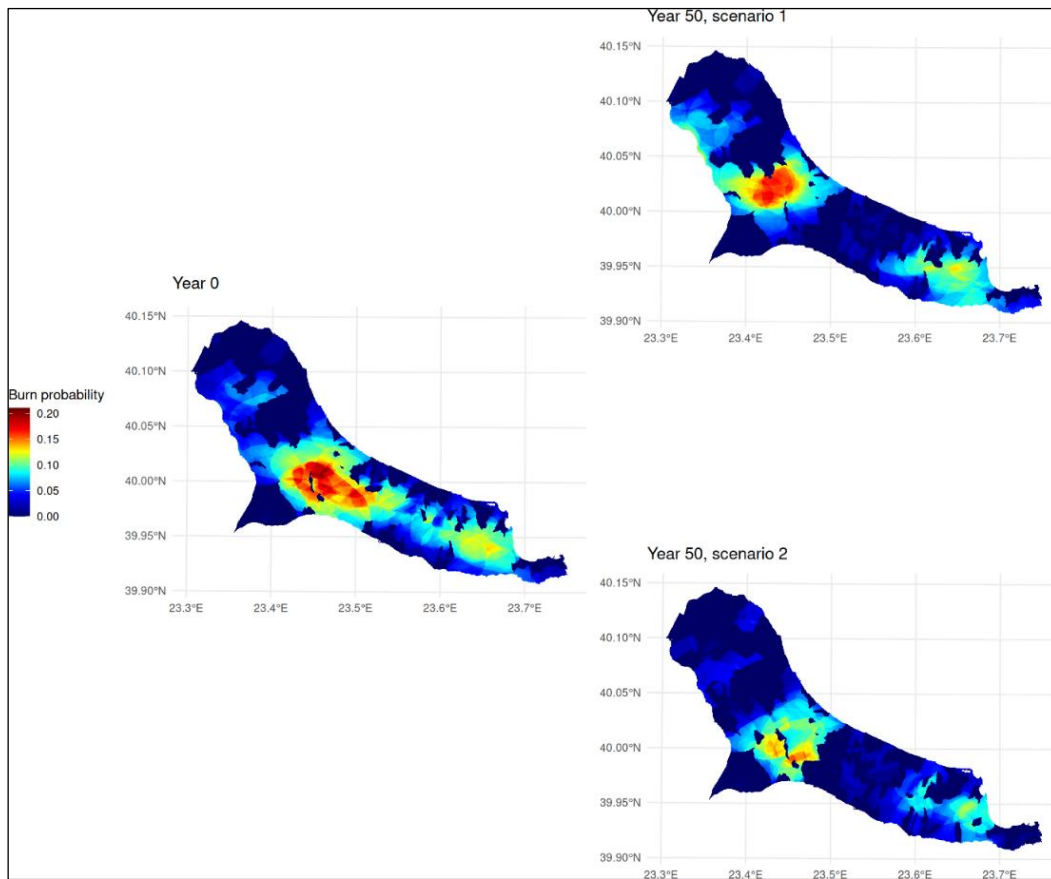


Figure 15: Spatial distribution of burn probability across two scenarios

A comparative summary of ecological, economic, and fire risk indicators (such as burn probability) is illustrated in Figure 16.

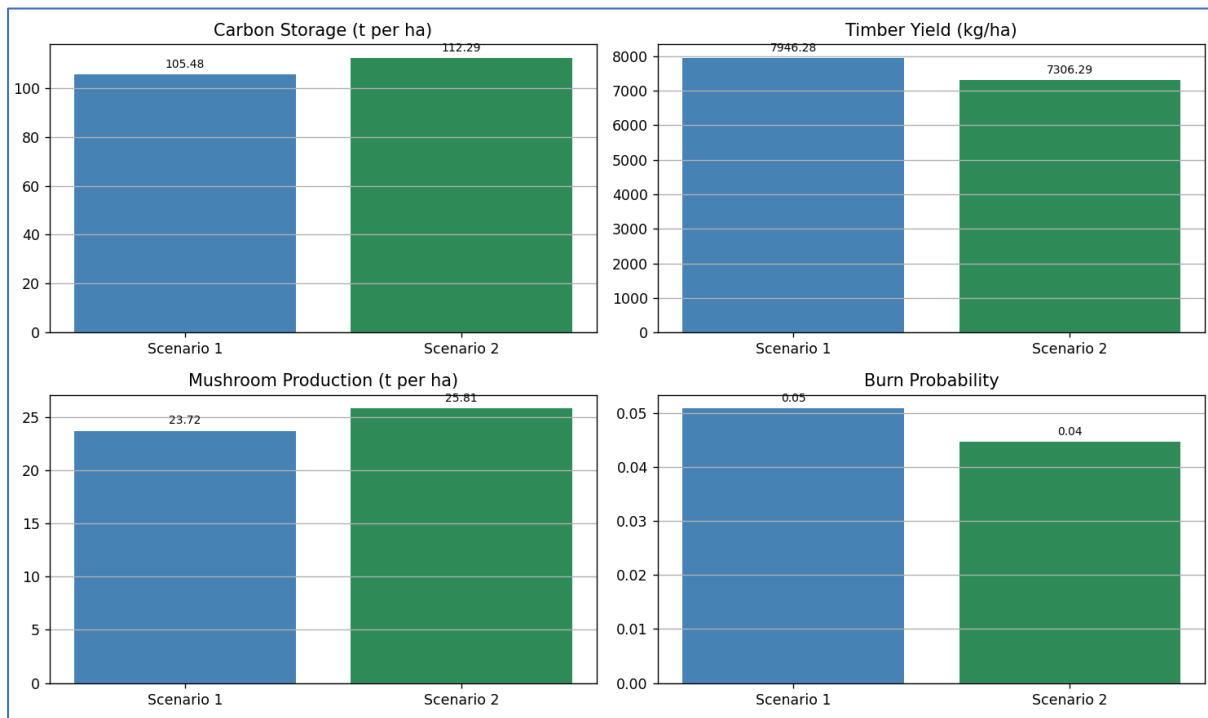


Figure 16: Comparison of key indicators by scenario (Kassandra)

Spatial Fire Behaviour Analysis

Spatial fire behaviour metrics revealed notable differences between the two scenarios. Table 14 presents the evolution of Flame Length and surface area affected by fire over time. **Scenario 2** consistently resulted in a smaller area burned compared to **Scenario 1**, with a noticeable divergence already by Year 10. By the end of the simulation (Year 50), the total burned area in **Scenario 2** was reduced to 151 km², while in **Scenario 1** it remained higher at 175 km².

Despite the reduction in burned area, **Scenario 2** showed slightly higher Flame Length values throughout the simulation. By Year 50, the average Flame Length reached 7.61 m in **Scenario 2**, compared to 7.56 m in **Scenario 1**. This suggests that while **Scenario 2** was effective in limiting fire spread across the landscape, the intensity of crown fires in burned areas may have increased slightly, potentially because of changes in vertical fuel structure or forest composition.

These patterns indicate a trade-off between fire extent and fire intensity, highlighting the need to balance interventions that reduce area burned while also mitigating potential increases in fire severity.

Table 14: Summary of Flame Length statistics across simulation years (Kassandra)

	SCENARIO1		SCENARIO2	
	Surface affected by fire (km ²)	Flame Length (m)	Surface affected by fire (km ²)	Flame Length (m)
Year0	199.97	6.45	199.97	6.45
Year10	200.75	6.86	159.98	7.16
Year20	199.32	7.18	158.97	7.41
Year30	197.50	7.30	159.83	7.66
Year40	195.46	7.70	156.70	7.80
Year50	175.47	7.56	150.86	7.61

Figure 17 illustrates the spatial distribution of Crown Flame Length under **Scenarios 1** and **2**.

This combined numerical and spatial analysis demonstrates clear trade-offs between ecosystem service provision and fire risk reduction. **Scenario 1** favors biomass accumulation and provisioning services such as mushrooms but suffers from higher fire risk and lower economic performance. **Scenario 2**, on the other hand, offers better fire resilience and economic outcomes, albeit with a reduction in some ecosystem services. These insights offer guidance for balancing ecological, economic, and risk mitigation goals in Mediterranean forest management planning.

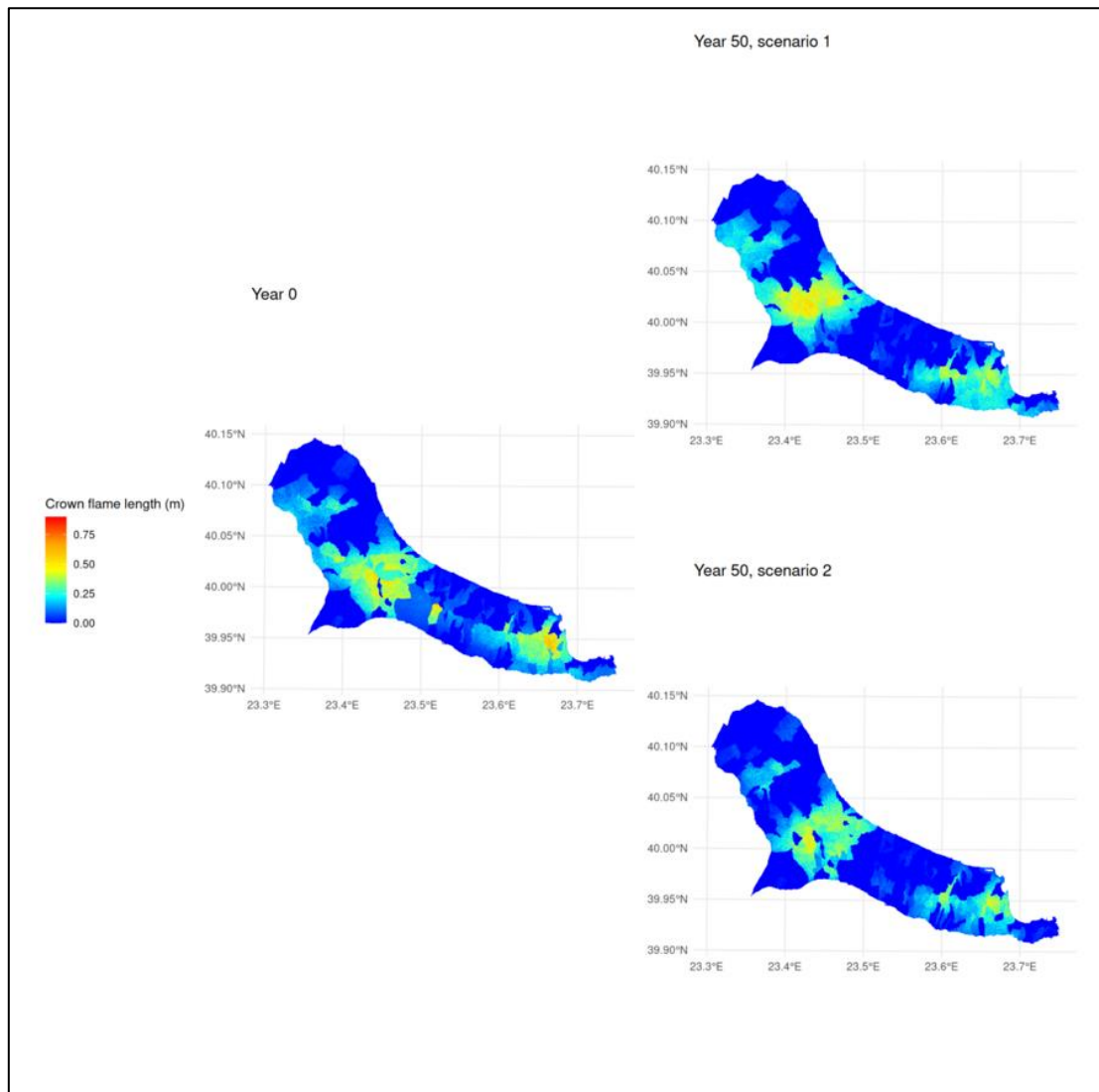


Figure 17: Comparison of fire behaviour (Kassandra)

3.3. Arauco (Biobío region, Chile)

3.3.1. Input data

The Arauco, located partly between Los Álamos and Curanilahue municipalities, in the Arauco province within Biobío region, Chile, was selected as the study area for the Chilean Living Lab. It covers 7 780 hectares and spans an elevation range from 122 to 773 meters above sea level.

The digital elevation model from NASA's Shuttle Radar Topography Mission (SRTM) was used for topographic information. This data has a resolution of approximately 30 meters.

Forest stand data was created based on CONAF's 2015 vegetation cadaster (<https://sit.conaf.cl/>), which is available in shapefile format and includes:

- Information on land use.
- Dominant vegetation types from Donoso (1981).
- Forest coverage.
- Forest structure (e.g. young, adult, etc.).
- Most dominant species

From this data, the species, age, location and management were obtained to use in the Forest Growth Simulations. From the location, the growth zone and site index can also be obtained.

The fuel map was also created based on CONAF's 2015 vegetation cadaster. Depending on dominant vegetation types, dominant species and age, a Kitral fuel model is assigned according to Table 15. The other fuel types were also assigned according to the dominant vegetation types and species. The resulting map is shown in Figure 18.

Table 15: Kitral fuel model according to species and age

Species	Age	Fuel Type
Pinus radiata	0-3	PL01
Pinus radiata	4-11	PL05
Pinus radiata	12-17	PL06
Pinus radiata	>17	PL07
Eucalyptus globulus	0-3	PL08
Eucalyptus globulus	4-10	PL09
Eucalyptus globulus	>10	PL10

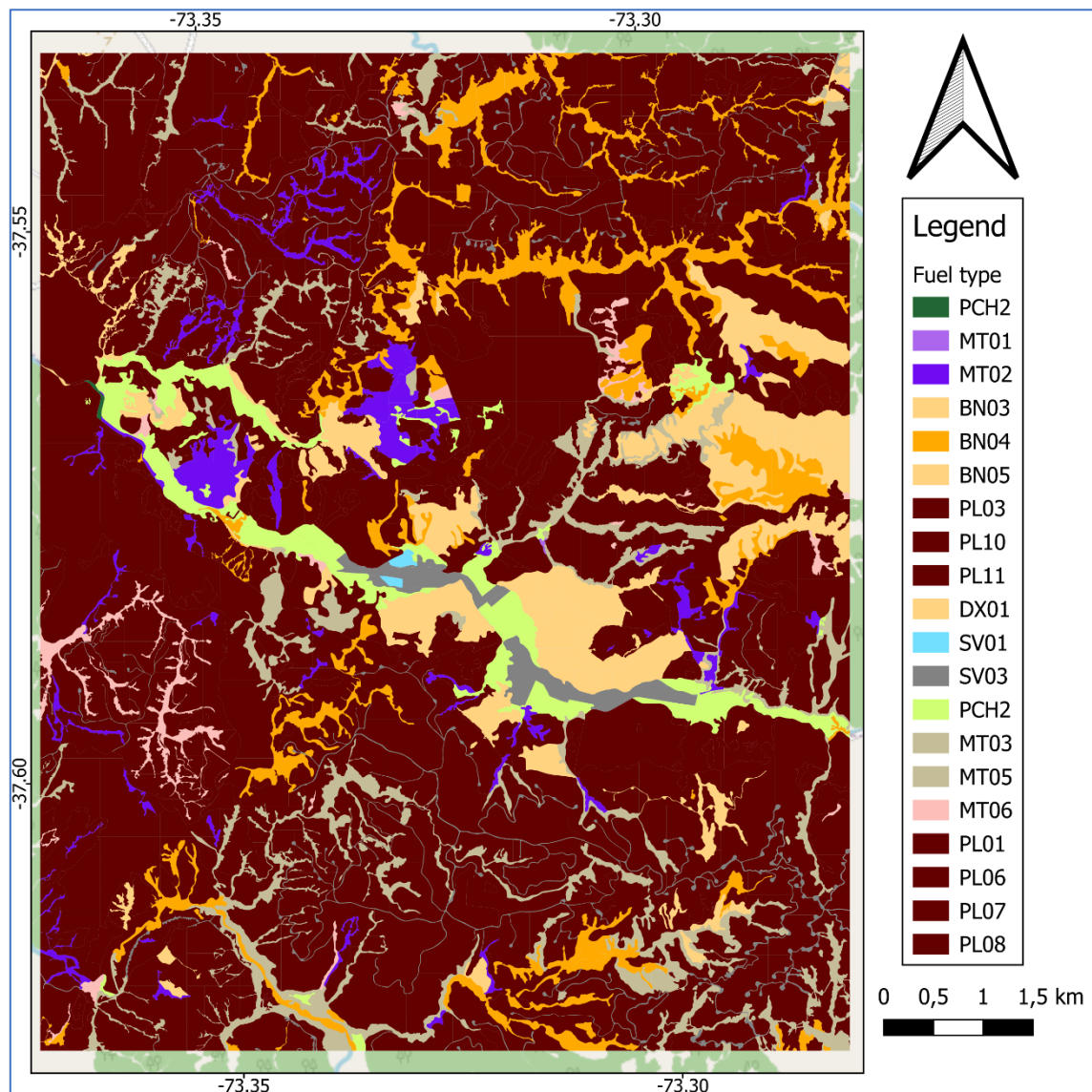


Figure 18: Living Lab Arauco, Chile. Fuel types according to Kitral fuel model

Weather scenarios

To generate the weather scenarios needed for fire spread simulation, data were collected from three nearest meteorological stations, strategically selected to capture the climatic variability of the area. From each station, the summer days with the highest recorded daily maximum temperatures over the past five years were identified, allowing for the determination of the most critical periods in terms of fire risk. Based on this selected data, a total of 100 meteorological scenarios were generated, each with a duration of 6 hours to match the duration determined for wildfires. These weather scenarios define the meteorological conditions under which fire events are modelled and are essential for simulating realistic fire behaviour. The same weather scenarios were used in all the management scenarios to isolate the effect of management.

Each weather scenario contains a set of key attributes:

- Scenario ID – the identifier of the scenario.
- Date and time – the timestamp associated with the weather conditions.

- Wind speed (WS) – a critical driver of fire spread dynamics.
- Wind direction (WD) – determines the main axis of fire propagation.
- Temperature (tmp) – the temperature per hour, a critical driver of fire spread dynamics.
 - Relative humidity (RH) – the Relative humidity per hour, a critical driver of fire spread dynamics.

These data were used to parameterize fire behaviour across a range of possible weather conditions, enabling a probabilistic and robust simulation approach. These weather scenarios represent critical periods in terms of fire risk.

3.3.2. Forest Growth Simulator

This simulator allows modelling the evolution of *Pinus radiata* (D. Don) and *Eucalyptus Globulus* (Labill) plantations based on various ecological processes and forest management. It predicts forest plantation biomass based on the age of the stand and on several aspects of the stand. The aspects considered depend on the species. For *P. radiata* biomass depends on the growth zone, the site index, management type and thinning occurrence. On the other hand, for *E. globulus* depends on growth zone, initial density (plant spacing) and the site index.

Forest Growth Simulation Models

Different combinations of levels of the aspects mentioned above were obtained for each species, resulting in a total of 20 models for *Eucalyptus globulus* and 14 models for *Pinus radiata*. The coefficients of each model were estimated using the nonlinear least squares method with the Levenberg-Marquardt algorithm, implemented in the `nlsLM` function of the `minpack.lm` package of the R statistical software. All the models have the same general equation:

$$Bt = \alpha \cdot E\beta + \gamma$$

where:

- Bt : Total Biomass
- E : The number of years (age) elapsed from planting to the time you want to assess aboveground biomass.
- α, β, γ : Model Coefficients

The data used to fit the models were obtained from standing aerial biomass yield tables in plantations of *Eucalyptus globulus* and *Pinus radiata* in Chile. The data was obtained from a total of 672 stands, with an average density of 870 trees per hectare (Corvalán & Hernández, 2011, 2012).

The values of the coefficients depend on the factors listed above, which are explained below:

- The growth zone: corresponds to the zone in Chile in which the stand is located. There are growth zones for *Eucalyptus globulus* (see Figure 19) and for *Pinus radiata* (see

Figure 20). Zones with the same number for both species may have different geographical locations.

- Initial density: corresponds to the initial density of trees per hectare in the stand. In this work, it only varies on *Eucalyptus globulus*.

- Site Index (SI): this is the average height of the thickest trees at 10 years of age. It is calculated by taking the total height of the 100 trees with the highest DBH (Diameter at breast height or 1.3 m above ground level) per hectare.

- Management applied to the stand: corresponds to the management scheme applied to the stand, which may correspond to any of the following:

- Pulpable: this is the case in which it has been thinned to waste.
- Multipurpose: this is the case in which pruning and thinning has been done twice.
- Intensive 1: it is the case in which it has been pruned three times and thinned twice.
- Intensive 2: the case where pruning has been done two or three times and thinning twice depending on the quality of the site.
- No management: when none of the above is applied.

- Condition: this is the condition that the stand is in relative to the management scheme. This can be after thinning or after pruning and thinning.

- Horizon time: is the number of years that the simulator will run.

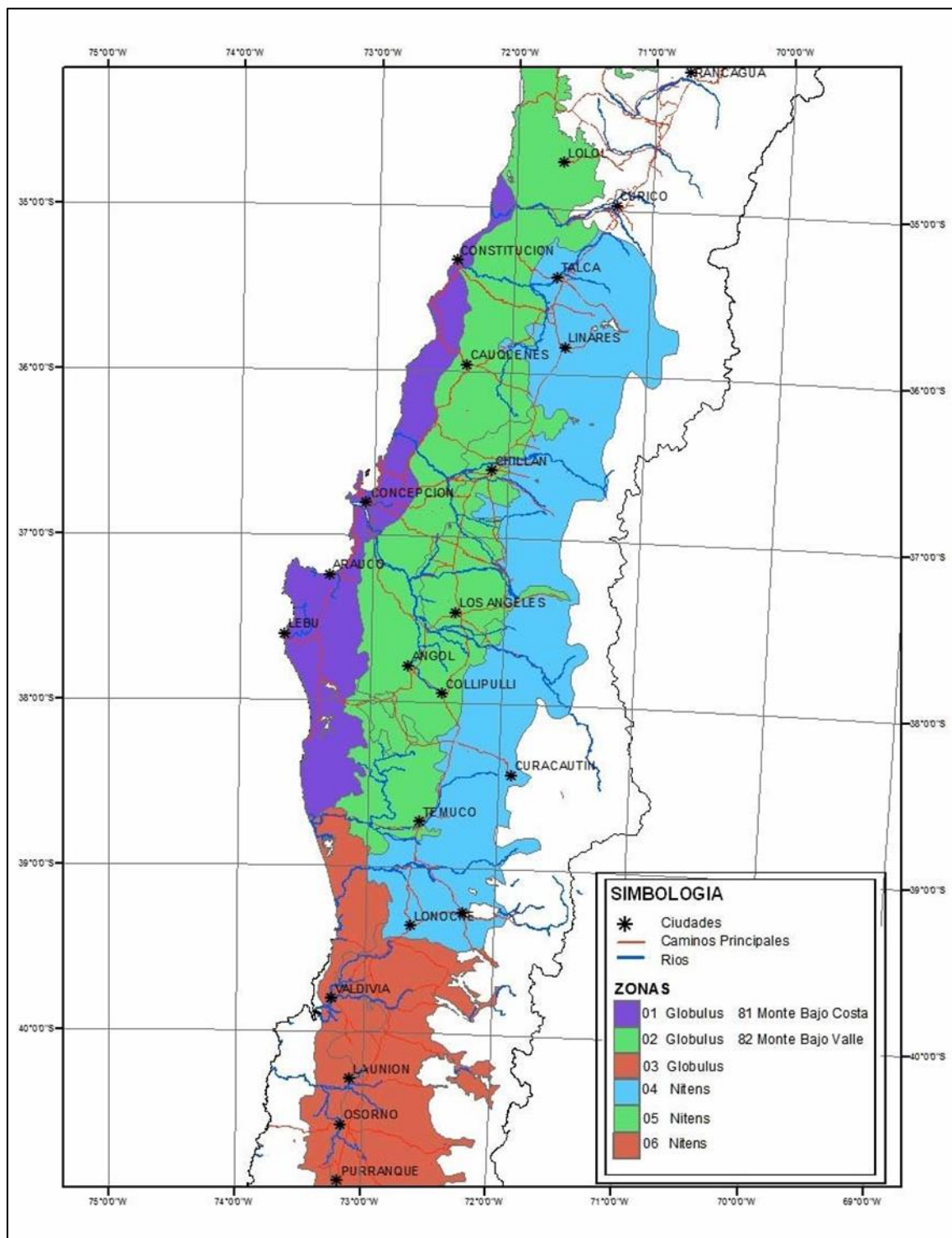


Figure 19: *Eucalyptus globulus* growth zones. Obtained from Corvalán & Hernández, 2012

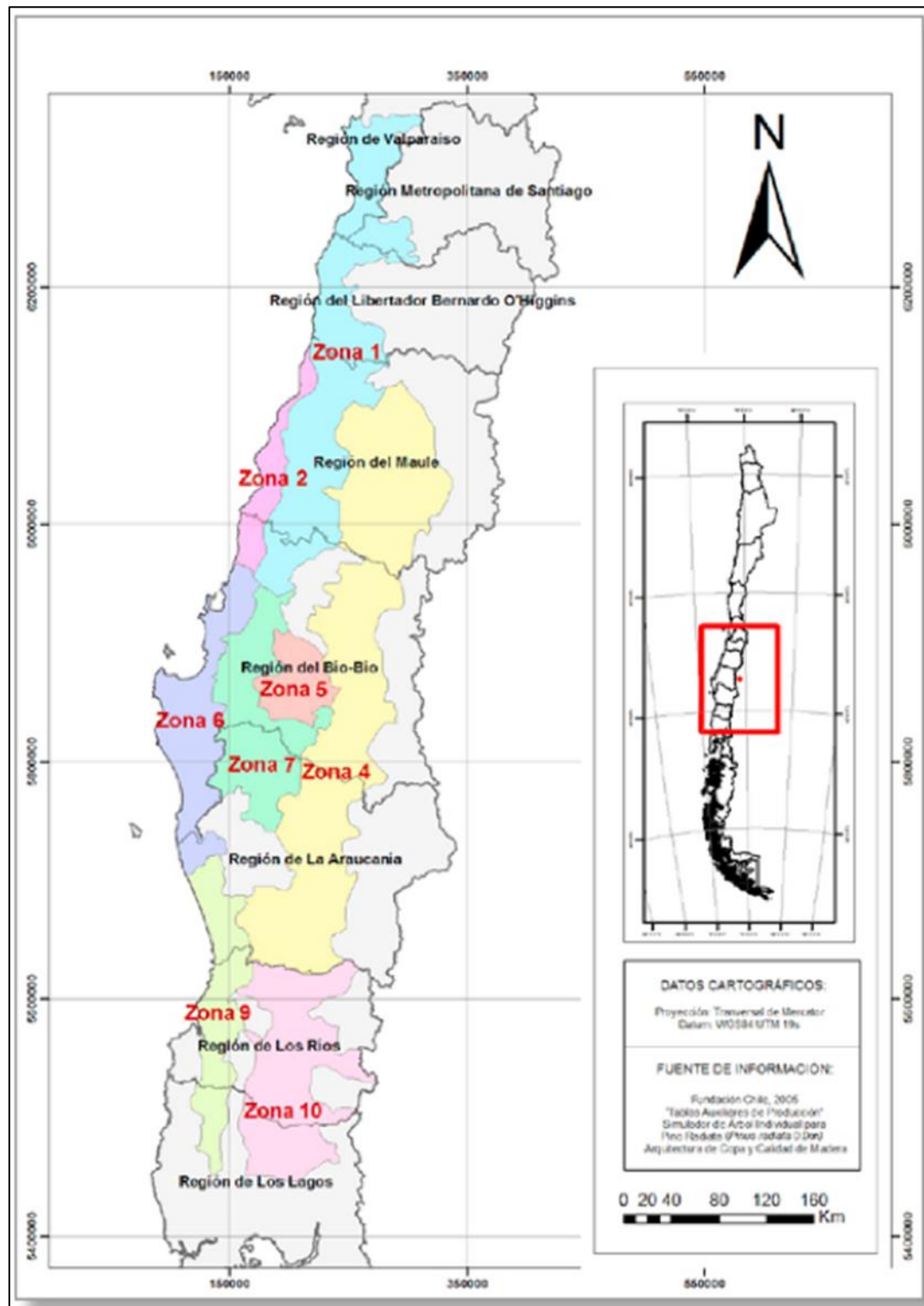


Figure 20: *Pinus radiata* growth zones. Obtained from Corvalán & Hernández, 2011

As mentioned above, the values of the coefficient of the models will vary depending on some factors of the stands (see Tables 16 and 17).

Table 16: Coefficients for the growth and yield models of *E. globulus*

Zone	Initial Density	Site Index (SI)	Management	Condition	α	β	γ
1	800	24	NA	No management	2.371	1.778	0.000
		26			2.371	1.778	0.000
		28			5.464	1.591	0.000
		30			7.709	1.519	0.000
		32			10.228	1.462	6.240
	1250	24			2.379	1.774	0.000
		26			3.794	1.666	0.000
		28			5.307	1.600	0.000
		30			7.779	1.513	0.000
		32			10.304	1.457	5.660
2	800	24	NA	No management	3.221	1.647	0.000
		26			3.612	1.656	0.000
		28			4.559	1.618	0.000
		30			5.926	1.567	0.000
		32			7.300	1.532	0.000
	1250	24			3.197	1.650	0.000
		26			3.729	1.645	0.000
		28			5.129	1.574	0.000
		30			6.201	1.547	0.000
		32			7.592	1.514	0.000

Table 17: Coefficients for the growth and yield models of *P. radiata*

Zone	Initial Density	Site Index (SI)	Management	Condition	α	β	γ
Z6	1250	32	Intensive 1	Post Thinning 1250-700	0.421	2.253	3.485
Z7					0.576	2.044	3.968
Z6				Post pruning and thinning 700-300	122.491	0.562	-416.814
Z7					22.934	0.936	-171.991
Z6		29	Intensive 2	Post Thinning 1250-700	0.421	2.253	3.485
Z7					0.070	2.850	7.522
Z6				Post pruning and thinning 700-300	122.491	0.562	-416.814

Z7				40.929	0.774	-227.526
Z6			Post Thinning 1250-700	0.069	2.791	1.441
Z7				0.047	2.905	8.454
Z6		26	Multipurpose	58.378	0.701	-298.450
Z7				56.816	0.666	-260.576
Z6		23	Pulpable	9.592	1.169	-97.246
Z7				20.852	0.844	-103.893

Forest Management

The entire forest area consisting of pine or eucalyptus is considered to be manageable, i.e. there are no restrictions limiting the management of certain stands.

- Reforestation: The stand species remains constant over time. This means that when a pine or eucalyptus stand is harvested, it is reforested with a tree of the same species and the same treatment (keeping the same identifier in the biomass simulator).
- Inventory and demand: No inventory of forest products is maintained. Everything extracted from the forest is sold immediately, with no demand restrictions, so it is assumed that there will always be buyers.
- Timing of management: All interventions in the forest (thinning and harvesting) occur at the end of the period. Consequently, the first period in the model is defined as period 0, with management applied at the end of the period.
- Stand management: Partial management, such as harvesting only a fraction of a stand, is not allowed. All management is applied to the entire stand.

Scheme of Growth Models and Forest Management integration

For every stand in the landscape, it is necessary to define the years when the management tools have to be applied. In the case of *Pinus radiata* it is possible to use thinning and harvesting, while in *Eucalyptus globulus*, just harvesting is available. Additionally, it is possible to include firebreaks in the landscape to diminish the effect of wildfires.

A general scheme of growth models is shown in Figure 21. The forest growth simulator starts with several stands with different ages, objectives, and characteristics, covering different combinations of values for the above-mentioned factors. Then, each stand will grow according to the corresponding model (parameters). Starting from the age of the stand, it will grow year by year. Since the models were parameterized with stand data from a certain age, it was necessary to perform a linear extrapolation from year 0 to the year in which data were available to fit the models. This was done so that the models would not give unreasonable values in the first years of growth.

In stands of *Pinus radiata*, every stand will grow with the same model until a thinning must be made. In that case, the stand will change according to the corresponding model from “Post Thinning 1250-700” to “Post pruning and thinning 700-300” (Table 17). From then, the stand will grow until the harvest period arrives. On the other hand, since thinning is not used in *Eucalyptus globulus*, it just grows until it is time to harvest the stand. Once the stand is harvested, it will start to grow again. This cycle will continue until the horizon time.

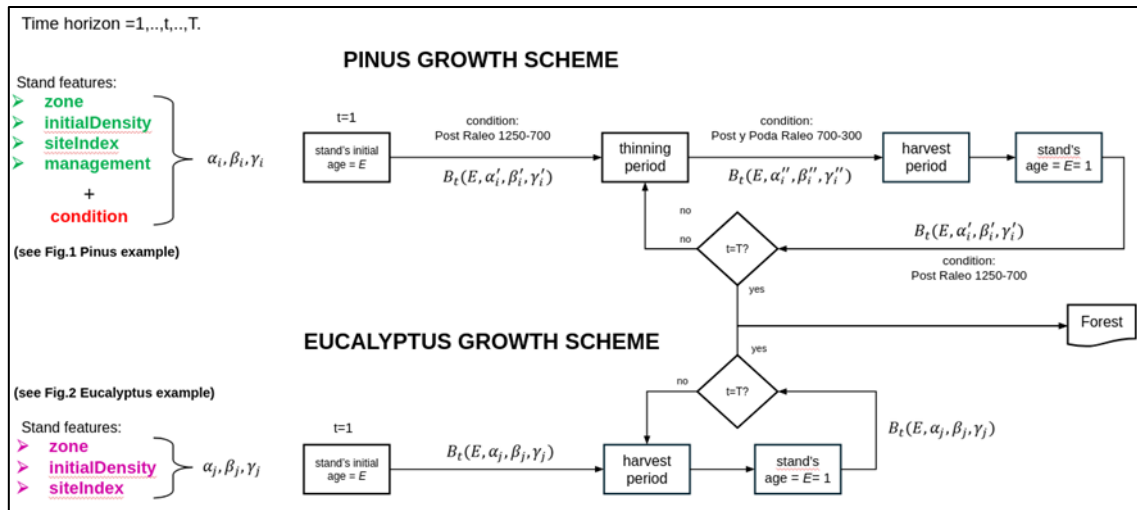


Figure 21: General scheme of growth simulator for both species

3.3.3. Optimization of Forest Management Strategies

A mixed programming model (MIP) was developed, whose objective was to optimize forest management to maximize economic gains using the Gurobi solver (Gurobi, 2024). Thus, the model determines which management to apply to each stand, considering the combination of thinning and harvesting policies and including the option of not intervening.

MIP formulation

Sets

- M : Possible management (m_{ij} management j for stand i ; for example, thin when it reaches age x and harvest when it reaches age y).

Parameters

- H : Simulation horizon.
- R : Total number of stands.
- A_{ijt} : Amount of biomass extracted from stand i with management j in period t (ton/ha).
- Bm_{ijt} : Amount of total biomass of stand i with management j in period t (ton/ha).
- $Bm_{no_pol_{it}}$: Amount of total biomass without management of stand i in period t (ton/ha).
- $rate$: Discount rate.
- P_t : Price per ton biomass in period t .

- D_t : Annual demand year t .
- C_{ij} : Cost to implement management cost j to stand i .
- B : Total budget.

Variables

- X_{ij} : Binary variable that establishes whether stand i has management j applied to it.

Restrictions

1. No more than one management per stand:

$$\sum_{i=1}^M X_{ij} \leq 1 \quad \forall i$$

2. Annual production:

$$\sum_{t=0}^R \sum_{j=0}^M X_{ij} A_{ijt} = v_t \quad \forall t$$

3. Meet minimum annual production:

$$v_t \geq D_t \quad \forall t$$

4. Stable biomass generation per period:

$$v_t - v_{t-1} \leq (v_{t-1}/10) \quad \forall t > 1$$

$$v_t - v_{t-1} \geq (-v_{t-1}/10) \quad \forall t > 1$$

5. Expenditure below budget:

$$\sum_{j=0}^M \sum_{i=0}^R C_{ij} X_{ij} \leq B$$

6. Final stand biomass (last period biomass with or without management):

$$\sum_{j=1}^M (Bm_{ijH} X_{ij}) + Bm_{no_pol_{iH}} (1 - \sum_{j=1}^M X_{ij}) = y_i \quad \forall i$$

7. Forest preservation:

$$\sum_{i=0}^R y_i \geq + \sum_{i=0}^R Bm_{no_pol_{i0}}$$

Target function

$$\max(X_{ij} \in \{0,1\}) \{ \sum_{i=0}^R \sum_{j=0}^M X_{ij} \sum_{t=0}^H (\frac{A_{ijt} P_t}{(1 + t_{asa})^t}) \}$$

It was also established that the optimization model chooses 90% of the forest for management, under the assumption that the budget is not enough to manage the entire forest.

For future prices based on the initial price, a standard initial price was chosen and subsequent prices were calculated using random walk. Thus, the next price (P_{t+1}) is calculated from the current price (P_t) using the exponential random walk model with drift (Hull & Basu, 2016):

$$P_{t+1} = P_t e^{\mu - 0,5\sigma^2 + \sigma Z_t}$$

Where:

- P_t : Price in the current period.
- μ : Expected rate of return (drift).

- σ : Volatility (standard deviation of the random shock).
- Z_t : Random number generated with a standard normal distribution ($Z_t \sim N(0, 1)$).
- e : Exponential function to model the percentage change.

The term $\mu - 0,5\sigma^2$ corrects for the bias introduced by the exponential transformation, ensuring that the model captures the expected rate of return correctly. On the other hand, σZ_t , known as Random shock, represents the random fluctuations in each period, modeled as white noise with variance proportional to σ .

Also, to improve the efficiency of the model and balance the quality of the solutions with the computation time, the following settings have been applied in Gurobi:

- MIPGAP (stop criterion by GAP): a MIPGAP of 1 % is set, which means that the solver will stop searching for new solutions once a solution is reached whose gap with respect to the optimum is less than 1 %. This reduces optimization time without significantly compromising the quality of the solution. In addition, it ensures that the five solutions generated do not have excessive differences in their pre-fire values, which facilitates their comparison in terms of fire impact on profitability.

- VarBranch (variables branching strategy): The strong branching strategy is used to improve the selection of variables in the exploration of the search tree. However, due to the computational cost of this technique, a more efficient variant known as pseudo strong branching is used, which allows accelerating convergence without drastically increasing the resolution time.

- Cuts: Gurobi is allowed to apply automatic cuts to improve the model formulation and reduce the size of the search space. The selection of specific cuts is managed internally by Gurobi, so it is not known exactly which ones are implemented, but it is known that they contribute to improve the efficiency of the optimization process.

- Presolve (model preprocessing): The preprocessing option is enabled so that Gurobi eliminates redundant variables and simplifies unnecessary constraints before starting the optimization. This allows speeding up the resolution by reducing the complexity of the model from the beginning.

- Heuristics (use of search heuristics): A heuristics parameter is set to 0.1, which means that Gurobi will spend approximately 10% of its time running heuristics to find feasible solutions quickly. This setting allows the solver to employ additional heuristics if necessary, making it easier to obtain good quality solutions in less time.

3.3.4. Studied Scenarios

Simulation scenarios were defined based on different stand management schemes and whether firebreaks were present in the landscape. To optimize firebreak placement, the Downstream Protection Value (DPV) metric was used, which identifies areas where fuel treatments provide the greatest protection to downstream assets like biomass, communities, or infrastructure. The Cell2FireW Polygon Knapsack tool applied this metric to select optimal firebreak locations, considering scenarios where firebreaks cover 1%, 2%, or 3% of the landscape. Additionally, five alternative management solutions were generated for the scenarios with and without firebreaks, each requiring at least 10% of stands to have a different management approach than the others.

To optimize the location of the firewalls, the Downstream protection value (DPV) metric values were used (Pais et., al 2021). DPV is introduced as a spatial optimization framework designed to identify critical zones for fuel treatment to mitigate wildfire risks. It assesses the potential downstream benefits of fuel treatments by evaluating how interventions in specific areas can protect assets located further along the path of potential wildfire spread. By integrating fire spread modelling with optimization techniques, the approach prioritizes treatment zones that offer the highest protective value to downstream assets, such as communities and infrastructure. This method enables more efficient allocation of resources by focusing on areas where fuel treatments can have the most significant impact on reducing overall wildfire risk. In this study, the value to be protected was defined as the biomass of the stand, obtained from the biomass simulator.

For this purpose, the Cell2FireW Polygon Knapsack tool is used, which solves a knapsack problem by considering the different DPVs as weights. The knapsack capacity - i.e., the quantity of firebreaks to be built - is determined by a sensitivity analysis based on three scenarios: 1, 2 and 3% of the landscape covered by firebreaks.

To evaluate the solutions generated by the optimization model, the net protective effect (NPE) of different firebreaks plans was compared. The NPE measures how much the expected losses are reduced after applying the optimal plan, considering also the losses due to the implementation of the firebreaks. The formula used for its calculation is as follows:

$$NPE = ELBT - (TRL + ELAT)$$

- *ELBT*: Expected losses before treatment
- *ELAT*: Expected losses after treatment
- *TRL*: Treatment-related losses

The general procedure for calculating the NPE is as follows:

1. Calculate DPV: Simulate fires in the untreated landscape.
2. Optimize firebreaks: Use the obtained metrics in an optimization problem to determine the best location of firebreaks.
3. Calculate ELAT and ELBT: Simulate fires in the treated landscape and recalculate expected losses.
4. Calculate NPE: Apply the equation to measure the effectiveness of the optimal plan.

In this way, the NPE measures how much the losses are reduced by the fire breaks after subtracting the losses associated with the treatment. If the SPN is high, it means that the fire breaks were effective in protecting the landscape from fire, considering also the implementation costs (how much biomass was removed by making the fire break).

Ten different solutions were generated, of which five included the implementation of firebreaks and five did not. Fires were then simulated for each of these solutions to estimate the amount of biomass lost due to fire and to calculate the expected remaining biomass for each year.

To consider the effect of firebreaks on production, the proportion of each stand that has been affected by firebreaks is calculated. Once the proportion of firebreak per stand is obtained, the total biomass and saleable biomass of the forest is modified by multiplying

the total biomass and saleable biomass of each stand by the factor $(1 - p_i)$, which adjusts the biomass according to the proportion of area affected by firebreaks. This adjusts the biomass considering the reduction of hectares in the stand due to the implementation of firebreaks.

3.3.5. Fire Behaviour Assessment

In this study, the Cell2FireW fire spread simulator was used, specifically the adapted version Cell2Fire+K (Carrasco et., al 2023). Same as Cell2Fire_SB, Cell2Fire+K integrates seamlessly with other modelling components, such as the forest growth simulator and optimization modules, allowing for the evaluation of fuel evolution, spatial allocation of treatments, and the impacts of management decisions over time. The simulator was used in the same way as for the Catalonian Living Lab, using the QGIS plugin and the same kind of inputs.

Wildfires Simulations

The historic wildfires in the area obtained from Conaf were analyzed. This database includes fires from the 2014-2015 to the 2023-2024 season. These data include the total number of fires, the area affected (in hectares) in each period and the duration of the wildfires. Based on these data, it was decided that 50 wildfires would be simulated for each period. In the same way, the length of the simulation was determined in 6 hours, corresponding to the mean of wildfires' duration in the area.

3.3.6. Integration of Forest Growth and Fire Spread Simulators

To connect both simulators used in the study for Chile, Kitral fuel models were assigned according to species and age as shown in Table 15. In this way, fuel patterns changed as stands grew. Additionally, a fuel type was assigned to the other non-plantations polygons, according to their characteristics based on CONAF's 2015 vegetation cadaster. It was determined that the fuel models of these polygons would remain fixed over time since the time for them to change fuel type is longer than the time horizon used in this study (10 years).

The initial fuel map, derived from CONAF's forest cadaster, is dynamically updated as forest stands develop and transition into different fuel types. For instance, when a *Pinus radiata* plantation grows from 3 to 4 years of age, its classification changes from PL01 to PL05, which is associated with different fire behaviour characteristics.

This dynamic update ensures that the outputs of the forest growth simulator directly inform the inputs of the fire spread simulator.

In this way, the two simulators are effectively coupled, enabling an integrated assessment of forest development and fire dynamics.

3.3.7. Analysis of results

Both the forest growth and fire spread simulations were conducted over a 10-year planning horizon with a 1-year time step, resulting in a total of 11 simulation time steps (Year 0 to Year 10). This temporal resolution enabled the assessment of forest dynamics and fire behaviour changes under various management scenarios.

The simulation outcomes for the Chilean Living Lab allowed for the assessment of economic and fire-related performance of landscape configurations, both with and without the integration of firebreaks. The analysis considered long-term dynamics over 10 planning periods.

Ecosystem Service and Economic Indicators

Economic profitability was evaluated under two landscape configurations: without firebreaks and with firebreaks.

Table 18 shows the economic gains before and after simulated fires in landscapes *without firebreaks*. The average value loss due to fire damage ranged from 8.32% to 8.43%, highlighting the economic vulnerability in the absence of fire mitigation strategies.

Table 18: Economic gains without integrating firebreaks in the landscape

Target values before fires (MM Chilean pesos)	Target values after fires (MM Chilean pesos)	Percentage of original value
44395.64	40652.13	91.57%
44387.35	40666.55	91.62%
44306.92	40605.49	91.65%
44399.70	40680.33	91.62%
44133.23	40460.76	91.68%

In contrast, Table 19 displays the economic performance when *firebreaks were included*. Although the initial production slightly decreased due to loss of productive area (e.g., firebreak locations), the average percentage of economic value preserved after fires was higher (around 92.82%–92.91%).

Table 19: Economic gains when firebreaks are considered in the landscape

Target values before fires (MM Chilean pesos)	Target values after fires (MM Chilean pesos)	Percentage of original value
44065.39	40901.39	92.82%
44151.09	41019.15	92.91%
44156.50	40980.95	92.81%
43994.95	40846.72	92.84%
43835.37	40715.91	92.88%

Looking at both tables, fires reduce profits in all cases. Additionally, the inclusion of firebreaks reduces production when fires are not considered, as firebreaks are often placed in productive areas. However, when the effects of fires are considered, these firebreaks help minimize damage, reducing biomass and economic losses.

In summary, while firebreaks lead to lower production in fire-free conditions, they provide significantly higher resilience to fire-induced economic losses, making them an economically advantageous intervention in fire-prone landscapes.

Figure 22 complements this economic analysis by showing the **saleable biomass** over time. Despite the minor reduction in productive area due to firebreaks, landscapes with firebreaks achieved a net gain of 5,502 tons of saleable biomass across the simulation period (625,347 tons vs. 619,845 tons), highlighting the long-term economic benefits of integrating fire mitigation structures.

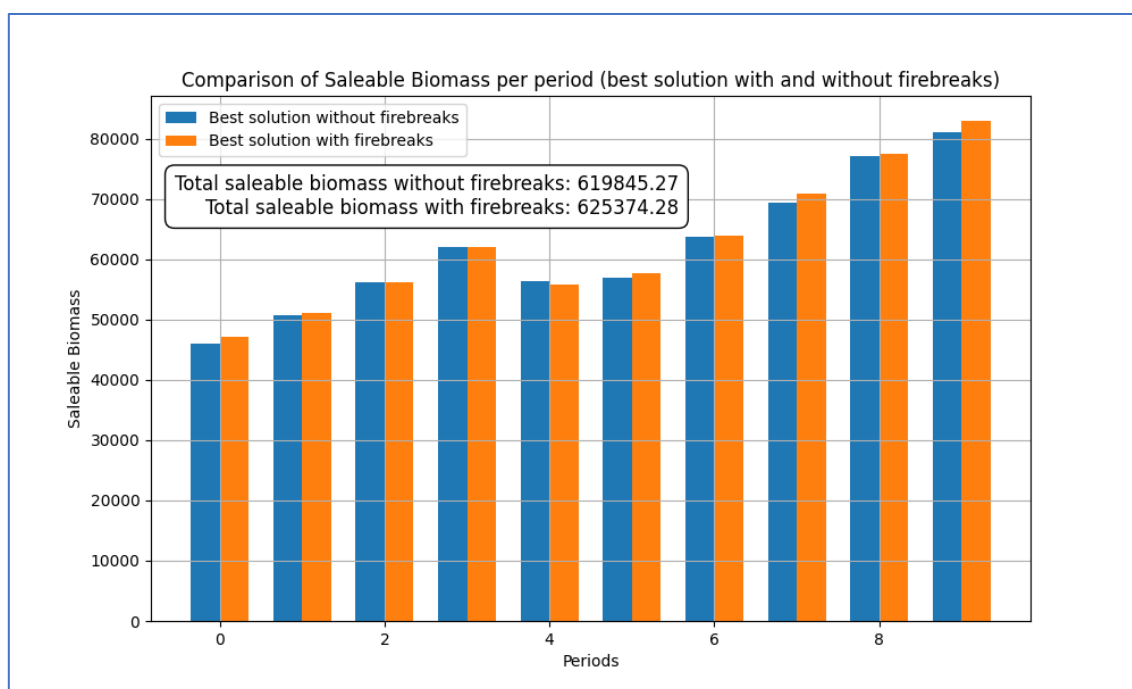


Figure 22: Comparison of saleable biomass by period

Spatial Fire Behaviour Metrics

Fire behaviour was analyzed in terms of biomass burned across time, comparing the fire impact in landscapes with and without firebreaks. Figure 23 illustrates this comparison across the 10 simulation periods.

The vertical axis shows the biomass burned in tons, while the horizontal axis shows the 10 periods. The orange bars represent the biomass burned in the landscape with the best solution with firebreaks for each period, while the blue bars correspond to the best solution without firebreaks.

It is observed that in each period the biomass burned is always higher in the landscapes without firebreaks. It is also observed that the total biomass burned in the landscape without firebreaks (1 400 734 tons) is much higher than in the landscape with firebreaks (1 130 850 tons), which corresponds to almost 24% more losses.

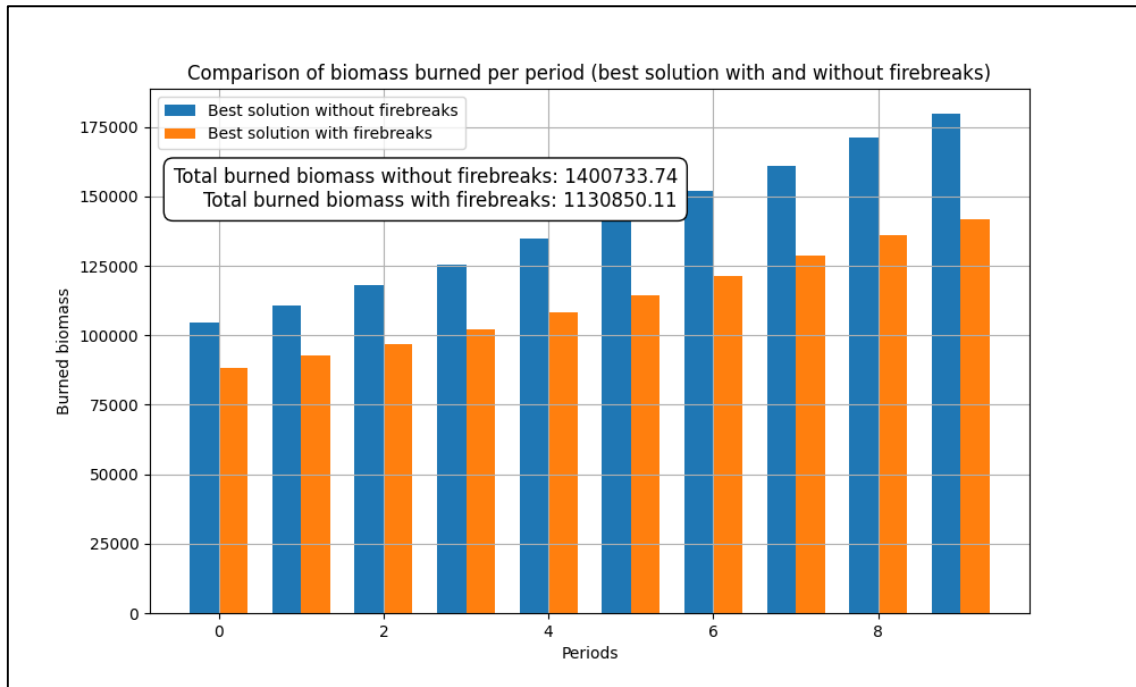


Figure 23: Burned biomass per period with and without fuel breaks

3.4. Portugal

3.4.1. Input Data

The Vale do Sousa Forest Landscape, located in the northwestern region of Portugal, approximately 50 kilometers east of Porto city, constitutes the primary case study area for this research (see Figure 24). Encompassing a total area of about 28 940 hectares, Vale do Sousa is dominantly covered with forests, occupying more than 70% of the total area. The forest structure is highly fragmented, reflecting the prevailing pattern of small-scale private ownership in Portugal, where holdings are often divided into multiple non-contiguous blocks. The landscape is primarily composed of two economically important plantation species: *Eucalyptus globulus* Labill (*eucalypt*), widely cultivated for pulpwood production, and *Pinus pinaster* Aiton (*maritime pine*), typically grown for sawlog markets. It also features a patchwork of native broadleaf species, including *oaks* (*Quercus spp.*) and *chestnuts* (*Castanea sativa*), particularly in less accessible areas and riparian corridors.

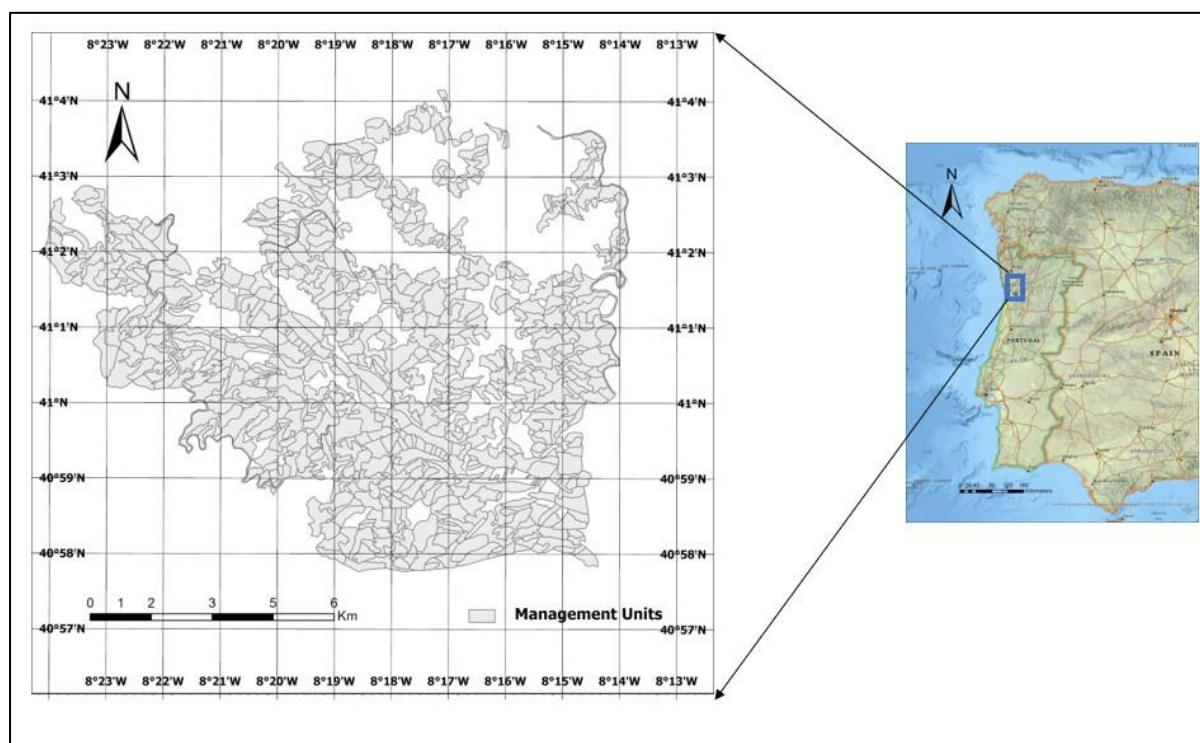


Figure 24: Living Lab Vale do Sousa, Portugal

The terrain across Vale do Sousa is diverse, with slope gradients ranging from 4% in valley bottoms to more than 60% in rugged hillsides. This topographic variability influences forest productivity, access for management operations, and the behaviour of wildfire spread, adding a further layer of complexity to landscape planning. The climate is characterized by mild, wet winters and hot, dry summers, conditions typical of the western Iberian Peninsula. The average annual rainfall is 1 240 mm, but it is unevenly distributed throughout the year, with three very dry months (June, July and August) with an average rainfall of 31.1 mm and three very wet months (October, November and December) with an average rainfall of 170.4 mm. The maximum temperature recorded in summer reaches over 40°C.

The Mediterranean climate regime, combined with dense and often unmanaged fuel loads in eucalyptus and pine stands, creates a high-risk environment for wildfire, especially during the summer and early autumn. Wildfire represents the most significant ecological and socio-economic threat to the region's forests. The landscape has experienced severe fire events in recent history, most notably during the catastrophic fire seasons of 2017/2018, which devastated extensive forest areas. Alarmingly, this trend continued in 2024, when another major fire once again impacted large sections of the forested area, underscoring the urgent need for adaptive and integrated fire management strategies. The high recurrence of fire events in Vale do Sousa is further compounded by the landscape's fragmented ownership, limited forest management interventions.

Forest stand characterization and inventory data

The forest landscape of Vale do Sousa was first characterized through a land use and land cover (LULC) classification using Geographic Information Systems (GIS). This classification process was supported by a combination of field-based forest inventory and remote sensing data. Field inventory plots were established across the landscape to collect essential structural information, including tree species, age, height, and diameter at breast height (DBH). These ground measurements provided the basis for calibrating and validating spatial data sources. The field campaign was then complemented by national land cover maps of Portugal (COS), satellite imagery, and airborne LiDAR data to generate a detailed LULC map.

Following the classification of land use and land cover, the delineation of forest management units was carried out. This involved incorporating additional site attributes, including slope and terrain features derived from digital elevation models. Site index (SI), which reflects potential productivity, was also calculated and used as a criterion for refining the management unit boundaries. This process resulted in a total of 3,205 distinct management units within the landscape. These include 1642 eucalyptus units covering approximately 15000 hectares, 169 maritime pine units (around 1 200 hectares), 358 hardwood units, and 111 riparian vegetation units totaling close to 768 hectares. And of which 633 units, close to 7650 ha, are agriculture, building area and water bodies. The spatial distribution of these management units is illustrated in Figure 25.

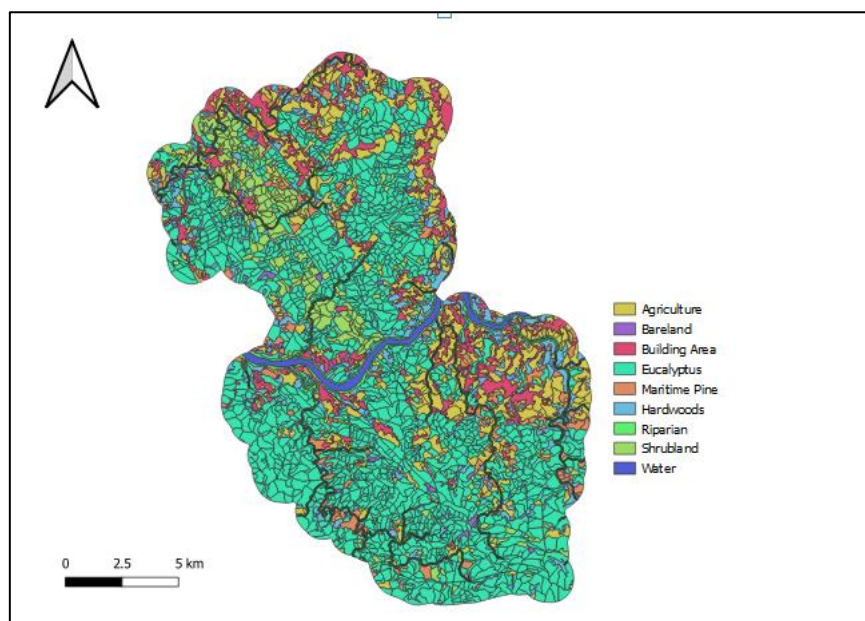


Figure 25: Distribution of Management units

Once the management units were delineated, stand-level inventory data were assigned to each unit using a combination of empirical models and remote sensing-derived metrics. Different approaches were applied depending on the dominant species in each unit. For Eucalyptus and Pine, structural attributes such as dominant height (Hdom), basal area (BA), number of trees per hectare (N), stand age, and site index (SI) were estimated using models calibrated with LiDAR metrics and field plot data. Due to occasional inaccuracies in stand age estimation from remote sensing sources, age values were manually corrected where necessary using time-series imagery from Google Earth.

For broadleaved hardwood stands (excluding riparian vegetation), the estimation of inventory attributes relied primarily on LiDAR-derived height and site index, supplemented by species data from the COS land cover map. Based on species proportions derived from the map, representative species such as Chestnut (*Castanea sativa*), Cork Oak (*Quercus suber*), and Pedunculate Oak (*Quercus robur*) were assigned to management units using a Monte Carlo sampling approach.

These stand-level data were then linked to yield tables based on species, dominant height, and site index to support growth and yield projections across the landscape.

The methodological steps followed for forest characterization and inventory assignment are consistent with those described in detail in earlier project deliverables and technical reports (please refer to those for a full methodological description). The resulting stand-level dataset provides the necessary input for subsequent modelling of ecosystem services and forest management scenarios.

Weather scenarios

Extreme fire weather conditions used in fire spread simulations were based on historical wildfire events in the Living Lab area, incorporating hourly wind speed and direction to represent worst-case fire seasons and simulate high-severity scenarios.

3.4.2. Forest Growth Simulator

Forest Growth Simulation Models

Forest stand growth and yield in the Vale do Sousa landscape were simulated using a suite of species-specific tools integrated within the **SIMFLOR** modelling platform (Lisbon, Portugal). The stands SIM-MD module was used to project growth for the main plantation species. Specifically, the **Globulus 3.0** and *Pinaster* models were applied for *Eucalyptus globulus* and *Pinus pinaster*, respectively. For *Quercus suber*, growth was simulated using the **SUBER v5.0** model, also developed within the **SIMFLOR** platform.

For *Quercus robur* stands, the **SimGaliza** simulator was adopted due to the similar soil and climatic conditions shared between the Vale do Sousa region and Galicia (Spain), where the model was originally developed. Growth projections for *Castanea sativa* were based on yield tables recommended by Mönkkönen (2014) and Carle et al. (2021).

Ecosystem service estimation

The estimation of ecosystem services across the Vale do Sousa Forest Landscape was based on the outputs of the forest growth and yield simulators described previously. These simulators were applied to all delineated management units under each of the management alternatives designed for the study. The simulations were carried out over a long-term planning horizon (e.g., 100 years), enabling the assessment of forest dynamics and service provision across temporal and spatial scales.

For each management unit and prescription combination, the simulator provided a set of detailed biophysical and economic outputs. These included stand-level variables such as average height, mean diameter, basal area, tree density (number of trees per hectare), and aboveground biomass components. Additionally, species-specific simulators estimated total wood volume, commercial product yields, and carbon stock over time. In some cases, the simulators also provided estimates for non-timber forest products, such as cork yield in *Quercus suber* and resin production in *Pinus pinaster*. Moreover, the simulations accounted for operating costs and economic returns, enabling a comprehensive evaluation of both ecological and financial aspects of forest management.

The variables generated through simulation formed the foundation for modelling ecosystem services. Each relevant indicator was derived by applying post-processing techniques to simulator outputs, enabling the quantification of multiple services at the stand and landscape levels. Main ecosystem services examined in the current project includes biodiversity and wood production. The biodiversity indicator considers the tree species composition (e.g., maritime pine, eucalypt, chestnut, pedunculate oak, cork oak, and riparian trees), stand age, and understory coverage (Botequim et al., 2021). The biodiversity score ranges from 1 (indicating minimal biodiversity or barren land) to 8 (representing the highest level of biodiversity).

Forest Management

The definition of management alternatives for the Vale do Sousa Forest Landscape was developed in close collaboration with AFVS (Associação Florestal do Vale do Sousa). These

alternatives consist of silvicultural prescriptions tailored to each management unit, incorporating combinations of harvesting methods, thinning regimes, shrub clearing frequencies, and cork extraction practices where applicable. The prescriptions were designed to reflect both ecological conditions and local forest management traditions.

Management of *Eucalyptus globulus* is primarily based on coppicing systems, involving successive cutting cycles. *Pinus pinaster* and *Castanea sativa* stands are managed under high-forest systems, incorporating periodic thinning to regulate stand structure and enhance timber quality, followed by harvesting. The management approach for *Quercus robur* (*pedunculate oak*) emphasizes structured thinning to promote stand stability and natural regeneration, with harvesting scheduled at the maturity of stand development. *Quercus suber* (*cork oak*) is maintained through successive thinning cycles, with no clear-cutting, and incorporates periodic cork extraction as a key non-timber output.

Beyond conventional silvicultural treatments, the management alternatives also incorporate species conversion pathways, particularly in homogeneous eucalyptus and pine stands. These options consider conversion into species such as maritime pine, chestnut, pedunculate oak, cork oak or strawberry tree, depending on site suitability. In the case of bare or unmanaged land, potential reforestation scenarios include the establishment of pure stands of pedunculate oak, maritime pine, chestnut, cork oak, and strawberry. The inclusion of strawberry trees reflects its ecological adaptability, role in fire-resilient landscapes, and its value for fruit production.

All management alternatives were developed and refined through structured engagement with stakeholders and validated in partnership with AFVS. The resulting options capture the diversity of regionally practiced silviculture and provide the flexibility needed for spatially explicit forest planning under different ecological and management constraints.

3.4.3. Optimization of Forest management strategies

The optimization modelling framework developed for the Vale do Sousa Forest Landscape aims to identify the most effective spatial allocation of forest management alternatives, with respect to ecosystem services and stakeholder-informed priorities. The landscape was structured into predefined management units, each associated with a set of applicable silvicultural prescriptions and corresponding ecosystem service outcomes. These outputs, derived from the growth simulation and ecosystem service models, form the input parameters of the optimization model.

A single-objective mixed-integer optimization model was formulated, where the binary decision variable takes the value 1 if management prescription $m \in M$ is assigned to stand $j \in J$ and 0 otherwise. The model includes the following core constraints:

$$\sum_{m \in M} X_{jm} = 1, \quad \forall j \quad (1)$$

$$\sum_{m \in M} \sum_{t \in T} \sum_{j \in J} e_{jmt}^{es} * X_{jm} = E^{es} \quad (2)$$

Where,

J : Set of stands ($j= 1,2,3, \dots, J$ stands)

T : Set of periods in the planning horizon ($t= 1, 2, \dots, 5$)

M : Set of management actions (prescriptions)

E : Set of ecosystem services ($1, 2, 3, \dots, E$)

E^{es} : Total amount of ecosystem service **es** in period

e_{jmt}^{es} : are the coefficients associated with amount of ecosystem service **es** (such as wood, cork, carbon stock, fire resistance etc) that would be obtained in period t if prescription m is applied to stand j .

Equation (1) ensures that only one prescription is assigned to a stand, and Equation (2) calculates the total amount of each ecosystem service across the planning horizon, based on simulator-derived coefficients for each prescription. The model was designed to maximize a specific ecosystem service (e.g., biodiversity), while incorporating constraints to ensure balanced outcomes over time and across the landscape. The main constraint considered was wood flow constraint where the total wood production across consecutive periods was regulated by constraining the model:

$$TWOOD_{t+1} \leq TWOOD_t (1 + \sigma) \quad (3)$$

$$TWOOD_{t+1} \geq TWOOD_t (1 - \sigma), \quad (4)$$

where $TWOOD_t$ is the total wood production in period t , and σ is the allowable fluctuation in percentage (20% was considered for the current case study).

The MIP optimization model for all scenarios were formulated for hundred years planning horizon, divided into ten 10-year planning periods. The model was then solved using IBM CPLEX.

3.4.4. Studied scenarios

In this study, two optimization scenarios were developed: one that maximizes Biodiversity (MAX_BIO) and another that maximizes Total wood Production (MAX_TIMB). The MAX_BIO scenario was designed to prioritize biodiversity-related regulating services, which are often considered "non-market" or "non-good" services – critical for ecosystem functioning but not directly extracted or sold. In contrast, the MAX_TIMB scenario focuses on provisioning services, specifically the production of timber – a tangible, marketable good. This scenario simulates traditional forest management approaches that aim to optimize economic returns from wood harvesting. By comparing these two contrasting management strategies – one targeting ecological integrity and the other economic productivity- we aim to uncover the differences in spatial patterns, service trade-offs, and potential synergies. This comparison provides insight into how prioritizing different ecosystem services influences forest landscape composition, structure, and multi-functionality.

3.4.5. Fire Behaviour Assessment

As with the previous Living Labs, the Cell2Fire — a spatially explicit wildfire behaviour simulator integrated within the QGIS environment — was also applied in the Vale do Sousa Forest Landscape.

The fire simulation was done for five different years, corresponding to the end of each of the five decadal planning periods: - 2031, 2041, 2051, 2061, and 2071, aligning with future landscape scenarios under varying management objectives (e.g., maximizing timber or biodiversity).

For the Cell2Fire simulations, extreme fire weather conditions were derived from historical wildfire events in the Living Lab region. These included hourly wind speed and wind direction data, representing worst-case fire seasons and enabling the simulation of high-severity fire scenarios.

3.4.6. Integration of Forest Growth and Fire Spread Simulators

Following the solution of the optimization problem, the resulting optimal solutions—consisting of the selected management prescriptions for each management unit—were exported and saved as text files. These files were subsequently converted to a structured CSV format, which enabled integration with spatial data and other modelling tools.

Using the optimal prescription assigned to each management unit, the forest landscape was characterized according to the expected future structure under the selected management strategy. Specifically, stand-level biometric attributes- such as dominant height, mean diameter, basal area, and tree density- were extracted from the forest growth simulator based on the prescription applied to each unit. These variables were then incorporated into the attribute table of a shapefile representing the management units of the Vale do Sousa Forest Landscape.

The updated shapefile, now containing spatially explicit forest structural attributes under optimized management, served as the primary input for Fire Spread Simulator *Cell2Fire*. By linking the outputs of the growth simulator to the fire behaviour model, the simulation framework allowed for an assessment of how optimized forest management strategies affect landscape-level fire behaviour, resistance, and potential fire impact. This integration of forest growth outputs with Cell2Fire enables a dynamic assessment of wildfire risk and mitigation effectiveness, forming the basis for evaluating the fire-related ecosystem service indicators under alternative management and spatial configurations.

Model Inputs

The following spatial and stand-level data were required for each analysis year:

a. Canopy Base Height (CBH)

$$CBH = HT - CL,$$

where crown length (*CL*) was derived from *hdom* and inter-tree spacing using a logistic model following *Nunes et al. (2022)*.

b. Canopy Bulk Density (CBD)

Calculated as the ratio of crown leaf biomass (*CLB*) to crown volume (*CV*):

$$CBD = CLB / ((\pi / 4) * CD^2 * CL),$$

where *CLB* is estimated from *dg* using allometric models, and *CD* is crown diameter.

c. Fraction of Canopy Cover (FCCL)

$$FCCL = (\pi / 4) * CD^2 * NHA / 10\ 000,$$

where *NHA* equals no. of trees per ha (tree density).

d. Fuel Model

Based on the dominant species and shrub biomass (tons/ha) present respective Portuguese Fuel Model was assigned to each stand.

e. Elevation

Elevation data were obtained from a Digital Elevation Model (DEM) at 30-meter resolution

f. Weather Data

Extreme fire weather conditions were derived from historical wildfire events in the Living Labs region.

3.4.7. Analysis of results

Optimization Model Solutions: values of the optimized ecosystem services

The results in Table 20 clearly illustrate the trade-offs between maximizing timber production and maximizing biodiversity in forest management. When the objective is to maximize biodiversity (MAX_BIODIVERSITY), timber production is significantly reduced across all planning periods compared to the scenario that maximizes timber production (MAX_TIMBER). The total timber output under MAX_BIODIVERSITY is approximately 3.48 million cubic meters over the five periods, while MAX_TIMBER yields a much higher total of around 11.62 million cubic meters. This indicates that biodiversity-oriented management strategies limit wood harvesting, likely due to the adoption of less intensive prescriptions or the promotion of native and diverse forest structures that are not optimized for timber yield.

Table 20: Periodic and overall timber production and biodiversity score under two studied scenarios

	Timber (106 m3)		Biodiversity Score	
	Max_Biodiversity	Max_Timber	Max_Biodiversity	Max_Timber
Period1	1.036	1.683	4.564	2.265
Period2	0.829	2.019	4.116	2.25
Period3	0.663	2.175	4.146	2.289
Period4	0.531	2.610	4.425	2.315
Period5	0.427	3.131	4.337	2.33
Overall	3.48	11.619	4.318	2.29

In contrast, the biodiversity scores are consistently higher under the MAX_BIODIVERSITY scenario, with values above 4.1 in every period and an overall score of 4.318. These high scores reflect the ecological benefits of management strategies that prioritize species richness, habitat quality, and structural diversity. On the other hand, the MAX_TIMBER scenario results in much lower biodiversity scores, with values around 2.2 to 2.3 and an

overall score of just 2.29. This suggests that intensive timber-focused strategies—possibly involving monocultures, shorter rotations, or lower structural heterogeneity—are associated with a decline in biodiversity.

These trade-offs between timber production and biodiversity also have important implications for wildfire risk and behaviour. Biodiversity-oriented management often results in more structurally diverse and heterogeneous forest landscapes, which can contribute to increased ecosystem resilience and potentially reduce the intensity and spread of wildfires. In contrast, timber-maximizing strategies may lead to more homogeneous stands and fuel structures that are more susceptible to severe fire behaviour. Therefore, understanding how these two management scenarios influence fire-related metrics is critical for assessing their long-term sustainability, especially in fire-prone regions. The following section explores this relationship by examining fire behaviour outcomes (Cell2Fire result) under the optimal solutions identified for each scenario.

Fire Behaviour Dynamics under the studied scenarios: result of Cell2Fire

Table 21 presents the mean annual burn probability across the landscape for each scenario at the end of the five planning periods. The MAX_TIMBER scenario consistently exhibits lower burn probabilities, decreasing gradually from 0.0589 in 2031 to 0.0482 in 2071. In contrast, the MAX_BIODIVERSITY scenario shows higher and more variable burn probabilities, starting at 0.0693 and rising to a peak of 0.0989 in 2041 before stabilizing around 0.09 in the final periods.

Table 21: Average Annual Burn Probability for Max Timber and Max Biodiversity at the end of each period

Scenario	Year	Mean BP
Max Timber	2031	0.0589
	2041	0.0573
	2051	0.0522
	2061	0.0476
	2071	0.0482
Max Biodiversity	2031	0.0693
	2041	0.0989
	2051	0.0827
	2061	0.0869
	2071	0.0933

This suggests that although the biodiversity-maximizing strategy supports ecological complexity, it may unintentionally sustain fuel loads or continuity that increase fire susceptibility. On the other hand, timber-focused management, through more frequent and intensive harvesting, appears to reduce burn probability over time, likely due to the associated reduction in biomass and fuel continuity.

Figure 26 illustrates the trajectory of average annual burn probability over the 50-year horizon for both scenarios. The graph confirms the trends observed in Table 21: the

MAX_TIMBER scenario exhibits a consistent downward trajectory, while the MAX_BIODIVERSITY scenario shows a mid-horizon spike followed by a plateau at elevated levels.

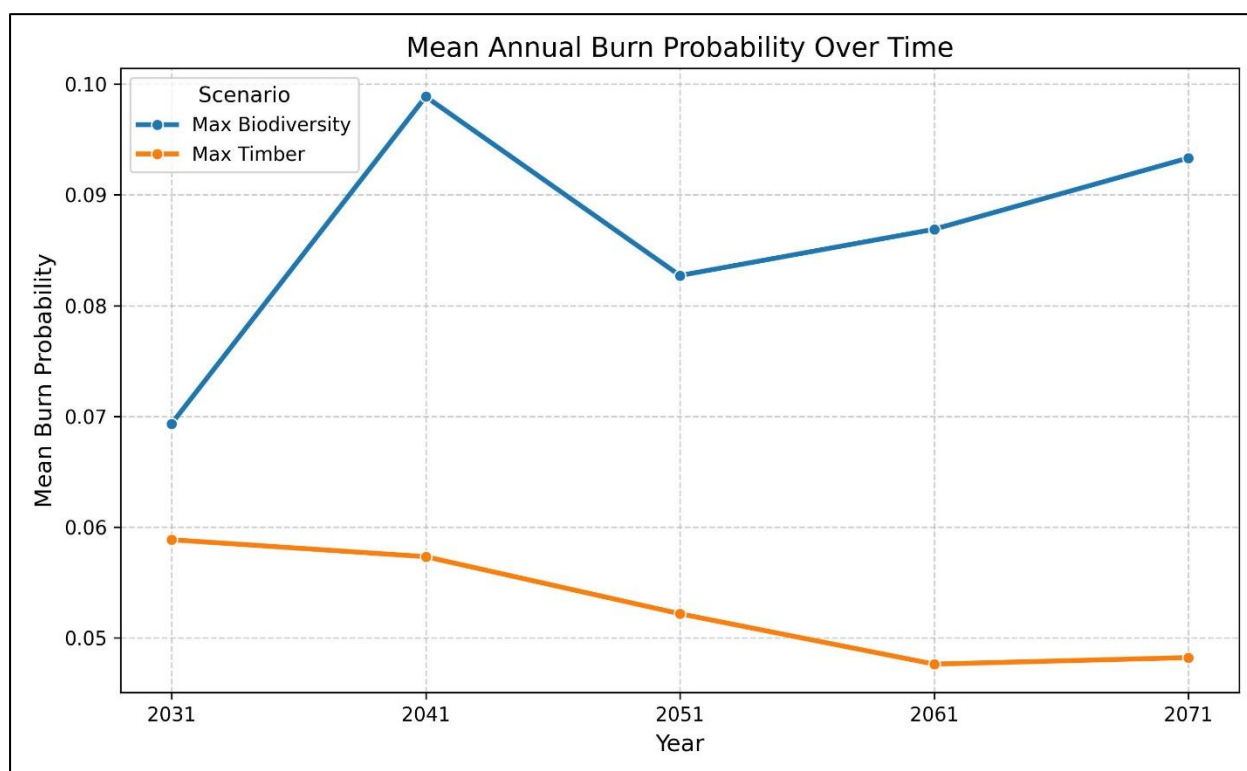


Figure 26: Line graph depicting Average Annual Burn probability over the planning horizon for Max Timber and Max Biodiversity scenarios

This temporal pattern may reflect delayed fuel accumulation in biodiverse systems, especially where harvesting is minimized. These results emphasize that decisions aimed at enhancing biodiversity may have long-term implications for fire risk, particularly in fire-prone landscapes.

Looking at the spatial pattern of the aforementioned fire metrics across the landscape, Figure 27 shows spatial heatmaps of burn probability for each period and scenario. The maps reveal that the MAX_BIODIVERSITY scenario results in broader and more dispersed areas with high burn probability values, especially evident in mid-to-late periods. In contrast, MAX_TIMBER shows more localized and less intense burn-prone areas, likely corresponding to areas with lower fuel accumulation due to harvesting interventions.

These spatial differences reinforce the idea that forest structure and composition—shaped by the management objective—directly influence landscape-level fire behaviour and risk distribution.

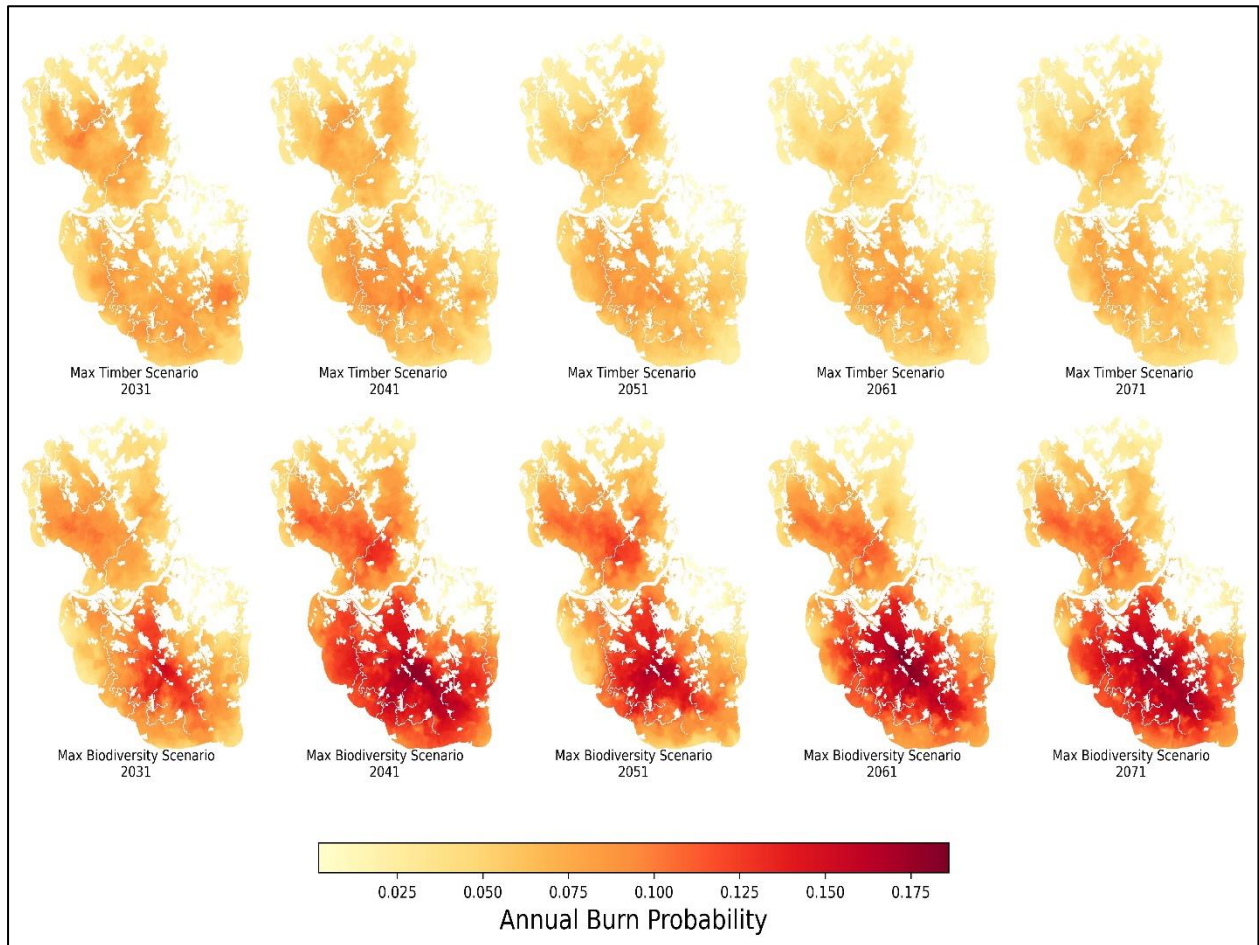


Figure 27: Heatmaps showing Annual Burn Probability for Max Timber and Max Biodiversity at the end of each period

Finally, Figure 28 displays heatmaps of the annual rate of fire spread under both scenarios. The MAX_BIODIVERSITY scenario shows larger contiguous patches where high spread rates occur. The MAX_TIMBER scenario, on the other hand, tends to break up these fuel-continuous patches probably due to harvesting activities, resulting in more fragmented areas with lower spread rates. These differences in fire spread highlight the importance of spatial configuration in fire planning and suggest that while biodiversity brings ecological benefits, it must be carefully balanced with structural fuel management to mitigate extreme fire behaviour.

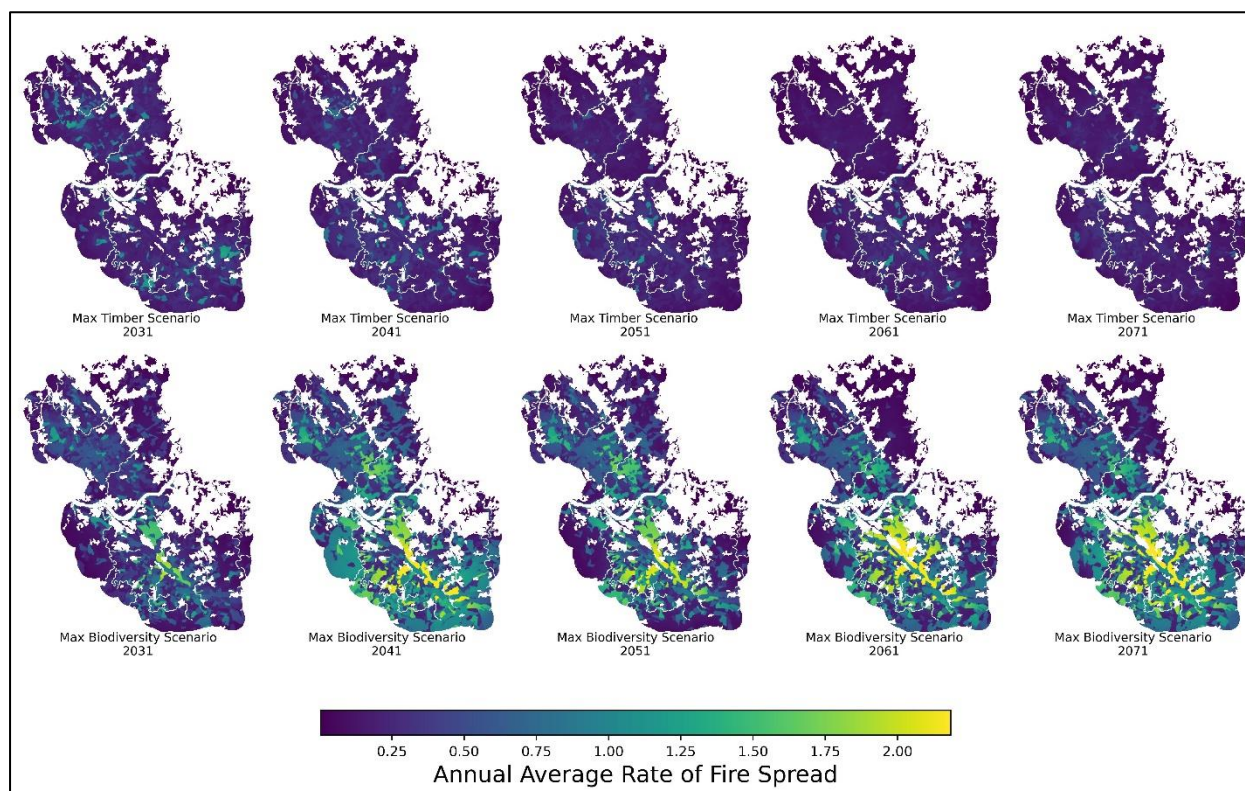


Figure 28: Heatmaps showing Annual Rate of Fire Spread for Max Timber and Max Biodiversity scenarios at the end of each period

Together, these results demonstrate that the choice of management objective—biodiversity versus timber—has cascading effects not only on ecosystem services but also on fire behaviour and risk. While maximizing biodiversity enhances ecological values, it may increase landscape vulnerability to wildfires if not paired with targeted fuel reduction strategies. This highlights the need for integrated forest planning approaches that explicitly incorporate fire behaviour metrics to ensure both ecological resilience and risk reduction. In this context, the integration of forest growth simulators with fire behaviour simulators plays a critical role. Growth simulators provide detailed information on stand development, species composition, biomass accumulation, and structural attributes over time, which directly influence fuel dynamics. These outputs are then used as inputs in fire simulators, such as Cell2Fire, to assess how changing vegetation conditions under different management scenarios affect fire probability, spread, and intensity. By linking ecological processes with fire dynamics in this way, we are able to evaluate not only the trade-offs between ecosystem services, but also the fire resilience of the resulting landscapes—thereby supporting more informed, multi-objective decision-making.

4. General remarks

Applying spatially explicit approaches in forest planning when fire risk is a factor is a complex process that remains far from being fully resolved. The specificity of conditions, objectives, data, or the availability of simulation tools offers opportunities for innovation but also introduces limitations when attempting to reach a consensus on how to address the issue.

Tactical planning allows for the evaluation of the provision of different products and ecosystem services while selecting a management plan for a landscape, including management schedules for stands within it. Although modifying the landscape influences fire propagation and impacts, fire risk—as a potential source of forest and timber loss—must be considered when evaluating and adjusting the provision of ecosystem services. Therefore, integrating fire risk into tactical forest planning is essential.

However, several aspects, perspectives, and limitations must be considered when incorporating fire risk into tactical forest planning. Fuel models—standard typologies of fuel accumulation and structure linked to specific fire behaviour—vary significantly across the world. There are various fire simulation tools and approaches, each with different requirements and outputs. Growth and yield models tend to be far more region- or site-specific than fire behaviour models, and most simulation tools that include tree- or stand-level modelling for tactical planning are developed for use in a specific country or region. Apart from a few applications where FVS and U.S. Forest Service fire simulators (e.g., FSim, FlamMap) have been linked, there is limited experience in integrating fine-scale growth simulators with fire behaviour modelling at the tactical scale. Tactical forest planning typically aims to optimize objectives that are not directly related to fire mitigation, and the inclusion of fire-related considerations in the optimization process can be approached from multiple perspectives.

In this innovation action, we allowed complete flexibility in how case studies integrated spatially explicit fire behaviour modelling, growth and yield models, simulation of management alternatives, and the optimization of defined problems. The diversity of conditions revealed both limitations and the unique ways in which each case addressed the challenge.

In the case of Catalonia, both the growth and yield simulator and the fire simulator were adapted to the regional context. The region's forest reality is defined by low productivity, high costs, and fragmented property ownership. Under such conditions, it is unrealistic to assume that fire mitigation can be a shared objective among numerous individual stakeholders. Thus, the optimization focused on maximizing ecosystem service yields and evaluating the resulting changes in fire risk. However, targeted actions to reduce risk—though intensive and geographically specific—can be implemented through administrative measures and subsidies for affected landowners. Accordingly, a two-step approach was adopted in Catalonia: first, the allocation of fuel treatments aimed at drastically altering the landscape (scenarios 2 and 3), followed by optimization of forest stands focusing solely on service provision.

In Greece, we encountered a similar landscape context in terms of fuels and objectives. Despite significant expertise in fire behaviour, fuels, and the use of strategic fuel

treatment planning tools, the region lacked experience in tactical approaches and linking optimal fuel treatment schedules with fire simulation. Due to similarities in tree species, climate, and fuel types, we chose to apply the same tools and optimization strategies used in Catalonia.

In Chile, the primary challenge was developing a growth and yield model to generate landscapes for fire simulation. Nevertheless, the conditions in the Biobío region allowed us to test a different approach. Most forested landscapes are owned by large companies focused on pulp and timber production, making it reasonable to assume that fire-oriented stand-level management would be accepted if it reduces losses across the landscape. The strength of this case study was its optimization process, which used mixed-integer programming to allocate fuel breaks and evaluate their effect on expected losses. Results showed that the timber production lost to fuel break allocation was offset by the reduction in expected fire damage.

In Portugal, strong collaboration among forest owners enabled the exploration of strategies involving shared efforts and benefits. In this case, the timing and spatial allocation of final clear-cuts were treated as a fuel break policy — a strategy generally not permitted in Mediterranean forests. A potential change in tree species was also considered, setting this case apart from the others. Instead of using a fire simulator, susceptibility to fire was assessed using a set of rules.

Overall, the four case studies demonstrated diverse realities in terms of simulation methods, risk assessment, integration into planning problems, and the development of policies to support multi-objective planning. Tactical planning presents an opportunity to transform landscapes through productive processes, and integrating fire risk is essential to realistically adjust expected ecosystem service outputs. However, it involves challenges that neither operational planning (focused on implementing approved activities) nor strategic planning (intended to guide policymakers) typically face. Tactical approaches are often limited to areas where decision-making is centralized and clearly defined — conditions not common in many regions. While tactical planning offers a wide range of potential solutions, it remains under development and largely restricted to research applications. Advances in computational capabilities have enabled progress in this field, and tactical planning is expected to become part of a broader strategy to reduce fire losses. Still, its maturity level is not yet sufficient for widespread implementation across real-world landscapes.

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