



# FIRE-RES

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

## D2.4 Recommendations for improving security on Wild Urban Interface at multiple scales

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## D2.4 RECOMMENDATIONS FOR IMPROVING SECURITY ON WUI AT MULTIPLE SCALES

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**Abstract:** This report aims to implement a methodology to reduce the impact of extreme wildfires through fuel treatment. Focusing on four case studies (Catalonia, Biobío, the Canary Islands, and Portugal), the report outlines an integrated approach combining stochastic fire simulations, risk metrics, and optimization models for the strategic allocation of fuel treatments. Using the Cell2Fire simulator and the Downstream Protection Value (DPV) metric, the study identifies optimal locations for interventions such as firebreaks to minimize expected losses across diverse landscapes. The results demonstrate reductions in wildfire impacts on the values at risk considered. The findings highlight the potential of leveraging this data-driven methodology to support decision-making processes to safeguard ecological, social, and economic values.

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## D2.4 RECOMMENDATIONS FOR IMPROVING SECURITY ON WUI AT MULTIPLE SCALES

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### LIST OF ACRONYMS

**ARCLim:** Atlas de Riesgos Climáticos para Chile.

**BAU:** business as usual.

**BP:** Burn probability.

**CBD:** canopy bulk density.

**CBH:** canopy base height.

**CONAF:** Corporación Nacional Forestal (Chile).

**CTFC:** Forest Science and Technology Centre of Catalonia.

**DPV:** Downstream Protection Value.

**EWE:** Extreme Wind Events.

**FBP:** Forest Fire Behaviour Prediction.

**FIRE-RES:** Innovative Technologies and Socio-Ecological-Economic Solutions for Fire Resilient Territories in Europe.

**GBIF:** Global Biodiversity Information Facility.

**ISCI:** Instituto de Sistemas Complejos de Ingeniería.

**LL:** Living Lab.

**ROC:** Red de Observadores de Aves de Chile.

**ROS:** Rate of spread

**SDM:** species distribution models.

**SEN:** National Electric System.

**SRTM:** NASA's Shuttle Radar Topography Mission.

**TRL:** Technology Readiness Level.

**WUI:** wildland urban interface.

**ZIFs:** forest management zones

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# 1. INTRODUCTION

Wildfire ignitions in Chile, Portugal, Catalonia, and the Canary Islands are predominantly anthropogenic in origin. In recent years, the intensifying effects of climate change have significantly increased the frequency and severity of wildfires in these Mediterranean and subtropical regions, leading to a rise in extreme wildfire events.

This escalating threat poses substantial risks to social, economic, and environmental assets dispersed across these vulnerable landscapes. In response, this report introduces a novel methodology grounded in operations research and advanced analytics. The proposed approach focuses on mitigating wildfire impact through the strategic treatment of fuels along pathways that fires are likely to take toward critical values at risk within the landscape.

The aim is to reduce the impact of extreme wildfires through fuel treatment in the Living Labs of Biobío, Portugal, Catalonia, and the Canary Islands. The goal is to develop a cost-efficient fuel treatment network design in rural areas of WUI to protect them against wildfires, taking into account social, ecological, and economic factors.

## 2.METHODOLOGY

We developed an open-source computational system with several tools to assist the management of fuel. This development corresponds to a plugin (Fire Analytics Processing-Toolbox) developed in QGIS, an open-source geographic information system software. The plugin includes a wildfire simulator, Cell2Fire, that could be used with different fuel models such as Scott & Burgan, FBP System and Kitral for Chile. The simulation uses the selected fuel model along with weather data and elevation to predict the spread of the fire. Also, it is possible to use ignition probability maps and canopy characteristics to consider where wildfires are more likely to start and to simulate canopy fire behaviour respectively. The system is also capable of estimating burn probability maps through an iterative and concatenated process of simulating spatially explicit fire ignition and fire growth scenarios. The system can also estimate the optimal way to allocate fuel treatments, primarily the placement of firebreaks, using various decision-making models and multiple wildfire simulations.

This report examines two distinct approaches to firebreak implementation. In the cases of LL Chile and the Canary Islands, firebreaks are established by removing vegetation at the pixel level, allowing each raster cell in the landscape to be treated independently. Conversely, for LL Catalonia and Portugal, firebreaks are implemented at the polygon level, where selecting a polygon for treatment entails considering all cells within it as firebreaks.

### 2.1. Study area data

Defining the study area where the fuel treatment will be applied is essential. Once the area is delineated, gathering the basic data required to generate simulations and carry out optimization is necessary. This data includes detailed layers of terrain elevation, a fuel map, canopy base height (CBH), and canopy bulk density (CBD). Additionally, meteorological scenarios are needed to capture the study area's climatic variability and extreme weather conditions. These scenarios are presented in tables containing hourly meteorological variables.

### 2.2. Fire simulations

Multiple stochastic fire simulations were conducted, with 10,000 simulations for each case study. These simulations were performed using the Cell2Fire software, a fire growth model based on cellular automata. In these simulations, ignition points are either random or quasi-random if an ignition probability map is used. One of the predefined meteorological scenarios is randomly selected for each ignition point.

### 2.3. Values at risk

Values at risk refer to any element susceptible to damage from a wildfire. Numerous variables can be considered values at risk, such as population, urban areas, protected natural areas, critical infrastructure, and forest plantations. The selection of values at risk will depend on the objectives set when applying this methodology.

## 2.4. Risk Metric

### 2.4.1. Burn Probability

The Burn Probability map (BP) represents the likelihood of different areas within a specific landscape burning. Multiple fire simulations are conducted using Cell2Fire with random ignition points to generate a BP, considering the area's landscape characteristics and climate variability. The ratio between the number of times the cell burned and the total number of simulations is calculated for each cell, yielding the burn probability. The final map displays these probabilities on a colour scale, with areas of higher burn probability shown in warm colours (red) and areas of lower probability in cool colours (blue).

### 2.4.2. Downstream Protection Value

To generate treatment areas, the Downstream Protection Value (DPV) metric is used, introduced by Pais et al. (2021b). To compute *DPV*, we first introduce the following notation. Let  $F = (N, E)$  be the graphical representation of the landscape,  $N$  the set of cells (automatically fixed by the resolution of the data layers), and  $E$  the set of edges (each cell having 8 neighbors). Nodes can be associated with different attributes such as urban zones. Similarly, edges can represent slope, distances between cell centers or transportation costs, among other possibilities (Pais et al., 2021a). When a fire occurs during a simulation, a messaging process is triggered between the nodes of  $F$  that generates a directed graph  $F_n = (N_d, E_d)$ , where  $N_d \subseteq N$  is the set containing all the cells burned during the replication.  $E_d$  is constructed from these signals to represent fire propagation between adjacent cells.

In specific terms, for all  $j \in N_d$  there is a directed subgraph  $T(j) = (N(j), E(j))$  of  $F_d$  such that  $N(j) \subseteq N_d$ , and  $E(j) \subseteq E_d$  so that the graph  $T(j)$  represents the shortest-path tree with root node  $j$ . For all  $i \in N$ ,  $T(i) = (N(i), E(i))$  is the shortest-path tree for which  $i$  is the root node. The downstream protection value  $DPV(i)$  was defined in Pais et al. (2021b) as

$$DPV(i) = \sum_{j \in N(i)} \alpha \cdot V_j \quad (1)$$

where  $V_j$  is an appropriate value at risk for the node/cell  $j$ , and is  $\alpha$  scalar that scales the relative importance of the attribute.

Intuitively, DPV in a cell  $i$  represents the values at risk that are affected “downstream” from that cell  $i$ , given a simulated wildfire. For multiple replicates/simulations, the DPV in a cell  $i \in N$  is estimated as the average of the DPVs calculated for each replicate.

### 2.4.3. Risk

Risk is the probability that a hazard will result in damage and potentially lead to a catastrophe. The extent of damage caused by a hazard will depend on the values exposed to it, such as urban areas or natural reserves. In this work, risk will be

estimated as the product of each area's hazard (burn probability) and exposed values (or value at risk).

### 2.5. Optimal location treatment

We formulate the fuel-treatment problem as an optimization model with the objective to find the subset of adjacent cells that maximise the disruption of the shortest propagation paths. Depending on the objective of the treatment plan, this value function could incorporate the impact of a unique fire behaviour output (e.g., burnt probability, Rate of Spread (ROS) and travelling times, fire intensity, flame length, etc.) or general metrics such as DPV including the relevant assets of the landscape (e.g., timber volume). The optimization problem formulation will depend on the considerations made in each living lab.

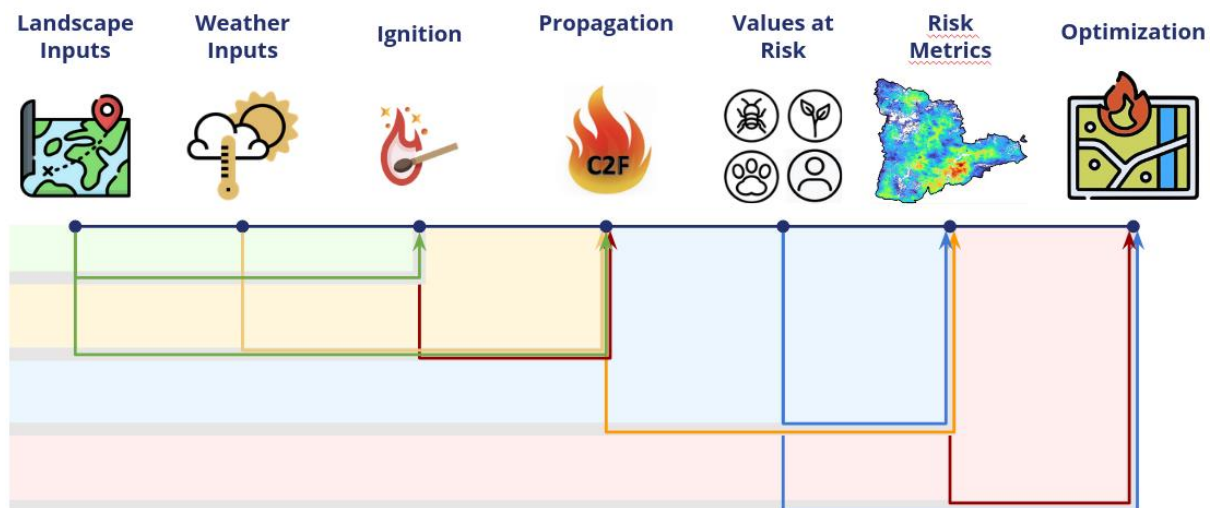


Fig 1: Flowchart of the fuel treatment optimisation process.

### 3. Study Case: Catalonia

As coordinator of this Living Lab, the CTFC actively participated in developing the methodology to address this issue and also provided all the necessary information (fuel, topography, meteorology, etc.) for its implementation.

#### 3.1. Study Area

The area chosen for our study covers the northwestern part of the autonomous region of Catalonia. With a surface of 5,600 km<sup>2</sup>, approximately 17.5% of Catalonia, the selected area encompasses eight adjacent zones of homogeneous fire regime that share similar meteorological conditions (Krsnik et al 2020). Being a mountainous part of Catalonia, the landscape on the study area is dominated by rangelands (53% forest; 15% bushlands; 14% grasslands) according to the Spanish forest map 1:25000 (MFE25). With a sizable portion of the area falling into oceanic, alpine or alpine influenced mediterranean climates, large fire events are not as prevalent in the study area as in other parts of the region where water deficit episodes are more common. Still, current landscape configurations derived from abandonment of rural activities (Ameztegui et al., 2010; 2021), and changes in weather conditions (Resco de Dios et al., 2021; Bento et al., 2023), foretell a future when large fires will not be uncommon in the Pyrenees.

#### 3.2. Fuel Map and geographical data

From the eight zones with homogeneous fire regimes in the study area, we extracted all necessary landscape information required for fire simulation from the Previncat server (González-Olabarria et al., 2019). The extracted data layers, including elevation models, fuel models, canopy base height (CBH), and canopy bulk density (CBD), were resampled from their original resolution of 20×20 meters to a less resource-intensive framework of 80×80 meters.

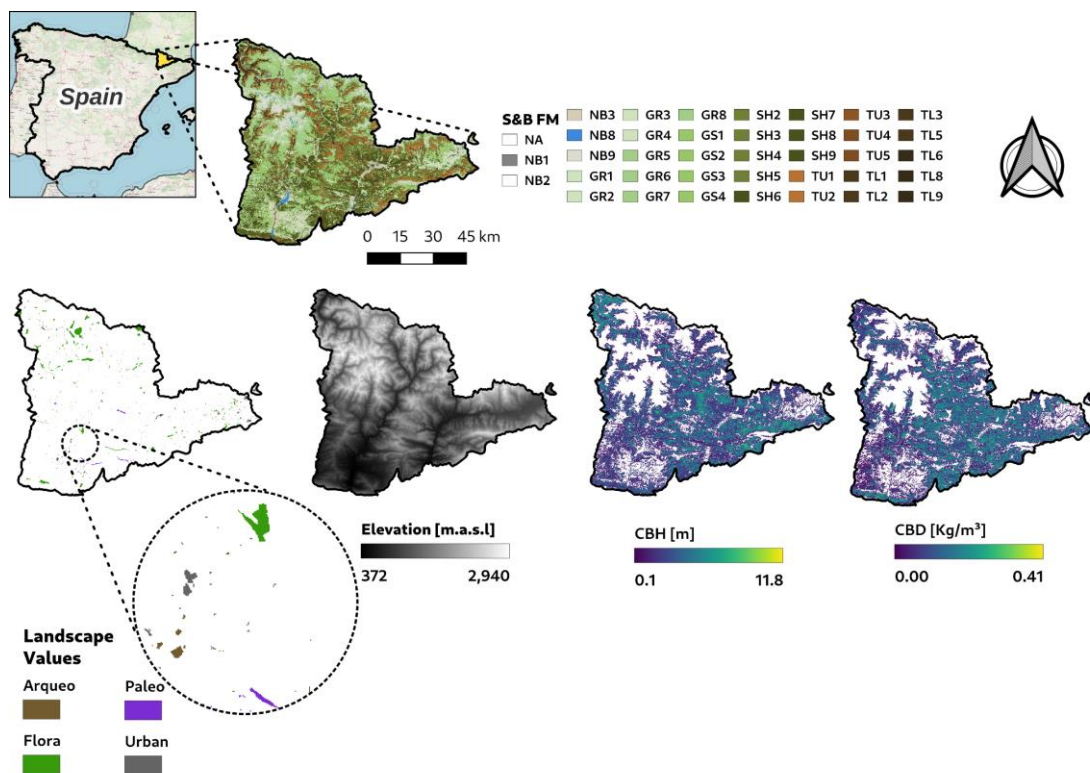


Fig 2: The study area: The top map displays the Catalonia region along with the Scott & Burgan fuel models. The lower maps emphasise the information layers (elevation, CBD, CBH) and the values at risk (urban areas, archaeological sites, paleontological sites, and flora).

### 3.3. Weather scenarios

We used 61 different dynamic weather scenarios from the Previncat server, based on the most hazardous historical conditions (Krsnik et al 2020). A distribution was established also for the generation of the moisture scenarios, with 70% of low humidity and 30% of moderate humidity scenarios (corresponding to D2L2 and D3L3 according to Scott and Burgman 2005). The combination of the weather and humidity scenarios being selected in order to emulate some of the worst fire weather conditions associated with the study area.

### 3.4. Values at risk

A set of valuable at-risk resources that must be protected from fire exposure was defined. To identify these resources, researchers from CTFC and ISCI used the expert criteria. The values at risk considered in the study

- Urbanized areas
- Archaeological and Paleontological sites (Generalitat de Catalunya, 2023)
- Elements of the nature 2000 network of special floristic or faunistic value.

Risk values must be normalized. They can represent the density of a variable or take boolean values to indicate the presence or absence of the value to be protected, depending on the nature of the variable.

### 3.5. Fire simulations

The landscape, weather and moisture scenarios were used to simulate 5,000 fire simulations in which each simulation corresponds to a fire generated by both a random ignition and a random climate scenario. The duration of the fires was also randomly selected, by setting by the length of the meteorological scenarios. In this case, we selected a distribution of 45 scenarios of 6 hours, 5 scenarios of 12 hours, 4 scenarios of 18 hours, 3 scenarios of 24 hours, 2 scenarios of 30 hours, and 2 scenarios of 36 hours. The Cell2Fire-SB system was utilized for wildfire simulation, enabling the simulation of surface and crown fires in heterogeneous landscapes.

### 3.6. Methodology

The following methodology was applied to select different treatment allocations for the study area:

1. Simulate 10,000 stochastic fire scenarios as described in the previous section.
2. Normalize and weight the three risk layers based on the "Values at Risk" section.
3. Calculate burn probability and DPV metrics using the risk layer.
4. Select cells with the highest DPV, according to the percentage of area allocated for treatment.
5. Run a new set of simulations using the selected treatment plan.
6. Recalculate the burn probability for the newly generated wildfire scenarios and weight them using the risk layer to compare the risk loss across all instances.

### 3.7. Risk Instances

Three instances were created to measure different criteria for prioritisation: R1, which only considers the burnt area as a value at risk. Meanwhile, R2 is considered a value at risk in both burnt areas and urban zones. Finally, R3 considers as value at risk the five values at risk previously depicted, which are: a) burnt area, b) urban zones, c) floristic zones, d) archeological zones, and e) paleontological zones.

### 3.8. Results

The number of burned hectares and risk before and after the placement of firebreaks is shown below. The impact of treating different percentages of fuel, 1%, 3%, and 5%, for the three risk instances will be evaluated.

3.8.1. Baseline Case

The scenario without treatment leads to the following maps

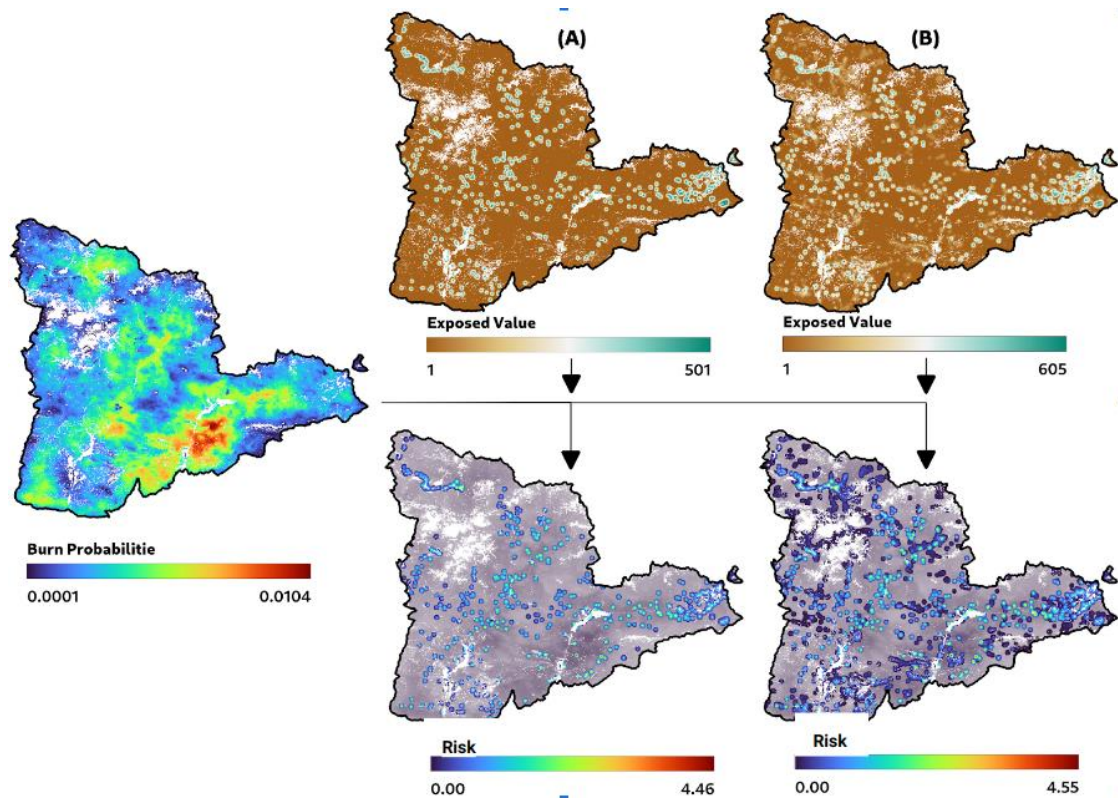


Fig 3. Baseline results.

In this case, the average number of hectares burned over the 10,000 simulations is 1,523, while the average risk of fires is 0.0958, considering the values at risk from R2 and 0.1284, considering the values at risk from R3.

This case gives rise to the DPVs that will allow us to build the treatments. These can be seen in Fig 4.

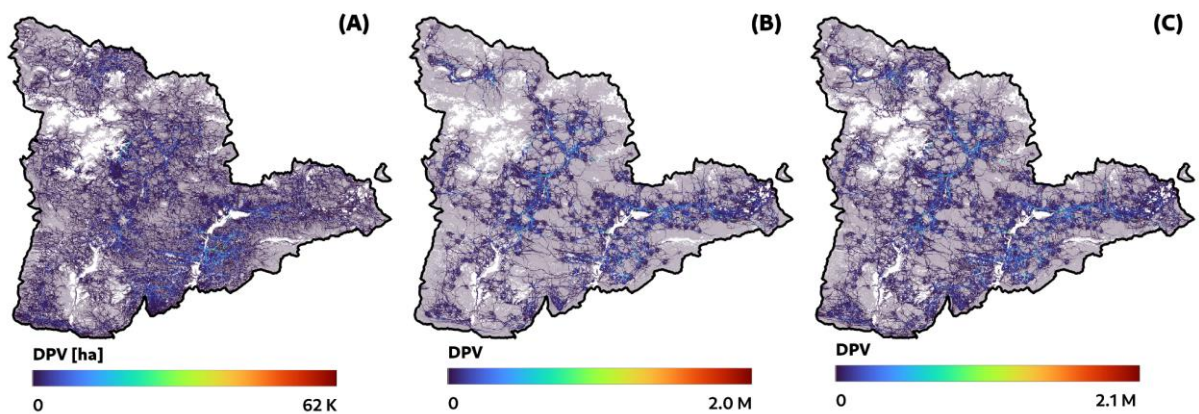


Fig 4: DPV for each instance, ( A ) for R1, ( B ) for R2, and ( C ) for R3.

### 3.8.2. 1% Treatment case

#### R1

In this case, the average number of hectares burned is 1,368, while the average risk of urban area is 0.0879, and the average of the multicriteria risk is 0.1165, which corresponds to a 10% reduction in the area burned, a 8.3% reduction in urban risk and a 9.25% reduction in multicriteria risk, considering the baseline case.

#### R2

In this case, the average number of hectares burned is 1,389, while the average risk of urban area is 0.0849, and the average of the multicriteria risk is 0.1136, which corresponds to a 8.8% reduction in the area burned, a 11.4% reduction in urban risk and a 11.57% reduction in multicriteria risk, considering the baseline case.

#### R3

The evaluation of the landscape with this treatment, obtained from another set of 10,000 simulations, generates the following maps of Burn probability and risk:

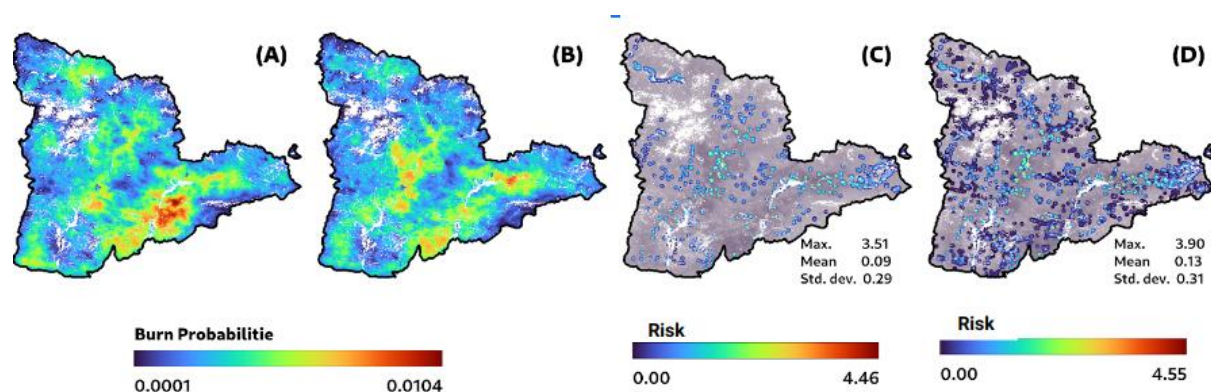


Fig 5: 1% treatment results. (A) shows the baseline burn probability, (B) shows the resultant burn probability, (C) shows the resultant urban risk and (D) shows the resultant multicriteria risk.

In this case, the average number of hectares burned is 1,387, while the average risk of urban area is 0.0858, and the average of the multicriteria risk is 0.1141, which corresponds to a 8.95% reduction in the area burned, a 10.4% reduction in urban risk and a 11.2% reduction in multicriteria risk, considering the baseline case.

### 3.8.3. 3% Treatment case

#### R1

In this case, the average number of hectares burned is 1,219, while the average risk of urban area is 0.0767, and the average of the multicriteria risk is 0.1019, which corresponds to a 20% reduction in the area burned, a 19.96% reduction in urban risk and a 20.65% reduction in multicriteria risk, considering the baseline case.

#### R2

In this case, the average number of hectares burned is 1,249, while the average risk of urban area is 0.0664, and the average of the multicriteria risk is 0.092, which corresponds to a 17.98% reduction in the area burned, a 30.7% reduction in urban risk and a 28.37% reduction in multicriteria risk, considering the baseline case.

#### R3

The evaluation of the landscape with this treatment, obtained from another set of 10,000 simulations, generates the following maps of BP and risk:

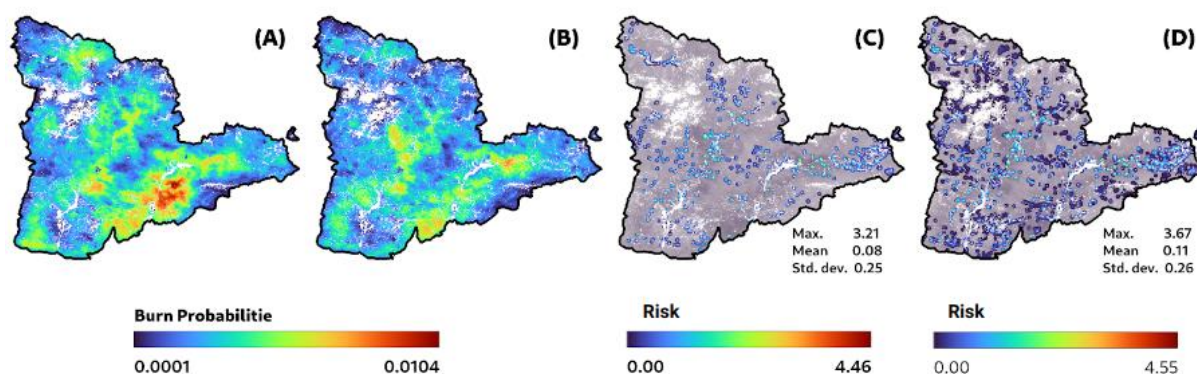


Fig 6: 3% treatment results. ( A ) shows the baseline burn probability, ( B ) shows the resultant burn probability, ( C ) shows the resultant urban risk and ( D ) shows the resultant multicriteria risk

In this case, the average number of hectares burned is 1,245, while the average risk of urban area is 0.0688, and the average of the multicriteria risk is 0.0933, which corresponds to a 18% reduction in the area burned, a 28.13% reduction in urban risk and a 27.37% reduction in multicriteria risk, considering the baseline case.

### 3.8.4. 5% Treatment case

#### R1

In this case, the average number of hectares burned is 1,127, while the average risk of urban area is 0.0701, and the average of the multicriteria risk is 0.0929 , which

corresponds to a 26% reduction in the area burned, a 26.9% reduction in urban risk and a 27.7% reduction in multicriteria risk, considering the baseline case.

### R2

In this case, the average number of hectares burned is 1,157, while the average risk of urban area is 0.0578, and the average of the multicriteria risk is 0.081, which corresponds to a 24% reduction in the area burned, a 39.7% reduction in urban risk and a 36.9% reduction in multicriteria risk, considering the baseline case.

### R3

The evaluation of the landscape with this treatment, obtained from another set of 10,000 simulations, generates the following maps of BP and risk:

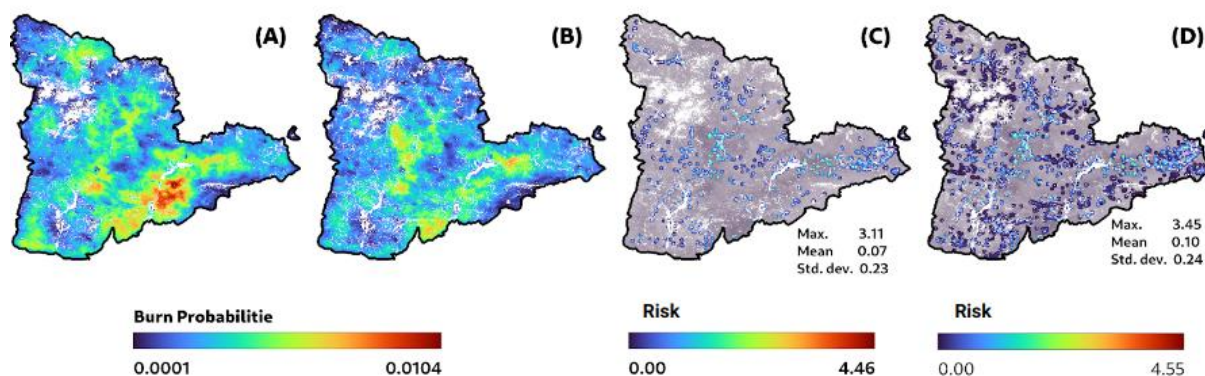


Fig 7: 3% treatment results. ( A ) shows the baseline burn probability, ( B ) shows the resultant burn probability, ( C ) shows the resultant urban risk and ( D ) shows the resultant multicriteria risk.

In this case, the average number of hectares burned is 1,146, while the average risk of urban area is 0.0599, and the average of the multicriteria risk is, 0.082 which corresponds to a 24.76% reduction in the area burned, a 37.4% reduction in urban risk and a 36.15% reduction in multicriteria risk, considering the baseline case.

### 3.8.5. Summarized results

The subsequent tables show a summary of the information presented earlier. They provide a concise and compelling summary of the previously presented information.

## D2.4 RECOMMENDATIONS FOR IMPROVING SECURITY ON WUI AT MULTIPLE SCALES

*Summarized results of 1% of treatment for the area in Catalonia*

1 %	Baseline	R1	R2	R3
<b>Mean burnt ha</b>	1.523	1.368	1.389	1.387
<b>Mean urban risk</b>	0.0958	0.0879	0.0849	0.0858
<b>Mean risk</b>	0.1284	0.1165	0.1136	0.1141
<b>Percentual reduction of burnt ha</b>	-	10	8.8	8.95
<b>Percentual reduction of urban risk</b>	-	8.3	11.4	10.4
<b>Percentual reduction of risk</b>	-	9.25	11.57	11.2

*Summarized results of 3% of treatment for the area in Catalonia*

3 %	Baseline	R1	R2	R3
<b>Mean burnt ha</b>	1,523	1,219	1,249	1,245
<b>Mean urban risk</b>	0.0958	0.0767	0.0664	0.0688
<b>Mean risk</b>	0.1284	0.1019	0.092	0.0933
<b>Percentual reduction of burnt ha</b>	-	20	17.98	18
<b>Percentual reduction of urban risk</b>	-	19.96	30.7	28.13
<b>Percentual reduction of risk</b>	-	20.65	28.37	27.37

*Summarized results of 5% of treatment for the area in Catalonia*

5 %	Baseline	R1	R2	R3
<b>Mean burnt ha</b>	1,523	1,127	1,157	1,146
<b>Mean urban risk</b>	0.0958	0.0701	0.0578	0.0599
<b>Mean risk</b>	0.1284	0.0929	0.081	0.082
<b>Percentual reduction of burnt ha</b>	-	26	24	24.76
<b>Percentual reduction of urban risk</b>	-	26.9	39.7	37.4
<b>Percentual reduction of risk</b>	-	27.7	36.9	36.15

## 4. Study Case: Biobio

### 4.1. Study Area

The Study Area comprises the entire Biobio Region. It has a very diverse composition not just at a landscape level but also at an anthropogenic level, with 2 major forestry companies, 100 medium and more than 4,000 small forest owners spread over 23,890 km<sup>2</sup>.

### 4.2. Fuel Map and geographical data

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

The fuel map was created based on CONAF's 2015 vegetation cadastre (<https://sit.conaf.cl/>), which is available in shapefile format and includes information on land use, dominant vegetation types, coverage, and structure. This data generated a fuel map for the Kitral fuel model system.

### 4.3. Weather scenarios

To generate the weather scenarios needed for the simulations, data were collected from three meteorological stations located in different parts of the Biobío region, strategically selected to capture the climatic variability of the area. From each station, the summer days with the highest recorded daily maximum temperatures over the past five years were identified, allowing for the determination of the most critical

periods in terms of fire risk. Based on this selected data, 100 weather scenarios were generated, each lasting 12 hours.

### **4.4. Values at risk**

The risk values used in this study are a weighted combination of three risk layers: population density (70%), bird biodiversity (20%), and proximity to electric lines (10%).

Population density data were obtained from high-resolution population density maps provided by Data for Good at Meta. This information was produced in 30-meter grids, making it the most accurate population density information currently available. The map was created using convolutional neural networks and using information from commercially available satellite images in combination with census-based data and other population statistics. Using a resampling method based on the weighted sum of pixels, population density values were interpolated to the pixel size of the Biobío region raster (100-meter grids).

The bird biodiversity data correspond to estimates of geographic distribution of bird richness (i.e., number of different species in each 100-meter grid). For this purpose, species distribution models (SDM) were developed using the maximum entropy algorithm (Phillips et al 2006). The SDMs were fitted by species using species occurrence as response variable and uncorrelated climatic variables as predictors. Species occurrence data were obtained from the Global Biodiversity Information Facility (GBIF) and from the Red de Observadores de Aves de Chile (ROC), while the climatic data were obtained from the Atlas de Riesgos Climáticos para Chile (ARClím). To reduce spatial clustering and sampling bias, species records were thinned to spatial resolution of climatic variables (5-kilometer grids). The SDMs were developed at country level and were evaluated by 5-fold spatial block cross-validation (Valavi et al 2018). Only SDMs with an area under the ROC curve value greater than or equal to 0.7 were retained. The SDM probabilities of each species were binarized into presence/absence values using the cutoff threshold that maximizes the sum of sensitivity and specificity (Liu et al 2013). Finally, the SDMs were stacked to obtain estimates of species richness distribution.

Finally, the electric lines data comes from the National Electric System (SEN). Only lines of less than 66 kv were included, since at higher voltage the lines do not have a risk of being burned by fires.

### **4.5. Fire simulations**

We conducted a series of 10,000 wildfire simulations, using a ignition probability map that indicates the likeability of wildfire starting in a specific cell, which was constructed using historical data and random samples of weather conditions.

## 4.6. Methodology

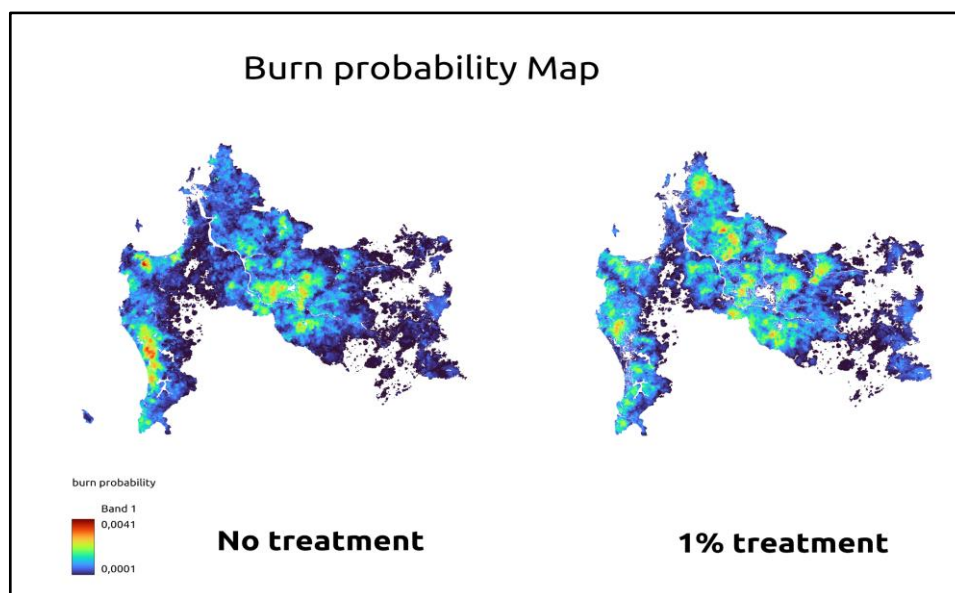
The following methodology was applied to select different treatment allocations for the study area:

1. Simulate 10,000 stochastic fire scenarios as described in the previous section.
2. Normalize and weight the three risk layers based on the "Values at Risk" section.
3. Calculate burn probability and DPV metrics using the weighted risk layer.
4. Select cells with the highest DPV, according to the percentage of area allocated for treatment.
5. Run a new set of simulations using the selected treatment plan.
1. Recalculate the burn probability for the newly generated wildfire scenarios and weight them using the risk layer to compare the risk loss across all instances.

## 4.7. Results

### 4.7.1. Burn probability

The following figures show the burn probability map before and after fuel treatment for different cases, considering 1%, 1.5%, 2%, and 2.5% of the treated area relative to the total area. The firebreaks were placed considering the protection of values at risk, with priority given to protecting the population.



*Fig 8: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 1% of the total area.*

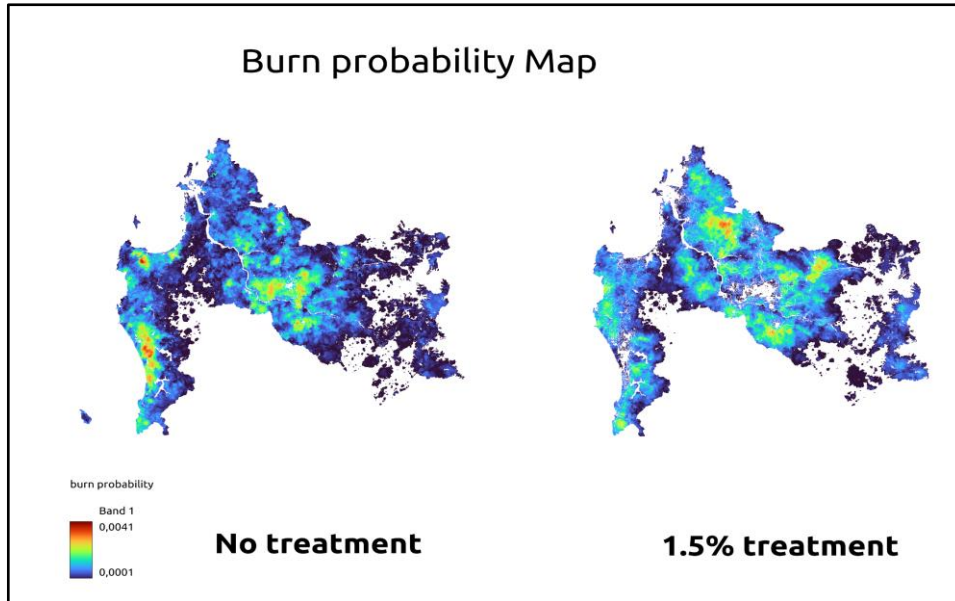


Fig 9: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 1.5% of the total area.

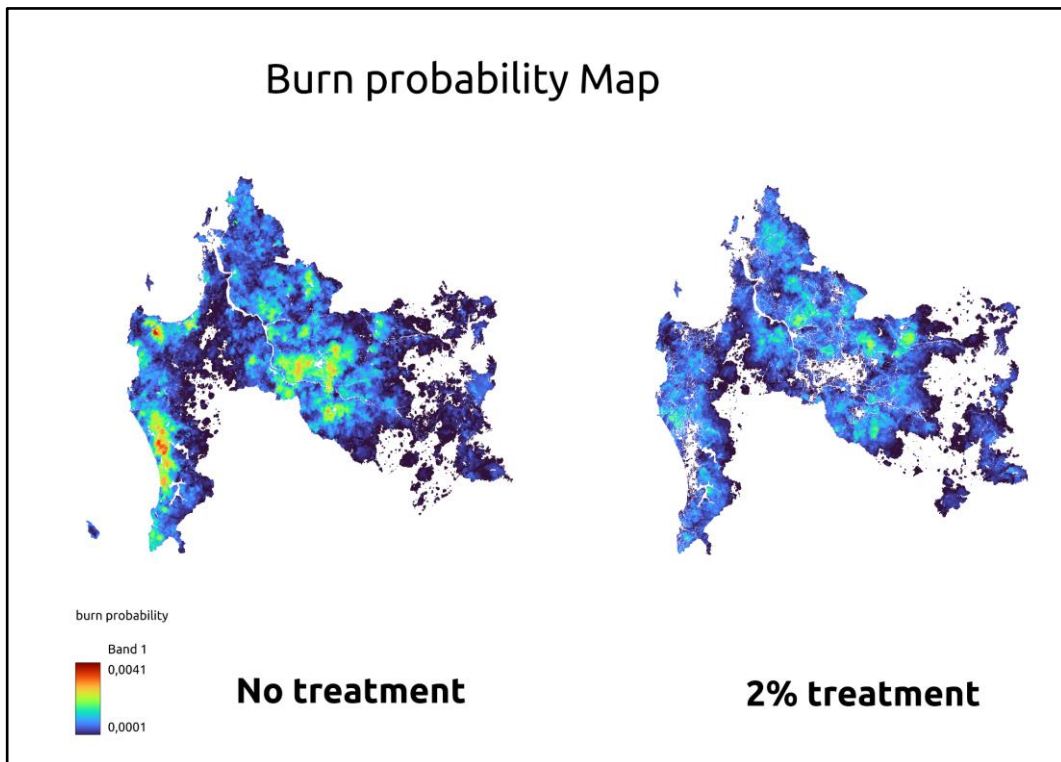


Fig 10: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 2% of the total area.

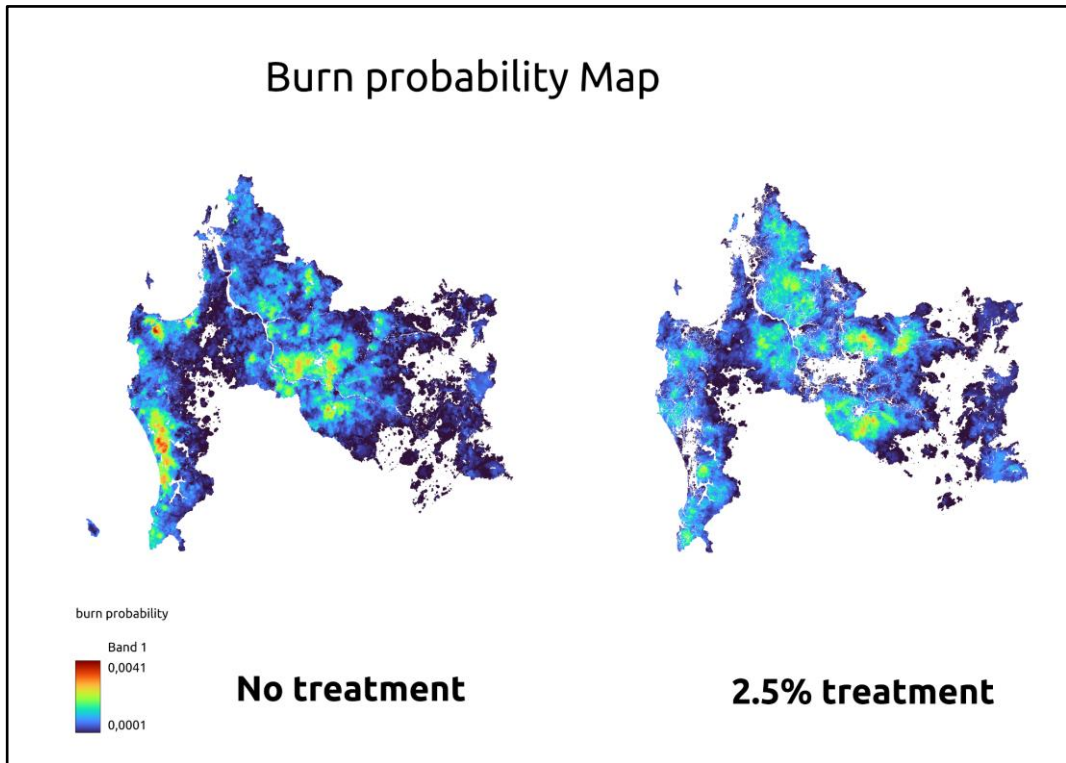


Fig 11: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 2.5% of the total area.

#### 4.7.2. Expected loss

The average number of hectares of vegetation lost (weighted by risk) due to fires was determined for the different percentages of fuel treatment.

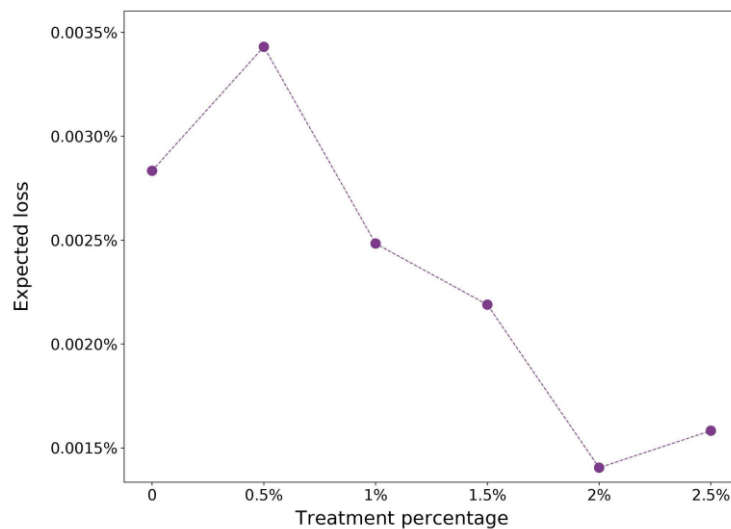


Fig 12: The weighted percentage of vegetation loss, based on risk values, as a function of the percentage of treated area.

## 5. Study Case: Canarias

### 5.1. Study Area

Gran Canaria Island. This is the second largest and most populated island in Canary, spanning over 1,560 km<sup>2</sup> and divided in 21 municipalities, holding a population of around 0.9 million people .

Gran Canaria Island, covering an area of 1,560 km<sup>2</sup>, is the third largest island of the Canary Islands archipelago, which is located in the Atlantic Ocean, offshore of the northwest African coast. Volcanic in origin, it has an average altitude of 1,500 m.a.s.l., and peaks at 1,950 m.a.s.l.

Its subtropical climate is highly influenced by the trade winds from northeast, which create a contrast between humid windward and arid leeward slopes. This, together with its complex topography, are the cause of its high microclimatic diversity. Yearly average rainfall is 280 mm with highly irregular spatial distribution, ranging from 60 mm in the southern coastal strip to 740 mm in the highest altitudes. Average annual temperature is 18.6°C.

The predominant forests in the Canary Islands Archipelago and, particularly, in Gran Canaria are Canarian pine (*Pinus canariensis* C.Sm.) forests (ca. 80% in Gran Canaria), an endemic species of the Archipelago characterized by its high resistance to fire mortality. Other forests present in Gran Canaria are Laurel forests (more humid forests represented by broadleaved species) and termophilous forests with species highly adapted to drought conditions.

The island is one of the most densely populated since it is home to almost 40% of the total population of the archipelago (857.171 inhabitants in 2023). Overall, approximately 80% of the island population resides in the coastal strip in the north, east and south. Its main economic driver is tourism (with more than 4M tourists per year), although agriculture (mainly banana and tomato crops), as well as livestock (especially goat breeding) and viticulture, are still relevant economic activities.

### 5.2. Fuel Map and geographical data

The stakeholders of this Living Lab were responsible for managing this information. The geographic information, fuel map, CBH, and CBD were provided by the company Tecnosylva, which created the raster data based on information from the Forest Map of Spain (MFE50).

### 5.3. Weather scenarios

To generate the weather scenarios, two predominant synoptic situations were considered: the first corresponds to standard summer conditions, and the second to conditions that favor Extreme Wildfire Events (EWEs). Additionally, it was taken into account that in the Canary Islands, wind stratification occurs in two layers: the lower layer, which is humid, and the upper layer, which is dry.

Based on these considerations, weather scenarios were created for the following conditions: standard conditions for the lower layer, standard conditions for the upper layer, EWE-favorable conditions for the lower layer, and EWE-favorable conditions for the upper layer.

The fuel moisture scenarios were determined with the help of the leader of the stakeholders of this Living Lab for each of the conditions described earlier. Using weather conditions and the Scott and Burgan model guide as a proxy, the following moisture scenarios were defined:

- standard conditions for the lower layer correspond to a D4L4 scenario,
- standard conditions for the upper layer correspond to a D2L2,
- EWE-favorable conditions for the lower layer correspond to a D3L3,
- EWE-favorable conditions for the upper layer correspond to a D1L1.

### 5.4. Values at risk

The Government of the Canary Islands, as a stakeholder of this Living Lab, was responsible for generating the data and layers of the values at risk considered for the optimization. The values at risk considered were: population (20%), buildings (20%), protected areas (40%) and burned area (20%).

### 5.5. Fire simulations

For this study area, 10,000 simulations were conducted for each of the four scenarios. To accurately model each scenario condition, an ignition probability map was used, restricting ignitions to areas below and above scenario's height thresholds.

### 5.6. Methodology

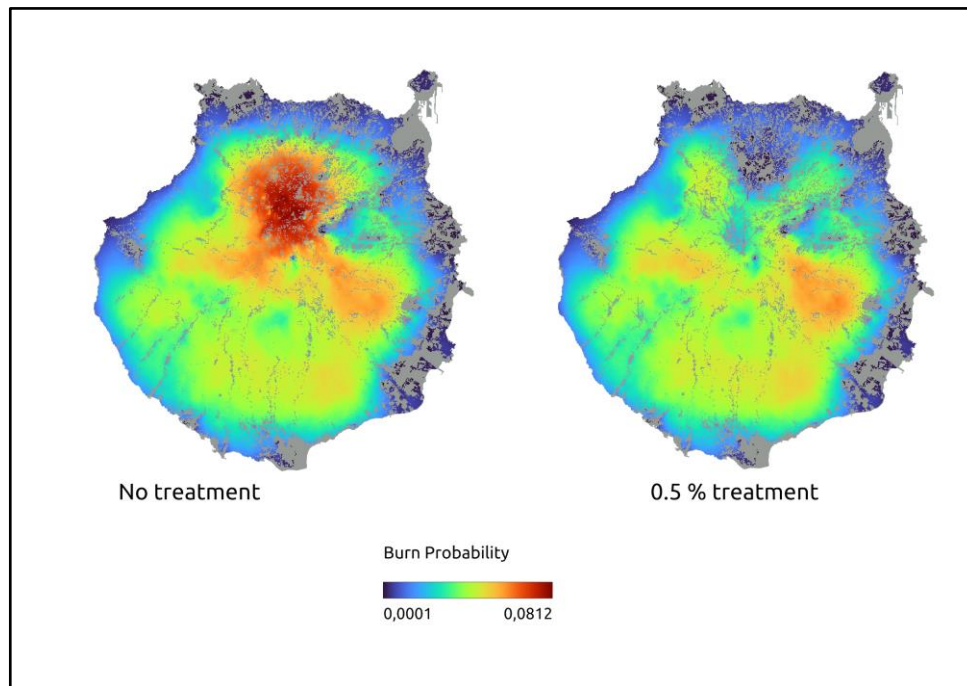
The methodology used is different to the one used in Biobio, the steps are specified below.

1. Simulate 10,000 wildfires for each weather scenario
2. Compute burn probability and weighted risk layer for each w.s.
3. Compute DPV using the risk layer for each w.s.
4. Combine all four DPV metrics using the following weights: D1L1 (0.35), D3L3 (0.35), D1L1 (0.15), D4L4 (0.15)
5. Select cells with the highest DPV, according to the percentage of area allocated for treatment.
6. Run a new set of 10.000 simulations for each w.s using treatments obtained in the previous step.
7. Recalculate the burn probability for the newly generated wildfire scenarios and weight them using the risk layer and the weights described in step 4 to compare the risk loss across all instances.

## 5.7. Results

### 5.7.1. Burn probability

The following figures show the burn probability map before and after fuel treatment for different cases, considering 0.5%, 1%, 1.5%, 2% and 2.5% of the treated area relative to the total area. The firebreaks were placed considering the protection of values at risk, with priority given to protecting the population.



*Fig 13: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 0.5% of the total area. The grey areas indicate the absence of forest fuel.*

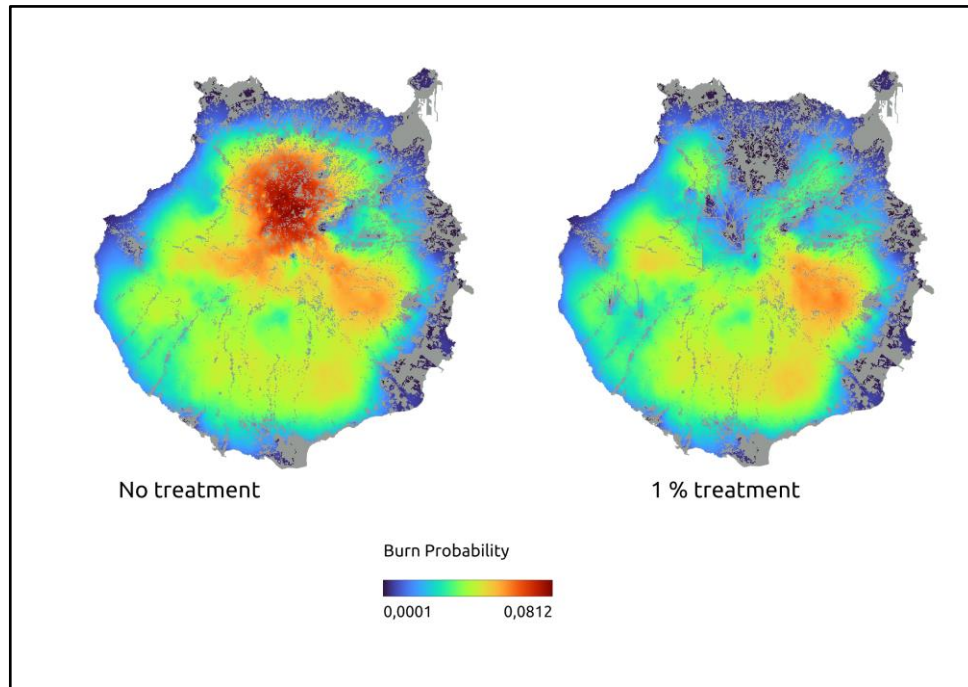


Fig 14: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 1% of the total area. The grey areas indicate the absence of forest fuel.

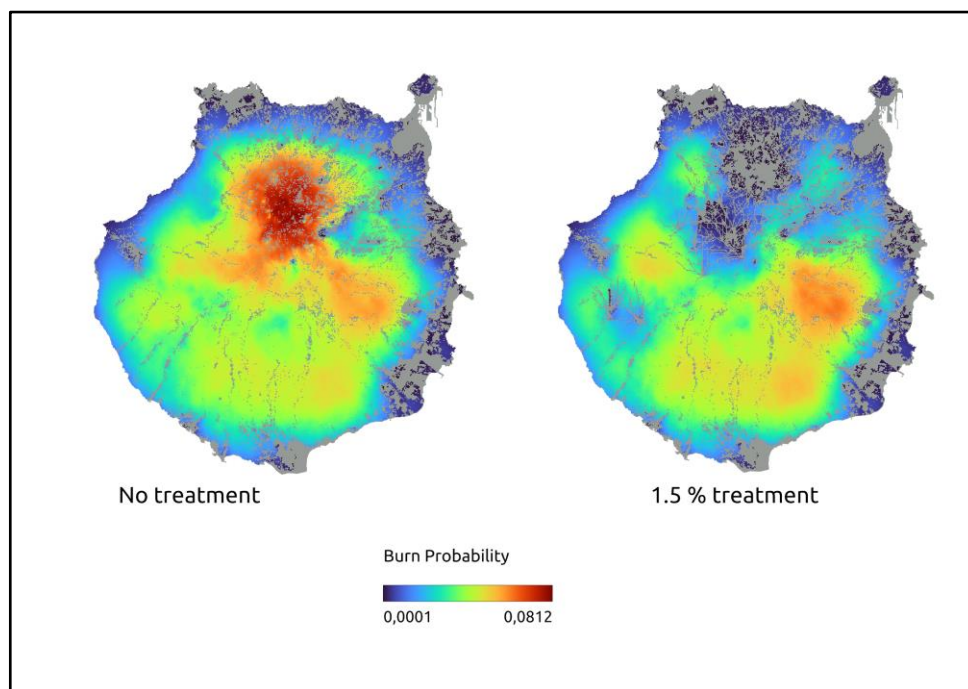


Fig 15: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 1.5% of the total area. The grey areas indicate the absence of forest fuel.

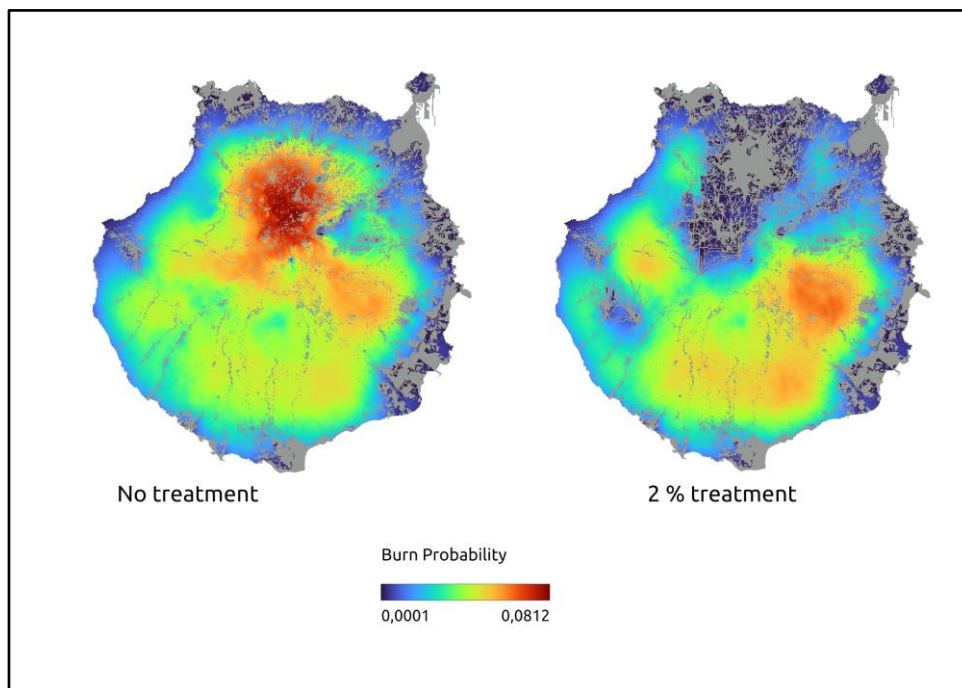


Fig 16: Burn probability before and after the placement of firebreaks. In this case, the firebreaks cover 2% of the total area. The grey areas indicate the absence of forest fuel.

### 5.7.2. Expected loss

The average number of hectares of vegetation lost (weighted by risk) due to fires was determined for different percentages of fuel treatment.

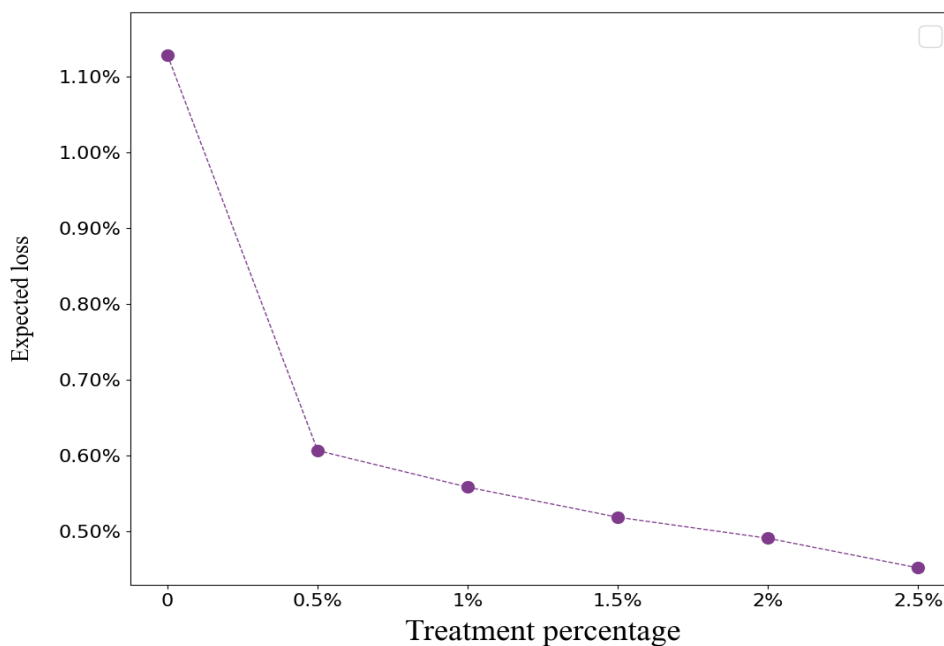


Fig 17: The weighted percentage of vegetation loss, based on risk values, as a function of the percentage of treated area.

## 6. Study Case: Portugal

### 6.1. Study Area

The study area is called Vale do Sousa, located in northwestern Portugal, about 50 km east of Porto, along both sides of the Douro River. This area includes two joint forest management zones (ZIFs): Entre-Douro-e-Sousa (north of the river) and Paiva (south of the river). Together, the Vale do Sousa covers 28,940 hectares, with 14,840 hectares belonging to these two ZIFs.

The whole area is represented by a set of rasters of 30x30m cell resolution.

### 6.2. Fuel Map and geographical data

The fuel map –fuel types, and vertical structure– was obtained from the forest inventory developed by Nunes et al. 2022. While the elevation raster was obtained from SRTM.

### 6.3. Weather scenarios

The study area is divided by a river that crosses it from east to west. Both zones, north and south, have different wind behaviours, hence 4 different sets of weather scenarios were created, 2 for each zone; one for extreme wildfire (EWE) conditions and the other for business as usual (BAU) conditions. Each set contains 100 weather scenarios taken from historical records.

### 6.4. Values at risk

In this study, six different values were selected for protection based on the consultation of stakeholders and the importance they assign to the ecosystem services provided by the forested landscape (Marques et al. 2021), each given equal weight in a linear combination:

1. Biodiversity: Measured by the Biod\_score, following the methodology of Botequim et al. (2023).
2. Cash: The estimated monetary value of the vegetation within the management unit.
3. Fire: An indicator of wildfire resistance, adapted from Ferreira et al. (2015), to assess the susceptibility of forest stands to wildfires.
4. Carbon: An estimate of the CO<sub>2</sub> stored within the forest stand (Marques et al 2024).
5. Erosion: Assessed using the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1991, Rodrigues et al. 2021).
6. Wood: The value of standing timber.

To combine these indicators, all values were normalized before summing them into a single index.

## 6.5. Fire simulations

For each management zone, 1,500 simulations were conducted under BAU conditions, and 3,500 simulations under EWE conditions. An equivalent number of simulations were also carried out before the treatments were defined by the optimization model.

For EWE scenarios fuel moisture content was set to 40% and Scott and Burgan's fire scenario were set t

For each management zone and weather scenario the ignitions were set randomly.

## 6.6. Methodology

This methodology is similar to the one used in Catalonia LL. The DPV for the aggregate value at risk was calculated. Then the DPV of each management unit is the total DPV of the cell within itself.

Then, the same optimization model as in the case on LL Catalonia was applied.

## 6.7. Results

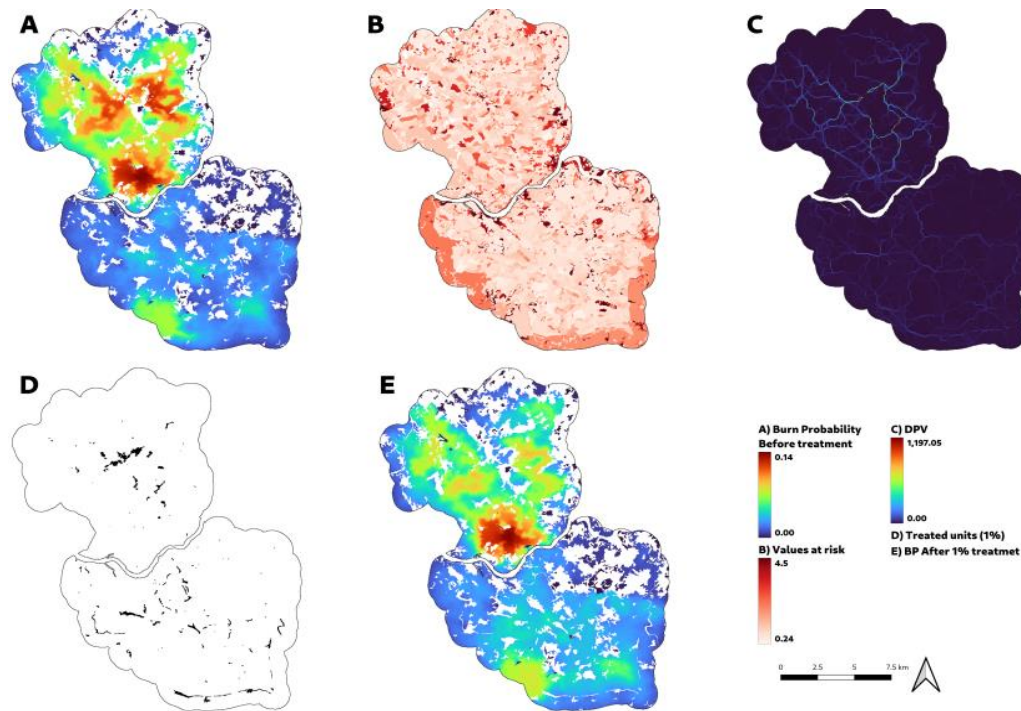


Fig 18. A) shows the Burn Probability of the Study Area before any treatment is applied, B) shows the value at risk, which is the sum of the normalized values named in the Values At Risk section, C) Shows the DPV by cell, D) Shows the DPV by polygon, which is the sum of the DPV of the cells within each of them and E) shows a treatment schema at 1% of the landscape.

*Summarized results of 1% of treatment for Portugal*

1 %	South	North
<b>Risk before treatment</b>	0.0288	0.0389
<b>Risk after treatment</b>	0.0192	0.0301
<b>Percentual reduction of risk</b>	33.5%	22.5%

## 7. CONCLUSION

The methodology described above, based on the Cell2Fire stochastic fire simulator and the Downstream Protection Value (DPV) metric, shows significant results regarding their capacity to protect several values at risk in the landscape with little percentage on the landscape treated in comparison with the reduction in expected losses. At this point, it is important to emphasize that these results do not necessarily show a reduction in burnt area in each landscape after treatment, but the potential reduction of expected losses in the values that are wanted to be protected. That is why, the more concentrated the values are in the landscape, the more efficient is the treatment (less area treated achieves a greater reduction in the expected losses). An example of this can be observed in Catalonia, where landscape loss and damage were evaluated considering different scenarios of values at risk. Significant differences can be seen by comparing scenario R1, where only the burned area is considered as the value at risk, with scenario R2, which prioritizes the protection of urban areas. In scenario R1, the average reduction of burned hectares is 10% when treating 1% of the landscape, compared to an 8.8% reduction in scenario R2 for the same percentage treated. However, when looking at risk reduction, scenario R2 shows an 11.4% decrease in urban areas with 1% of the landscape treated, compared to an 8.3% reduction in scenario R1.

## 8. RECOMMENDATIONS

In light of the aforementioned considerations, it is advised that those responsible for decision-making utilize these methodologies to support the allocation of fuel treatments, thereby ensuring their efficacy in safeguarding the values exposed in the landscape. Given that Cell2Fire is an open-source wildfire simulator, it can be used within other software if well integrated, as well as with its own QGIS toolbox, that provides a user friendly visual interface.

## 9. JUSTIFICATION FOR TRL INCREASE

Cell2Fire was initially designed to simulate wildfires using the Canadian Forest Fire Behaviour Prediction (FBP) System. At the beginning of the FIRE-RES project, its application in decision-support models was at an early prototype stage (TRL 4).

Through the FIRE-RES project, Cell2Fire was significantly advanced to support additional fuel models, including the Scott and Burgan system and the KITRAL system, increasing its relevance across diverse geographic and ecological contexts. These adaptations have been validated through rigorous testing. For instance, Cell2Fire was successfully tested against real wildfires in Chile using the KITRAL system, with the results published in a pre-print publication (Carrasco et al. 2023). Additionally, the adjustments to integrate the Scott and Burgan fuel system were documented and published (Gonzalez-Olabarria et al. 2023).

A major milestone was the creation of the QGIS Fire Analytics Toolbox, which consolidates these capabilities into a user-friendly graphical interface. This toolbox has enabled independent application by researchers, such as the team at ISA in Portugal, who use it to identify optimal fuel treatments and their locations within landscapes. Its replicability is further underscored by adoption at the MFFF & CP Advanced Training Center, where Cell2Fire is used to train future firefighters in tactical firefighting planning and to support evacuation triggers. These applications in both real-world wildfire response and planning scenarios demonstrate that Cell2Fire has been operationally tested and validated in realistic environments.

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**FIRE-RES**