D2.6 Designing strategic networks of managed areas to improve suppression efforts against EWE

www.fire-res.eu

fire-res@ctfc.cat

Project Acronym: FIRE-RES

Project name: Innovative technologies and socio-ecological-economic solutions for fire resilient territories in Europe

Call ID: H2020-LC-GD-1-1-2020 (Preventing and fighting extreme wildfires with the integration and demonstration of innovative means)

Work Package: 2

Task Number: 2.3

Lead beneficiary: CTFC

Contributing beneficiary(ies): Forest Science and Technology Centre of Catalonia (SP), Instituto superior de Agronomia (PT), University of forestry Sofia (BUL)

This document was produced under the terms and conditions of Grant Agreement No. 101037419 of the European Commission. It does not necessarily reflect the view of the European Union and in no way anticipates the Commission's future policy in this area.

Publication

Publication date: 29/11/2024

Authors: Jose Ramón González-Olabarria; Goran Krsnick; Eduard Busquets; and Míriam Piqué (CTFC); Vassil Vassilev, Nadya Cvetkova (Geopolymorphic GIS Company) ; Nikolai Ivanov (Regional Forestry Directorate) ; Momchil Panayotov, Georgi Kostov (UF) ; José Borges and Sergio Rodriguez-Fernandez (ISA) ; Keith M. Reynolds (USDA-FS) ; Philip Murphy (InfoHarvest Inc.)

Abstract: Fire has long been a defining element of many global landscapes, causing significant environmental, societal, and economic impacts. Factors like land abandonment, fuel accumulation, fire suppression, and climate change contribute to changing fire regimes. This study introduces a spatial prioritization methodology for identifying fire management zones using a multi-criteria approach. The process was implemented across three Living Labs—Catalonia (ESP), Vale do Sousa (PT), and Stara Zagora (BUL)—through participatory stakeholder involvement. Using Multi-Attribute Utility Theory (MAUT) and Geographic Information Systems (GIS), criteria, indicators, and weights were defined to efficiently allocate management resources, aiming to enhance fire prevention strategies in diverse regions.

Key words: Multi-criteria, participatory processes, spatial, fire prevention

Quote as: González-Olabarria, J.R., Krsnick, J., Busquets, E., Piqué, M., Vassilev, V., Cvetkova, N., Ivanov, N., Panayotov, M., Kostov, G., Rodriguez-Fernandez, S., Reynolds, K.M., Murphy., P., Borges, J. 2024). Defining fuel management priority areas to facilitate support efforts, through multicriteria participatory processes. DOI: 10.5281/zenodo.13990213

DOI: 10.5281/zenodo.13990213

Dissemination level

[X] PU- Public: must be available in the website

[ ] CO- Confidential: Only for members of the Consortium and the Commission Services

[ ] CI – Classified: As referred in to Commission Decision 2001/844/EC

Document history

Edition	Date	Status	Author
Version 1	25/10/2024	Draft	JR González-Olabarria; G Krsnick; E Busquets; and M Piqué (CTFC); V Vassilev, N Cvetkova (Geopolymorphic GIS Company); N Ivanov (Regional Forestry Directorate); P Panayotov, G Kostov (UF); J Borges and S Rodriguez-Fernandez

Edition	Date	Status	Author
			(ISA); K Reynolds (USDA-FS); P Murphy (InfoHarvest Inc.)
Version 2	7/11/2024	Revision	Susete Marques (ISA)
Version 3	14/11/2024	Revision	Vitor Reis (ENB)
Version 4	15/11/24	Revised Version	JR González-Olabarria; G Krsnick; E Busquets; and M Piqué (CTFC); V Vassilev, N Cvetkova (Geopolymorphic GIS Company); N Ivanov (Regional Forestry Directorate); P Panayotov, G Kostov (UF); J Borges and S Rodriguez-Fernandez (ISA); K Reynolds (USDA-FS); P Murphy (InfoHarvest Inc.)

Table of Contents

List of figures

List of tables

1. Introduction

Fire has long been a defining feature of several landscapes across the world. While major fires are infrequent, they are recognized as significant disturbances that can lead to serious negative impacts on the environment, society, and economy (Bowman et al., 2011; Strauss et al., 1989). Various factors contribute to the occurrence of fires and potential swifts on fire regimes, including land abandonment, fuel accumulation, fire suppression efforts, and climate change (Syphard et al., 2007). Given the significant uncertainty surrounding these factors, there is a need for improved methodologies and enhanced fire prevention strategies (San-Miguel-Ayanz et al., 2013).

The complexity of natural systems complicates the prediction of fire occurrences, as multiple interrelated factors are at play. Beyond weather conditions, topography, and vegetation traits, different regions are defined by diverse socioeconomic realities, relation of society with landscapes, perception of fire and associated regulations and ways to implement them. Even if there are multiple tools for fire and fuel management, those tools often are focussed on specific problems, regarding objectives and way to solve them.

For example, when selecting fuel management strategies for fire mitigation we found the complexity of the problem that can be approached at the operational, tactical, or strategic planning levels (Gonzalez-Olabarria et al., 2023). Operational planning should concentrate on specifying how particular management practices can be implemented across a landscape to minimize fire spread and damage, without regard for the long-term changes in fuel conditions. In contrast, strategic planning focuses on establishing management policies that consider the impact of fire regimes on large study areas over extended periods. Tactical planning, on the other hand, is designed to identify management alternatives for medium-sized landscapes over intermediate timeframes.

While the number and complexity of tools to solve landscape planning problems has increase over the past decades, the capacity to reach and convince non-academic users not always has been accomplished. On this regard participatory and co-creation processes have shown a clear potential to involve end-user on the planning process and favour the acceptance of provided solutions (Albert et al., 2019). One of the straighter forward problems was this co-design principles can be applied is spatial prioritization problems.

Spatial prioritization is an essential tool for integrating data on the distribution of features of interest, their associated threats, and potential managerial actions. A well-structured prioritization approach can offer valuable information for the allocation of limited resources (Kyttä et al., 2023). Classifying and combining criteria, along with mapping the resulting priorities, are crucial steps in defining landscape planning strategies. The spatial representation of needs and objectives generated through prioritization should support the presentation and acceptance of specific management measures (Ignatieva, 2017).

The same principles, previously mentioned, can be applied to allocate which areas are of high priority for applying fuel management strategies on fire prone landscapes. The selection and parameterization of indicators and criteria for prioritizing management zones aimed at preventing large forest fires, is a requirement for allocating resources on an efficient way, supporting strategic decisions. Simple processes that encourage participation of several actors and experts, should be the basis for a methodology that can be replicated across different problems. Assuming that different areas are to be affected by a certain level of specificity, different perception on necessities, and when moving across Europe also a different set of data sources, due to harmonization limitations of nation or regional level data, the simplicity and robustness of the method to deal with diverse criteria and data should be encouraged.

The present action focus on testing a method to spatially prioritize management areas, according to multiple criteria. Based on the idea of the Areas for Fire Suppression Support (MASS) framework, from Gonzalez-Olabarria et al. (2019) that aimed at improving management actions considering the biogeophysical characteristics of the landscape, the potential for fire hazards, the capacity for fire extinction, and fire exposure of valuable resources. Through a multifactor-based and solution complexity-oriented approach, the Priority Management Zones framework emphasizes the significance of the MASS methodological basis, but being applied to the reality of a region (Krsnick et al., 2024) of landscape. It introduces participatory planning, selects consistent criteria and rules, and includes a robust spatial component, with the aim of efficiently allocating fuel management actions, not only based on a fire risk analysis, but searching from a plural approach for reaching consensus between actors.

The method will be applied in Catalonia (Spain), Vale do Sousa (Portugal), Stara Zagora (Bulgaria). We applied Multi-Attribute Utility Theory (MAUT) alongside spatial modelling using Geographic Information Systems (GIS) (Roe, 2012) to frame the prioritization process. In this action we did not desire to test a closed planning problem, to solve a specific problem, but to generate a common framework that can be adjusted to the specific necessities of our Living Labs and their actors. This flexibility was achieved through a participatory process, that required the selection of an actor's panel to refine the problem definition, selection of relevant indicators and criteria influencing the priority level, definition of rules for standardization of metrics, plus the weighting of the criteria. By integrating the data and rules on selected decision support systems, for building a hierarchical spatial model, it was possible to establish Priority Management Zones along with key rules.

In addition to the testing process of the methodology, we worked on developing a decision support system that facilitates a prioritization assessment of areas to be managed combining multiple criteria and data (fuel hazard, fire behaviour, values at risk, and infrastructures or features that facilitate or hamper the work of firefighters). Finally, we started developing systems that optimize the allocation of management prescriptions in a manner that exists an explicit linkage between the tactical solution (which management actions are to be allocated where), and the strategic solution derived from the prioritization problem.

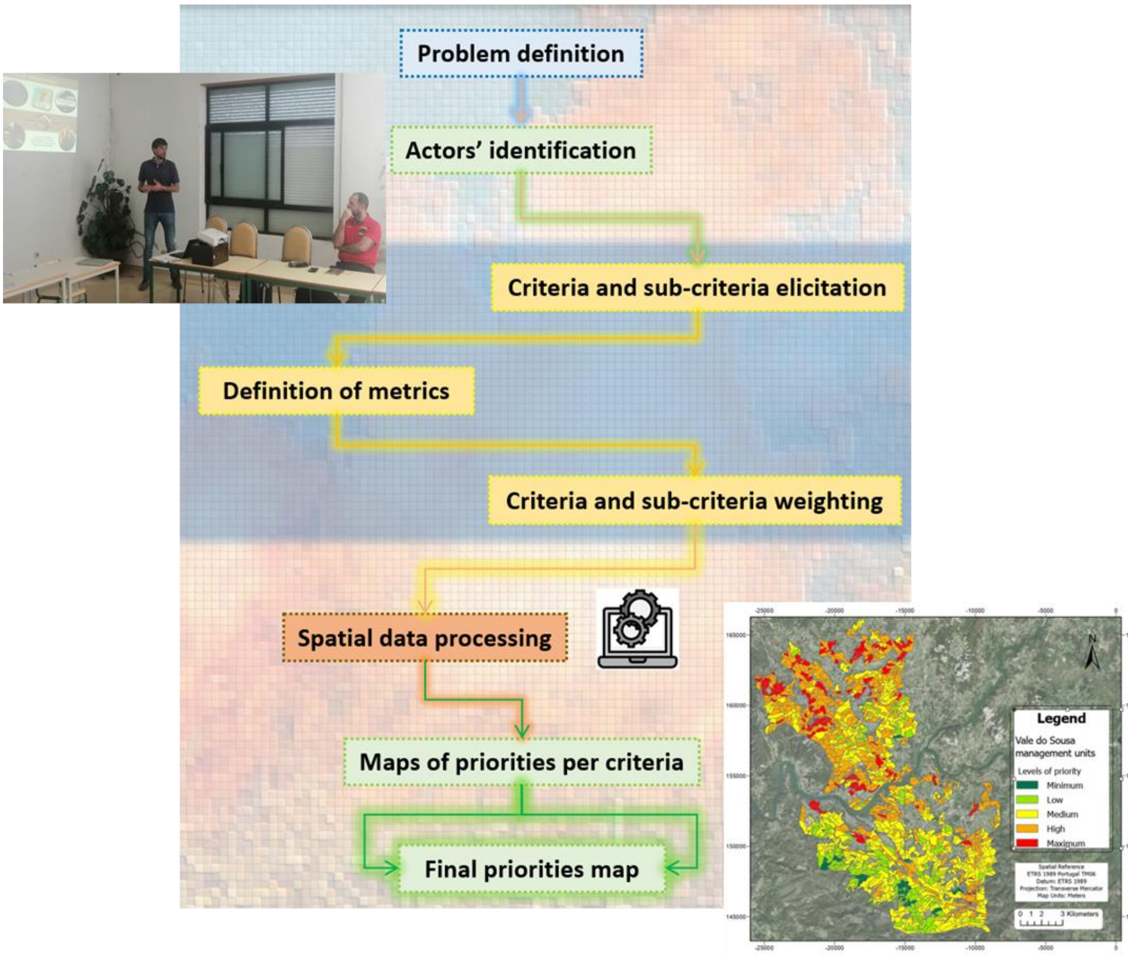


Figure 1: General overview of the spatial prioritization process

2. Methods

The primary objective of this research is to delineate Priority Management Zones aimed at mitigating the occurrence of large-scale forest fires by defining their spatial boundaries through advanced cartographic analysis. The methodology integrates a participatory process involving stakeholders and key actors, utilizing innovative spatial-based technologies to ensure collaborative decision-making. This approach was structured into three sequential main steps to achieve comprehensive and accurate outcomes (Figure 2):

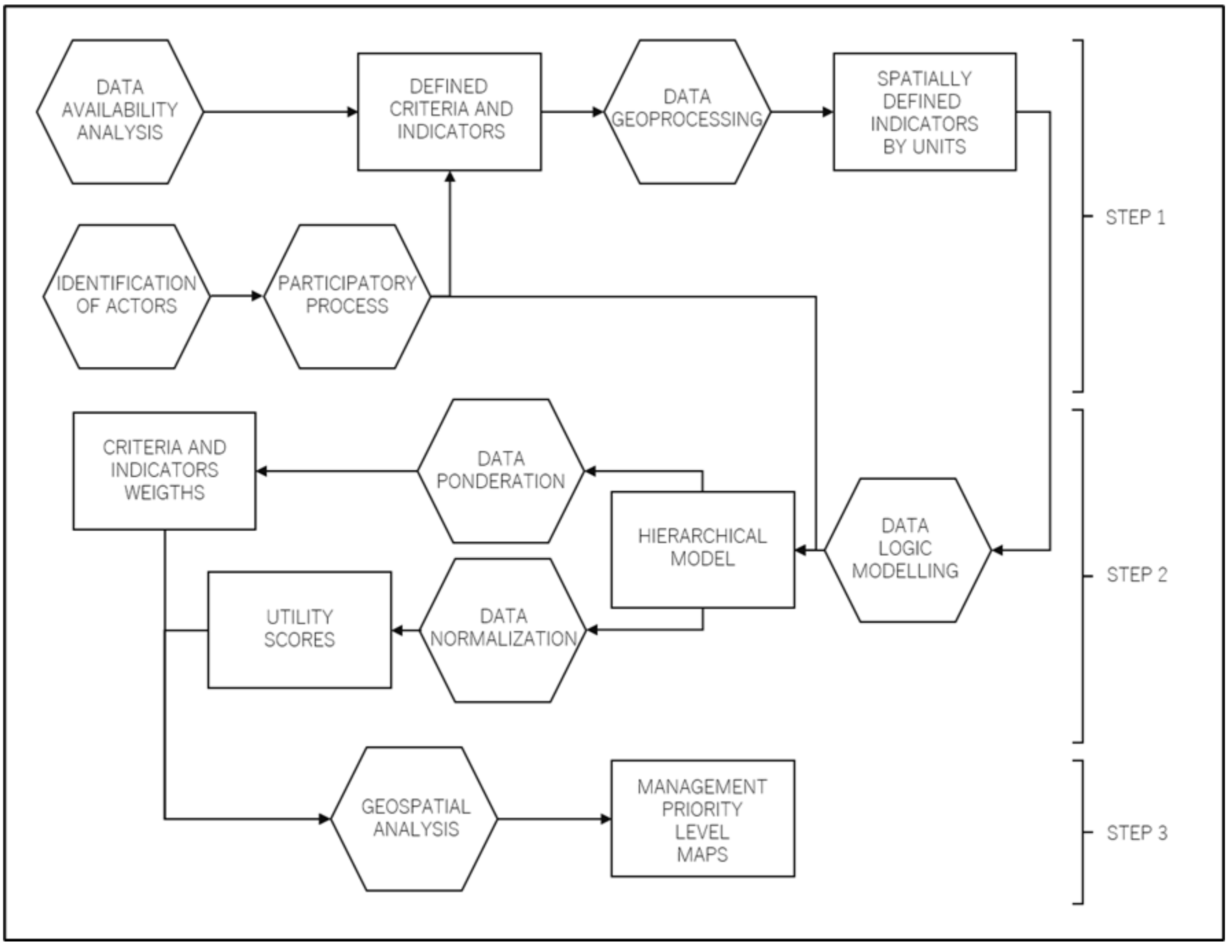


Figure 2. Workflow of the participatory process, encompassing three main steps: 1) Problem definition and criteria selection; 2) Multi-Attribute Utility Theory (MAUT) Analysis; 3) Priority map generation

Although there is a vocation of flexibility within the methodology and application of the action, leaving freedom to the living labs to adjust the steps according to their necessities, the spatial prioritization follows the steps of figure 1, explained as:

1) Problem definition and criteria selection:

• Initial Analysis: A comprehensive assessment was conducted to determine which was the main objective of the prioritization, selection of relevant stakeholders to participate on the participatory process, and implementation of an initial review of potential data sets to be used or required. The aim being to provide a general understanding of the problem to be solved.

• Participatory Process: Key stakeholders, including forest managers, local communities, and experts, were identified and invited to participate in a participatory process. This process involved discussions, workshops, and interviews to gather insights and establish shared priorities for forest fire prevention. The interaction with stakeholders should help to **refine the objective of the study, selection of criteria, and spatial definition of the problem**, among other general requirements to formally frame the problem.

• Spatial Indicators and Criteria: Key factors, such as vegetation type, topography, climate, historical fire data, infrastructures, were identified by the stakeholders as crucial indicators that influence fuel and fire hazard, values at risk, and other metrics associated to fire suppression activities (depending on the LL). These indicators not only should be relevant, but also available, and were then used to establish specific criteria for prioritizing prevention efforts. In general, this step consisted of geographic data gathering and transformation processes. In the case of fire hazard estimations, fire simulation may be required.

2) Multi-Attribute Utility Theory (MAUT) Analysis:

• Data Normalization: To ensure comparability and consistency, the collected data were normalized, first by aggregating it into specific management areas (stands, land patches, etc..), and secondly by **generating utility functions for each indicator or metric**. In terms of unit transformation, a utility function can undergo transformations like scaling or translation without affecting the ranking of preferences. This flexibility is why utility is often treated as an ordinal concept in economic theory, focusing on the order of preferences rather than the actual numerical value of the utility. The process of defining the utility functions, in our case is determined by a combination of literature and expert assessments.

• Weight Assignment: Through participatory planning, stakeholders were involved in **determining the relative weights of each indicator and criterion**. This collaborative approach ensured that the priorities reflected local knowledge, concerns, and values and represented their relative importance within each indicator. Prior to the weigh assignment required to implement additive operation among criteria, a hierarchical representation of the problem is required, as each of the priority levels (Total, or N criteria related) should add 1 once the N weight within each level are added.

3) Prioritization Maps Generation:

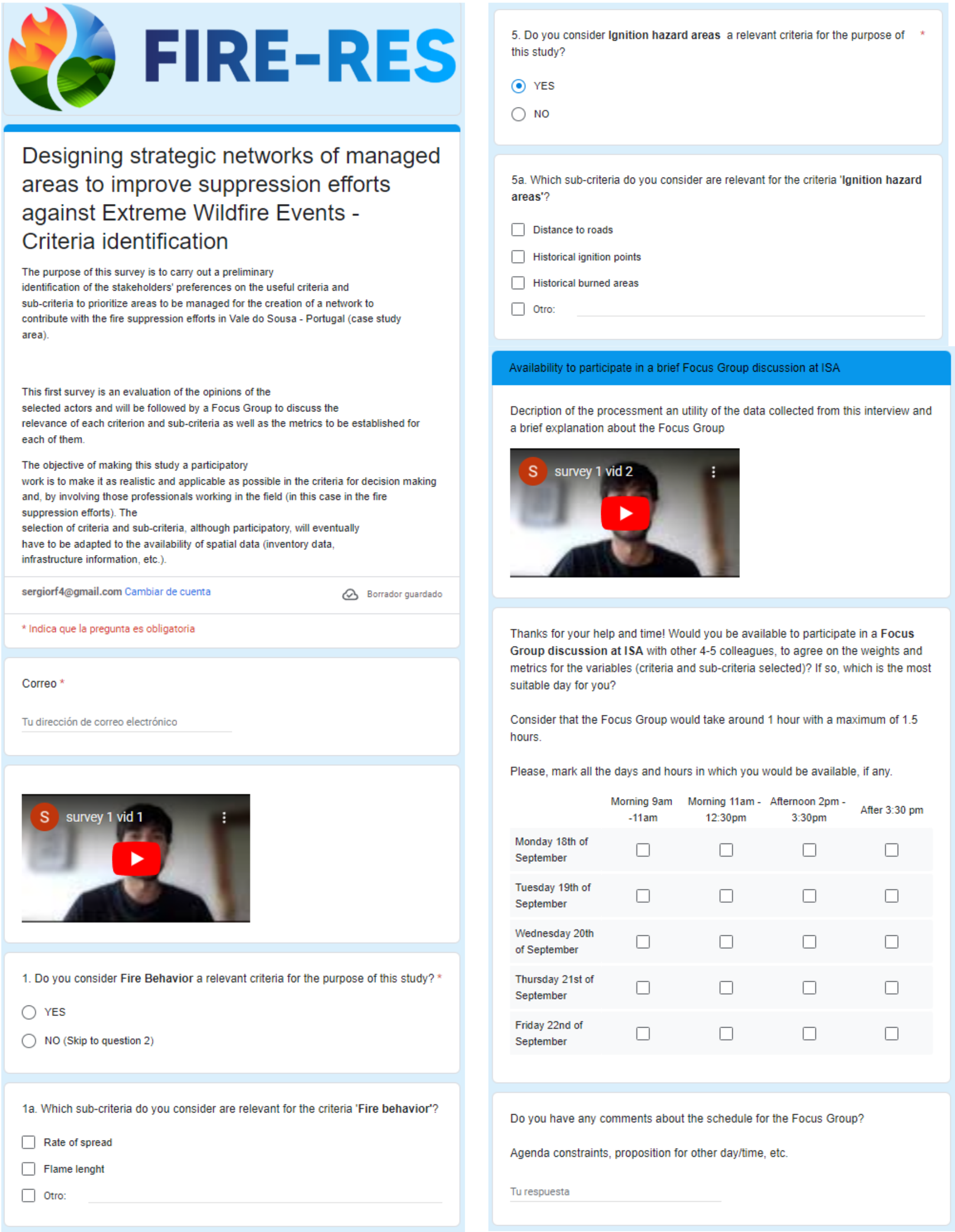
• Integration of Data and Weights: The normalized data (utility scores) for each indicator were combined with their corresponding weights to create a quantitative assessment of the level of priority, for **each spatial management unit**. Being the overall priority the result of adding the weighted priority of the criteria, and the priority provided by each criterion, the result of the weighted scores of sub criteria, in this case estimated by the transformations of original metrics into utility scores, in the case of lover hierarchy sub criteria.

- Spatial Representation: The results were then visualized on maps, providing a clear spatial representation of the prioritized areas for forest fire prevention measures. It is relevant that if a validation with stakeholders is implemented, **an evaluation of the of priority provided by the individual criteria can be as relevant as the overall priority**.

2.1. Problem definition and criteria selection

The methodology began with a comprehensive assessment of the problem, which focused on evaluating key indicators and criteria that influence fire prevention measures, the potential spatial extent of the problem. This involved an in-depth assessment of data availability and suitability to support the definition and quantification of Priority Management Zones.

An expert or stakeholder participatory process was employed from the beginning of the prioritization process, incorporating focus groups to integrate local knowledge and expertise into the assessment. This process was done in live focus groups or online (depending on the living lab) (Figure 3; Figure 4). Each living lab (case study area) independently selected the way to define the prioritization problem general necessities and specificities. Before addressing more complex issues related to the multicriteria decision analysis, the initial requirements for the stakeholders were to define a set of criteria relevant to its specific context, with each criterion defined by a set of indicators tailored to the local environment and conditions.



FIRE-RES

Designing strategic networks of managed areas to improve suppression efforts against Extreme Wildfire Events - Criteria identification

The purpose of this survey is to carry out a preliminary identification of the stakeholders' preferences on the useful criteria and sub-criteria to prioritize areas to be managed for the creation of a network to contribute with the fire suppression efforts in Vale do Sousa - Portugal (case study area).

This first survey is an evaluation of the opinions of the selected actors and will be followed by a Focus Group to discuss the relevance of each criterion and sub-criteria as well as the metrics to be established for each of them.

The objective of making this study a participatory work is to make it as realistic and applicable as possible in the criteria for decision making and, by involving those professionals working in the field (in this case in the fire suppression efforts). The selection of criteria and sub-criteria, although participatory, will eventually have to be adapted to the availability of spatial data (inventory data, infrastructure information, etc.).

sergiorf4@gmail.com Cambiar de cuenta Borrador guardado

* Indica que la pregunta es obligatoria

Correo *

Tu dirección de correo electrónico

S survey 1 vid 1

1. Do you consider **Fire Behavior** a relevant criteria for the purpose of this study? *

- YES
- NO (Skip to question 2)

1a. Which sub-criteria do you consider are relevant for the criteria '**Fire behavior**'?

- Rate of spread
- Flame lenght
- Otro:

5. Do you consider **Ignition hazard areas** a relevant criteria for the purpose of this study? *

- YES
- NO

5a. Which sub-criteria do you consider are relevant for the criteria '**Ignition hazard areas**'?

- Distance to roads
- Historical ignition points
- Historical burned areas
- Otro:

Availability to participate in a brief Focus Group discussion at ISA

Decription of the processment an utility of the data collected from this interview and a brief explanation about the Focus Group

S survey 1 vid 2

Thanks for your help and time! Would you be available to participate in a **Focus Group discussion at ISA** with other 4-5 colleagues, to agree on the weights and metrics for the variables (criteria and sub-criteria selected)? If so, which is the most suitable day for you?

Consider that the Focus Group would take around 1 hour with a maximum of 1.5 hours.

Please, mark all the days and hours in which you would be available, if any.

	Morning 9am -11am	Morning 11am - 12:30pm	Afternoon 2pm - 3:30pm	After 3:30 pm
Monday 18th of September	☐	☐	☐	☐
Tuesday 19th of September	☐	☐	☐	☐
Wednesday 20th of September	☐	☐	☐	☐
Thursday 21st of September	☐	☐	☐	☐
Friday 22nd of September	☐	☐	☐	☐

Do you have any comments about the schedule for the Focus Group?

Agenda constraints, proposition for other day/time, etc.

Tu respuesta

Figure 3. Example of online survey used for the selection of criteria and sub-criteria on the Living Lab Portugal.

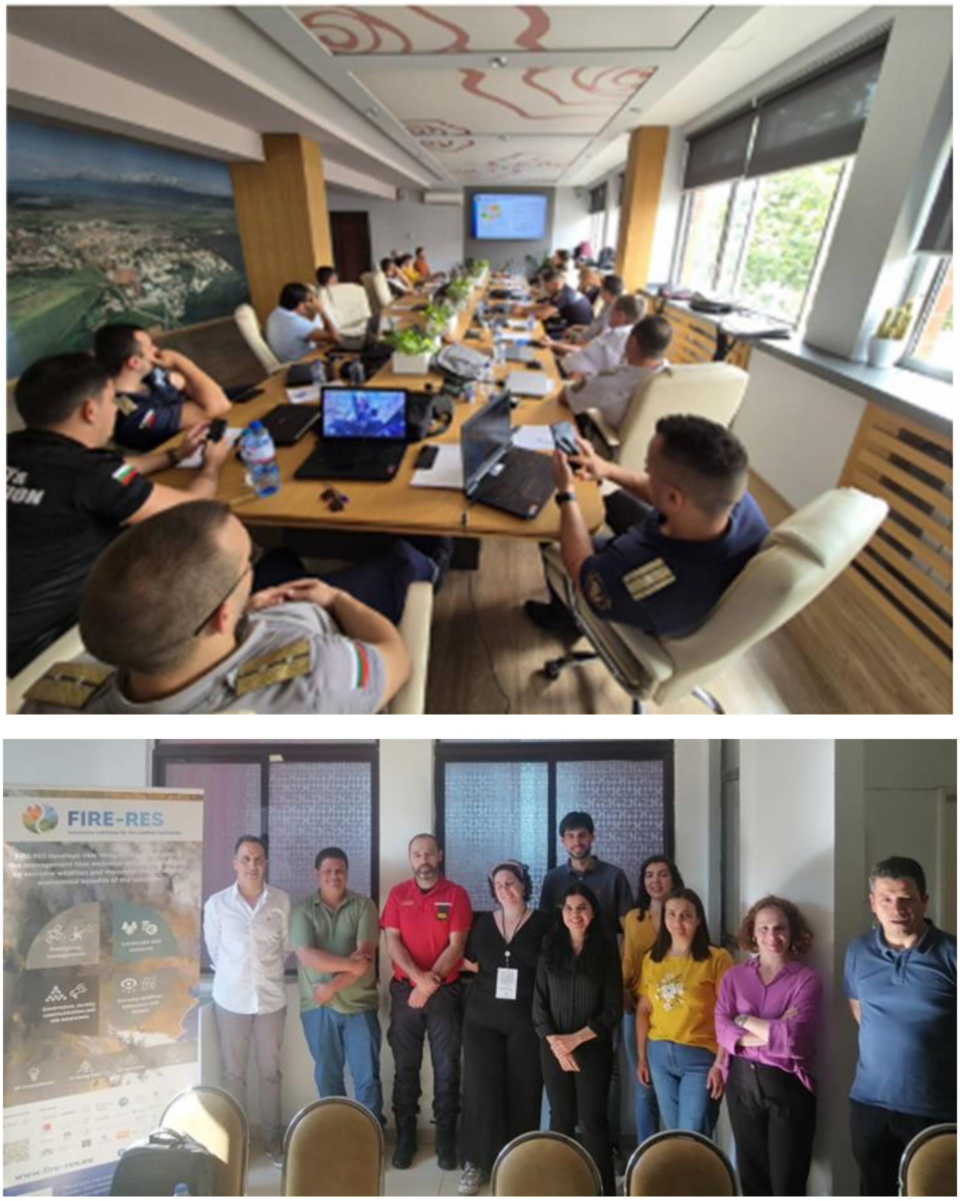


Figure 4. Examples of the focus group meetings: for the LL Bulgaria (above) and Portugal (bellow)

The process of identifying key actors was critical for engaging a reliable and diverse group of stakeholders with substantial knowledge of wildfire prevention, suppression, and forest management, as well as those involved in implementing or accepting any decision supported by our methods /actions. A systematic internal search and brainstorming process was conducted to identify participants with varied backgrounds, representing different institutions, teams, and levels of expertise. Emphasis was placed on assembling a group with heterogeneous characteristics, such as diversity in gender, age, and experience. After recruiting the first participants, a snowball sampling technique was utilized to identify additional key stakeholders, leveraging the knowledge of existing participants to recommend others with relevant expertise.

Once the stakeholders were identified, the first interaction was initiated. Despite the participatory nature of the process, it was necessary to acknowledge certain limitations in eliciting criteria and sub-criteria due to the availability of spatial data for each case study. To address this, the research team first reviewed the available data to ensure the feasibility of supporting the proposed criteria with existing spatial datasets. After this review, an online survey was developed to present participants with a pre-selected list of criteria and sub-criteria, aligned with the overall project objectives. Sub-criteria, representing measurable variables, were defined as attributes of broader criteria. Participants were then asked to evaluate the relevance of each criterion and sub-criterion, ensuring that the selection process reflected both expert insights and practical data constraints.

This collaborative and data-driven approach laid the groundwork for the accurate delineation of Priority Management Zones, ensuring that the forest fire risk assessment was informed by both local expertise and spatial analysis. Other inputs and applications of the participatory process are explained within the Step 2.

2.2. Multi-Attribute Utility Theory (MAUT) Analysis

Once the criteria and associated indicators for the allocation of Priority Management Zones were defined, the next step involved conducting a Multi-Attribute Utility Theory (MAUT) analysis. This approach was used to systematically evaluate and prioritize the defined zones based on multiple criteria. The MAUT analysis required the elicitation of utility functions and the assignment of weights to each criterion, allowing for the calculation of overall utility scores from the aggregated model.

The applied model follows a hierarchical structure, with the allocation of Priority Management Zones positioned at the top of the model tree. This top-level objective is supported by a set of criteria (C1–Cn), each representing a different dimension of fire risk and management priorities. Each of these five criteria is further broken down into a series of specific indicators (I1–In) that provide detailed quantitative or qualitative measures relevant to fire prevention (example on Figure 5).

By organizing the model hierarchically, the analysis allows for a clear delineation of how different criteria and indicators contribute to the overall goal of Priority Management Zones allocation. The utility functions capture the relative importance of each indicator, while the weights reflect stakeholder preferences and data-driven insights. The aggregation of these utility scores provides a comprehensive assessment of which zones should be prioritized for fire prevention efforts, ensuring that the final allocation is both data-informed and aligned with expert judgments. This structured approach facilitates the integration of diverse factors and data sources, resulting in a robust, multi-dimensional model for Priority Management Zones allocation.

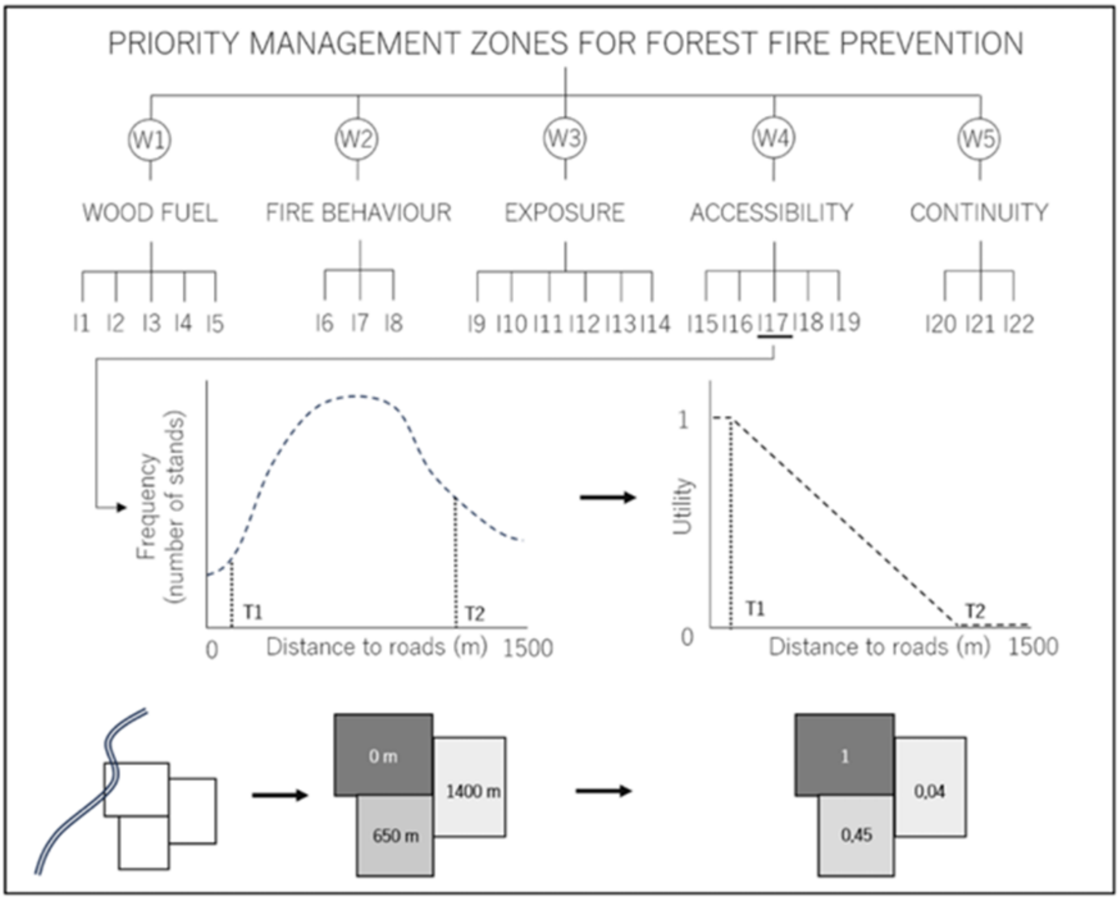


Figure 5: Example of hierarchical structure of the prioritization problem, where the overall priority depends on five different criteria, each one explained by a set of sub-criteria or indicators, normalized though a utility function. (from Krsnik et al., 2024)

Indicators represent the lowest level of the model, with their sole input being raw data (metrics). To convert this data into a format suitable for analysis, fuzzy membership functions are applied, **transforming each observed dataset into utility values that range from 0 to 1**. These utility values quantify the degree to which the data supports the logical statement associated with each indicator. By standardizing and normalizing the values in this way, the model enables direct comparisons between variables at all levels of the hierarchical tree structure, regardless of the original data formats or scales.

For example, as shown in Fig. 5, the model might include an indicator (I17) related to the proximity of forested areas to roads that are accessible to fire engines. Areas closer to suitable roads would be assigned higher utility values, reflecting a reduced risk of large-scale forest fires due to improved access for firefighting efforts. Conversely, forest stands located farther from accessible roads would receive lower utility values, indicating a higher risk level (Figure 6). The thresholds that determine whether a utility value is considered low or high are defined individually for each indicator through a participatory evaluation process, ensuring that local context and expert judgment are incorporated (Figure 7). To each different indicator a distinct fuzzy membership function was employed to normalize it. In most cases a Piecewise linear function (as in figure 6), defined by two saturation points (max and min utility) and an in-between linear interpolation was selected to define the utility function.

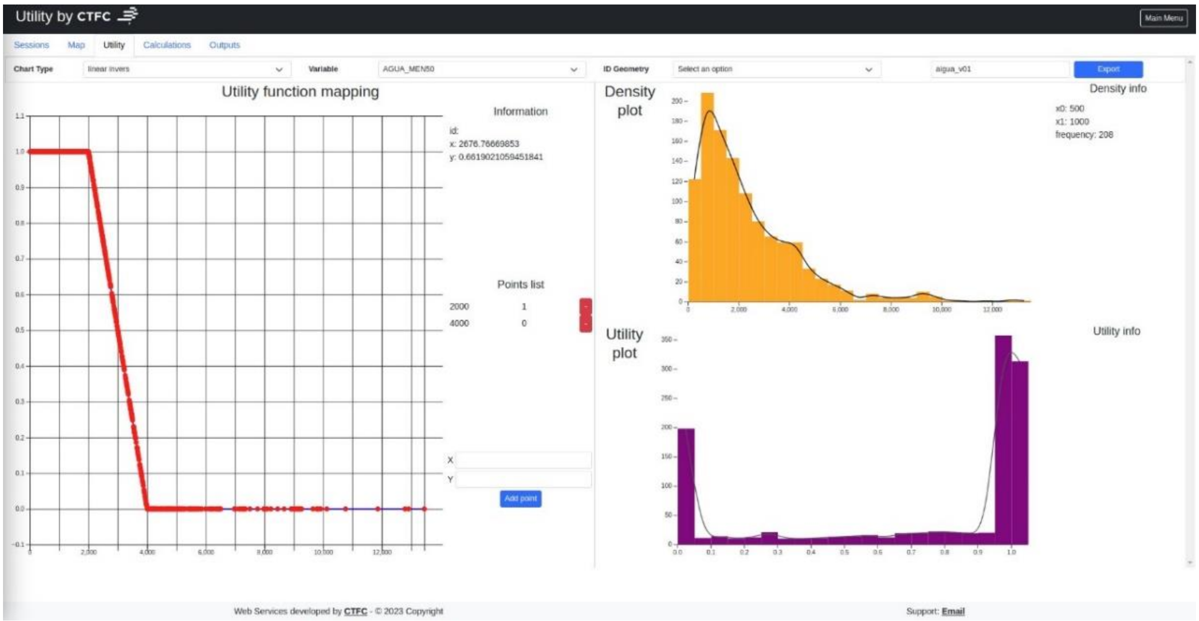


Figure 6. Example of the relationship between observed values and utility scores after the definition of thresholds. The transformation in this case being implemented using the CTFC_utility software

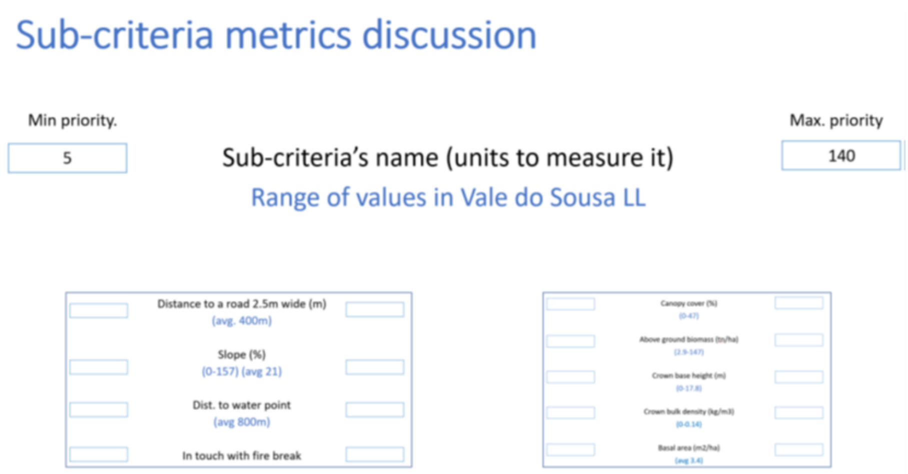


Figure 7. Visual support for the metrics selection and utility function definition during the focus groups in LL Portugal

Once utility values are assigned to each indicator, these values propagate upwards through the model hierarchy. This process results in utility values being calculated at all levels, from individual indicators to the overarching criteria that define the allocation of Priority Management Zones. The contribution of each indicator to its corresponding criterion is further refined by the assignment of fixed weights. These weights were determined through collective expert evaluation. An initial definition of weights, especially when involving large groups is the AHP (Satty ,1980; 1982), Analytic Hierarchy Process. In this process, each indicator was compared pairwise to others within the same criterion group (Figure 8), allowing for the derivation of preliminary weights that represent the relative importance of each indicator within its criterion.

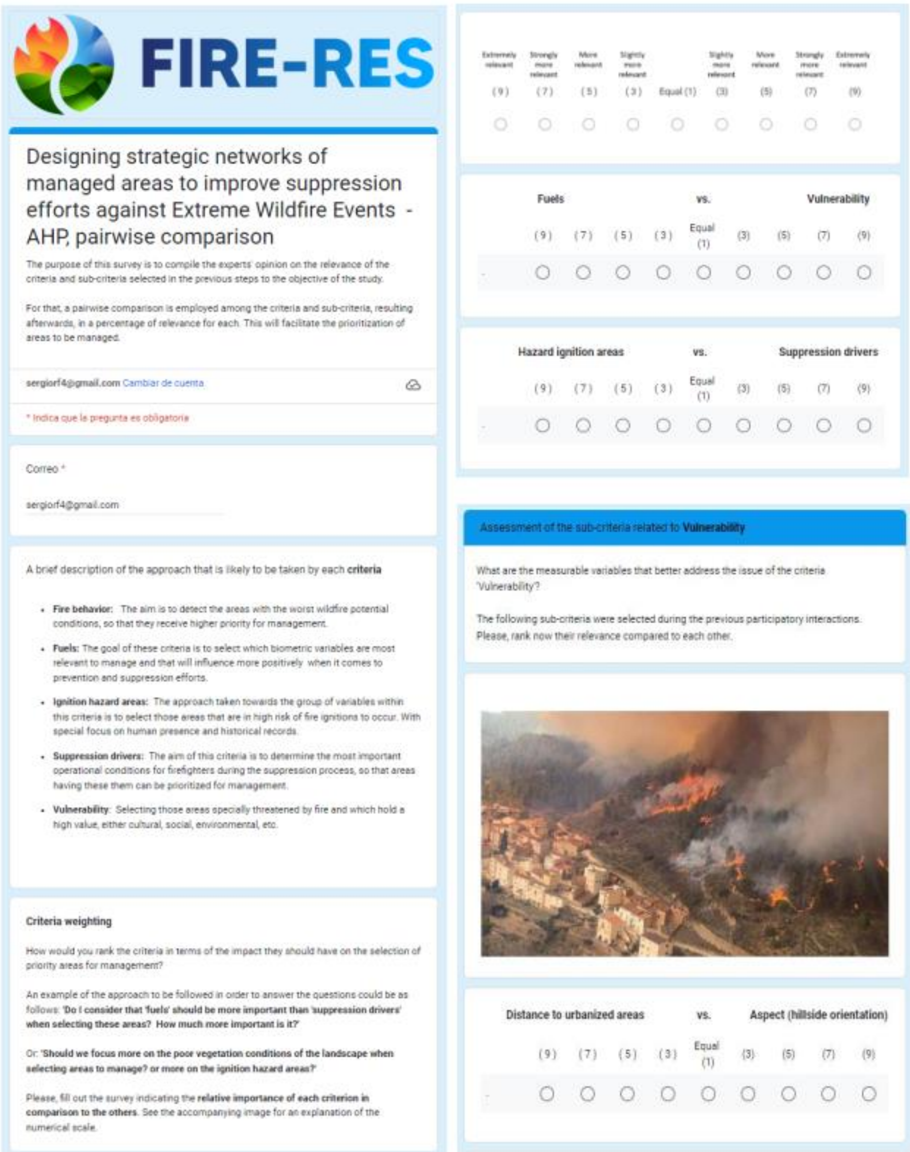


Figure 8. Example of visualisation of the AHP survey for weighting criteria in the LL Portugal

For example, on the case of the Portugal LL a specific assessment and use of the consistency of the judges was implemented. Weighting participants' performance is instrumental to ensure the reliability and validity of the participatory process. High

Consistency Ratios (CR) in participants' responses can arise due to several reasons: lack of expertise in the specific area, or misunderstandings in the pairwise comparison process. To address participant inconsistencies, the method suggested by Srđević et al. (2008) was adopted. This encompassed the assignment of weights to participants based on the normalization of reciprocal values of their consistency ratios (CR). This approach was influential to assessing participant performance down weighting their preferences based on the reasonable assumption that large inconsistencies in their preferences indicate a lack of knowledge of the area or an inability to use pairwise comparisons. By incorporating this method, the process aimed to achieve a balanced and representative aggregation of participant inputs, enhancing the robustness and reliability of the final prioritization outcomes.

In addition to weighting the indicators, each criterion (C1–Cn) was also assigned a weight (W1–Wn), reflecting its relative importance in the overall model, following the hierarchical structure defined in previous steps (Figure 5). These weights play a critical role in the final allocation of Priority Management Zones, as they indicate the relative significance of each criterion in shaping the decision-making process. It is important to note that the weights used in this study are preliminary and context-dependent. They are subjective and may vary based on the specific characteristics of the territory under consideration. For example, while an open participatory process involving several stakeholders or judges, can greatly benefit from a AHP method, a small case study with a limited number of highly involved decision makers, probably required a closed meeting were selecting the weights require from consensus and exercises were the impact of defining weights and criteria is evaluated.

2.3. Prioritization Maps Generation

The cartographic representation of the fire Priority Management Zones corresponds to the spatial distribution of utility values associated with the highest level of the model's hierarchical structure. These maps offer a visual interpretation of management priorities based on the calculated utility values. A priority value, equalling the utility score, was assigned to each of the polygons within the study area, indicating the relative priority for fire management interventions. These priority values were derived from the aggregated criteria utility levels and their respective weights, providing a spatially explicit representation of areas with varying levels of fire management priority.

To facilitate the cartographic visualization, the priority values could be visualized according to criteria or the overall priority from the additive weighted utility. This classification method allows for a consistent and balanced distribution of polygons across the different priority levels. It is important to note that the delineation of these categories is inherently subjective and was established specifically for visualization purposes. The categorization is not intended to reflect definitive thresholds for management actions but rather to provide a clear visual gradient of priority across the study area. These categories may be adjusted or refined based on the specific objectives of future research or management strategies, allowing for flexibility in interpreting and applying the cartographic outputs in different contexts.

The methodology was easy to implement in different platforms for mapping and presenting the results. In the case of the Portuguese LL, the use of the new EMDS version for ArcGIS Pro (similar to Marques *et al.*, 2021) was used to frame the problem and map the results (Figure 9). For the Bulgarian LL The processing of the data was done with ArcGIS and QGIS. The final datasets were organised in a GIS database compatible with the Forest Management Plans, which are also a GIS dataset in scale 1:10 000. Normalisation and Multiple-criteria decision analysis were performed with Python. Hence Jupyter Lab notebooks were created allowing further repeatability of the model once having new improved/updated datasets, or in case changes in normalisation or weights are needed. For the Catalonian LL, it was decided that a new software was to be implemented, tailored to the specific action, allowing to link the data normalization, the model hierarchy definition, and a direct visualisation of results (Figure 10).

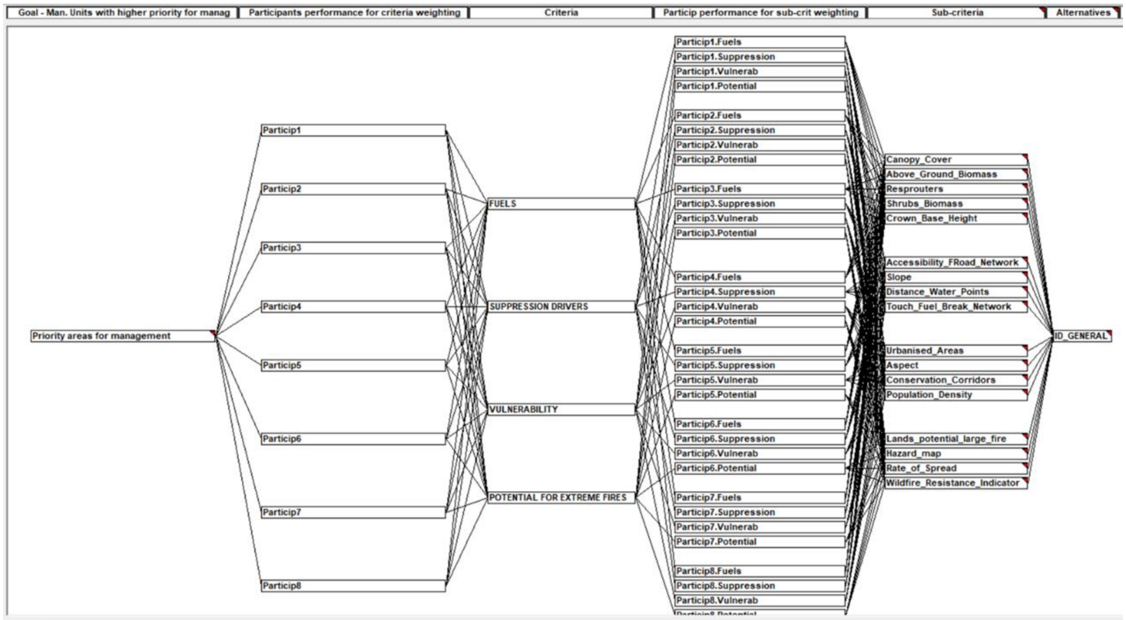


Figure 9. Example of the decision model defined in criterion decision plus to integrate judges preferences and consistency in EMDS before visualizing results. Method applied in the Portuguese LL

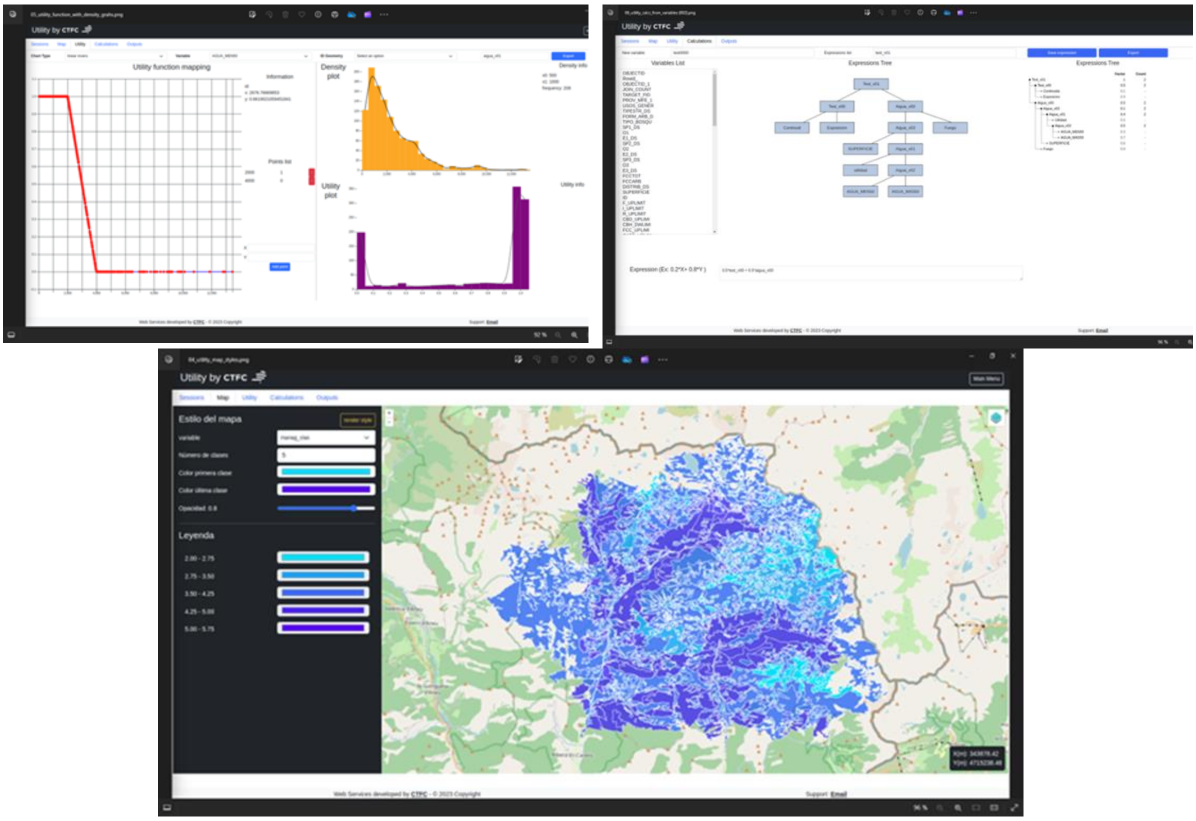


Figure 10: Screenshots of the new spatial prioritization software CTFC-utility, that allows to normalize variables using utility functions, define hierarchy of criteria within the priority problem, and visualize results, before exporting them to a GIS, when required.

The resulting priority maps could be used for open discussion on identifying the factors that should be considered in future assessments and needs of additional data. Regarding direct applications, the strategic knowledge provided by priority assessment and mapping is useful for selecting areas where fuel management is necessary (Keane et al., 2010), and define where public money is more efficiently allocated (Reynolds et al., 2009).

2.4. Multicriteria prioritization DSS: from easy strategic assessment to tactical

As shown in Figure 6 and 10, the CTFC has being involved on a tool to facilitate the process of normalizing variables, define hierarchy of criteria, and visualize results, all for the purpose of solving spatial multicriteria prioritization problem easily, **and when possible, with stakeholders present**.

For implementing the problem, the system allows to:

1) Create a project, main user/technician, and upload your data, providing different levels of accessibility to other users (from full access to edit, to just visualizing).

2) Select different metrics and normalize them using a utility/fuzzy model. The system allows to observe at the same time the distribution of the values (original and transformed on utility scores: as in Figure 6). The transformation will finish with the generation of a new variable and scores, linked to the spatial management units.

3) Defining the hierarchical setting of the additive MAUT problem. On a highly intuitive graphical interface it is possible to define which sub criteria/indicators define the value of a compound criteria, according to their values and relative weighs.

4) Visualize the values of any of the attributes of the spatial features of the project, including original data, value of the criteria, or overall priority (the process being faster that on most GIS, and within the project).

5) Export results, in the same format as were uploaded, but with the new results (generally .shp), or just the .csv or .xlsx, in a way that the user can implement additional tests, or work on a platform for reporting that suits her/him. Additionally, on a developing phase, and for more advanced users, the system is also able to export the prioritization problem on a structure that fits its use for selecting optimal management alternatives, that relate to the priority areas and associated rules.

2.4.1. From strategic to tactical: optimizing allocation of alternatives

Often, prioritization processes stay on a strategic phase, supporting policies, and helping to fully understand the interconnection between factors and opinions related to the problem. But his information seldom translates explicitly into the selection of management actions. Meaning that a tactical process of optimizing the allocation of management action follows an independent path (Carwardine et al., 2012; Game et al., 2013). Tactical planning, based on a prior strategic prioritization process, should consider the ability of management actions to impact the current landscape and strive to achieve a balanced state that meets the needs of all stakeholders. Specially, on a resource limited basis, it is clear that linking tactical optimization with a previously developed participatory prioritization process, should help to better allocate those limited resources, but more importantly generate a level of trust between stakeholders and planners, helping to cross the perception that optimization in planning process is a kind of "Black box".

For this purpose, we started to work on a system that uses the frame of the prioritization problem through Multi Attribute Utility Theory (MAUT), to maximize the impact of management, while considering budget, feasibility, or other constraints.

For this new task or line of applied research, we work with the University of Talca (Chile), having as result a first methodology that combines MAUT with Mix integer programming, to generate what we decline the **"The spatial multi-criteria prioritisation management problem**

(SMCPP)". Were the impact of management actions on the overall prioritization is maximized, or in our fuel management problem the priority is minimized. An important issue is that the management action affects the values of initial indicators, for example: Canopy base height (meters), Density of fuels in canopy (kg/ha), flame spread (meters/min). So, the optimization system reconverts the value of the indicator criteria into changes of the utility scores, and weights them similarly as in the original prioritization problem (Figure 11).

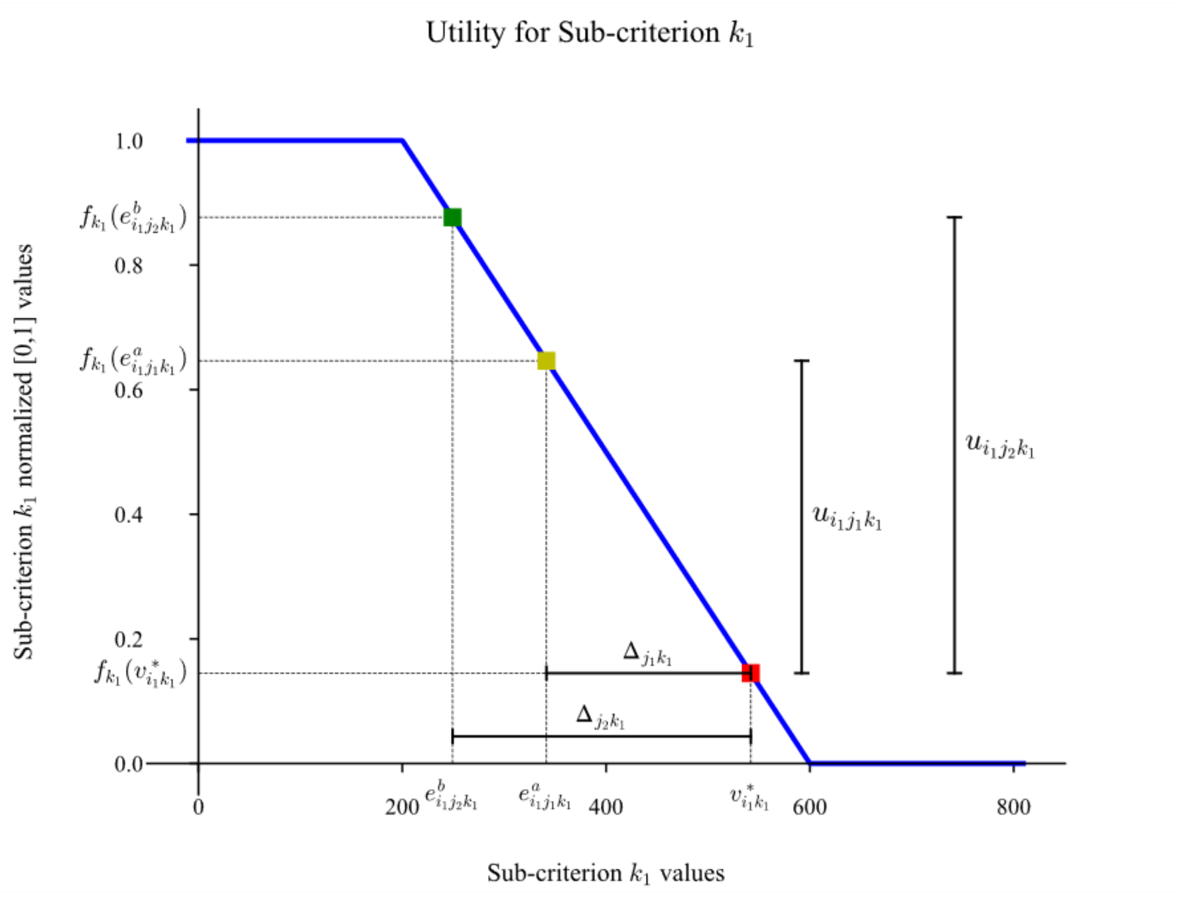


Figure 11: Example of two different prescriptions j_1, j_2 applied over a single management unit i_1 characterized with a unique sub-criterion k_1. The normalized values according to the utility function f_{k_1} allows to obtain the utility $u_{i_1 j_1 k_1}$, $u_{i_1 j_2 k_1}$ measures. (from Ulloa-Fierro et al., manuscript)

While the spatial prioritization system as in figure 10, has being tested and will be open soon, the optimization system still has only being tested on a theoretical frame, and we expect to use it in a real-world problem soon, as well as provide an adequate interface for linking the strategic and tactical part of the software. One of the relevant parts of the tactical optimization, is that it will use management alternatives and their impact from other FIRE-RES tasks (Task 1.4.3 and Task 2.1.3).

3. Results

As previously mentioned, a general problem and methodology was set for the implementation of the innovation action, but living a high degree of freedom to the living labs to define the extent, criteria, and adjustments to the method and tools that they thought adequate.

3.1. Vale do Sousa (LL PT)

3.1.1. Study area and Stakeholders

The case study area for this research is Vale do Sousa, located in northwestern Portugal, approximately 50 km east of Porto. This region extends over 28,941 hectares and includes joint collaborative management areas (ZIFs): Entre-Douro-e-Sousa (north of the Douro River) and Paiva (south of the Douro River). The primary land use in Vale do Sousa is forestry. The predominant species are eucalypt and maritime pine (*Eucalyptus globulus* Labill and *Pinus pinaster* Ait) while other species include pedunculate oak, chestnut and cork oak (*Quercus robur* L., *Castanea sativa* Mill., and *Quercus suber* L.).

Vale do Sousa has faced significant wildfire challenges. Notable extreme wildfire events include those in 2016, which burned 2,923 hectares (10.1% of the total area), and in 2017, which burned 7,428 hectares (25.7% of the total area), and 15% and 39% of the area covered with trees. These recurrent wildfires underscore the critical need for effective forest management and wildfire risk reduction strategies in the region.

The area is characterized by a fragmented forest ownership structure, with predominantly small, privately-owned forest holdings. The area has over 360 forest owners as members of the joint management areas. Previous studies (Borges et al., 2017; Marques et al., 2020) have highlighted a strong stakeholder interest in wildfire risk reduction, making Vale do Sousa an ideal location for this research. The local stakeholders include a diverse group of actors with varied interests and goals, ranging from timber production to wildfire risk reduction. This fragmented ownership and diversity of interests complicates forest management and necessitates collaborative approaches.

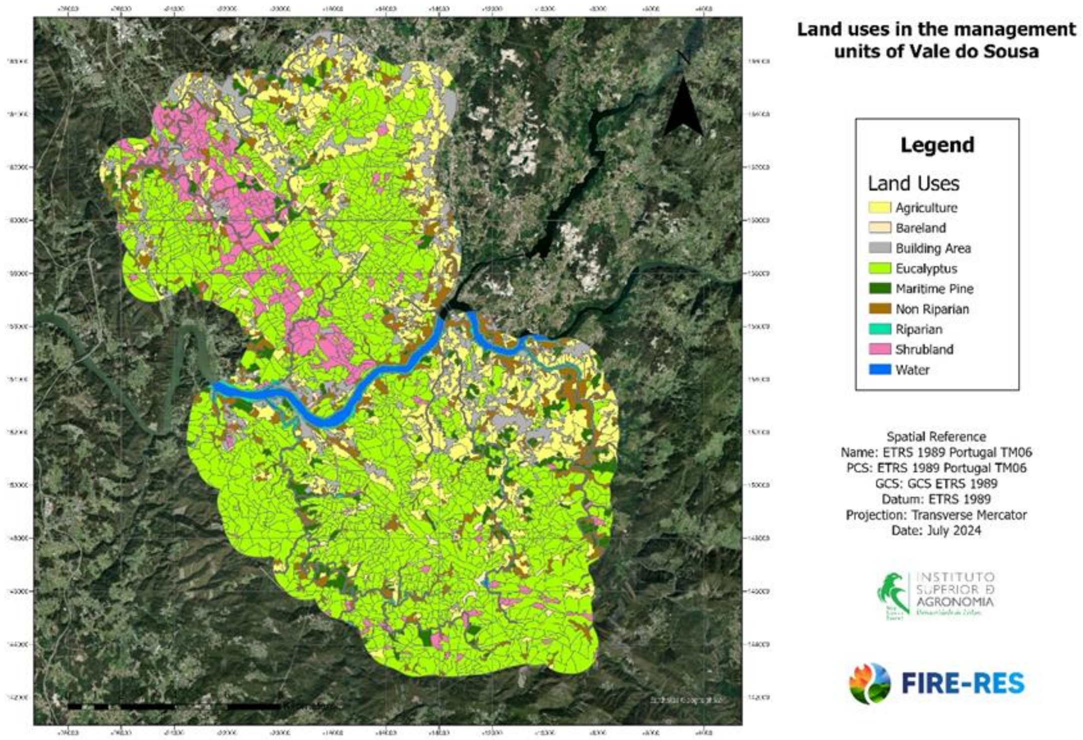


Figure 12: Study area of the Portuguese living lab in Vale do Sousa, and associated land uses

To address these challenges, the forest association 'Associação Florestal do Vale do Sousa' (AFVS) was established 29 years ago and leads the development of forest management plans within a complex decision-making context. This research took advantage of the existence of a Community of Wildfire Innovation (CWI) that includes a diverse group of stakeholders with representatives from the two AFVS local firefighters' brigades, eight municipalities, NGOs, forest industry, government and non-governmental organizations (D9.4 Technical Periodic Report 1, FIRE-RES Project).

A systematic approach was used to identify and engage a reliable and heterogeneous group of key stakeholders in wildfire prevention, suppression, and forest management from the Vale do Sousa CWI. A total of 22 people was contacted, with 19 ultimately participating in the first stage of the study. The participants represented a broad range of entities, including four municipal communities, the National Republican Guard, two public agencies responsible for environmental protection, a company specializing in forest fire protection and rural firefighting, two pulp and paper companies, an electric utility company overseeing powerline management, two local forest associations, three local firefighting organizations, and the National Authority for Emergency and Civil Protection.

3.1.2. Selection of Criteria, utility functions and weighs

Through a combination of online surveys (figure 3) and presential meeting, a set of criteria and sub-criteria ser defined. The Criteria for this Living lab and the other (BUL, CAT) being the result of adding the weighted score of lower-level indicators or sub-criteria, what can be called a composite criterion, and at the lower level the sub-criteria associated to indicators or metrics existing in current data.

In the case of Vale do Sousa, the participatory process resulted on the selection of 4 Criteria, and 17 sub-criteria or associated indicators (Table 1).

Table 1. Selected Criteria and Sub-criteria for the definition of areas to prioritize for management, LL Portugal

Criteria	Sub-criteria	Description	Units
Potential for extreme fires	Wildfire resistance indicator	Class in which the MU falls. Priority for stands with lower resistance	Class (1-5)
	Rate of spread	Calculated using Flammap. Priority for stands with higher potential ROS	m/min
	Hazard map	Obtained from ICNF. Ranked in 5 hazard classes	Classes (1-5)
	Potential large fires map	Obtained from ICNF. Percentage of the stand that falls within the areas holding this potential	Binary (0-1)
Fuels	Canopy cover	% of the stand covered by trees canopies	%
	Above ground biomass	Sum of the biomass of trees and shrubs	tn/ha
	Resprouters	% of resprouters in the stand vs. seeders.	%
	Shrubs biomass		m3/ha
	Crown base height	It defines the vertical continuity in the stand. A matter for crown fires	m
Suppression drivers	Accessibility for fire trucks	Euclidean Distance over the >2m roads and ZonalStats by mean	m
	Slope	Average percentage of slope of the stand.	%
	In touch with fire breaks	% of the MU that falls inside a planned Fuel Management Break	%
	Distance to water point	Euclidean Distance over the terrestrial-usage water points and ZonalStats by mean	m
Vulnerability	Distance to urbanized areas	Euclidean Distance over the urbanised areas and ZonalStats by mean	m
	Aspect	Classes. 4 max priority (East), 3 (West), 2 (South), 1 (North), 0 min. priority (flat)	Classes (1-4)
	Conservation corridors	% of the MU that is inside a conservation corridor	%
	Population density	People per km2. ZonalStats by mean	People/km 2

As mentioned in the methodology chapter, the use of MAUT requires for setting a utility function that converts our current data, and units, into a normalized unitless score that informs when a unit provides a maximum, minimum, or intermediate level of Utility/priority. For this purpose, the participatory process, in this case usually more restricted to experts, had to define the threshold for maximum and minimum priority levels (Table 2), if the values in between follow a linear interpolation. In some cases when the indicators are defined by categorical classes, each class is provided with an individual score (in the case of Vale de Sousa, the value corresponding to a linear interpolation).

Table 2. Assigned parameters to the sub-criteria for assigning utility functions, LL Portugal

Criteria	Sub-criteria	Parameters (min prior – max prior)
Potential for extreme fires	Wildfire resistance indicator	5 - 1
	Rate of spread	2 – 6
	Hazard map	1 - 5
	Potential large fires map	20 - 90
Fuels	Canopy cover	60 - 20
	Above ground biomass	5 - 300
	Resprouters	90 - 10
	Shrubs biomass	1 - 10
	Crown base height	2.5 - 4
Suppression drivers	Accessibility for fire trucks	100 - 80
	Slope	40 - 5
	In touch with fire breaks	15 - 60
	Distance to water point	1000 - 500
Vulnerability	Distance to urbanized areas	300 - 50
	Aspect	1 - 4
	Conservation corridors	0.2 -0.6
	Population density	20 - 250

Finally, wat is required for adding the scores of sub-criteria into criteria and criteria into overall priority are the relative weights of each. In the case of Portugal being obtained through AHP and adjust in results according to the consistency of the judges answers.

At the end the weights of the *composite* or main group criteria being as in Table 3, and those of the sub-criteria as in Table 4.

Table 3. Criteria main groups' weights, LL Portugal

Criteria weights (0-1)			
Fuels	Potential for extreme fires	Suppression Drivers	Vulnerability
0.389	0.36	0.068	0.183

Table 4. Sub-criteria weights grouped by their corresponding criteria, LL Portugal

Criteria	Sub-criteria	Weights (0-1) Per criteria group
Potential for extreme fires	Wildfire resistance indicator	0.072
	Rate of spread	0.464
	Hazard map	0.078
	Potential large fires map	0.383
Fuels	Canopy cover	0.108
	Above ground biomass	0.275
	Resprouters	0.085
	Shrubs biomass	0.337
	Crown base height	0.195
Suppression drivers	Accessibility for fire trucks	0.456
	Slope	0.265
	In touch with fire breaks	0.162
	Distance to water point	0.118
Vulnerability	Distance to urbanized areas	0.245
	Aspect	0.333
	Conservation corridors	0.257
	Population density	0.169

3.1.3. Resulting priority levels

By using the EMDS last version for ArcGis Pro, it was possible to map scores and priority levels for each sub-criteria, grouped criteria, and overall combined priority. In this case we present the results defined by 5 priority levels (set by score quintile divisions), for each of the grouping criteria, and the overall priority level (Figure 14)

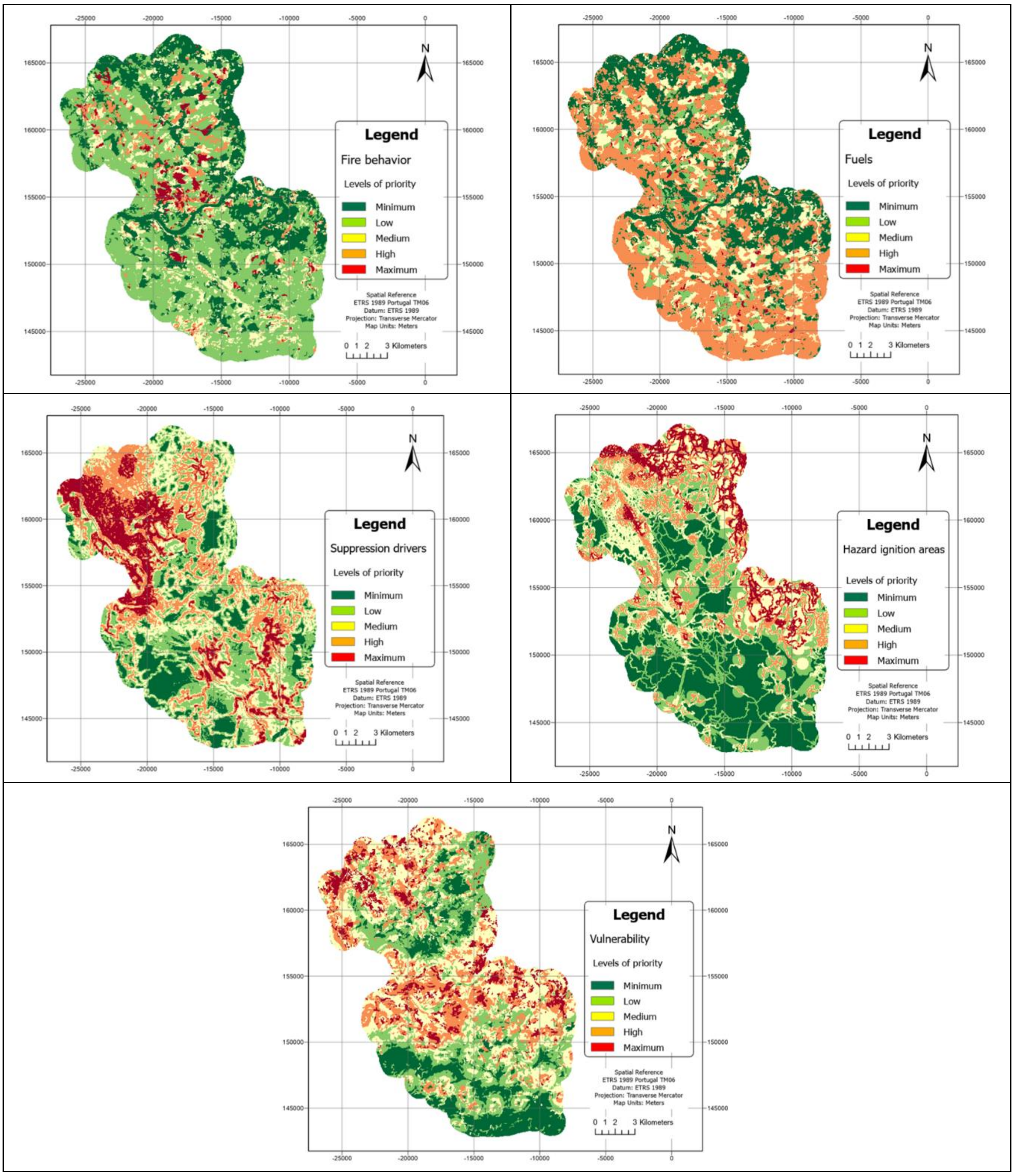


Figure 13: Priority levels associated to the 4 main criteria groups in Vale do Sousa

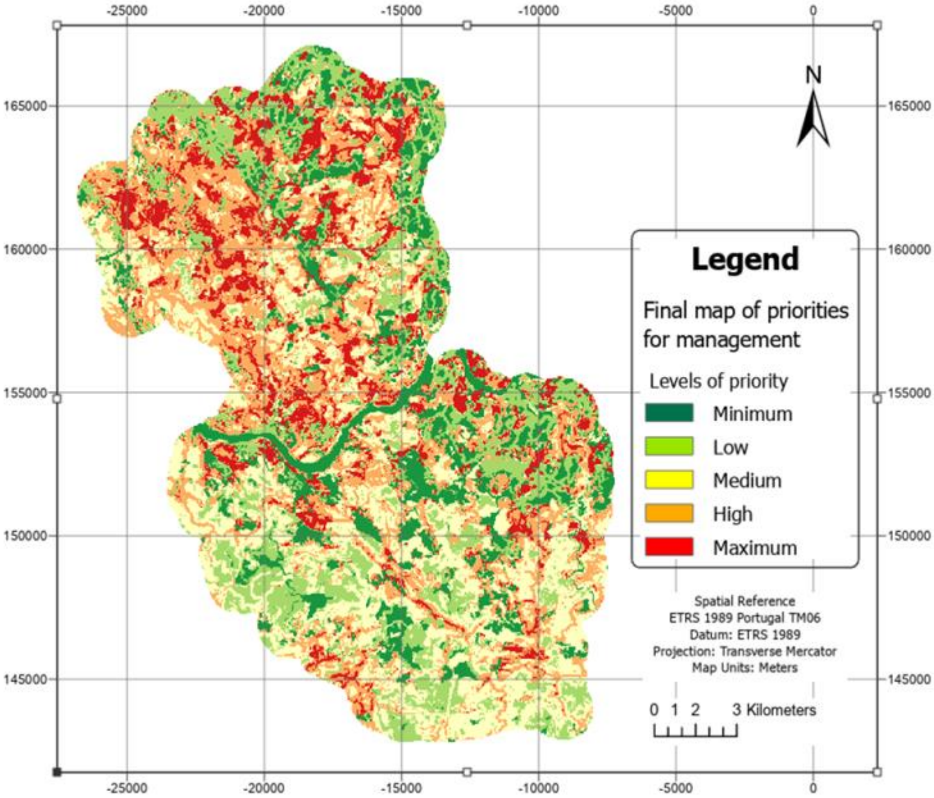


Figure 14: Final priority map, considering the added value of all criteria.

3.2. Stara Zagora (LL BUL)

3.2.1. Study area and Stakeholders

The case study area for this research is the Regional Forest Directorate (RFD) Stara Zagora (Figure 15) which comprise of 6 Forestries: Gurkovo, Kazanlak, Maglizh, Stara Zagora, Chirpan and Mazalat. The area of the RFD Stara Zagora 5154 sq.km. and is situated in south-central part of the country. The territory is representative of forestry in the plain and low-mountainous part of the country. In the area are also part of the southern slopes of the Balkan Mountain, with the characteristic features of the mountain nature. The climate is typical temperate continental with sub-mediterranean elements in the southern regions. Altitude of the area varies from 105 m to 2,276 m. The total area of the forests is 163,900 ha. The coppice oak forest stands are dominant, followed by artificial conifer plantations. They most often suffer from forest fires, because they are located in the inhabited areas up to about 1100 m above sea level. The high deciduous forests remained in the typical mountain areas of the Balkan Mountain. The main wood species in them is Common beech (*Fagus sylvatica* L.).

Current forest management models (cFMMs) relate to varying proportions of coppice oaks stands (*Quercus cerris* L., *Q. frainetto* Ten., *Q. sessiliflora* Salisb.) and artificial stands of Scots pine (*Pinus sylvestris* L.) and Black pine (*P. nigra* Arnold), The low forests are dominated by Eastern hornbeam (*Carpinus orientalis* Mill.) and are not actively managed today. They most often represent bush-forest formations on hard-to-reach low mountain slopes with relatively little fuel. Mountain high beech forests are the least affected by fires historically because they are in an area with a typical mountain climate.

The region of RFD Stara Zagora was subject to many forest fires. Between 2000 and 2021 more than 510 forest fires occur in the area. Even not all of the fires were large, more than 20 reached an area bigger than 200 ha, with the largest fires (4 cases) exceeding 1300 ha. The main problem here is the proximity of the fires to the settlement areas.

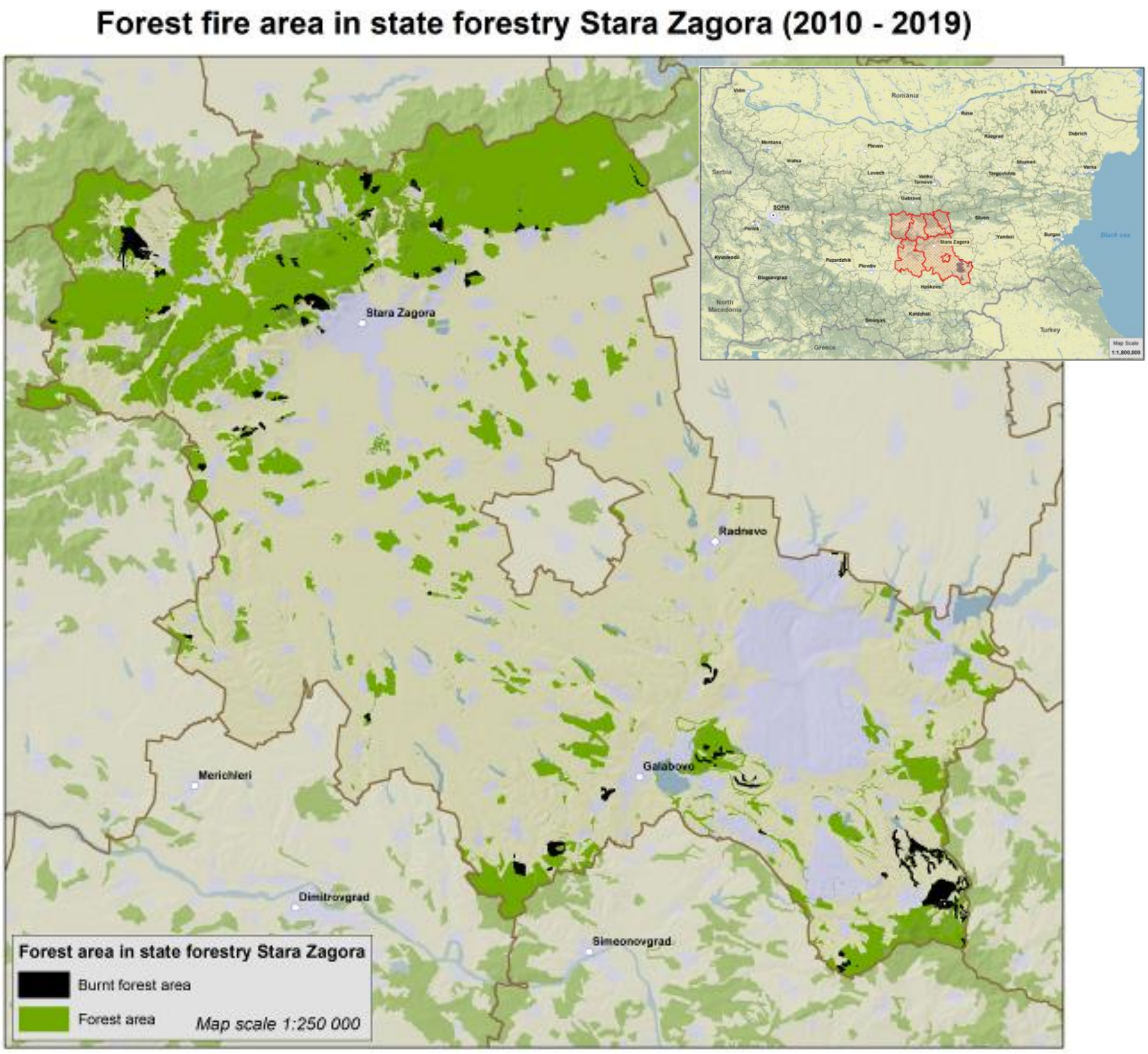


Figure 15: Study area of Stara Zagora in Bulgaria living lab

A total of 15 people were participated in the research as stakeholders and experts, on all the steps of the process, selection of criteria, definition of utility functions, and providing relative weighs. The experts and stakeholders were selected from the administrative staff, but also field experts form the forest management institutions, such as RFD Stara

Zagora, State Forestries, as well as firefighters from Regional Directorate "Fire Safety and Protection of the Population".

The involvement of the stakeholders included several meetings with additional e-mail exchange to clarify the scope of the research. The first meeting with stakeholders was held online on 26.09.2023 to define the main problems and requirements. The proposed approach was presented, emphasizing the clarification of the research's primary goal, including the collection of data from various institutions. Following the meeting, stakeholders were contacted via email to assist the research team with data collection and to help refine the research scope.

3.2.2. Selection of Criteria, utility functions and weighs

Through the engagement explained above, a set of criteria and sub-criteria ser defined. In the case of Stara Zagora, the different levels of criteria and indicators were defined prior to reach the overall priority. Four general criteria were derived from 14 criteria that were at the same time derived from a group set of 33 indicators (Table 5).

Table 5. Selected Criteria and Sub-criteria for the definition of areas to prioritize for management, LL Bulgaria

Criteria group	Criteria subgroup	Indicators	Description of the indicator	Units
Fire Hazard	Fuel Characteristics	1.1.1. Canopy cover	Canopy cover in a stand	numeric
		1.1.2. Canopy base height	Average height from the ground to a forest stand's canopy bottom	m
		1.1.3. Canopy bulk density	The mass of available canopy fuel per canopy volume unit	kg/m3
		1.1.4. Tree height	The average height of the top of the vegetated canopy	float
		1.1.5. Fire hazard class (FMP)	Classes of fire hazard	Class (1-3)
		1.1.6. Forest Type (FMP)	Type of forest in the stand	Class (1-3)
		1.1.7. Understory	Coefficient between Cover/Height/Three Species in a stand	float
	Fire Behavior	1.2.1. Flame length	Flame length	m
		1.2.2. Rate of spread	Rate of fire spread	m min-1
		1.2.3. Fireline Intensity	Fireline intensity	kW min-1
		1.2.4. Reaction Intensity	Rate of the energy release per area	kJ/min/m2

Criteria group	Criteria subgroup	Indicators	Description of the indicator	Units
		1.2.5. Crown Fire Activity	Classes of Crown Fire Activity	Class (1-3)
		1.2.6. Slope		degree
	Past Fire Events	1.3.1. Number of Past events	Number of past fire events per unit 2000-2020	Class (1-3)
		1.3.2. Total burned area per fire event	Total burned area per event in which the current unit is burned	float
	Fire Susceptibility	1.4.1. Distance to arable land and pastures	Distance to agricultural land for arable farming and pastures	m
		1.4.2. Distance to road infrastructure	Distance to roads, railroads (without forest roads)	m
		1.4.3. Distance to settlements borders	Distance to the borders of the settlements	m
Exposure/Vulnerability	Human Health	2.1.1. Distance to urban areas	Distance to residential areas	m
		2.1.2. Distance to schools, hospitals and other social institutions	Distance to the infrastructure object	m
	Economic Activity	2.2.1. Distance to industrial areas	Distance to the industrial areas	m
		2.2.2. Distance to pollutant sources	Distance to the facilities in the registries of the MoEW	m
	Cultural heritage	2.3.1. Distance to cultural heritage	Distance to the cultural area	m
	Environment	2.4.1. Distance to protected areas Protected Areas Law	Distance to the areas from Protected Areas Law	m
		2.4.2. Distance to protected areas Biodiversity Law	Distance to protected areas Biodiversity Law (NATURA 2000)	m
	Critical Infrastructure	2.5.1. Distance to critical infrastructure	Distance to the infrastructure subject to importance for the Fire Brigades	m
Management Activities	Topographic characteristics	3.1.1. Slope	The percent change in elevation over a certain distance	degree
		3.1.2. Topographic complexity	Measure of topographic heterogeneity	float
	Access to infrastructure and facilities	3.2.1. Distance to roads	Distance to roads (including forest roads)	m
		3.2.2. Distance to water bodies and hydrants	Distance to water bodies - main rivers and standing water bodies	m

Criteria group	Criteria subgroup	Indicators	Description of the indicator	Units
		3.2.4. Distance to fire service units	Distance to the location of the fire brigades	m
Long-term Changes	Climate changes	4.1.1. Habitat	Habitat type	Classes (1-4)
	Territorial development	4.2.1. Distance to new territorial development areas	Distance to new territorial development areas defined in the Territorial Management Plans	m

As in the case of LL Bulgaria, at the lowest level of the priority, indicator level, the experts defined values and functions to comber the values of the indicators into a utility function and be able to normalize the results into prioritization score (Table 6).

Table 6. Assigned parameters to the sub-criteria for assigning utility functions, LL Bulgaria

Criteria group	Criteria subgroup	Indicators	Parameters (min prior – max prior)
Fire Hazard	Fuel Characteristics	1.1.1. Canopy cover	2 - 6
		1.1.2. Canopy base height	Min-Max Normalisation
		1.1.3. Canopy bulk density	Min-Max Normalisation
		1.1.4. Tree height	1 - 10
		1.1.5. Fire hazard class (FMP)	3 - 1
		1.1.6. Forest Type (FMP)	0: broadleaf 1: coniferous
		1.1.7. Understory	Ratio between height and cover of understory for all forest level
	Fire Behaviour	1.2.1. Flame length	Min-Max Normalisation
		1.2.2. Rate of spread	Min-Max Normalisation
		1.2.3. Fireline Intensity	Min-Max Normalisation
		1.2.4. Reaction Intensity	Min-Max Normalisation
		1.2.5. Crown Fire Activity	1 - 3
		1.2.6. Slope	5 - 25
	Past Fire Events	1.3.1. Number of Past events	0 - 2
		1.3.2. Total burned area per fire event	0 - 20
	Fire Susceptibility	1.4.1. Distance to arable land and pastures	1000 - 200
		1.4.2. Distance to road infrastructure	1000 - 200

Criteria group	Criteria subgroup	Indicators	Parameters (min prior – max prior)
		1.4.3. Distance to settlements borders	1000 - 100
Exposure/Vulnerability	Human Health	2.1.1. Distance to urban areas	7500 - 500
		2.1.2. Distance to schools, hospitals and other social institutions	7500 - 1000
	Economic Activity	2.2.1. Distance to industrial areas	7500 - 500
		2.2.2. Distance to pollutant sources	7500 - 1000
	Cultural heritage	2.3.1. Distance to cultural heritage	5000 - 2500
	Environment	2.4.1. Distance to protected areas Protected Areas Law	1500 - 250
		2.4.2. Distance to protected areas Biodiversity Law	1500 - 0
	Critical Infrastructure	2.5.1. Distance to critical infrastructure	5000 - 250
Management Activities	Topographic characteristics	3.1.1. Slope	30 - 5
		3.1.2. Topographic complexity	Min-Max Normalization
	Access to infrastructure and facilities	3.2.1. Distance to roads	1500 - 500
		3.2.2. Distance to water bodies and hydrants	3000 - 100
		3.2.4. Distance to fire service units	7000 - 2000
Long-term Changes	Climate changes	4.1.1. Habitat	1 - 3
	Territorial development	4.2.1. Distance to new territorial development areas	7500 - 250

Also, weights were defined for each of the 3 hierarchical levels that had to be grouped to obtain the overall priority. While in table 7 the final column, named *weights i* indicates the weighs of the individual indicators, the weights of the Second level of Criteria, named in this case Criteria Subgroups, are presented in the column *weights sc*. Finally, the weights of the 4 large criterion groups are presented in table 8.

Table 7. Indicator and criteria subgroup weights, LL Bulgaria.

Criteria group	Criteria subgroup	Weights sc	Indicators	Weights i
Fire Hazard		0.4	1.1.1. Canopy cover	0.2

Criteria group	Criteria subgroup	Weights sc	Indicators	Weights i
	Fuel Characteristics		1.1.2. Canopy base height	0.05
			1.1.3. Canopy bulk density	0.05
			1.1.4. Tree height	0.05
			1.1.5. Fire hazard class (FMP)	0.1
			1.1.6. Forest Type (FMP)	0.3
			1.1.7. Understory	0.25
	Fire Behaviour	0.3	1.2.1. Flame length	0.1
			1.2.2. Rate of spread	0.2
			1.2.3. Fireline Intensity	0.2
			1.2.4. Reaction Intensity	0.2
			1.2.5. Crown Fire Activity	0.2
			1.2.6. Slope	0.1
	Past Fire Events	0.1	1.3.1. Number of Past events	0.3
			1.3.2. Total burned area per fire event	0.7
	Fire Susceptibility	0.2	1.4.1. Distance to arable land and pastures	0.5
			1.4.2. Distance to road infrastructure	0.25
			1.4.3. Distance to settlements borders	0.25
Exposure/Vulnerability	Human Health	0.5	2.1.1. Distance to urban areas	0.3
			2.1.2. Distance to schools, hospitals and other social institutions	0.7
	Economic Activity	0.2	2.2.1. Distance to industrial areas	0.3
			2.2.2. Distance to pollutant sources	0.7
	Cultural heritage	0.02	2.3.1. Distance to cultural heritage	1
	Environment	0.05	2.4.1. Distance to protected areas Protected Areas Law	0.8
			2.4.2. Distance to protected areas Biodiversity Law	0.2
	Critical Infrastructure	0.2	2.5.1. Distance to critical infrastructure	1
Management Activities	Topographic characteristics	0.35	3.1.1. Slope	0.6
			3.1.2. Topographic complexity	0.4
	Access to infrastructure and facilities	0.65	3.2.1. Distance to roads	0.4
			3.2.2. Distance to water bodies and hydrants	0.3

Criteria group	Criteria subgroup	Weights sc	Indicators	Weights i
			3.2.4. Distance to fire service units	0.3
Long-term Changes	Climate changes	0.7	4.1.1. Habitat	1
	Territorial development	0.3	4.2.1. Distance to new territorial development areas	1

Table 8. Criteria main groups' weights, LL Bulgaria

Group Criteria weights (0-1)			
Fire Hazard	Exposure/Vulnerability	Management Activities	Long-Term Changes
0.3	0.3	0.3	0.1

3.2.3. Resulting priority levels

When representing the priority levels of the 53 223 stands on the living lab, the final datasets were organized in a GIS database compatible with the Forest Management Plans, which are also a GIS dataset in scale 1:10 000.

The analyses, GIS datasets, and maps were presented to stakeholders during a specially organized training session in Kazanlak Municipality in August 2024. The meeting was attended in person by 20 stakeholders from the forestry sector and firefighting services. Each participant received open-source GIS software, the developed GIS database, and maps for each indicator, subgroup, and group. A short GIS training was provided, with a special focus on utilizing the produced datasets—covering how to perform queries, extract information, and prepare maps.

Additionally, an introduction to the use of satellite data from the EU's Earth Observation Programme, Copernicus, was given. This session covered how to detect fires, calculate damaged areas, and integrate data from FIRMS with local forest datasets.

Next, we show the main results of the main group criteria an overall priority (Figure 16 and 17).

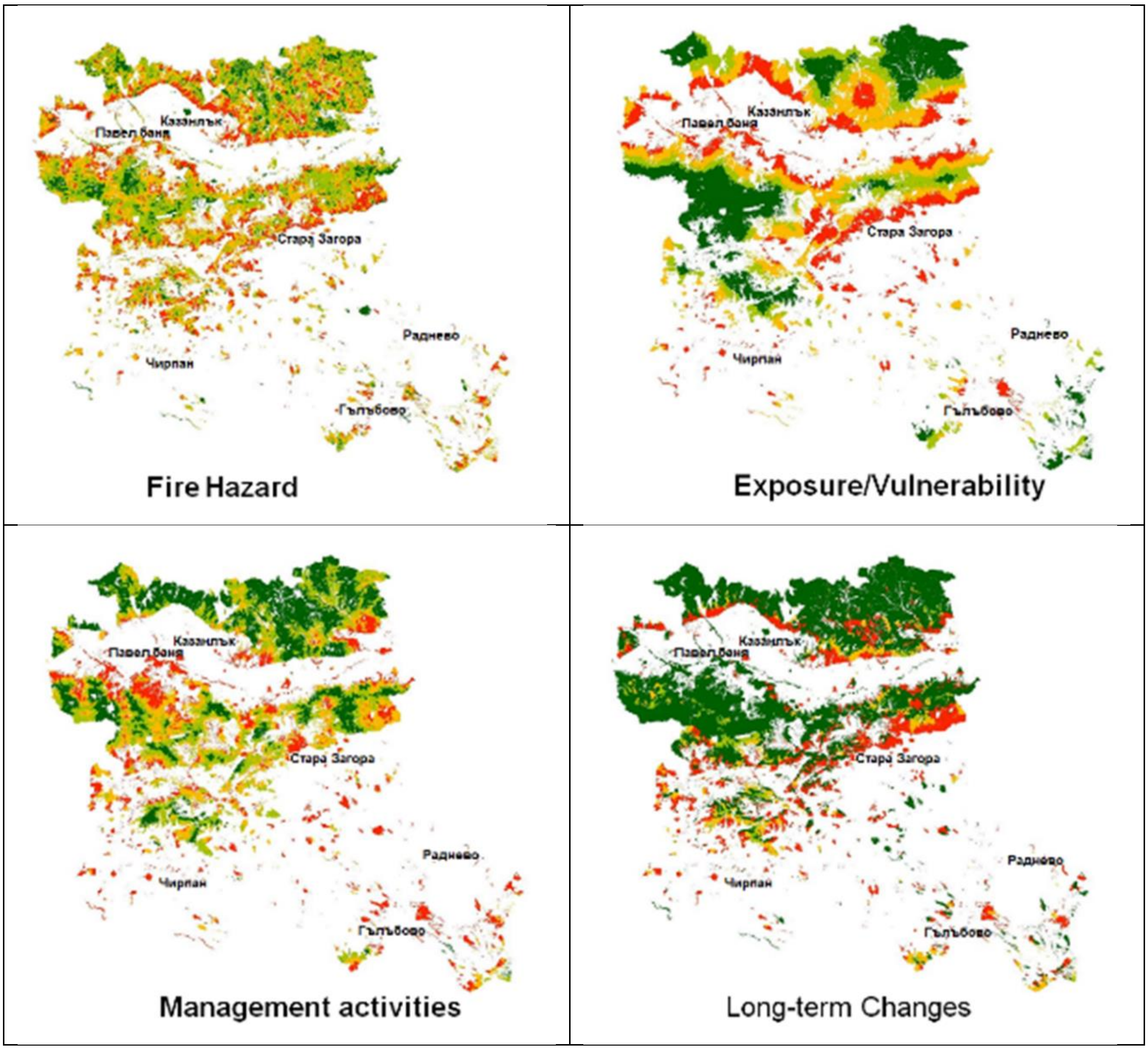
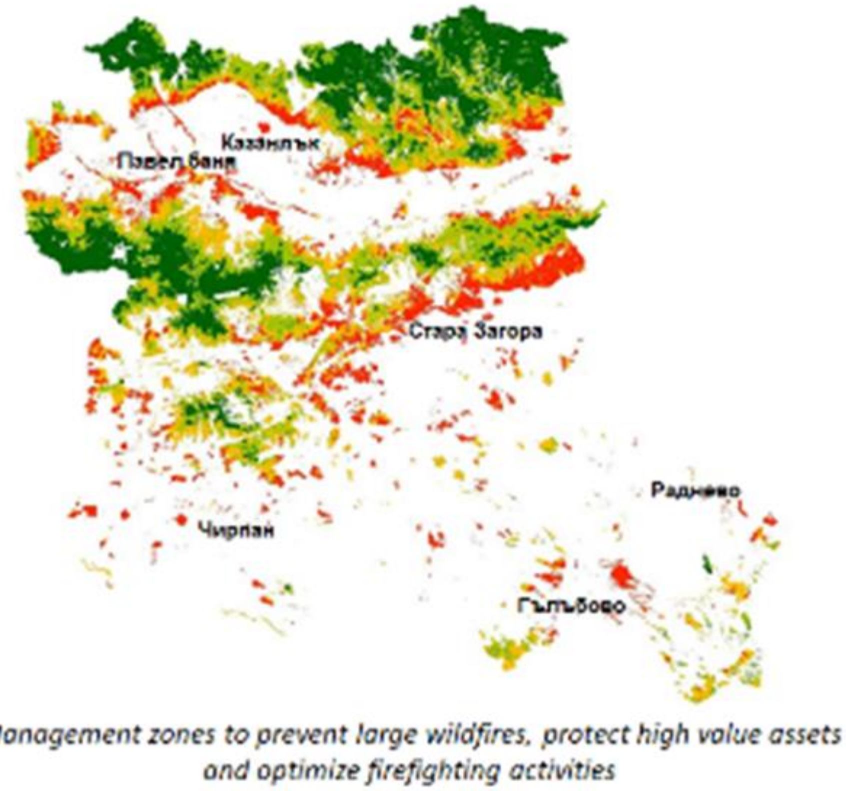


Figure 16: Priority levels associated to the 4 main criteria groups in Stara Zagora



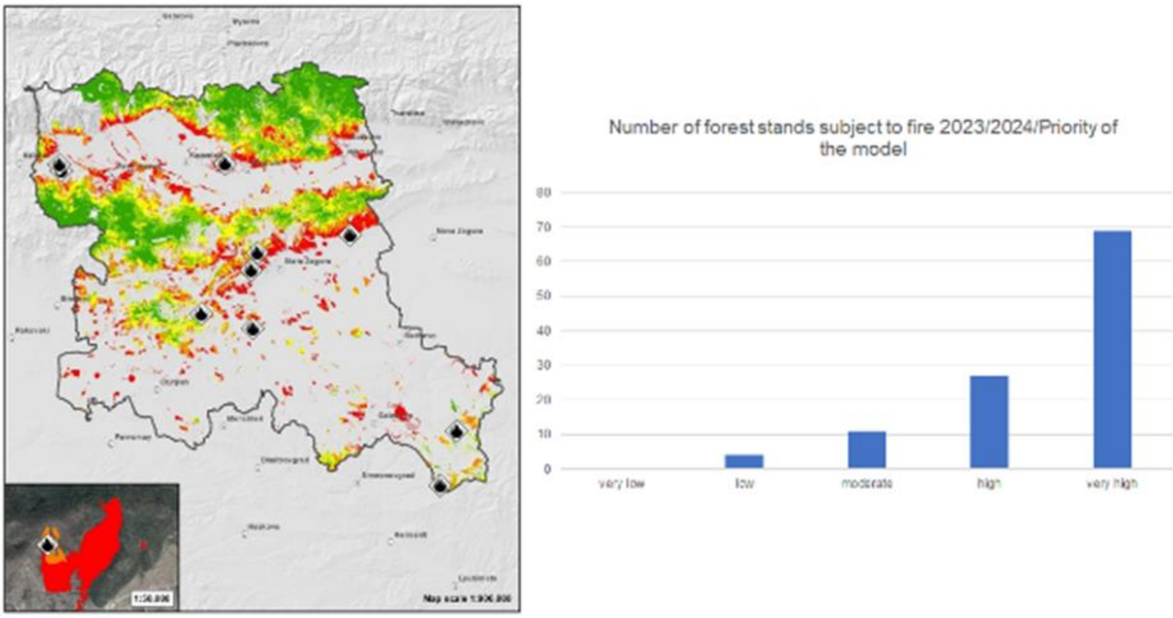


Figure 17: Overall Priority levels in Stara Zagora, and evaluation with historical fire data

3.3. Catalonia (LL CAT)

3.3.1. Study area and Stakeholders

Our research was conducted within the autonomous community of Catalonia, situated in the northeastern region of Spain. Based on data from the Land Cover Map of Catalonia, about 42% of the approximately 32,000 square kilometres of Catalan land are categorized as wooded forest areas. Of the total forested area, approximately 75% is under private ownership. The region faces difficulties in formulating and executing effective forest management strategies due to the significant fragmentation of land ownership. The primary tree species in terms of abundance include *Pinus sylvestris*, *Pinus halepensis*, and *Quercus ilex*. The region exhibits significant orographic variation, encompassing altitudes spanning from sea level to over 3000 meters. These elevational differences exert considerable impacts on the local climate, which ranges from semi-arid conditions to subarctic climates with Mediterranean influences, affecting fire susceptibility. Over the past three decades, Catalonia has experienced the detection of 21,686 forest fires, resulting in the scorching of approximately 265,000 hectares of wooded terrain. As such, the imperative of forest fire management becomes evident, necessitating the exploration of effective strategies to mitigate the impacts of fire damage. For this purpose, our study utilized stand-level information extracted from the Spanish Forest Map 1:25,000 to compute the metrics. In entirety, a total of 238,096 polygons were employed to conduct the MAUT analysis.

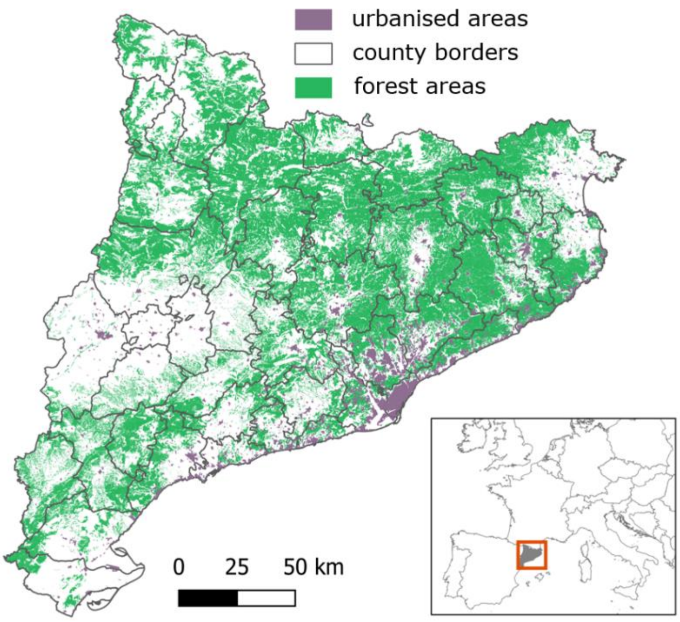


Figure 18. Whole region Catalonia living lab

A total of 14 participants took part in the participatory process conducted in the Catalonia Living Lab. These participants, representing a diverse range of expertise, engaged in several focus group sessions where they collaboratively contributed to the selection of criteria and indicators, as well as the definition of utility rules and the assignment of weights for each included variable. The group was carefully selected to ensure comprehensive representation, drawing participants from regional and local forest administrative authorities, forest management institutions, firefighting services, and forestry research institutes.

3.3.2. Selection of Criteria, utility functions and weighs

The stakeholder involvement spanned multiple phases and included a series of both in-person and online meetings. Initial contact was made via email, inviting participants to attend live focus group discussions. These smaller group sessions were designed to foster active engagement and open discussion on relevant aspects of the study. During these meetings, the primary focus was on defining the hierarchical structure of the decision-making model, and selecting the appropriate criteria and indicators (Table 10) for the analysis.

In addition to the participatory discussions, a combination of expert knowledge and a thorough review of existing literature was employed to determine parameterization thresholds and establish utility rules for each indicator (Table 11). This ensured that the decision-making process was not only grounded in local knowledge but also informed by scientific evidence and best practices in wildfire prevention and forest management.

Finally, the stakeholders were engaged through an online Analytic Hierarchy Process (AHP) questionnaire, which was used to finalize the weighting of criteria and indicators. This step was critical in determining the relative importance of each factor within the multi-criteria analysis. The combination of focus group discussions and the AHP methodology ensured a balanced, transparent, and data-driven approach to the participatory process, incorporating both expert judgment and collaborative decision-making (Table 12), although the regional assessment being so strategic in nature, would require from a larger more carefully elaborated decision theatre.

Table 9. Selected Criteria and Sub-criteria selected in the Catalonia LL, in some cases the metrics of the indicators were defined by the share of area within a stand above or below a certain threshold that the experts considered extremely hazardous (in case of fuels and fire behaviour)

Criteria	Indicators	Description	Applied threshold and/or unit
Wood fuel (C1)	Canopy base height (I1)	% of the stand area with values below the established threshold	5.5 m
	Canopy cover (I2)	% of the stand area with values above the established threshold	50 %
	Canopy bulk density (I3)	% of the stand area with values above the established threshold	0.15 km/m3
	Understory cover (I4)	% of the stand area with values above the established threshold	30 %

Criteria	Indicators	Description	Applied threshold and/or unit
	Vertical continuity (I5)	% of the stand area with values below the established threshold	5 m
Fire behaviour (C2)	Fire intensity (I6)	% of the stand area with values above the established threshold	350 Kw/m
	Spread speed (I7)	% of the stand area with values above the established threshold	1.2 km/h; 0.33 m/s
	Flame height (I8)	% of the stand area with values above the established threshold	3 m
Exposure (C3)	Urbanised areas (I9)	Distance to the closest urbanised area from each stand centroid	m
	Recreational areas (I10)	Distance to the closest homologated hiking trail from each stand centroid	m
	Capitalisation (I11)	Comparison between mean basal area and the established threshold	40 m2/ha
	Protected nature (I12)	Distance to the closest RedNatura 2000 area from each stand centroid	m
	Cultural heritage (I13)	Distance to the closest architectonic, archaeological or paleontological monument from each stand centroid	m
	Strategic infrastructure (I14)	Distance to the closest powerline or highway from each stand centroid	m
Accessibility (C4)	Aspect (I15)	Terrain slope	%
	Road density (I16)	Density of path and roads wider than 2.5 m (suitable for fire engines) within each stand	km/km2
	Road distance (I17)	Distance to the closest path or road wider than 2.5 m (suitable for fire engines) from each stand centroid	m
	Water availability (I18)	Distance to the closest water body or well with the capacity of more than 50 m3 from each stand centroid	m
	Strategical management areas (I19)	Distance to the closest area classified as strategical management area from each stand centroid	m
Continuity (C5)	Fire risk level (I20)	Fire risk level based on intrinsic forest fire characteristics	Categorical 1-4
	Agroforested areas (I21)	% of agroforested area within 1 km buffer from each stand centroid	%
	Return period (I22)	Return period in case of forest fire	years

Table 10. Assigned parameters to the sub-criteria for assigning utility functions, LL Catalonia

Criteria	Indicators	Unit	Utility 0 threshold	Utility 1 threshold
Wood fuel (C1)	Canopy base height (I1)	%	30	60
	Canopy cover (I2)	%	30	60
	Canopy bulk density (I3)	%	30	70

Criteria	Indicators	Unit	Utility 0 threshold	Utility 1 threshold
	Understory cover (I4)	%	30	70
	Vertical continuity (I5)	%	0	25
Fire behaviour (C2)	Fire intensity (I6)	%	10	50
	Spread speed (I7)	%	10	50
	Flame height (I8)	%	10	50
Exposure (C3)	Urbanised areas (I9)	metres	7500	0
	Recreational areas (I10)	metres	1000	0
	Capitalisation (I11)	m2/ha	0	40
	Protected nature (I12)	metres	1500	250
	Cultural heritage (I13)	metres	5000	250
	Strategic infrastructure (I14)	metres	2500	0
Accessibility (C4)	Slope (I15)	%	45	5
	Road density (I16)	km/km2	180	90
	Road distance (I17)	metres	1000	150
	Water availability (I18)	metres	1200	0
	Strategical management areas (I19)	metres	175000	1300
Continuity (C5)	Fire risk level (I20)	Cat. 1-4	1=0; 2=0.33; 3= 0.66; 4=1	
	Agroforested areas (I21)	%	80	20
	Return period (I22)	years	500=0; 100=5; 30=1	

Table 11. Indicator weights, LL Catalonia

Criteria	Indicators	Weights
Wood fuel (C1)	Canopy base height (I1)	0.21
	Canopy cover (I2)	0.13
	Canopy bulk density (I3)	0.13
	Understory cover (I4)	0.3
	Vertical continuity (I5)	0.24
Fire behaviour (C2)	Fire intensity (I6)	0.42
	Spread speed (I7)	0.25
	Flame height (I8)	0.33
Exposure (C3)	Urbanised areas (I9)	0.33
	Recreational areas (I10)	0.15
	Capitalisation (I11)	0.09
	Protected nature (I12)	0.21
	Cultural heritage (I13)	0.14
	Strategic infrastructure (I14)	0.07
Accessibility (C4)	Slope (I15)	0.24
	Road density (I16)	0.22
	Road distance (I17)	0.21
	Water availability (I18)	0.12
	Strategical management areas (I19)	0.2
Continuity (C5)	Fire risk level (I20)	0.22
	Agroforested areas (I21)	0.42
	Return period (I22)	0.36

Table 12. Criteria main groups' weights, LL Catalonia

Group Criteria weights (0-1)				
Wood Fuel	Fire Behaviour	Exposure	Accessibility	Continuity
0.12	0.35	0.17	0.18	0.19

3.2.3. Resulting priority levels

While visualizing the results, we tried to define different scenarios in terms of relative weight distribution, although we show the ones defined through AHP (Figure 19, and figure 20). From the regional study, it was clear that the generated information was of high interest for policy makers, that required a spatial distribution of priorities for redistributing budgets, and being able to explain clearly why an area had higher priority.

Even if the final priorities at a regional level, are related to policies and may require further participatory processes, the data gathering and utility rules definition by experts has been accepted by other stakeholders outside the initial group, which is an accomplishment.

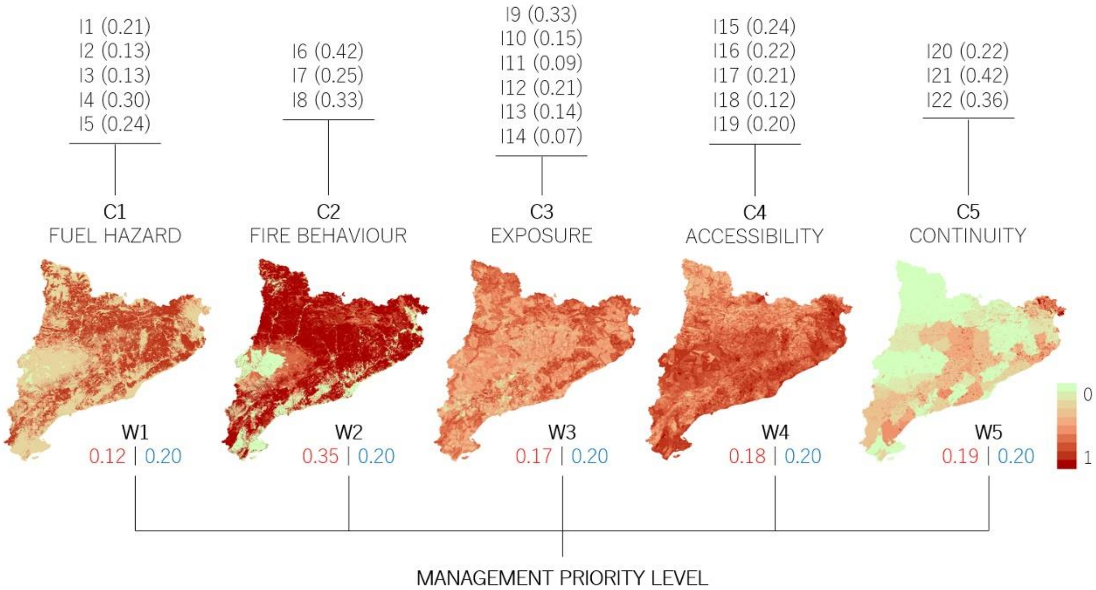


Figure 19. Criteria maps of Catalonia living lab

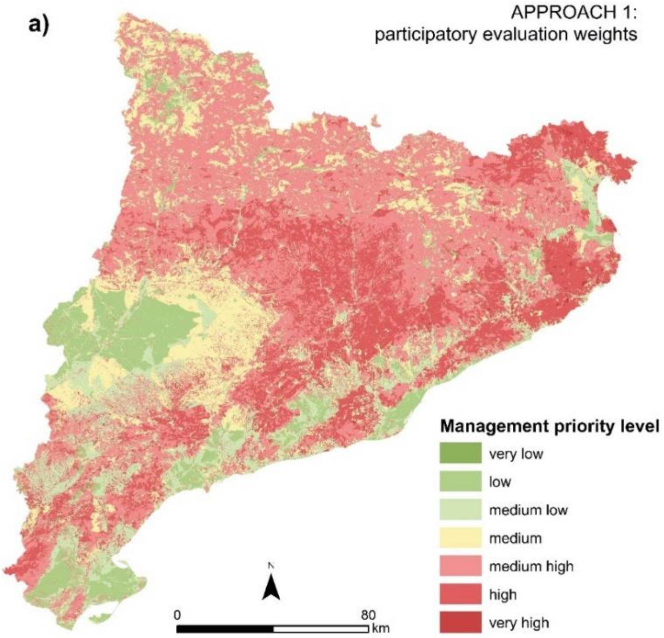


Figure 20. Final priority map of Catalonia living lab

The relevant, but too strategic results at regional level, make the team think about the potential use of the approach into a smaller more homogeneous reality, meaning a landscape where the stakeholders can discuss a more specific and closer to them problem.

3.3a. La Garrotxa (sub-LL CAT)

After implementing the regional assessment of priorities, the Girona province government showed interest in scale down the methodology into a county. This opportunity allowed not only to check data accuracy concerns that may occur at regional level, but also integrate a more involved stakeholder group with specific knowledge of the area, its objectives and challenges.

3.3a.1. Study area and Stakeholders

La Garrotxa d'Empordà is a landscape unit (Figure 21) with a total of 20,784.94 ha, of which 74% is forest land. The wooded forest area represents 59% (12,308.60 ha) and the formations the dominant trees are: pine forests of white pine and oak groves. In 2012, the Jonquera fire burned a total of 3,844.92 ha within this landscape (Figure 2). La Garrotxa d'Empordà is included, for the most part, in the Uniform Regime Zone (ZHR, Piqué et al. 2011) number 9. ZHR 9 is characterized by having a return period of 180 years and the dominant type of fire is that of wind with relief. This landscape has been chosen to apply the downscaling of the innovation action because it has a forest area remarkable, has a high risk value according to the ZHR (Piqué et al. 2011).

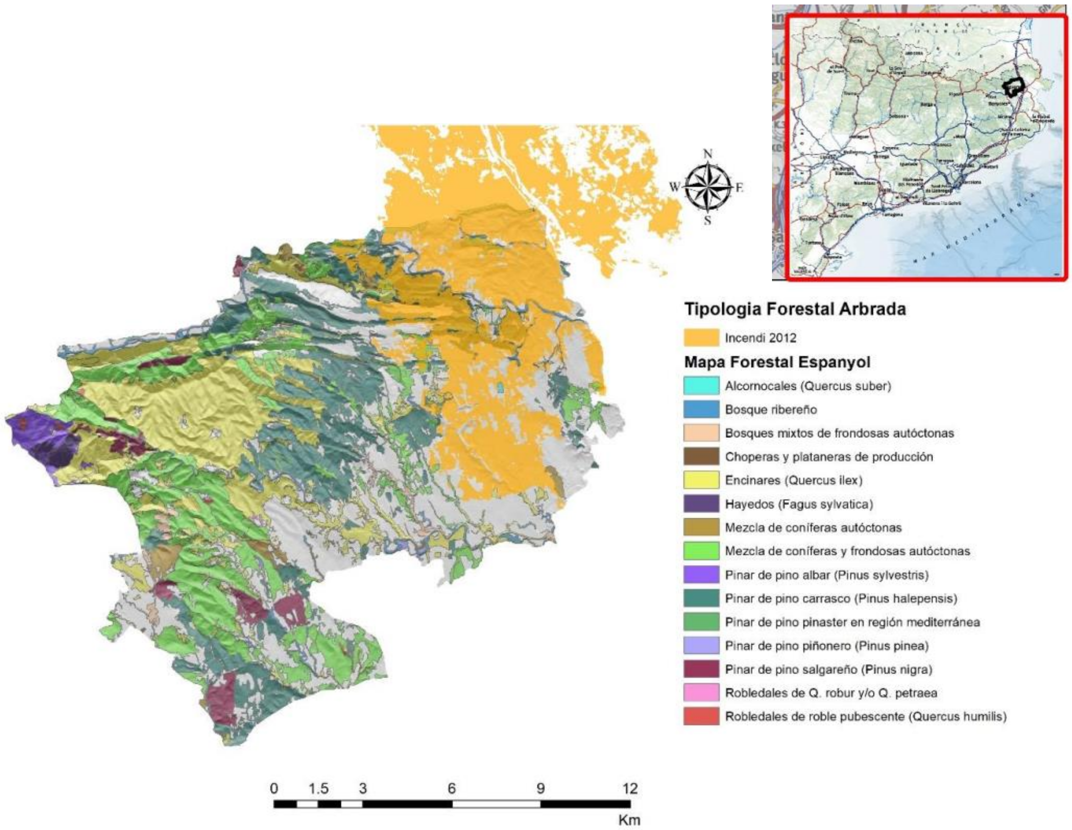


Figure 21: Allocation and main vegetation typologies of the Garrotxa d'Empordà

In the case of this landscape, instead of relying on official geographic information datasets, we implemented a refinement and updating of the "management" units, including fires and land use transformations occurring after 2016 (in some cases recover of pasture lands), silvicultural treatments implemented after 204, and other operations or actions that may have a relevant impact on changing the landscape. The refinement also included identify when a potential management unit, showed heterogenous distribution of vegetation justifying a division. After the updating process the initial 1045 polygons or management units, that were selected for the landscape based on the regional maps, the study was divided into 1142 polygons.

The participatory process for this case was based on a core group of CTFC researchers, 2 leading the participation steps and providing necessary background, and 2 experts on forest management participating as stakeholders, from the local and provincial forest administration another 3 stakeholders were selected, as well as 2 firefighters analysts and 2 members of the environmental conservation agency. This core group allowed to work on a meeting basis, to define criteria and weights. This was possible as the initial criteria and rules from the regional study case was assumed to be an adequate as framework for an initial problem that could be modified *in situ*.

3. 3a.2. Selection of Criteria, utility functions and weighs

For the case of La Garrotxa del Ampurda, it was decided that the basis of criteria and utility rules should be kept the same as those defined in the regional Catalan case (Table 10 and table 11). However, that specificity of the local needs and objectives was set when weights were to be defined. In this case the selection of weights (Table 14) was done by consensus in a meeting after discussion and seeing the influence of changing the weights in the mapped results

An interesting aspect of the weight selection, in this case, was that it become in some case a criteria selection, as 1 of the main criteria, the spatial continuity, was defined as nonrelevant for smaller spatial scales. Also, for some sub-criteria or indicators, the modification of weights resulted in some of them being eliminated of the prioritization (Table 15)

Table 13. Criteria main groups' weights, sub-LL La Garrotxa

Group Criteria weights (0-1)				
Wood Fuel	Fire Behaviour	Exposure	Accessibility	Continuity
0.26	0.24	0.25	0.25	-

Table 14. Indicator weights. Three indicators were removed from the study, in addition to those related to the Continuity criteria group. Sub-LL La Garrotxa

Criteria	Indicators	Weights
Wood fuel (C1)	Canopy base height (I1)	0.13
	Canopy cover (I2)	0.10
	Canopy bulk density (I3)	0.26
	Understory cover (I4)	0.23
	Vertical continuity (I5)	0.29
Fire behaviour (C2)	Fire intensity (I6)	-
	Spread speed (I7)	0.47
	Flame height (I8)	0.53
Exposure (C3)	Urbanised areas (I9)	0.27
	Recreational areas (I10)	-
	Capitalisation (I11)	0.14
	Protected nature (I12)	0.19
	Cultural heritage (I13)	0.19
	Strategic infrastructure (I14)	0.22
Accessibility (C4)	Slope (I15)	0.20
	Road density (I16)	-
	Road distance (I17)	0.36
	Water availability (I18)	0.12
	Strategical management areas (I19)	0.32
Continuity (C5)	Fire risk level (I20)	-
	Agroforested areas (I21)	-
	Return period (I22)	-

3. 3a. 3. Resulting priority levels

An interesting aspect of the prioritization process of the Garrotxa d'Empordà Landscape, was the full use of the CTFC-Utility software, during the final stakeholders' meeting. Even the normalization process was not implemented, as it was decided that the rules and utility functions previously defined by experts were valid. Visualizing the results with a set of weights, and then be able to modify the weights and visualize again the new results (Figure 21), was found interesting by the stakeholders for reaching consensus. Even so, the technical personal of CTFC involved in the periodization process, thinks that this is eased by the use of small focus group, very linked to the local reality.

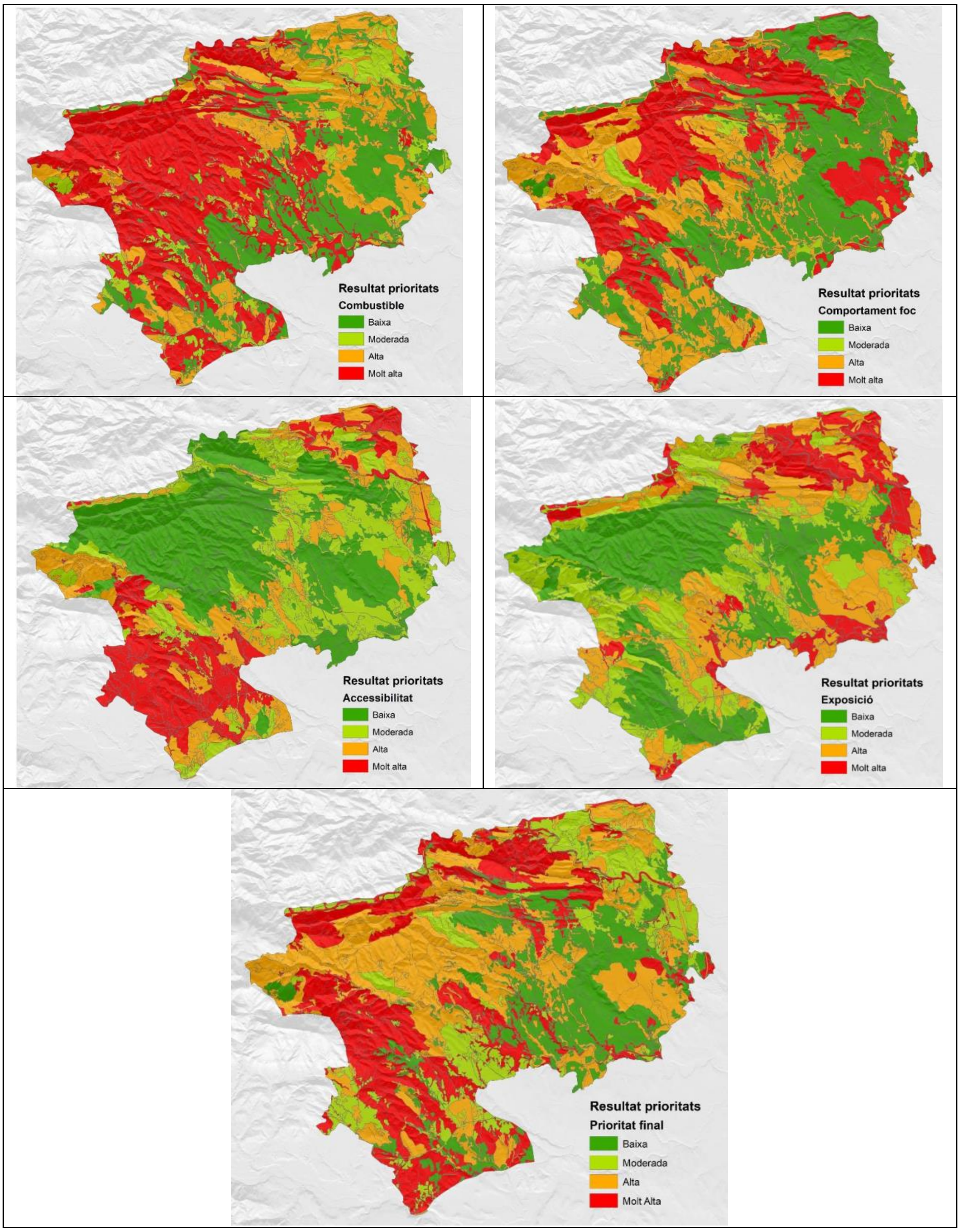


Figure 22: General priority levels, and those from the main criteria groups

4. Achievement and future developments

4.1. Acceptance by Living labs

The prioritization methodology was found easy to understand and to apply by the living labs. The flexibility in terms of defining the specific necessities and data availability, allowed a site-specific approach that helped when interacting with stakeholders.

In general, it can be said that the methodology represents a good compromise between an attempt of harmonization of goals and methods, and a flexibility to adapt to specific realities.

Selecting the spatial framework, in terms of the total extent of the study area and decision units (ex. Stands), was quite relevant. While a regional assessment is interesting for policy related strategic purposes and provide a relevant set of easy to defend decisions and information, it does not allow to reach a level of consensus on the problem formulation required for approve field implementation. A landscape level approach, dealing with 20k to 100k ha, seems an adequate size to focus on a problem with enough homogeneity of factors, and understanding and involvement of stakeholders.

Even so, the method is flexible enough, and the basis to obtain good results is understanding the problem and decision makers

4.2. Scientific and academic achievements

- A Master thesis in ISA, dealing with the Vale de Sousa Living lab: "A proposal and test of a participatory multi-criteria approach with GIS-based AHP to detect high priority areas to facilitate suppression efforts against wildfires – An application in Portugal" by Sergio Rodríguez Fernandez. A manuscript is being prepared for Citation Index journal submission.

- Research for a PHD thesis on the U. of Talca in Chile, about the use of the methodology to select optimal management options. A manuscript submitted, on generating a mathematical optimization method linked to the prioritization process: *Ulloa-Fierro, Felipe and Álvarez-Miranda, Eduardo and Krsnik, Goran and Garcia-Gonzalo, Jordi and González-Olabarria, José Ramón, Combining Multi-Attribute Utility Theory (Maut) & Mixed Integer Programming (MIP) as a Framework for the Spatial Multi-Criteria Prioritisation Management Problem. Available at SSRN: http://dx.doi.org/10.2139/ssrn.4767427*

- A Publication on the regional case of Catalonia: *Krsnik, G., Busquets Olivé, E., Piqué Nicolau, M., Larrañaga, A., Terés, J. Á., Garcia-Gonzalo, J., & González Olabarria, J. R. (2024). Spatial Multi-Criteria Analysis for Prioritising Forest Management Zones to Prevent Large Forest Fires.* https://doi.org/10.2139/SSRN.4733505
- An additional study relating the La Garrotxa study case and the mathematical optimization, to test the methos and tools on a real environment

4.3. Interaction with other Innovation actions

Among the advantages of the innovation action is the possibility of integrating data and information from other actions, and provide a flexible framework that can be applied for multiple problems, if they require spatial prioritization depending on multiple criteria.

- The Bulgarian living lab, lacking information on fuels to generate fuel and fire related indicators, was contacted by the group of fuel modelling of the **IA 5.10**, and access to the **pan-European fuel server** was provided to them. It can be said that this prioritization problem was the first taking advantage of this new dataset generated by FIRE-RES
- As mentioned, the ***CTFC-Utility* DSS** will be open soon, meanwhile access will be provided to other partners within FIRE-RES. For example, the **IA 2.6** on post-fire restoration will test the tool, for finalizing their action.
- Through the exercise of *Ulloa et al.,* it was identified that is possible to link explicitly a strategic prioritization with a tactical selection of optimal management, a process as logic as seldom applied. Additionally, during the research process we identify the lack of studies **describing numerically the efficiency of management actions on reducing fuels or taming fire behaviour.** In the near future we will use the results of **IA 2.2**, that will provide, according to us, the first available set of fuel management actions, with all the parameters on impact, that the new method requires.

4.4. Future developments

The method provides a unique opportunity to harmonize ideas and information, while allowing flexibility to adjust to specific contexts. We plan to provide open access to the DSS (CTFC-Utility) as well as to provide tutorials for non-academic users. The goal is to facilitate the application to other project LLs as well as to other forested landscapes.

Incorporating mathematical programming into the MAUT framework provides an explicit linkage between strategic prioritization and tactical allocation of measures. Starting next year, we will offer a post-doctoral position to continue investigating the issue, specifically by tackling spatial complexity and enhancing the integration of the CTFC-Utility with the Optimizer, while also improving tool accessibility through interface development.

The method's ability to incorporate new data will enable regular updates to address context specific questions once criteria and indicators are established. For instance, understanding the factors that trigger the occurrence of EWE should be a top priority. As outlined in the project, Extreme Wildfire Events (EWE) refer to wildfires characterized by large-scale, complex interactions between fire and the atmosphere, leading to pyro-convective behaviour and coupled processes that produce rapid, intense, and unpredictable fire behaviour. The uncertainty surrounding EWE behaviour and its triggering factors poses challenges for effectively incorporating EWE into landscape management planning. Planning is often described as a practice that exists at the crossroads of knowledge and action (Campbell, 2012). Planning requires the translation of knowledge into operational criteria that may guide action.

For instance, it is not practical to use atmospheric factors associated to the initiation of pyro-convection at a highly dynamic time resolution in the framework of landscape management planning. The most practical approach to integrate these factors would be the design of a quasi-static atmospheric hazard map based on the likelihood of extreme weather conditions. Moreover, addressing the EWE in landscape management planning may take advantage of the exploration of spatial metrics to support the prioritizing of fuel distribution changes.

In our study cases we identify thresholds related to fuel characteristics, fire behaviour and, in some instances, fuel aggregation patterns, that are associated to high-intensity fires, capable to release sufficient energy to trigger a coupling process under specific atmospheric conditions. However, there remains an opportunity for improvement through the incorporation of more specific EWE triggering conditions. For example. incorporating maps that show the accumulation of significant amounts of available fuels or patterns of hazardous conditions (Beverly et al., 2021) could enhance the current analysis. While the emphasis has been on large, intense fires and hazardous conditions, it remains important to take advantage of the information provided by currently available fire simulators.

4.5. Readiness advances

When defining the expected advance in IA readiness, we mentioned that the tools and methods were at a TRL5. In that sense it is clear that different studies on prioritization have been implemented across the years, and for example González-Olabarria et al., 2019, proposed a theoretical problem similar to the one on this Innovation action, and solve it with EMDS.

We have been able to test the approach on 3 living labs, and 4 landscapes, engaging multiple stakeholders/experts/judges, to solve a general problem, and adjusting to the peculiarities of each living lab, the problem was understood, solved, and increasing interest created. Additionally, a Software has being developed and tested, to facilitate the process of implementing this type of problems, and soon should disseminated to increase the impact. In that sense the promised **TRL8 level of readiness, in the case of the prioritization process to create a network of areas to be managed, has being reached**.

On the other hand, allocating the optimal management actions, with mixed integer programming and MAUT, is far from reaching a TRL8, as we just generated and tested the method on a theorical environment. Although we are creating a linkage with the existing DSS, and adjusting all present and future advances to the prioritization processes implemented on the LLs, still the system is not as mature al the MAUT alone. While the expected TRL is not reached, we can mention that the initial point of this methodology was closer to a TRL2-3, as we are exploring a completely new process of linking strategic and tactical landscape planning. At the end of the project, we expect to try it on the Garrotxa landscape, reaching around a TRL7, but expecting to open a new line of research and technology innovation on the topic.

5. References

Albert, C., Schröter, B., Haase, D., Brillinger, M., Henze, J., Herrmann, S., Gottwald, S., Guerrero, P., Nicolas, C. and Matzdorf, B., 2019. Addressing societal challenges through nature-based solutions: How can landscape planning and governance research contribute?. Landscape and urban planning, 182, pp.12-21.

Beverly, J.L., McLoughlin, N. and Chapman, E., 2021. A simple metric of landscape fire exposure. Landscape Ecology, 36, pp.785-801.

Borges, J.G., Marques, S., Garcia-Gonzalo, J., Rahman, A.U., Bushenkov, V., Sottomayor, M., Carvalho, P.O. and Nordström, E.M., 2017. A multiple criteria approach for negotiating ecosystem services supply targets and forest owners' programs. Forest Science, 63(1), pp.49-61.

Campbell, H. (2012). Planning to change the world: Between knowledge and action lies synthesis. Journal of Planning Education and Research, 32(2), 135–146. https://doi.org/10.1177/0739456X11436347

Carwardine, J., O'Connor, T., Legge, S., Mackey, B., Possingham, H. P., & Martin, T. G. (2012). Prioritizing threat management for biodiversity conservation. Conservation Letters, 5(3), 196–204. https://doi.org/10.1111/J.1755-263X.2012.00228.X

Game, E. T., Kareiva, P., & Possingham, H. P. (2013). Six Common Mistakes in Conservation Priority Setting. Conservation Biology, 27(3), 480–485. https://doi.org/10.1111/COBI.12051

Gonzalez-Olabarria, J.R., Reynolds, K.M., Larrañaga, A., Garcia-Gonzalo, J., Busquets, E. and Pique, M., 2019. Strategic and tactical planning to improve suppression efforts against large forest fires in the Catalonia region of Spain. Forest ecology and management, 432, pp.612-622.

Gonzalez-Olabarria, J.R., Carrasco, J., Pais, C., Garcia-Gonzalo, J., Palacios-Meneses, D., Mahaluf-Recasens, R., Porkhum, O. and Weintraub, A., 2023. A fire spread simulator to support tactical management decisions for Mediterranean landscapes. Frontiers in Forests and Global Change, 6, p.1071484.

Ignatieva, M., 2017. Three pillars of landscape architecture: design, planning and management. New visions: Conference proceedings Eds: Ignatieva M., Melnichuk I., Saint-Petersburg State Polytechnic University, ISBN: 978-5-7422-5780-6

Keane, Robert E.; Drury, Stacy A.; Karau, Eva C.; Hessburg, Paul F.; Reynolds, Keith M. 2010. A method for mapping fire hazard and risk across multiple scales and its application in fire management. Ecological Modelling. 221: 2-18.

Krsnik, G., Busquets Olivé, E., Piqué Nicolau, M., Larrañaga, A., Terés, J. Á., Garcia-Gonzalo, J., & González Olabarria, J. R. (2024). Spatial Multi-Criteria Analysis for Prioritising Forest Management Zones to Prevent Large Forest Fires. https://doi.org/10.2139/SSRN.4733505

Kyttä, M., Randrup, T., Sunding, A., Rossi, S., Harsia, E., Palomäki, J., & Kajosaari, A. (2023). Prioritizing participatory planning solutions: Developing place-based priority categories based on public participation GIS data. Landscape and Urban Planning, 239, 104868. https://doi.org/10.1016/J.LANDURBPLAN.2023.104868

Marques, M., Juerges, N. and Borges, J.G., 2020. Appraisal framework for actor interest and power analysis in forest management-Insights from Northern Portugal. Forest Policy and Economics, 111, p.102049.

Marques, M., Reynolds, K.M., Marques, S., Marto, M., Paplanus, S. and Borges, J.G., 2021. A participatory and spatial multicriteria decision approach to prioritize the allocation of ecosystem services to management units. Land, 10(7), p.747.

Reynolds, Keith M.; Hessburg, Paul F.; Keane, Robert E.; Menakis, James P. 2009. National fuel-treatment budgeting in US federal agencies: capturing opportunities for transparent decision-making. Forest Ecology and Management. 258: 2373-2381.

Roe, S., 2012. Spatial Prioritisation of REDD+ Sites in the Philippines, p. 36

Saaty, Thomas L. 1980 The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, ISBN 0-07-054371-2, McGraw-Hill

Saaty, Thomas L. Decision Making for Leaders: The Analytical Hierarchy Process for Decisions in a Complex World (1982). Belmont, California: Wadsworth. ISBN 0-534-97959-9; Paperback, Pittsburgh: RWS. ISBN 0-9620317-0-4. "Focuses on practical application of the AHP; briefly covers theory."

San-Miguel-Ayanz, J., Moreno, J.M., Camia, A., 2013. Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. For. Ecol. Manage. 294, 11–22. https://doi.org/10.1016/j.foreco.2012.10.050.

Srdjevic, B. and Srdjevic, Z., 2008. Multilevel participatory model for decision making on regional hydro-system basis: Serbian case study. In Sustainable use and development of watersheds (pp. 201-213). Springer Netherlands.

Syphard, A.D., et al., 2007. Human influence on California fire regimes. Ecol. Appl. 17(5), 1388–1402. https://doi.org/10.1890/06-1128.1

Ulloa-Fierrro, F., Álvarez-Miranda, E., Krsnik, G., Garcia-Gonzalo, J., Gonzalez-Olabarria, J.R. Combining Multi-Attribute Utility Theory (Maut) & Mixed Integer Programming (MIP) as a Framework for the Spatial Multi-Criteria Prioritisation Management Problem. Manuscript submitted for revision.

FIRE-RES