FIRE-RES

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

D2.7 IA brief 2.6: Designing post-fire restoration strategies

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Abstract: Following a wildfire, it is essential to quickly define explicit management interventions for specific vulnerable areas. This is particularly important in areas affected by large wildfires, as the identification of priority areas for restoration may be especially challenging due to the extent of the burned area compared to the limited resources available. In this study, we present a methodology to efficiently identify high-priority restoration areas by leveraging existing cartographic layers and expert knowledge. This approach was applied in the Living Labs of Catalonia, Portugal, and Canary Islands. Key factors influencing post-fire regeneration were identified through expert panel discussions, and corresponding weights and utility functions were assigned to each criterion. These elements were then integrated to generate a final priority restoration map, designed to support decision-making following an EWE. The resulting maps were validated using recent EWEs in each Living Lab, demonstrating their practical applicability.

Key words: expert knowledge, restoration priority map, soil erosion, vegetation recovery, vulnerable areas

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1. Introduction

The overall aim of this deliverable is to present the process of selecting and defining criteria to identify priority areas in urgent need of restoration after a forest fire, which leads to the development of different restoration priority maps in three Living Labs (LLs) of FIRE-RES project (Catalonia, Canary Islands and Portugal). This report details the process made to obtain restoration priority maps in these LLs.

As already presented in the literature review of Deliverable 1.12. part I "Innovative post-fire strategies and adaptation to the current context of increasing environmental uncertainties", the main factors driving post-fire restoration needs include the type of the pre-fire vegetation community, soil characteristics, characteristics linked to the fire event itself, topography, and pre- and post-fire climatic conditions.

Soil loss is an irreversible impact on a human scale and entails the loss of most of the services provided by the affected system. After a forest fire, the soil becomes drastically unprotected against erosion by losing the protective forest cover, leading to a decrease in soil porosity and infiltration rates (Robichaud et al. 2016). Soil degradation can hinder vegetation recovery. Soil erosion susceptibility is estimated according to geomorphological, lithological, edaphic and vegetation cover characteristics. The risk of erosion decreases with the recovery of vegetation, which retains the soil and reduces the impact of raindrops and runoff.

Natural recovery of vegetation after a fire depends mainly on the regenerative strategy of the dominant species (Vallejo & Alloza 2015). In general, plant communities dominated by resprouting species exhibit high survival rates and rapid regeneration of aerial parts after fire, leading to faster recovery of vegetation cover (Vallejo & Alloza 1998, Tangney et al. 2022). In contrast, the recovery of plant communities dominated by germinating species depends on the effect of fire on the seed banks (aerial and edaphic, Bukh et al. 2007), the composition of the post-fire understory (Vallejo et al. 2012) and the meteorological conditions after the fire.

Recent works highlighted that post-fire natural recovery does also rely on the duration of drought episodes (Bautista et al. 2009, Blanco-Rodríguez et al. 2023), the coverage of obligate seeder species and the occurrence of heatwaves episodes after fire (Paneghel et al. 2024). However, in case of urgent forest restoration, relying solely on meteorological variables to determine whether restoration actions are necessary is not advisable, as these variables are subjected not only to inter-annual variability, but also to intra-fire variability, especially in extreme wildfire events (EWE), which tend to affect large areas.

Additionally, fire severity affects both soil erosion hazard and natural recovery potential of the vegetation. Higher severities are related to the development of hydrophobic and hyper-dry soil conditions (Keizer et al. 2008), reductions in aggregate stability (Mataix-Solera et al. 2011), soil porosity (Neary et al. 2005) and infiltration rates (Robichaud et al. 2016), all of them leading to higher soil losses. Fire severity also influences forest recovery, with a different effect depending on the presence or not of fire-related vegetation traits before the fire. Obligate seeders usually rely on colonization from unburned patches (Ordóñez et al. 2006, Martín-Alcón & Coll 2016) and seed germination from the soil seed bank. In some cases, seeder species show additional adaptations, such as serotiny, which allow them to regenerate without the presence of living trees. Previous studies have shown that seeder species adapted to forest fire regimes are capable of regenerating well even after high severity fires (Moya et al. 2020), being the type of fire which becomes important, as crown fires expose serotinous cones to temperatures that compromise seed viability (Herrero de Aza et al. 2004, Maia et al. 2012). In contrast, the resprouting ability is generally unaffected by fire severity (Vallejo et al. 2012), except in the most intense wildfires, where the bud reserves could be damaged (Casals et al. 2018).

Topography influences fire propagation and severity, but also post-fire restoration ability. In Mediterranean areas, northern slopes are more likely to be successfully regenerated than southern ones, as the former are more humid and have less stressful evapotranspiration conditions in summer. Studies involving both obligate seeders and resprouters have shown reduced regeneration on southern slopes in the Mediterranean (Pausas & Vallejo 1999 in *Q. coccifera*, Pausas et al. 2004 in *P. halepensis* or Calvo et al. 2008 in *P. pinaster*). Slope steepness plays a more pronounced role in obligate seeders than in resprouters. Previous studies have identified that steeper slopes hinder post-fire regeneration (Ruiz-Gallardo et al. 2004). This may be due to increased vulnerability to soil erosion, poorer soil development and higher seed run-off compared to flatter areas.

In conclusion, areas with slow plant recovery and a high risk of soil erosion should be prioritized for restoration (Vallejo et al. 2012). Given the limitations of economic and technical resources, efforts should focus on providing spatially explicit tools to rapidly identify these areas, especially when the affected area is large and structurally complex. As the need for restoration can be very urgent, providing forest managers with cartographic information on vulnerable areas through an accessible tool could be essential. One example of such a solution is POSTFIRE (see Alloza et al. 2021 for additional details).

In the following sections, we present the development processes of three different prioritization methodologies as applied in three Living Labs of the FIRE-RES project: Catalonia, Portugal and the Canary Islands, as well as their application after a forest fire.

2. Methodology

We present the methodologies developed by the different scientific teams involved in this Deliverable, individually. However, they all converge in their use of the factors to be considered for post-fire restoration, as described in the introduction and in Deliverable 1.12 part I. These methodologies rely on publicly available cartographic layers or on data easily obtained through GIS processing of existing information, and they create prioritization maps by assigning weights and utility functions to different factors (hereafter, criteria and sub-criteria). This process is informed by meetings with local experts and stakeholders in Catalonia and Portugal, as well as expert knowledge in Canary Islands.

2.1. Catalonia Living Lab

2.1.1. Study area

This work has been carried out taking as case study the Ribera d'Ebre forest fire (Tarragona), which occurred in June 2019. This fire affected about 6,800 ha of forest and agricultural crops. It is one of the last major forest fires in Catalonia and it was caused by a combination of spontaneous combustion of waste from a cattle farm. The severe drought affecting the area that year and the occurrence of winds exceeding 60 km/h helped to the propagation of the fire.

The area affected by the wildfire comprised small mountain ranges with a hilly relief. According to the World Reference Base classification, soils in the area are common or calcic Xerothents, formed from rocks of different lithologies and deposits resulting from weathering at the base of mountains. They can be superficial or deep and are generally well-drained, with medium textures and few coarse elements. Soils may also present secondary accumulations of calcic carbonate in the form of nodules and/or coatings of coarse elements that give rise to a limbic horticulture. Their pH ranges from medium basic to slightly alkaline and the calcium carbonate content from high to very high.

Before the fire, the area presented a mixed of olive, almond and cereal crops (some of them unmanaged) combined with forest patches composed by shrubs and scattered Aleppo pine (*P. halepensis)*. The main phytosociological association presented in the area was *Erico-Thymelaetum,* linked to a medium resprouting ability, and areas with varying abundance of *P. halepensis*, a pine species adapted to forest fires due to its serotinous cones.

2.1.2. Identifying key criteria and sub-criteria for post-fire regeneration

Prior to the meeting with stakeholders, key variables for post-fire recovery were identified and obtained from different sources. These variables included: soil erodibility, slope and aspect (and its combination), fire severity, resprouting ability of the vegetation community and coverage of *Pinus halepensis* (a serotinous pine very well represented in the forested area of the living lab). Chosen factors were grouped according to two main criteria: the potential risk of soil erosion and the natural recovery capacity of the vegetation.

Soil erosion

To characterize the soil erosion criterion, three sub-criteria were used: soil erodibility (through the K factor of the RUSLE, Revised Universal Soil Loss Equation), slope length (LS factor of the RUSLE) and fire severity.

- **K factor** was extracted from cartography of the National Inventory of Soil Erosion, provided by the Ministry for Ecological Transition (MITECO), with a resolution of 25x25 meters (Figure 1).

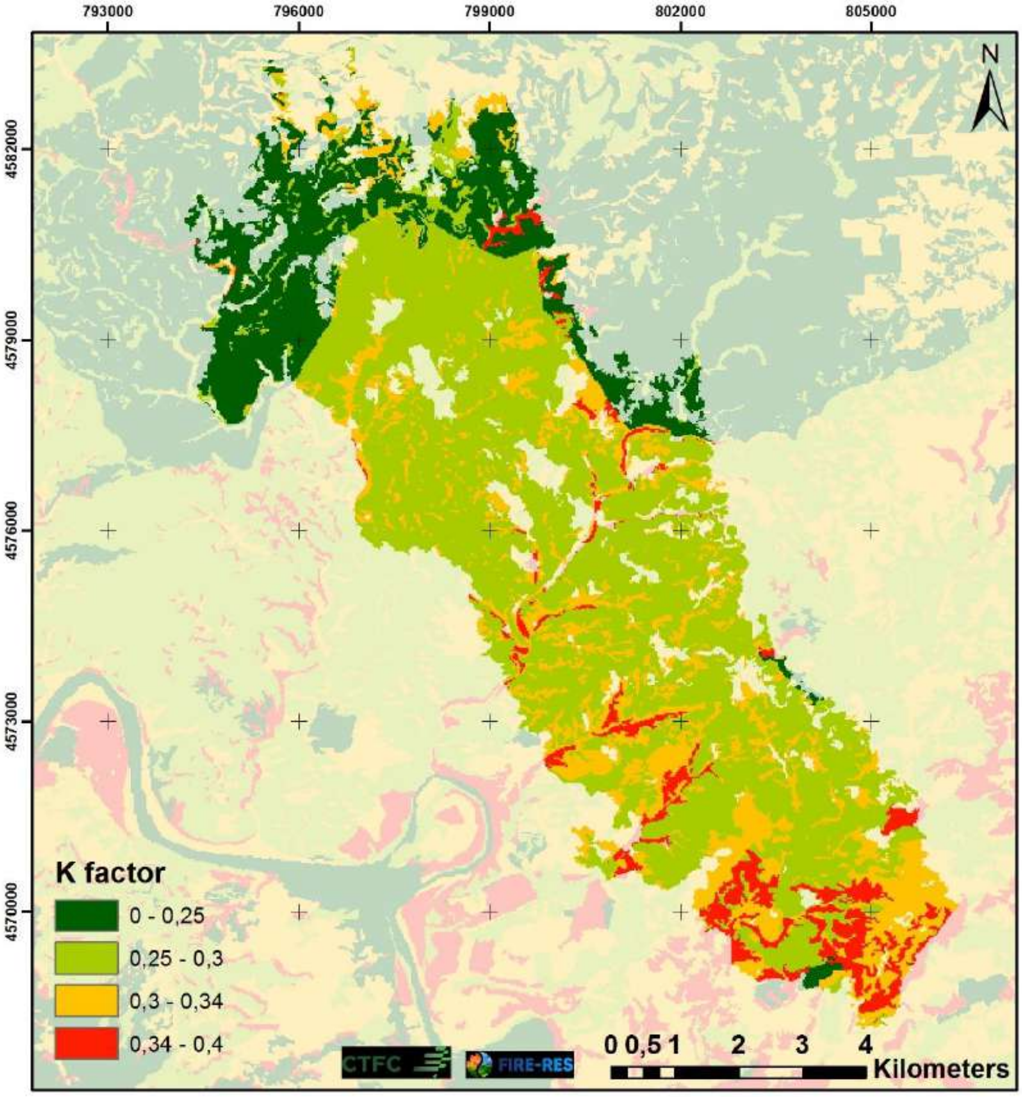


Figure 1. K factor distribution in Ribera d'Ebre wildfire

- **LS factor** (Figure 2) was obtained through geoprocessing, following the equations outlined by Desmet & Govers (1996) and McCool et al. (1997).
    - For the calculation of the length, **subfactor L**, the digital terrain model (DTM) of the National Geographic Institute (IGN) at 2x2 m resolution was first obtained. This DTM was filled in to correct the existence of false endorheic depressions produced by the acquisition and interpolation of topographic data. Then, the flow direction and accumulation layers (catchment basin at each pixel) were generated. On the other hand, a series of intermediate calculations were performed to obtain the coefficients "*β*" and "*m*" related to this subfactor (Eqs. 1, 2, 3 and 4).

$$L = \left(\frac{L_{i,j}}{22.13}\right)^{m} \quad [1]$$

$$L_{i,j} = \frac{(A_{i,j}+D^2)^{m+1} - A_{i,j}{}^{m-1}}{x^m D^{m+2} 22.13^m} \quad [2]$$

where $A_{i,j}$ is the catchment area at each pixel, x = (sen $\alpha_{i,j}$ + cos $\alpha_{i,j}$; α = orientation of the flow direction), D = cell size

$$m = \frac{\beta}{1+\beta} \quad [3]$$

$$\beta = \frac{\frac{sin\,(\theta)}{0.0896}}{3*sin(\theta)^{0.8}+0.56} \quad [4]$$

where θ is the slope angle in radians

- For the calculation of the slope, **subfactor S**, the RUSLE equations developed by McCool et al. (1997) (Eqs. 5 and 6) were used, based on the DTM of the IGN at 2x2 m resolution.

$$S = 10.8sen(\theta) + 0.03 \qquad \text{if slope} < 9\% \quad [5]$$

$$S = 16.8sen(\theta) - 0.5 \qquad \text{if slope} \geq 9\% \quad [6]$$

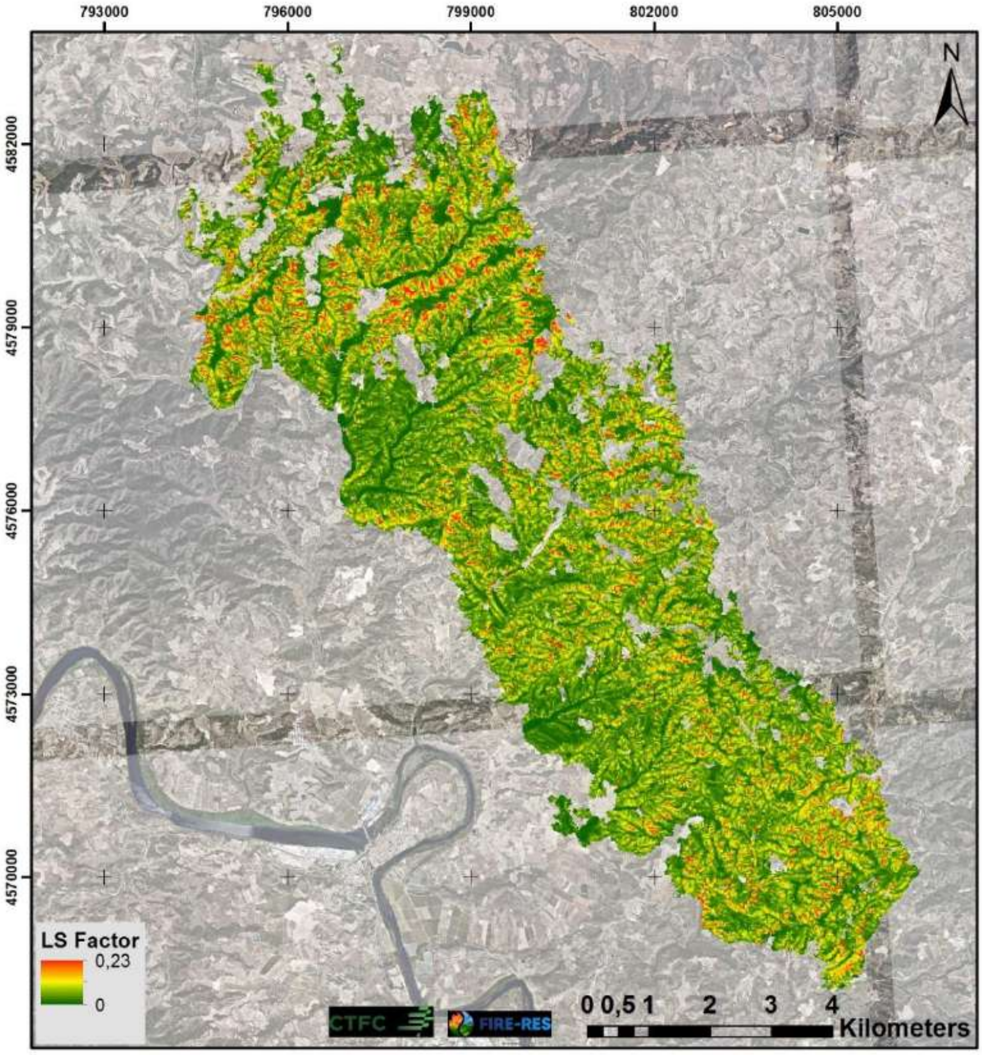


Figure 2. LS factor distribution in Ribera d'Ebre wildfire

- **Fire severity** (Figure 3) was obtained through the difference of the normalized spectral index of burned area (NBR) between the closest available satellite images to the pre- and post-disturbance dNBR (Eqs. 7 and 8).

$$NBR = \frac{NIR-SWIR}{NIR+SWIR} \quad [7]$$

$$dNBR = NBRpre - NBRpost \quad [8]$$

where NIR is near infrared and SWIR is shortwave infrared.

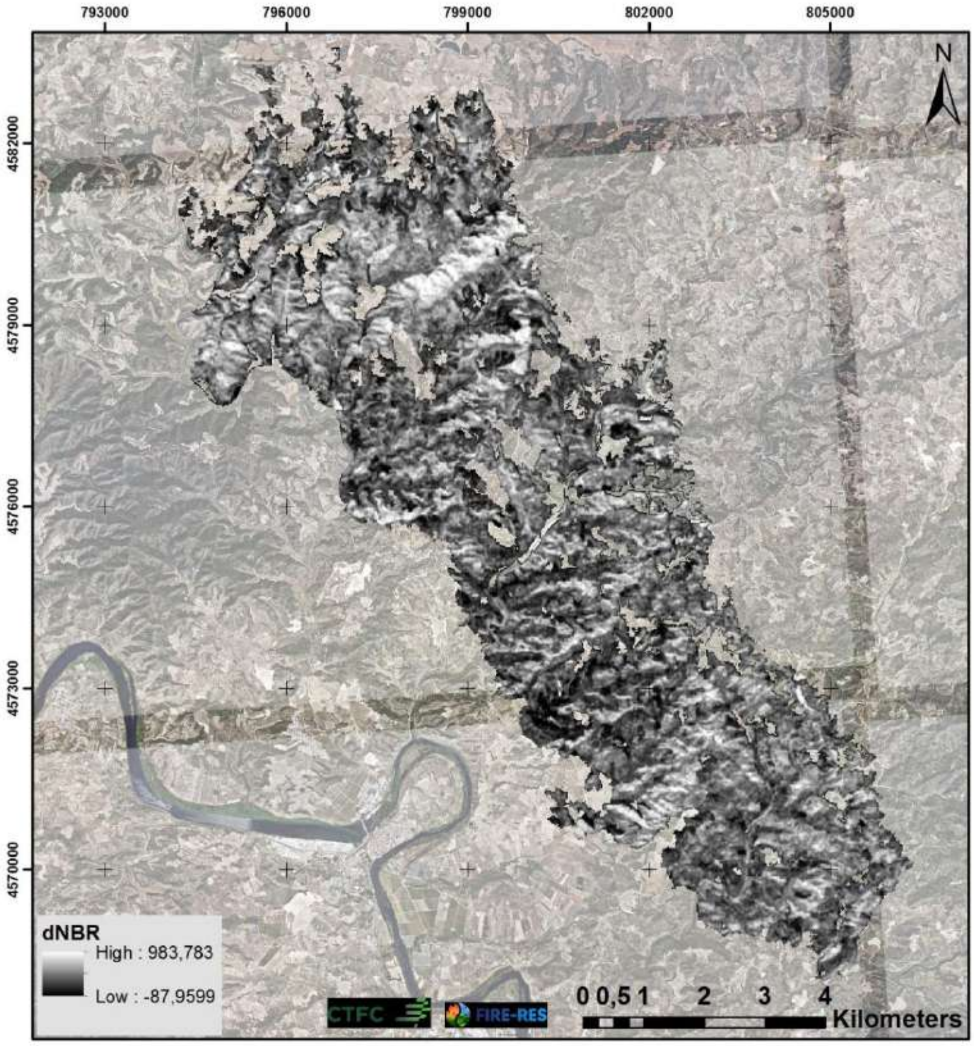


Figure 3. Severity (dNBR) distribution in Ribera d'Ebre wildfire

Vegetation natural recovery capacity

To characterize the criterion associated to the natural recovery capacity of the vegetation, the following sub-criteria were used; fire severity, aspect, resprouting ability of the existing community, and coverage of the main overstory species (*P. halepensis)*.

- **Fire severity** has been previously presented.
- **Resprouting ability** (Figure 4) of the plant community prior to the fire. Resprouting ability was derived from the Habitats Map of Catalonia, available at a scale of 1:50,000. We assigned a resprouting potential to each existing community based on its specific composition and the resprouting capacity of its species. From the existing floristic inventories in the Biodiversity Data Bank of Catalonia (Font, 2011), the percentage of cover for species with resprouting or germinating strategies was calculated for each phytosociological association in each given habitat. The post-fire strategy was obtained from the BROT database (Tavsanoglu & Pausas 2018).

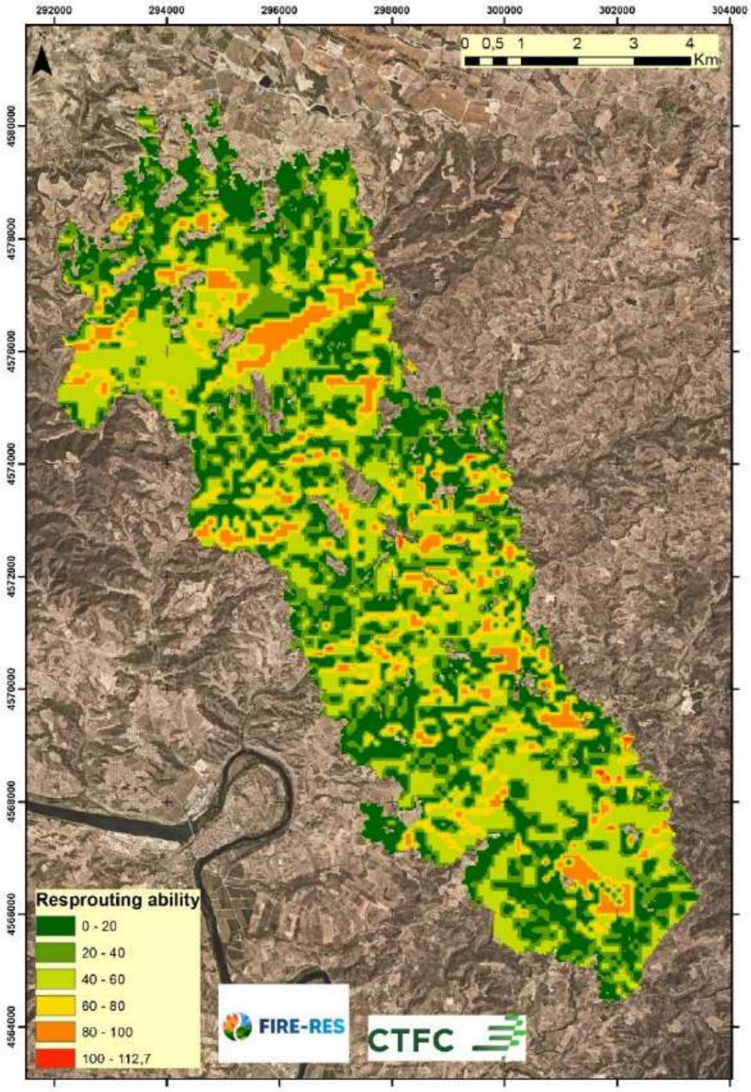


Figure 4. Resprouting ability per habitat in Ribera d'Ebre wildfire

- **Aspect** (Figure 5) was obtained through the DTM at 2x2 m scale, with a simple GIS processing, plus a transformation to continuous values via northness index, so that (-1) corresponds to northern aspects and 1 to southern ones (Eq. 9)

$$northness = -\cos(aspect) \quad [9]$$

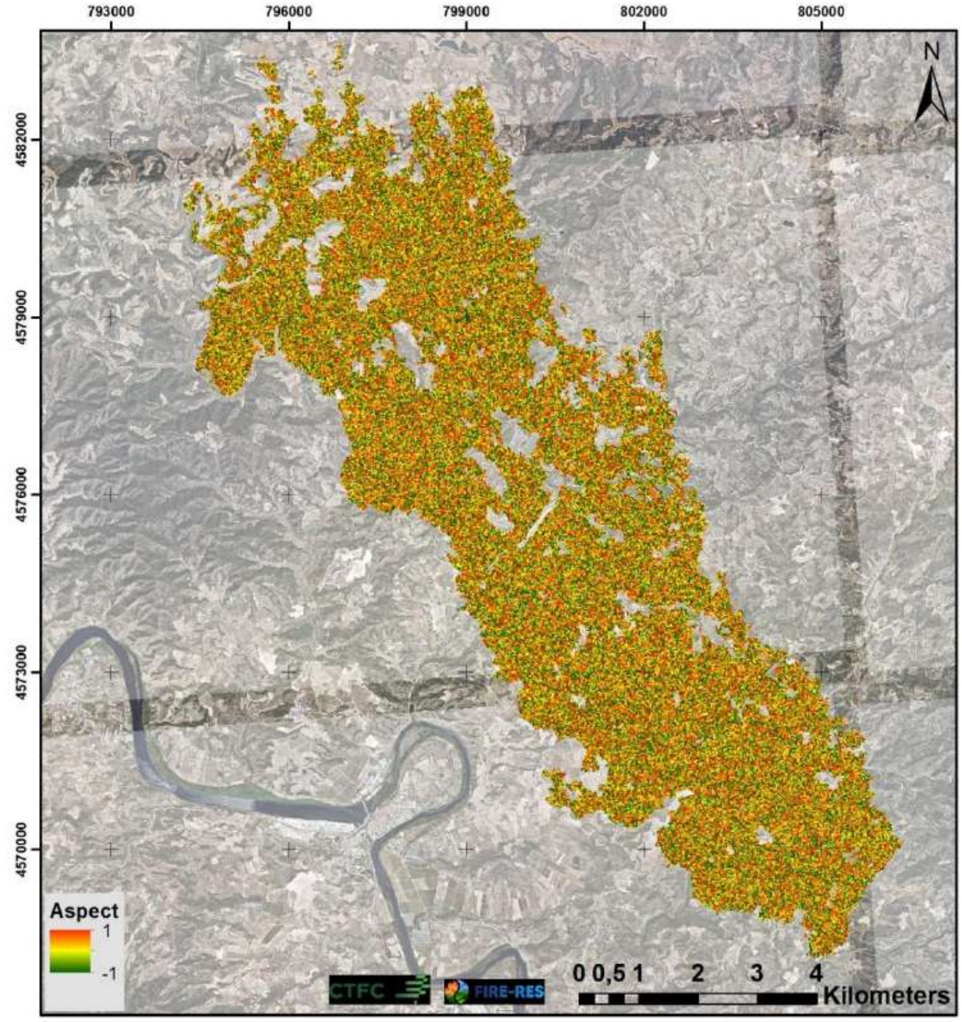


Figure 5. Aspect distribution in Ribera d'Ebre wildfire

- **Coverage of *Pinus halepensis*** was obtained by applying several steps. First, all polygons classified as forested areas were selected using data from the Spanish Land Occupation Information System (SIOSE). Then, the layer was intersected with that of the National Forest Map, scale 1:25,000 (MFE25), selecting only the polygons in which the main species was *P. halepensis*. Finally, the coverage for these polygons was assigned using the second LiDAR dataset from the Spanish National Orthophoto Program (PNOA) (Figure 6).

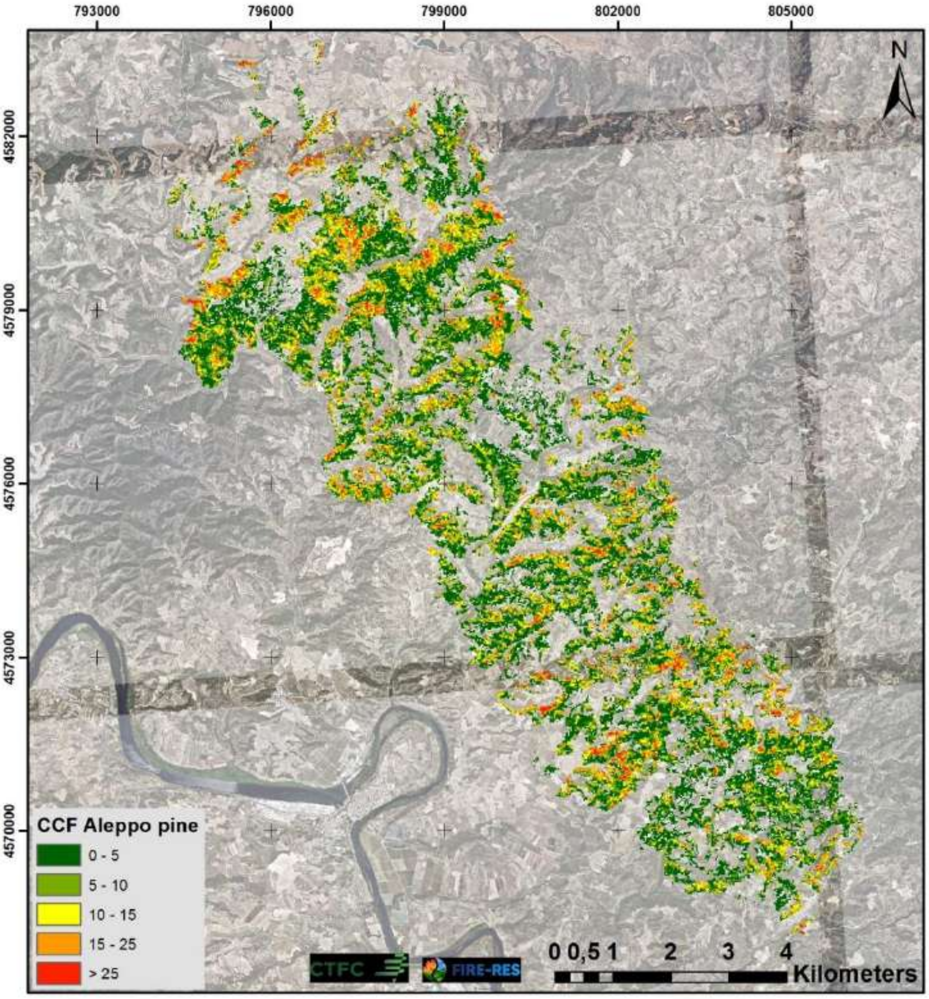


Figure 6. Coverage of Aleppo pine (P. halepensis) in Ribera d'Ebre wildfire

2.1.3. Definition of utility functions and weighting of criteria and sub-criteria

All the previously explained criteria and sub-criteria were shared with wildfire and post-fire restoration experts before the meeting (Figure 7). During the meeting, we discuss individually the pertinence of considering each criterion and we established utility functions and determined the weights based on their importance for each of them.

The final selection of criteria and sub-criteria was based on three premises:

- The information required is freely available and can be accessed immediately.
- The priority for restoration is inversely proportional to the capacity of the ecosystem to recover naturally.
- The priority for restoration is defined in the short term.

Figure 7. Meeting with post-fire restoration experts in Catalonia

Based on these premises, the sub-criterion “coverage of *P. halepensis*” was discarded, since while serotinous species are among the fastest to establish among seeder species, trees take longer to establish than herbs and shrubs, resulting in a slower recovery of vegetation cover. Given our definition of priority, this sub-criterion was not considered applicable. As a result, we updated the habitats database to include those habitats where *P. halepensis* is the dominant species, with resprouting shrubs in the understory (Figure 6).

The rest of variables were all selected by the experts. Then, utility functions were established for each sub-criterion (Figure 8)

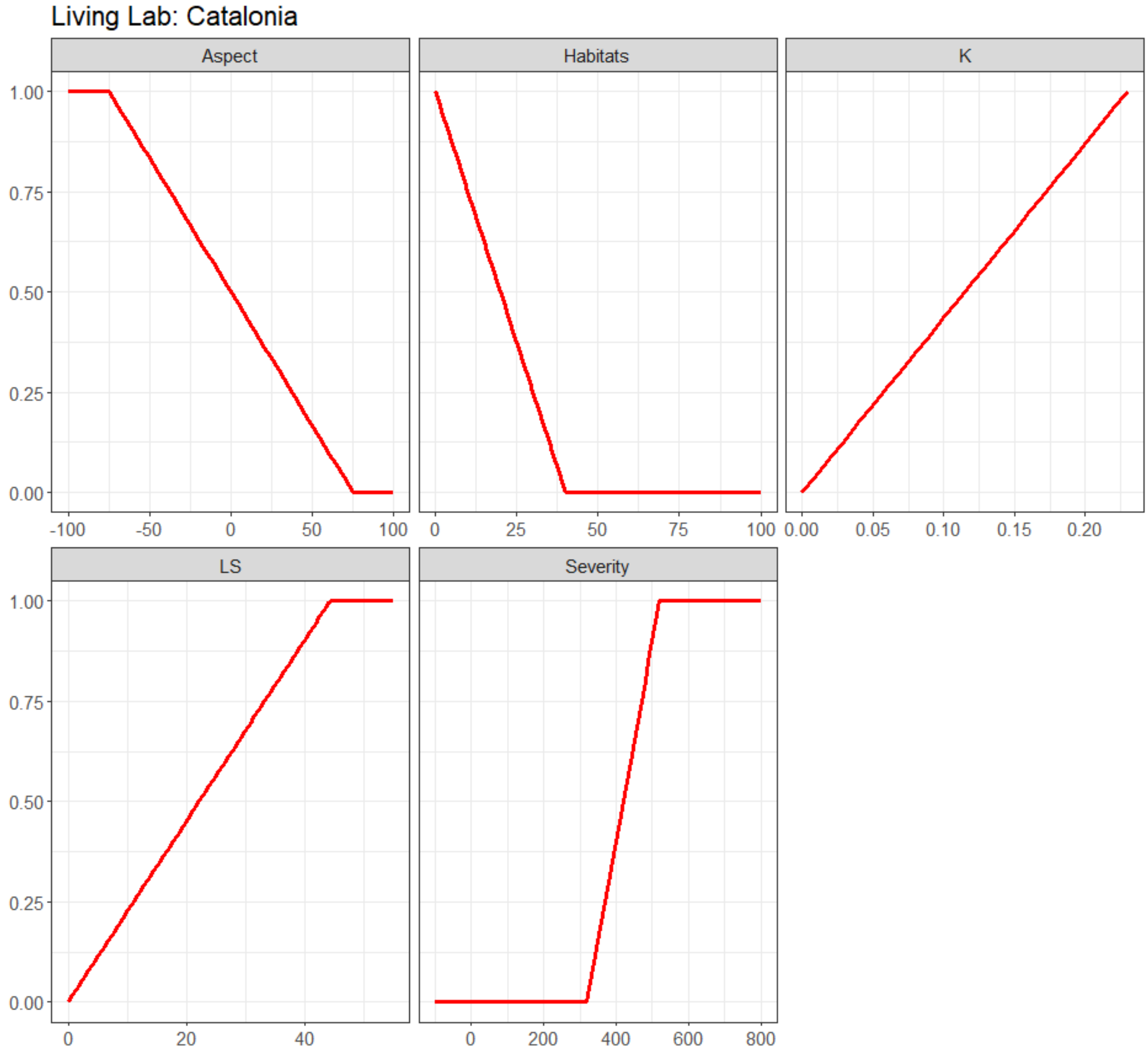


Figure 8. Utility functions of the selected subcriteria during the wildfire experts meeting in Catalonia. Habitats refers to the percent cover of resprouter species.

For the **K factor**, a linear utility function was chosen for the entire range of factor values.

For the **LS factor**, as it was divided into two sub-factors, utility functions were established for each of them. Thus, for the **L subfactor**, a linear utility function was developed between the values 0 and 60 m of slope length, from which the subfactor takes value 1. For **S subfactor**, a linear utility function was established between values 0 and 40% slope (transformed to angle), from which the subfactor takes value 1. In Figure 8 we present a combination of the two utility functions that integrates LS.

For the **fire severity factor**, the values established in García-Llamas et al. (2020) were selected. Thus, unburned or burned areas with low severity take value 0, which is equivalent to dNBR <317. The factor grows linearly between 317 and 527 (moderate intensity) and from 527 onwards it is considered severe intensity, and the factor takes value 1.

For the **resprouting coverage factor**, we first considered that post-fire coverage could reach about one third of the pre-fire coverage in the short term (i.e., less than one year) (Kuenzi et al. 2008). Subsequently, the utility function was established in such a way that below 40% cover, the factor decreases linearly, and from that 40% cover, it is considered 0.

For the **aspect factor**, it starts from values between -1 and 1. Thus, in pure shady orientations (considered between -1 and -0.75), the factor takes a value of 0, grows linearly between -0.75 and 0.75, and takes a value of 1 in pure sunny orientations.

The last step was the establishment of weights for the criteria and sub-criteria. At the meeting, the following equation [10] was reached by consensus:

$$Restoration\ priority = 0{,}75 * (0{,}5 * K + 0{,}4 * LS + 0{,}1 * Severity)$$

$$+0{,}25 * (0{,}7 * Habitats + 0{,}2 * Aspect + 0{,}1 * Severity) \quad [10]$$

2.2. Portugal Living Lab

For the case of Portugal, the study employs a Multi-Criteria Decision Analysis (MCDA) approach to identify and prioritize the criteria and sub-criteria for defining the areas within wildfire perimeters where restoration is most urgent. The prioritization for restoration is determined using an initial set of proposed criteria (drawn from Sara Casados' Master's thesis at the School of Agronomy at the University of Lisbon, Casados, 2024), which are then weighted based on their importance during the stakeholders' meeting. Specifically, the Analytic Hierarchy Process (AHP) is used within a Geographical Information System (GIS) environment, which provides a spatially explicit framework that considers multiple preferences as well as social and ecological drivers. First, the gathered information reflecting stakeholder's preferences and weights associated to each criterion and sub-criterion is normalized into the same scale. Then, it is combined to generate individual prioritization maps for each criterion. A final prioritization map combining all criteria and sub-criteria is developed, categorizing areas by restoration priority levels, from lowest to highest. This map is an influential tool for the effectiveness of restoration decision-making processes, identifying regions where restoration is more urgent.

2.2.1. Study area

The research took place in Vale do Sousa, NW Portugal, 50 km east of Porto, covering 28,940 ha, with 14,320 ha in Zonas de Intervenção Florestal (ZIF). The ZIF areas, divided by the Douro River, support collaborative forest management with diverse land ownership, including private, industrial, and municipal stakeholders. The Associação Florestal do Vale do Sousa (AFVS) was founded 29 years ago to address small-scale, fragmented land ownership. Vale do Sousa has uneven terrain (20–710 m elevation), poor, well-drained soils (Umbric Leptosols, Leptic Regosols), and a Mediterranean climate with Atlantic influence.

According to the simulated inventory generated at ISA 2022, Vale do Sousa showcases a diverse land-use mosaic: *Eucalyptus globulus* Labill. dominates the landscape, covering more than half (51.8%) of the total area, followed by agriculture (16% coverage). Building areas cover just over 8% of the landscape, indicating a moderate level of urban development and human settlement. The rest of land-use cover corresponds to non-riparian vegetation (7.5%), shrublands (6.8%), maritime pine (4.1%), riparian vegetation (2.8%), water bodies (2.3%), and bareland (0.6%). Eucalypt is the most important pulpwood producing species in Portugal, which is the key raw material of the pulp and paper industry (Marques et al., 2011).

In both the 2017 and 2022 wildfires, eucalyptus stands were consistently the most affected forest type (ISA, 2022), despite the significant reduction in the total burned area, from 5.1 hectares in 2017 to 775 hectares in 2022. Eucalyptus accounted for 59% of the total area burned in 2017 and 40.5% in 2022. In contrast, shrublands, which accounted for only 1% of the burned area in 2017, experienced a sharp increase in 2022, comprising 27.1% of the total area affected. When left unmanaged, shrublands act as high-risk ignition and propagation zones, amplifying fire behavior and complicating suppression efforts. Maritime pine, another common forest species in Portugal, showed relatively stable and low percentages of burned area: 3.4% in 2017 and 2.6% in 2022.

2.2.2. Spatial identification of 2017 EWE event and analysis of selected criteria and sub criteria

The study examined yearly burned areas within the Vale do Sousa region by consulting national databases provided by the Instituto da Conservação da Natureza e das Florestas (ICNF). Two different cases were selected in Vale do Sousa: a continuous burned area that occurred in 2017, which affected 8,000 hectares approximately, and small, scattered burned areas from a fire that occurred in 2022 (total area corresponding to 635 hectares, approximately).

The prioritization of areas for post-fire restoration was based on two key criteria: erosive potential and the natural recovery capacity of vegetation. Within these criteria, a set of sub-criteria and indicators was defined for operational implementation and analysed using spatial data.

Criteria and sub-criteria were pre-selected mainly based on relevant databases at ISA, particularly studies from the FIRE-RES project. Additionally, the pre-selection was informed by a review of literature, including municipal and national studies in Portugal. Criteria and sub-criteria are presented in Table 1.

Table 1. Pre-selection of criteria and sub-criteria prior to the interaction of stakeholders

Criteria	Sub-criteria	Units
Soil erosion	Soil erodibility (K factor) Slope length and steepness (LS factor) Vegetation cover (C factor) Fire severity (dNBR)	$Mg \cdot ha^{-1}$ $MJ \cdot mm^{-1}$ Dimensionless Dimensionless Dimensionless
Natural recovery capacity of vegetation	Natural recovery potential of species after a fire Fire severity (dNBR)	Dimensionless Dimensionless
Social areas	N/a	Mts

The **soil erodibility factor (K factor)** was estimated using the methodology proposed by Rodrigues et al. (2020, 2021), as part of the RUSLE equation framework (Renard et al., 1991; Constantinho and Coutinho, 2001). The K factor was calculated using GIS techniques; the equation includes soil properties representing the susceptibility of soil to erosion, transportability of the sediment, and the amount and rate of runoff given a particular rainfall input (USDA, 2001; Figure 9). Source information about soil types was extracted of the Regional Soil Department in Portugal.

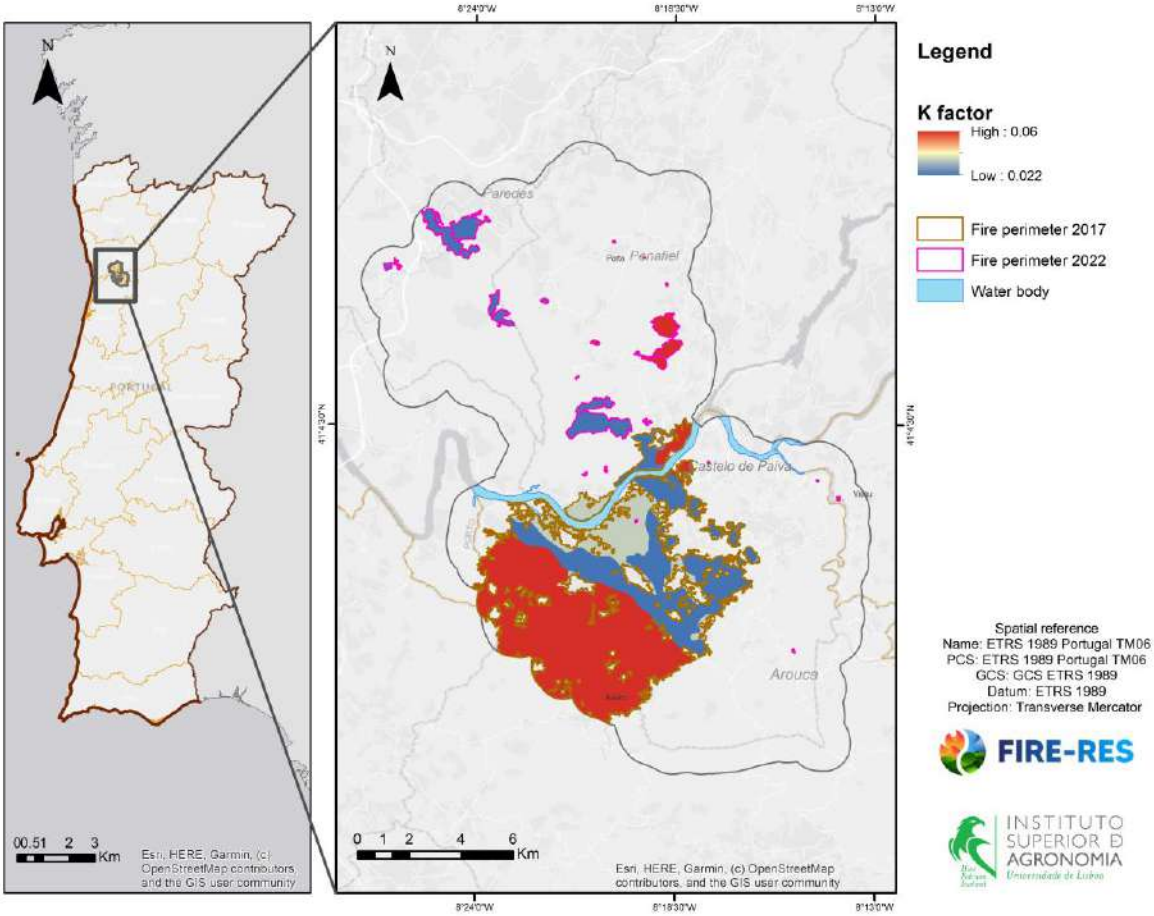


Figure 9. Soil erodibility (K factor) for the burned areas 2017 and 2022.

On the other hand, the effects of the **topographic factor** on soil loss are represented by the **LS factor** (described in Section 2.1.2). As for the LS factor, it has been obtained following the equations set by Desmet and Govers (1996) and McCool et al. (1997), the same methodology applied in Catalonian Living Lab (Figure 10). The Digital Elevation Model (DEM) (30x30 raster format) necessary to obtain these factors for the Vale do Sousa region was obtained from the Direção-Geral do Território (DGT), the national authority responsible for geographic information in Portugal.

The **cover management (C factor)** was included as a function of tree canopy cover density (Rodrigues et al. 2020), reflecting the effect of vegetation cover on soil erosion rates. In other words, higher canopy cover densities are generally associated with lower rates of erosion (Figure 11).

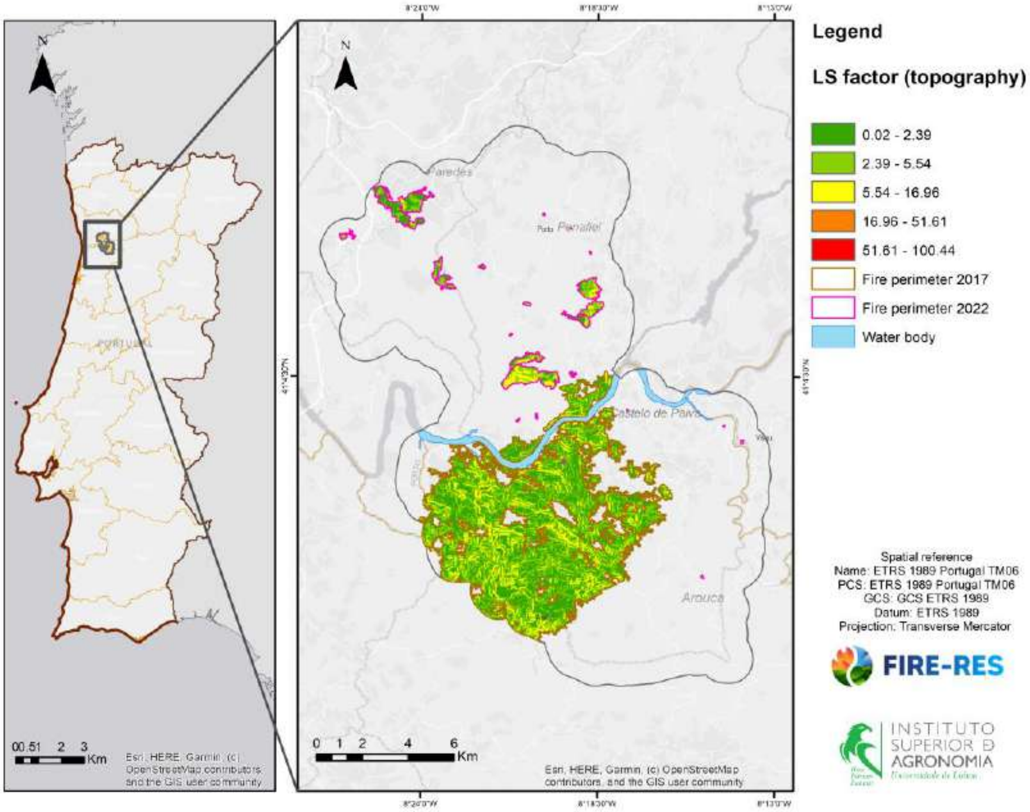


Figure 10. Topographic LS factor for the burnt areas of 2017 and 2022

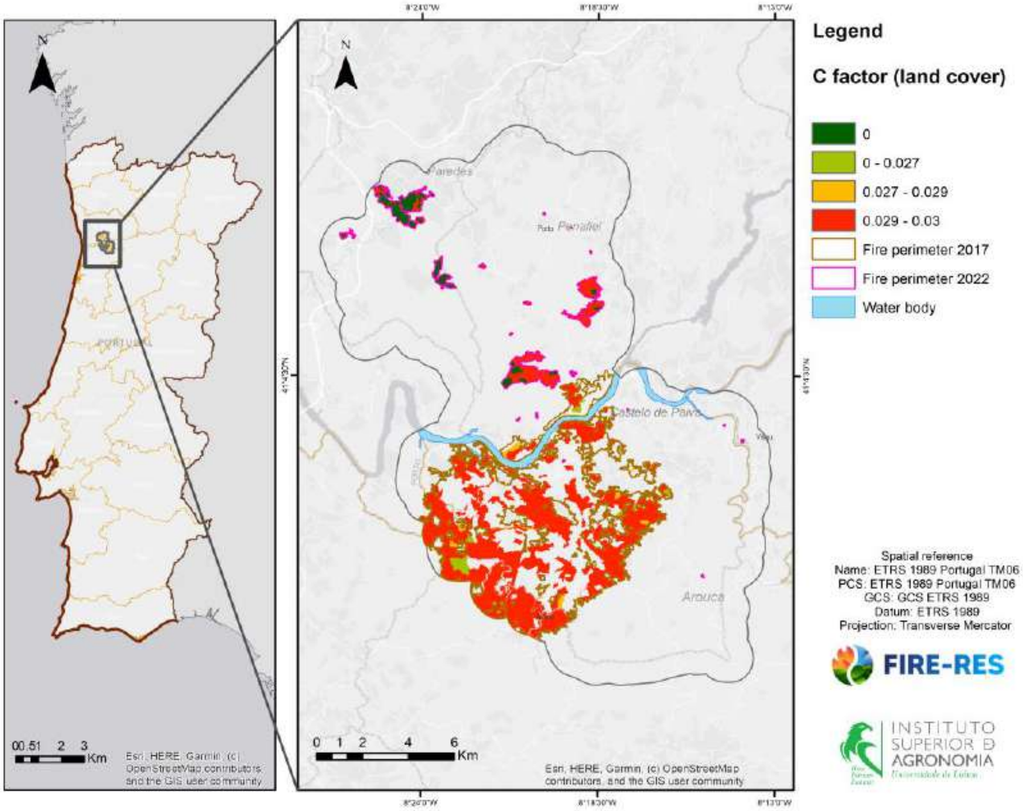


Figure 11. C factor for the burnt areas of 2017 and 2022

Fire severity factor was obtained, as in Catalonian Living Lab, via dNBR (Figure 12), which was reclassified using USGS criteria (Table 2).

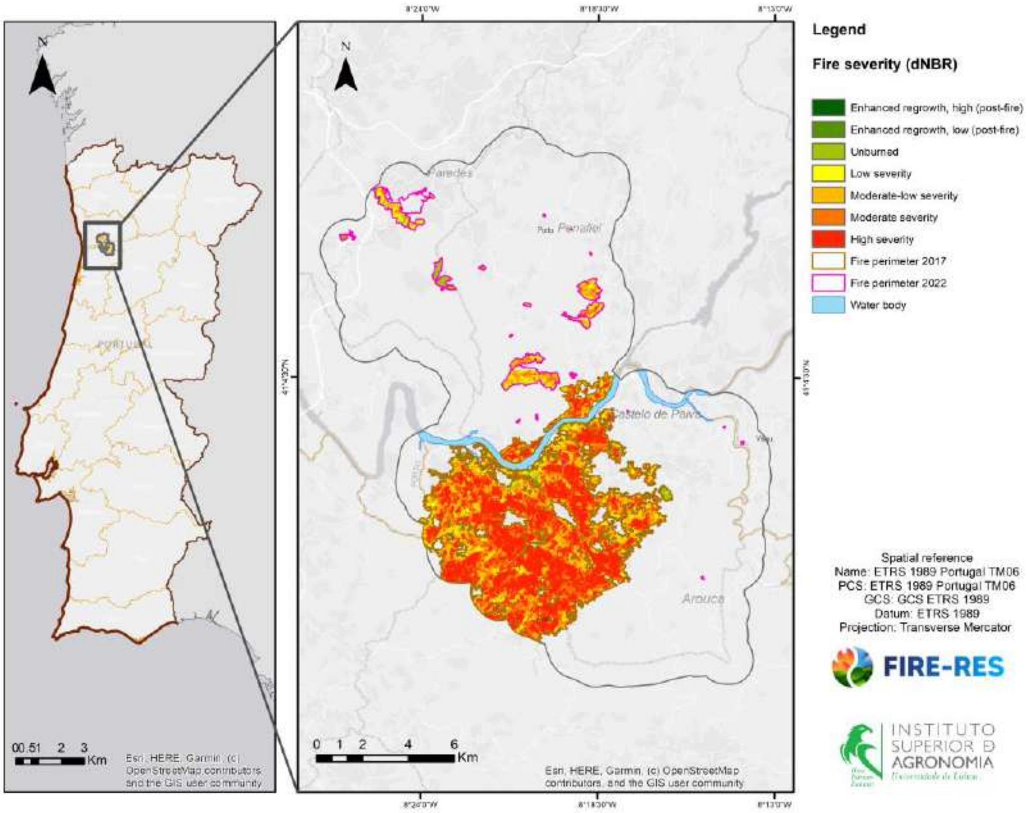


Figure 12. Fire severity for the burnt areas of 2017 and 2022

Table 2. Burn severity classes and thresholds proposed by USGS

Severity level	dNBR range
Enhanced regrowth, high (post-fire)	-500 to -251
Enhanced regrowth, low (post-fire)	-250 to -101
Unburned	-100 to +99
Low severity	+100 to +269
Moderate-low severity	+270 to +439
Moderate severity	+440 to +659
High severity	+600 to +1,300

The criterion of **natural recovery capacity of the vegetation** assesses vegetation's ability to regenerate after a wildfire based on the species regrowth potential. Fire severity influences plant recovery, with stem and crown damage being key indicators for trees (Catry et al., 2013). Species' natural recovery potential reflects their ability to regenerate post-fire. Understanding these factors helps prioritize restoration and select species. Thus, considering the main species present in the area and their abilities to resprout, each species was assigned a resprouting potential, as seen in Figure 13.

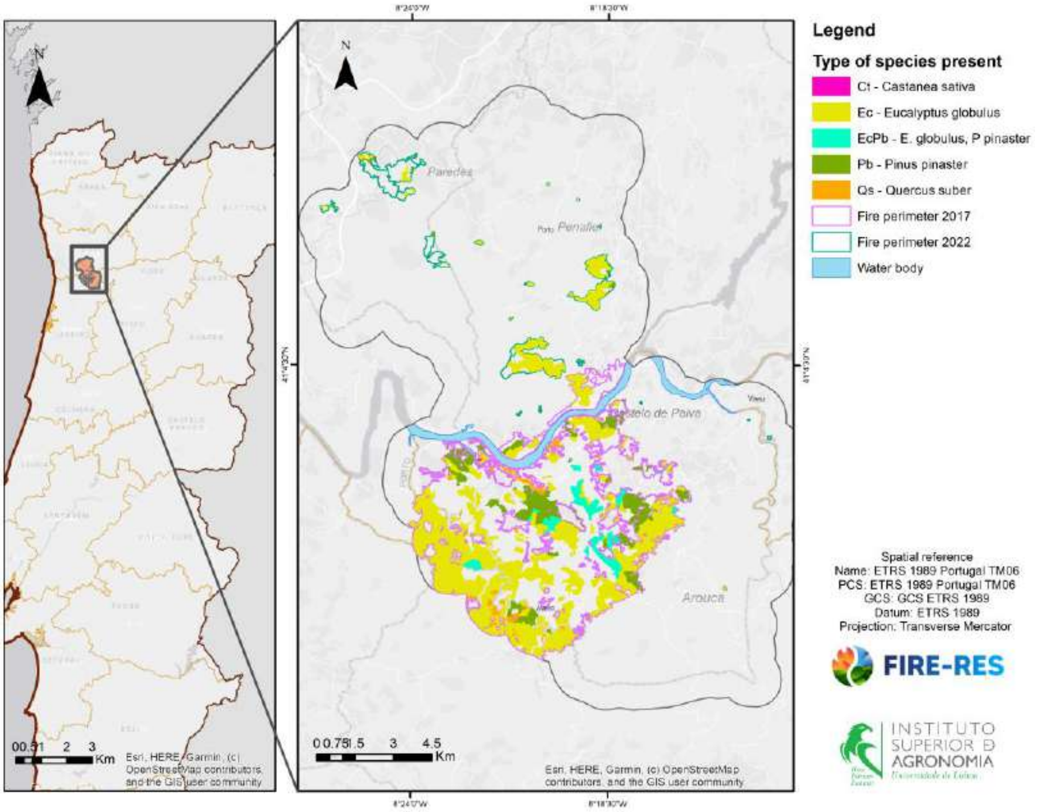


Figure 13. Species present in the burnt areas of 2017 and 2022. Own elaboration based on LiDAR flight data collection.

Although the primary focus was on restoring ecologically critical areas, group discussions highlighted the importance of **proximity to social areas** (Figure 14) as a key criterion for post-wildfire restoration. This perspective underscores that in a diverse group, additional factors—such as local social and economic conditions—must also be considered. Ultimately, incorporating proximity to social areas into decision-making aligns with core principles of public safety and risk mitigation.

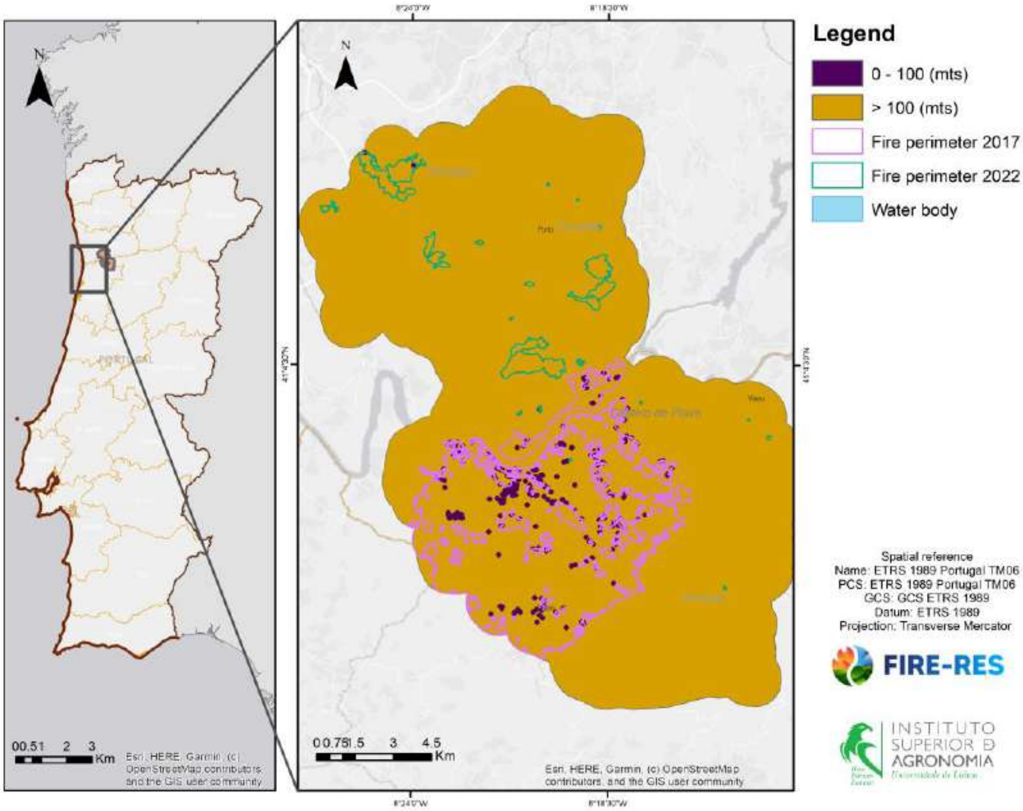


Figure 14. Criteria of "Proximity to Social Areas" within the burned areas for 2017 and 2022

2.2.3. Expert Panel

Stakeholders included representatives affiliated with the Instituto Superior de Agronomia (ISA) at the University of Lisbon, and representatives from group ForestWise, a private organization that works closely with ISA. Each person was individually invited to participate to the Focus Group (FG) discussion on the relevance of the pre-selected criteria and sub- criteria.

2.2.4. Finalized criteria, sub criteria and parameters for prioritization

Three main criteria groups were established during the FG and a total of 6 sub-criteria were selected to reflect key ecological and social factors influencing post-fire prioritization areas.

Figure 15. Meeting with post-fire restoration experts in Penafiel (Portugal)

Table 3. Final set of criteria and sub-criteria for restoration prioritization areas

Criteria	Sub criteria	Units
Soil erosion	Soil erodibility (K factor) Topography (LS factor) Vegetation cover (C factor) Fire severity (dNBR)	Mg·ha− 1 MJ·mm− 1 Dimensionless Dimensionless Dimensionless
Natural recovery capacity of vegetation	Natural recovery potential of species after a fire Fire severity (dNBR)	Dimensionless Dimensionless
Proximity to social areas	Social areas	Mts

Note: “Proximity to social areas” was added based on stakeholders’ input.

The criterion of **proximity to social areas** prioritizes interventions to minimize fire-related impacts on communities to reduce risks to people and infrastructure and was added during the focus group (Figure 16). Participants highlighted its importance in guiding interventions based on risk, not just restoration goals.

In this study, utility values for each criterion and sub-criterion were defined based on the FG session. Each criterion and sub-criterion hold values ranging from the maximum/minimum threshold (determined during the FG) and the maximum/minimum existing value in that area.

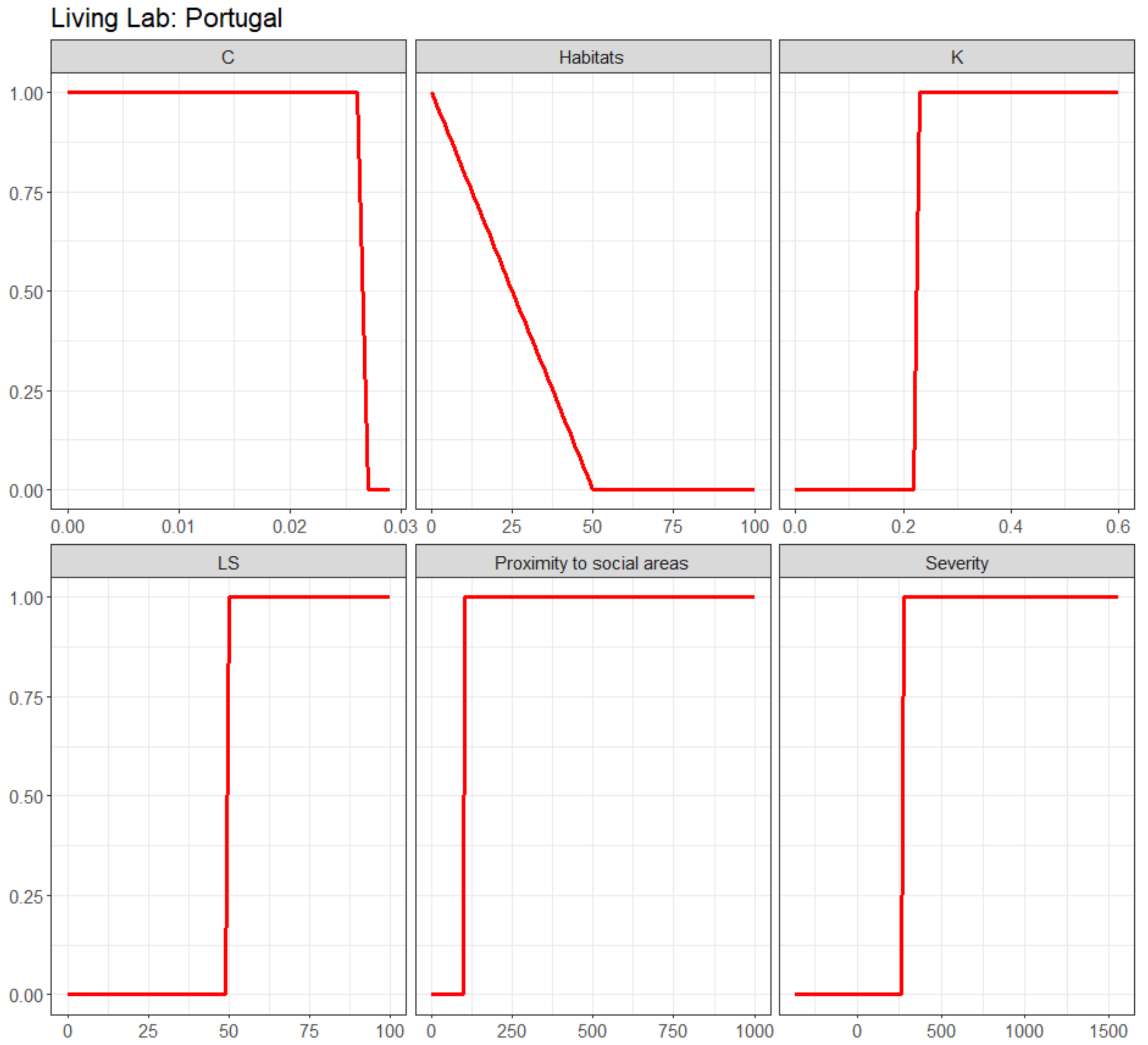
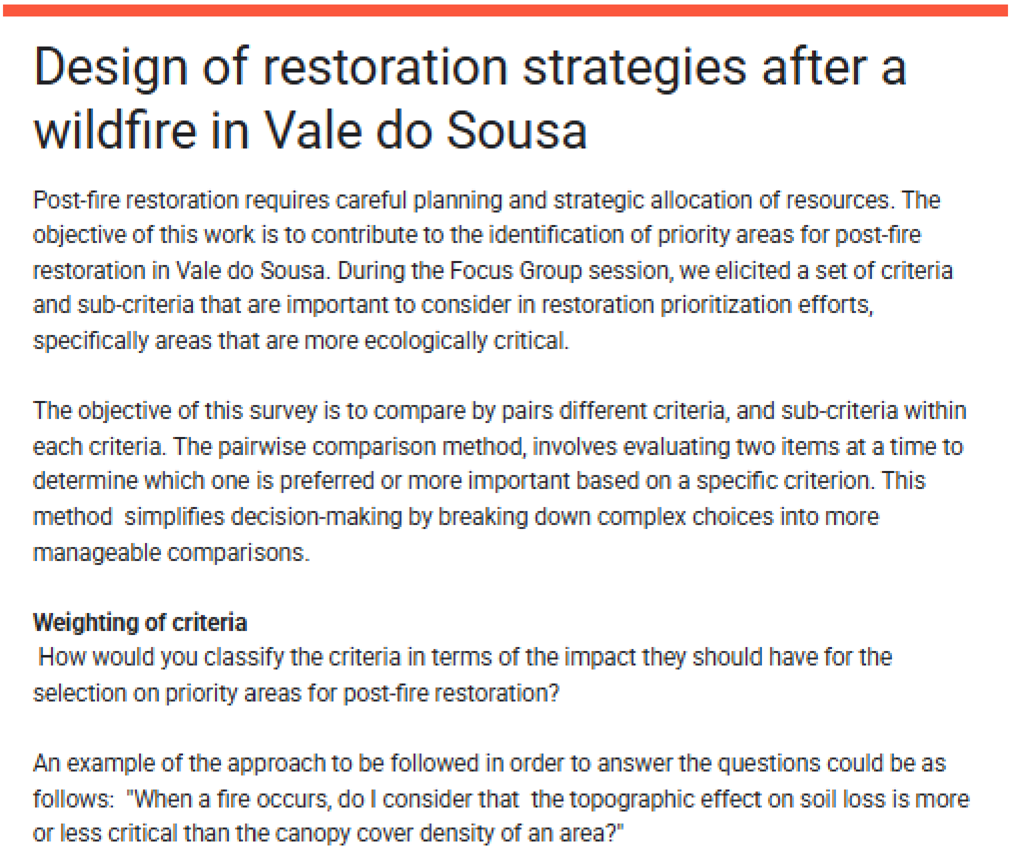


Figure 16. Utility functions of the selected subcriteria during the wildfire experts meeting in Portugal. Habitats refers to the percent cover of resprouter species

2.2.5. Participants´ performance weighting of the criteria and sub-criteria

After the final set up of the criteria and sub-criteria during the meeting at ISA, weights were obtained from each individual participant. An online survey was distributed to participants from the Focus Group (FG) to efficiently gather their inputs on the relative importance of each factor. The Pairwise Comparison Method from the Analytic Hierarchy Process (AHP) (Saaty, 1980) was applied to assign weights to each criterion and sub-criterion.

This survey included the pairwise comparison of the criteria. The pairwise comparison method involves comparing variables one at a time to determine which one is more or less important to consider in a restoration prioritization area. This method simplifies decision-making by breaking down complex choices into more manageable comparisons.



Design of restoration strategies after a wildfire in Vale do Sousa

Post-fire restoration requires careful planning and strategic allocation of resources. The objective of this work is to contribute to the identification of priority areas for post-fire restoration in Vale do Sousa. During the Focus Group session, we elicited a set of criteria and sub-criteria that are important to consider in restoration prioritization efforts, specifically areas that are more ecologically critical.

The objective of this survey is to compare by pairs different criteria, and sub-criteria within each criteria. The pairwise comparison method, involves evaluating two items at a time to determine which one is preferred or more important based on a specific criterion. This method simplifies decision-making by breaking down complex choices into more manageable comparisons.

Weighting of criteria
How would you classify the criteria in terms of the impact they should have for the selection on priority areas for post-fire restoration?

An example of the approach to be followed in order to answer the questions could be as follows: "When a fire occurs, do I consider that the topographic effect on soil loss is more or less critical than the canopy cover density of an area?"

Figure 17. First part of the online survey for defining weights

In the context of AHP, consistency is interpreted as the degree of logical coherence between paired comparisons and is defined as the cardinal transitivity between comparisons (FMCN, 2009). The Consistency Index (CI) was calculated using the following equation, as given by Saaty (1987):

$$CI = \lambda - n / n - 1 \qquad [11]$$

where n is the number of factors being compared in the matrix and λ max is the highest eigenvalue of the pairwise comparison matrix (Saaty, 1987). The CI was calculated for the weights assigned to each criterion by the participants to identify any outliers in the analysis. If outliers were detected, weights were recalculated before proceeding to the final stage.

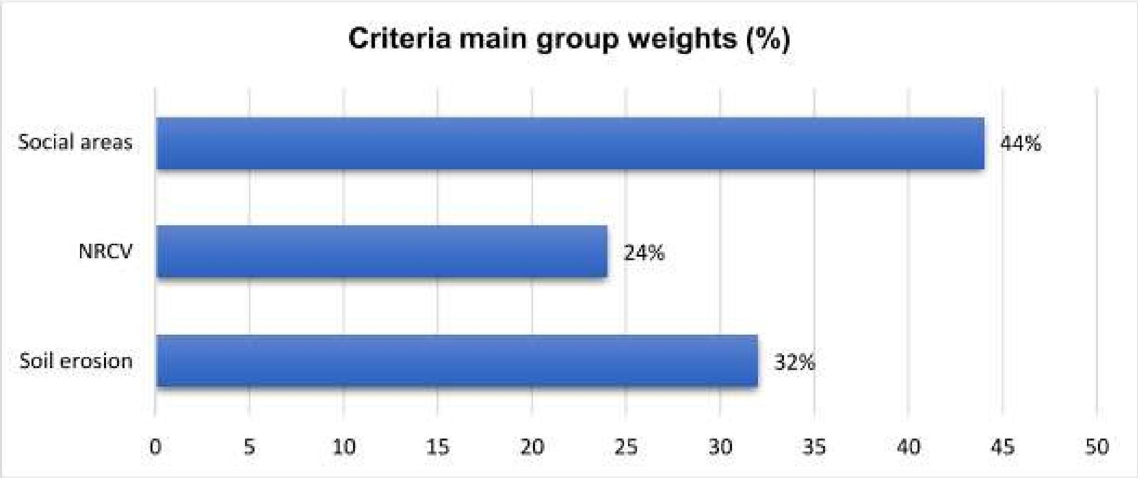


Figure 18. Weights of the main criteria assigned by stakeholders. NRCV: Natural Recovery Capacity of the Vegetation.

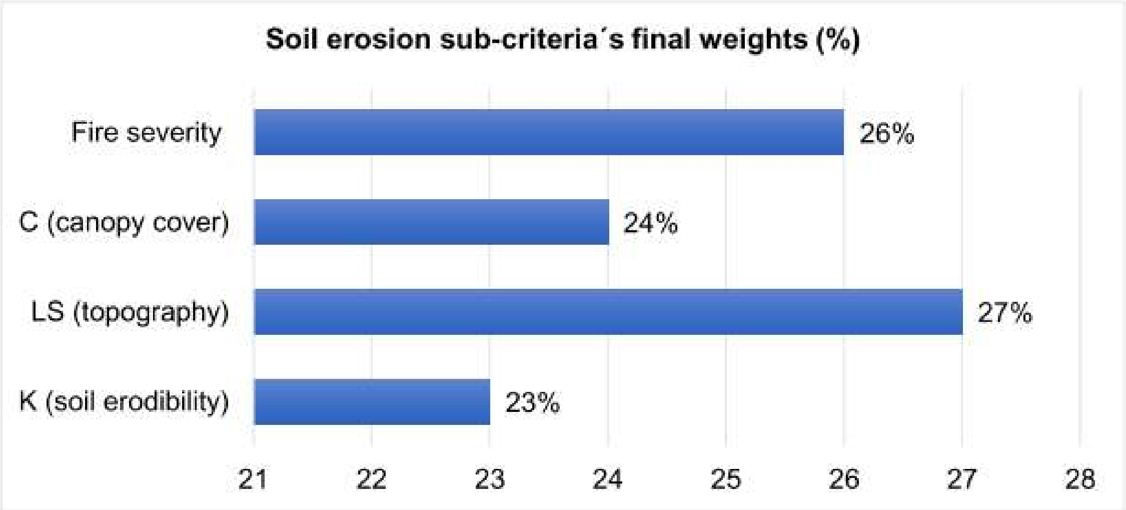


Figure 19. Weights of the sub-criteria under to soil erosion criterion.

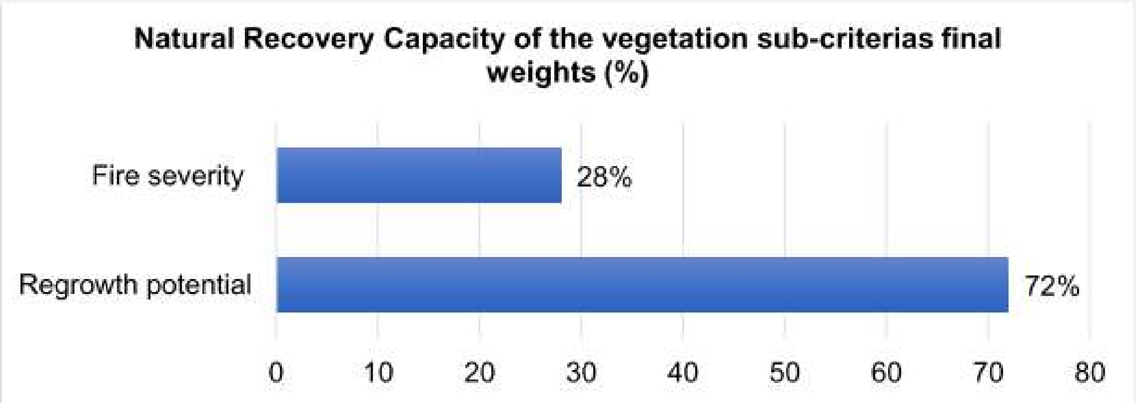


Figure 20. Weights of the sub-criteria under to natural recovery capacity of the vegetation criterion.

The final priority map was computed by combining the criteria priority maps using the same procedure as before.

$$\mathrm{X\ (i) = X\ (ia) * W\ (ia) + X(ib) * W\ (ib) + X\ (ic) * W\ (ic) + \ldots + X\ (in) * W\ (in)} \quad [12]$$

where Xi is the layer of criterion *i*, X (ia) is an input layer that contributes to the composition of X(i), and W (ia) is the weight of the sub-criterion *a*.

$$\mathrm{M\ (i) = (Xi - low(i))\ /\ up(i) - low(i)} \quad [13]$$

where M (i) is the map of criterion *i*, Xi is criterion *i* layer before the normalization, and low(i) and up(i) are the lower and upper values of Xi.

The following equation [14] presents the final weights, which are also represented in the following figures.

$$\begin{aligned} Restoration\ priority &= 0.32 * (0.23 * K + 0.27 * LS + 0.24 * C + 0.26 * Severity) + 0.24 \\ &* (0.72 * Resprouting + 0.28\ Severity) + 0.44 * SocialAreas \quad [14] \end{aligned}$$

For each individual map and the final map of priorities, a reclassification with 4 levels of priority was applied, making it easier to interpret and apply the results.

2.3. Gran Canaria Living Lab

2.3.1. Study area

On August 10th and 17th 2019, the island of Gran Canaria (Canary Islands) experienced two significant wildfires almost consecutively and in the same area (Figure 21). The first one, which started in the municipality of Artenara, affected 1,164 hectares and was stabilised after three days. The second wildfire, which originated in the town of Valleseco, affected 8,637 hectares and was stabilised after 4 days.

The wildfires impacted the mountainous central region of the island, which is characterised by a complex topography and steep slopes. Approximately 40% of the total burned area in both wildfires comprised woodland primarily dominated by *Pinus canariensis*, although other non-native pine forests, chestnut groves, eucalyptus forests, willow stands, and formations typical of laurisilva forests were burned as well. Finally, the wildfires also affected agricultural land (around 397 ha) and several Natural Protected Areas, such as the Tamadaba Natural Park.

These wildfires are regarded as one of the worst emergencies experienced in Gran Canaria in recent years, not only in terms of affected area but also due to the challenges faced by the firefighting teams. The extreme conditions of high temperatures, low air humidity and strong winds in which the fires developed contributed to their extreme behaviour, which included the massive propagation of embers and the formation of pyrocumulus clouds. These incidents also constituted a civil protection emergency, since they forced the evacuation or confinement of thousands of people and affected 91 properties across 11 different municipalities (Dalmau-Rovira et al., 2020).

For the purpose of the present Deliverable and, given the temporal and spatial overlap of both wildfires, we decided to examine these incidents together and treat them as a single case study.

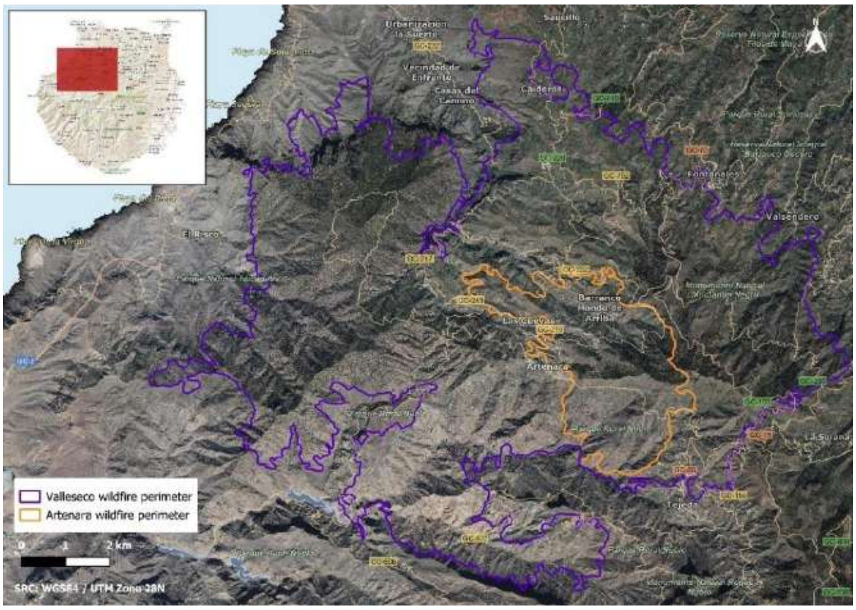


Figure 21. Perimeters of the Valleseco and Artenara wildfires occurred in August 2019

2.3.2. Description of the selected criteria

The methodology implemented in the Canary Islands Living Lab is a simplified version of the preliminary methodology developed by the Government of the Canary Islands in 2017 for the identification of priority post-fire restoration areas in the Canary Islands. This, in turn, is based on the Guide for the Management of Burned Forests published by the Ministry of Agriculture, Food, and the Environment (MAGRAMA) of the Spanish Government in 2014 (Alloza et al., 2014). The decision to adopt these existing methodologies was agreed upon with stakeholders at the first CWI meeting held in November 2024.

Since the main objective is to generate a simple tool that provides an approximate first identification of priority restoration zones, only three key variables were considered: the natural recovery capacity of the affected plant communities, their ecological value, and the potential for soil erosion, all weighted by the fire severity. To ensure practical applicability, the most up-to-date and publicly accessible thematic cartography were used to characterise these variables. Detailed descriptions of each variable are provided below.

Vegetation natural recovery capacity

As previously mentioned, the recovery capacity of vegetation is influenced by both the fire regime and severity, and the reproductive strategies of the affected species. Regarding the latter factor, an evaluation is proposed based on the intrinsic self-succession capacity and the regeneration rate:

- The **intrinsic self-succession capacity** refers to the ability of vegetation to reproduce after a fire, considering the level of adaptation to fire and the reproductive maturity.
- The **regeneration rate** refers to the response time of the vegetation to cover the ground immediately after the fire. It primarily depends on the regenerative strategy of the species, with resprouting species showing a greater capacity compared to germinating species.

To characterise these variables, the Spanish National Forest Map at a scale 1:25,000 (MFE25) was used as the base map. This cartography not only provides information about the composition and structure of tree cover but also contains specific data on the shrub and herbaceous layers composition.

As shown in Figure 22, *Pinus canariensis* was the predominant tree species in the perimeter of both wildfires. This species is one of the most resistant *Pinus* species to fire-induced mortality, since it possesses several fire-resistant traits such as thick bark, serotinous cones and resprouting capacity (Climent et al., 2004). Consequently, its presence significantly influences the potential for post-fire regeneration.

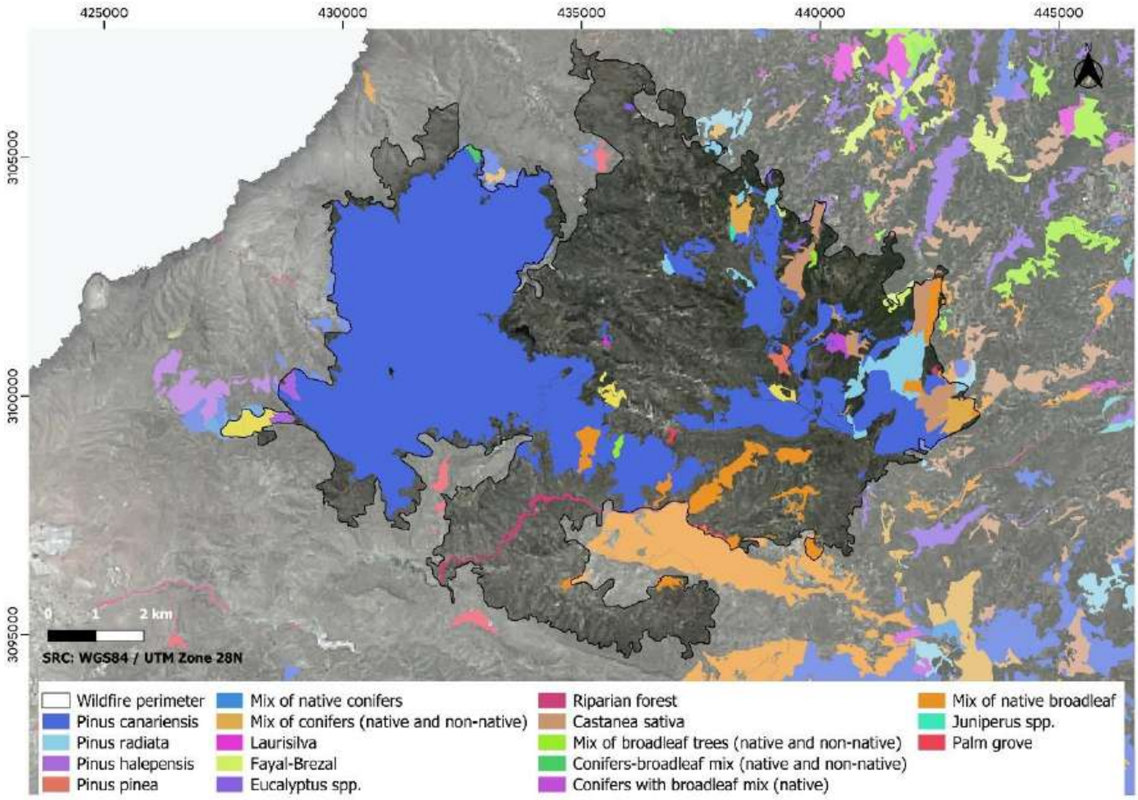


Figure 22. Main arboreal formations present in Valleseco and Artenara wildfires. Source: Spanish National Forest Map

Ecological value

Given the high biological richness of the Canary Islands (Salas Pascual & Naranjo Cigala, 2015), an ecological quality indicator was included to account for the vulnerability of these unique communities and ecosystems in the prioritisation process. The layers considered to evaluate ecological quality are the following:

- **Species richness**: Obtained from the Protected Species Map developed by the Government of the Canary Islands, based on the Biodiversity Data Bank of the Canary Islands. This layer represents the number of protected species within 500x500 m grids, regardless of individual species abundance. Last update in March 2025.

- **Network of natural protected areas in the Canary Islands**: This cartographic delimitation, developed by the Planning of Protected Natural Spaces and Landscape Service of the Government of the Canary Islands, includes zoning based on protection requirements for each protected figure.

- **Natural habitats of communitary interest**: Developed by the Biodiversity Service of the Government of the Canary Islands in compliance with Directive 92/43/EEC. Last update in 2016.

- **Natura 2000 network**: This cartography includes Sites of Community Importance (SICs), Special Areas of Conservation (SACs), and Special Protection Areas for Birds (SPAs). Last update December 2024.
- **Biosphere reserve**: Geographical delimitation of Biosphere Reserves, which are areas belonging to terrestrial or coastal ecosystems recognised internationally by the "Man and Biosphere" program. Last update December 2024.

As illustrated in Figure 23, almost the entire area impacted by Valleseco and Artenara wildfires was under some form of protective status. This highlights the significant threat that EWE pose to the vulnerable ecosystems of the Canary Islands.

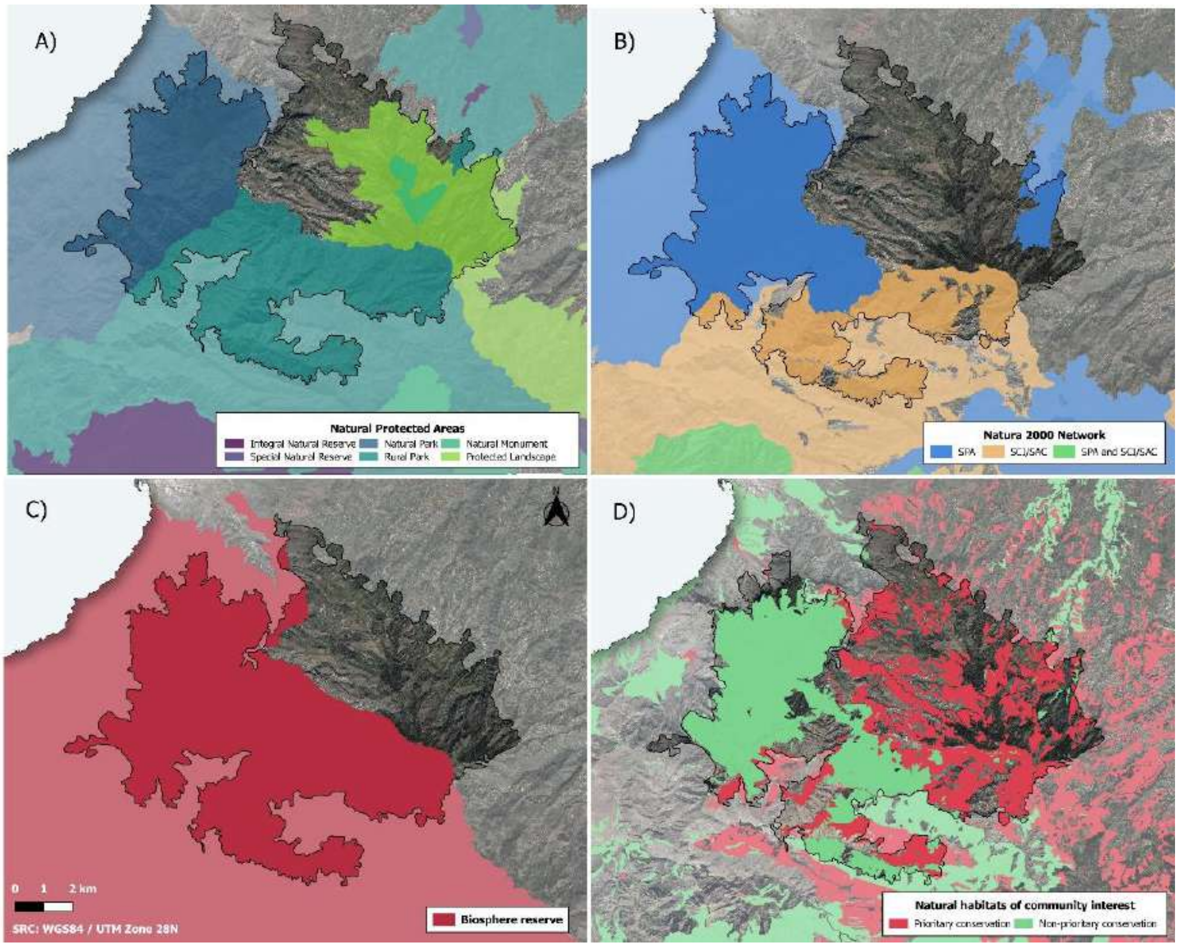


Figure 23. Main natural protected figures affected by the Valleseco and Artenara wildfires. A) Network of Natural Protected Areas in the Canary Islands. B) Natura 2000 Network protected areas. C) Biosphere Reserve. D) Natural habitats of communitary interest.

Potential Soil Erosion

The cartography of the Spanish National Soil Erosion Inventory (INES, for its acronym in Spanish), available at a scale of 1:50,000, was used to characterise the post-fire risk of soil erosion. This resource is the most comprehensive and up-to-date at the national level. Specifically, the potential soil erosion cartography derived from the RUSLE model (Revised Universal Soil Loss Equation) was used. This cartography synthesises the combined potential of terrain, climate, and soil to trigger erosive processes. Although it does not reflect actual post-fire erosion, it provides an approximate classification of the territory, serving as a basis for identifying high-risk areas.

Fire severity

To calculate fire severity, the Relative Differenced Normalized Burn Ratio (RdNBR) was used (Eq. 17). Some authors point out that absolute indices, such as the Differenced Normalised Burn Ratio (dNBR) (Eq. 15 and 16), are correlated with the chlorophyll content of the vegetation prior to the fire and, therefore, can lead to an incorrect characterisation of severity in pixels that inherently contained less chlorophyll before the disturbance (low NBRpre values will generally result in low dNBR values regardless of the degree of impact) (Miller and Thode, 2007; Miller et al., 2009; Parks et al. 2014; Botella-Martínez and Fernández-Manso, 2017). The RdNBR removes the influence of pre-fire vegetation, hypothetically allowing for the creation of categorical classifications using the same thresholds for fires occurring in similar vegetation types, without the need to acquire additional calibration field data for each fire (Miller et al., 2009).

$$NBR = \frac{NIR-SWIR}{NIR+SWIR} \quad [15]$$

$$dNBR = NBRpre - NBRpost \quad [16]$$

$$RdNBR = \frac{dNBR}{\sqrt{ABS(NBRpre)}} * 1000 \quad [17]$$

Thus, for the severity analysis, images from the Sentinel-2 satellite of the Copernicus program were used, with L2A processing level, which already includes the atmospheric correction. The pre-fire image used was from 09/08/2019, and the post-fire image was from 29/08/2019. The result is a raster layer with a resolution of 10x10 m.

2.3.3. Generation of priority maps per criteria

It is important to note that raster format information was preferred over shape format for the development of the priority restoration map. This format allows for the standardisation of all data layers to the same resolution, facilitating their integration. Consequently, the necessary transformations were performed on layers originally in shape format, setting a common resolution of 25x25 m, except for the severity layer, which kept a resolution of 10x10 m.

Vegetation natural recovery capacity

As mentioned in the previous section, the vegetation recovery capacity depends on species intrinsic capacity for self-succession and regeneration rate. To characterise these variables, it is necessary to understand the reproductive strategy and the percentage of cover of all affected species.

Thus, each of the species considered in the National Forest Map was assigned a reproductive strategy (categorised as germinating, resprouting, or mixed-strategy species) and also those species with serotinous cones were identified. The necessary information for this assignment was primarily extracted from the MAGRAMA Guide (Alloza, et al., 2014), although other bibliographic sources were consulted for species not included in this guide. Once this categorisation was obtained, the Intrinsic Self-Succession Capacity and the Regeneration Rate were calculated according to the following criteria:

- **Intrinsic self-succession capacity**: A value was assigned to each forest formation based on its species composition. Broadly speaking, high values were assigned to pixels occupied by resprouting or serotinous species (such as *Pinus halepensis* or *Pinus pinaster*) in mature stages. On the contrary, low values were assigned to pixels occupied by pine forests and other non-native conifers, as well as to serotinous species in the early stages of development. Regarding herbaceous and shrub formations, high values were assigned to plots occupied by resprouting species, while mixed strategy or germinating species were assigned a value based on the shrub percentage of cover. Specifically, intrinsic capacity was rated as low for cover percentages below 20% and medium for those exceeding 20%. Reclassification values are presented in Table 4.

Table 4. Reclassification values of the output raster for the variable Intrinsic self-succession capacity.

Raster value	Intrinsic self-succession capacity
0	Not applicable
1	Low
2	Medium
3	High

- **Regeneration rate**: This is calculated based on the total percentage of cover occupied by resprouting (and adult serotinous) tree, shrub, and herbaceous species. Effective soil protection by vegetation is assumed to begin at 30-40% coverage. According to this, high values were assigned when total cover percentage exceeded 40%. Low values were assigned when resprouting species covered less than 10% or when only germinating species were present. Medium values were assigned for cover fractions between 10-40% or when mixed-strategy or adult serotinous species were present. Reclassification values are presented in Table 5.

Table 5. Reclassification values of the output raster for the variable "regeneration rate"

Raster value	Regeneration rate
0	Not applicable
1	Low
2	Medium
3	High

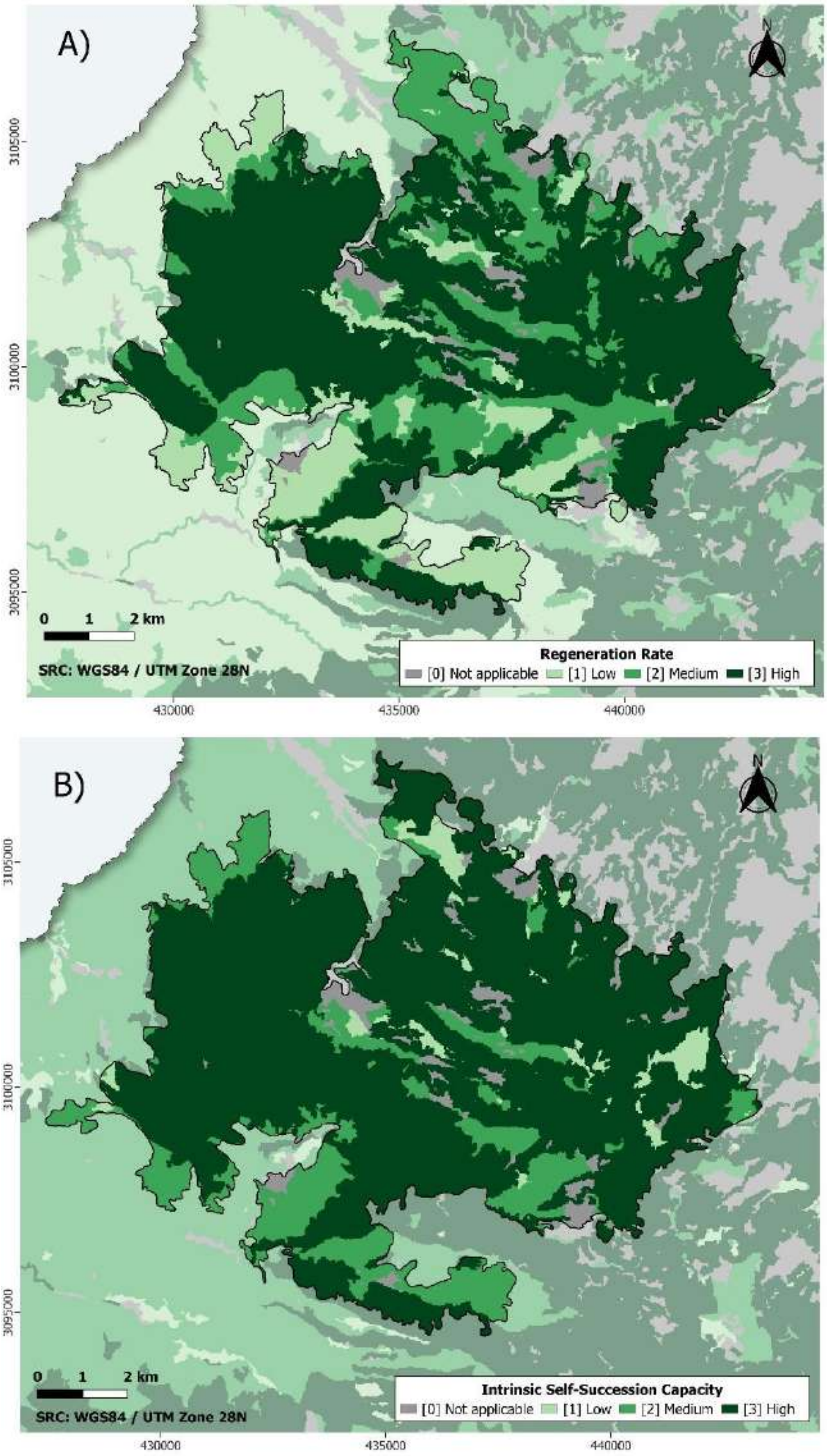


Figure 24. Regeneration rate (A) and Intrinsic self-succession capacity (B) in the study area

As illustrated in Figure 24, the highest values of regeneration speed and intrinsic self-succession capacity are found in areas dominated by *Pinus canariensis* and other native species, such as those characteristic of Fayal-Brezal formations (e.g., *Myrica faya* and *Erica arborea*) or laurisilva forests, as well as shrub species like *Adenocarpus sp*. and *Teline sp.* communities. Indeed, many Canarian species are all highly adapted to fire and possess several fire-resistant traits (Höllermann, 2000). On the other hand, the lowest values mostly correspond to areas dominated by non-native *Pinus* species or xerophilous shrub communities (e.g., *Euphorbia sp.*).

Ecological value

Each figure of protection presented in the previous section was assigned numerical values to quantify its ecological importance based on the criteria defined in Table 6. These layers were integrated afterwards to obtain the total ecological quality (or ecological vulnerability) of the study area (see next section). Results of the reclassification are presented in Figure 25.

Table 6. Reclassification values of the output raster for each figure of protection considered

Layer	Raster value
Species richness	[0] Without species [25] < 5 species [50] 5 - 10 species [75] 10 – 20 species [100] > 20 species
Canarian Network of Natural Protected Areas. Zonification	[0] Outside of a Natural Protected Area [10] ZUT. Traditional Use Zone [20] ZUG. General Use Zone [25] ZUM. Moderate Use Zone [35] ZUE. Special Use Zone [50] ZE and ZUR. Exclusion and Restricted Use Zones
Natural habitats of communitary interest	[0] Outside of habitat [10] Non-prioritary habitat [15] Prioritary habitat
Natura 2000 Network	[0] Outside of Natura 2000 Network [10] Included in Natura 2000 Network
Biosphere reserve	[0] Outside of Biosphere Reserve [10] Included in Biosphere Reserve

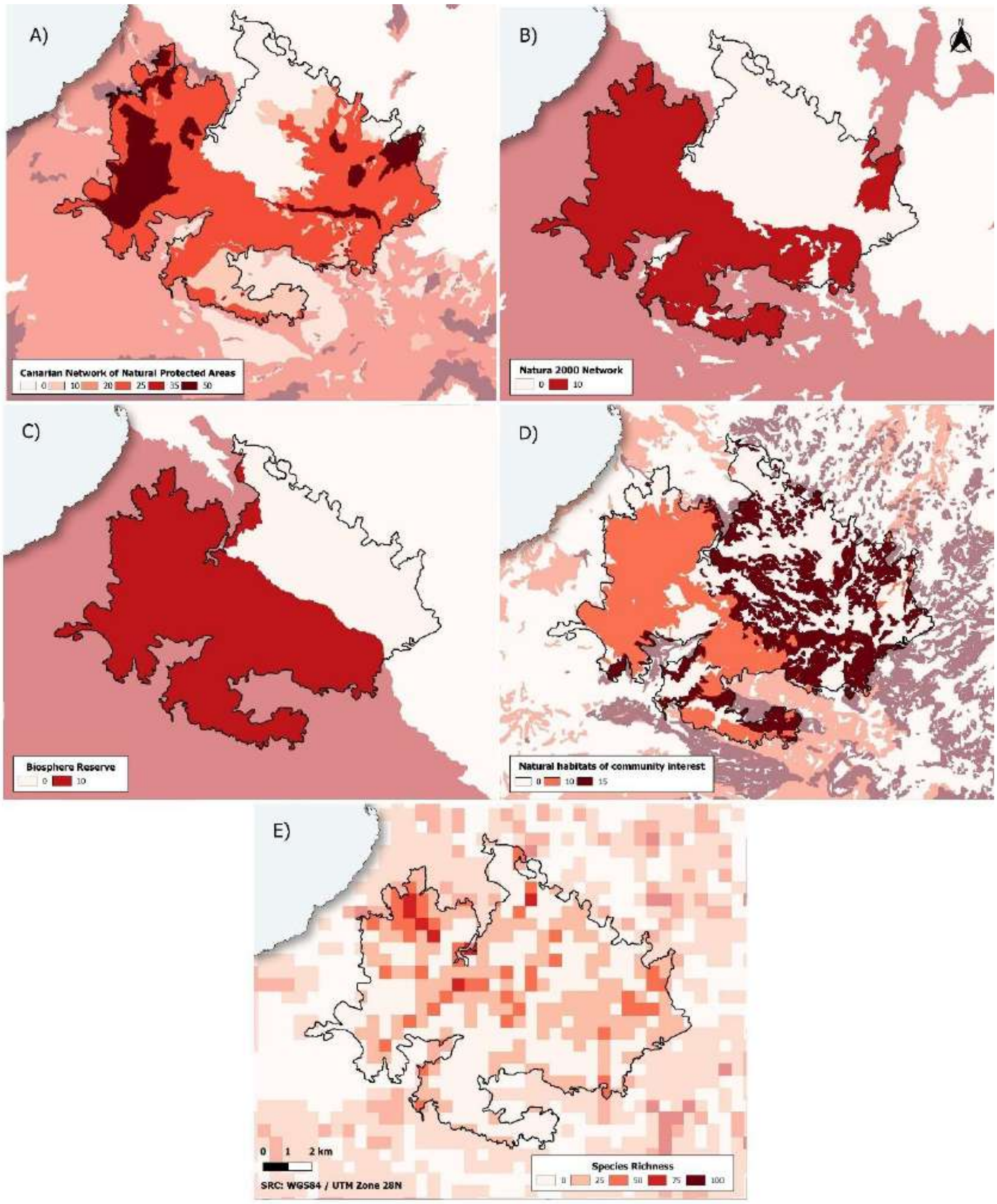


Figure 25. Ecological value of the different figures of protection considered for the study case area.

Potential Soil Erosion

The cartography of the National Soil Erosion Inventory (INES, for its acronym in Spanish) is provided in raster format and classified in 9 different categories. To simplify subsequent calculations, a reclassification was carried out to reduce it to 4 classes, as presented in Table 7. According to Figure 26, most of the area affected by the wildfires is at very high risk of soil erosion, except for the southern zone, which exhibits a low risk.

This can be explained by the nature of the soils present in this environment. As an example, andisols, which are the characteristic soils of volcanic regions, such as the mid-elevation and humid slopes of the most mountainous islands of the Canarian archipelago, exhibit high instability to environmental disturbances like fires. This instability, combined with their location on steep slopes, renders them highly susceptible to severe erosion (Neris Tomé, et al. 2015).

Table 7. Reclassification values of the output raster for Potential Soil Erosion

Raster value	Potential Soil Erosion
0	Not applicable
1	Low (1-25 t/ha/year)
2	Medium (25-50 t/ha/year)
3	High (50-100 t/ha/year)
4	Very high (>100t/ha/year)

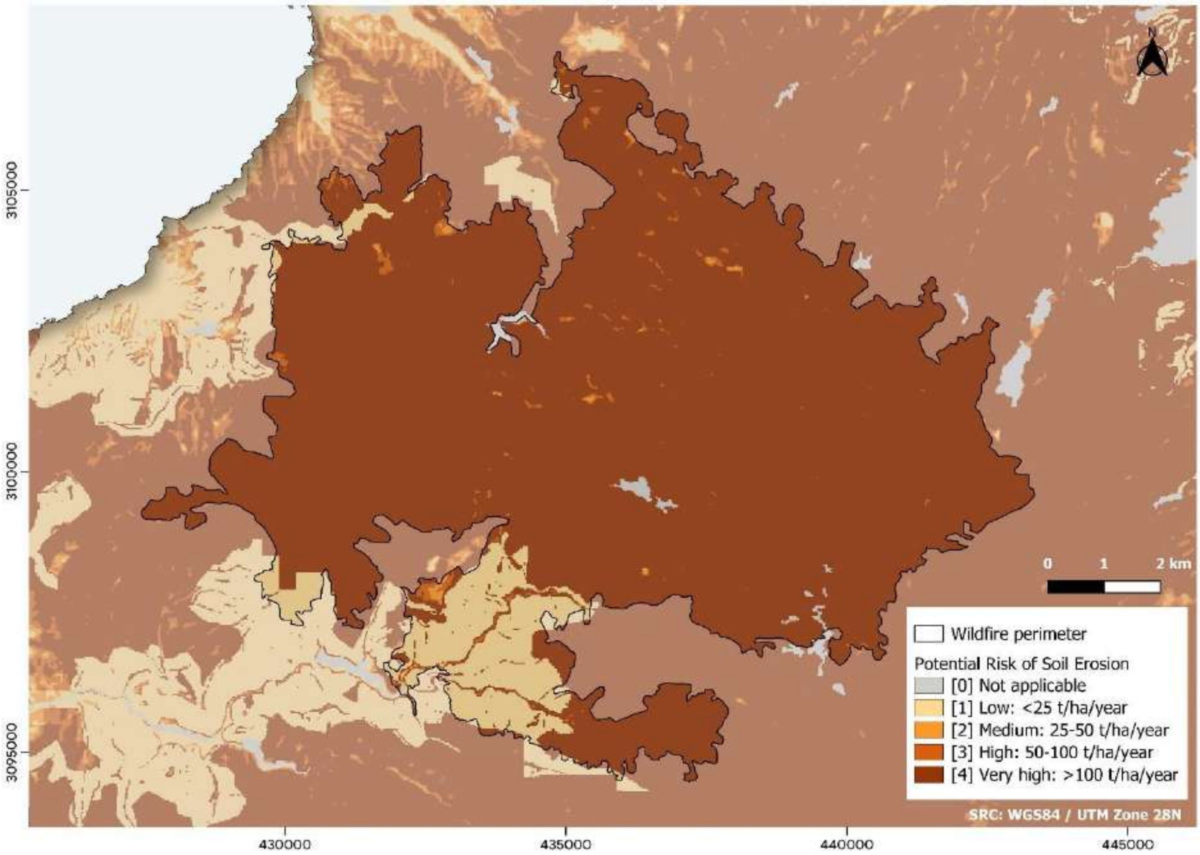


Figure 26. Potential Risk of Soil Erosion in the study case area

Fire severity

To classify severity into discrete categories, the thresholds proposed in Botella-Martínez and Fernández-Manso (2017) were used. These thresholds are calibrated for an evaluation immediately after the occurrence of the wildfire. The different severity categories considered are described as follows:

- **Low severity** (230-475): Tree canopies remain largely unaltered and almost entirely green. Shrub cover shows signs of scorching, but burned patches are not predominant.

- **Moderate severity** (475-835): More than half of the tree canopy area is scorched, but leaves or needles are still present, resulting in a predominantly brown appearance. Shrub cover is mostly calcined.
- **High severity** (>835): Over 50% of the tree canopy area is completely burned, leaving no leaves, needles, or fine elements, and resulting in a predominantly black appearance. Shrub cover is entirely calcined.

As presented in Figure 27, the lower severity values were concentrated in the western part of the wildfire, where the Tamadaba Natural Park is located. This is mainly due to the low-medium intensity behaviour of the fire front in this area, which spread from higher towards lower altitudes and thus, against slope. Additionally, this behaviour was reinforced by the improvement in weather conditions.

Regarding the affected vegetation types, the highest severity values were predominantly found in grassland and shrub fuel models. This suggests that the fire mainly spread at the surface level, with less than a third of the trees experiencing crown fires or torching. However, a significant portion of the remaining tree crowns suffered scorching damage, as indicated by the moderate severity values.

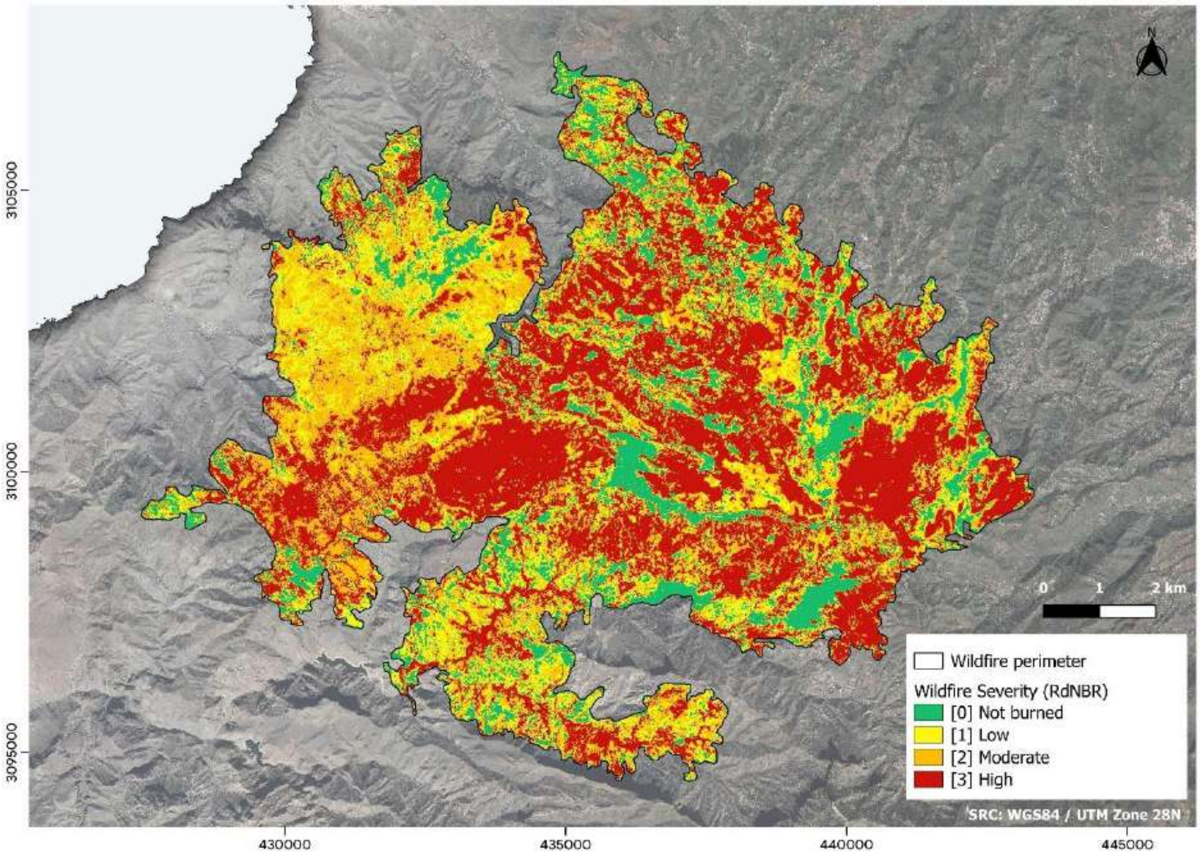


Figure 27. Fire severity of Valleseco and Artenara wildfires

3. Results from the priority maps in the different LLs

3.1. Catalonia Living Lab

The maps of the different sub-criteria discussed above, after applying the utility functions are presented in Figure 28. The two factors from the RUSLE (K and LS) do not offer much variability within the chosen fire, presenting mostly low values within the theoretical range of the variable. The same occurs, but in the opposite direction, with resprouting cover, which is generally high throughout the affected area. Severity and orientation are, therefore, the two variables with the greatest variability.

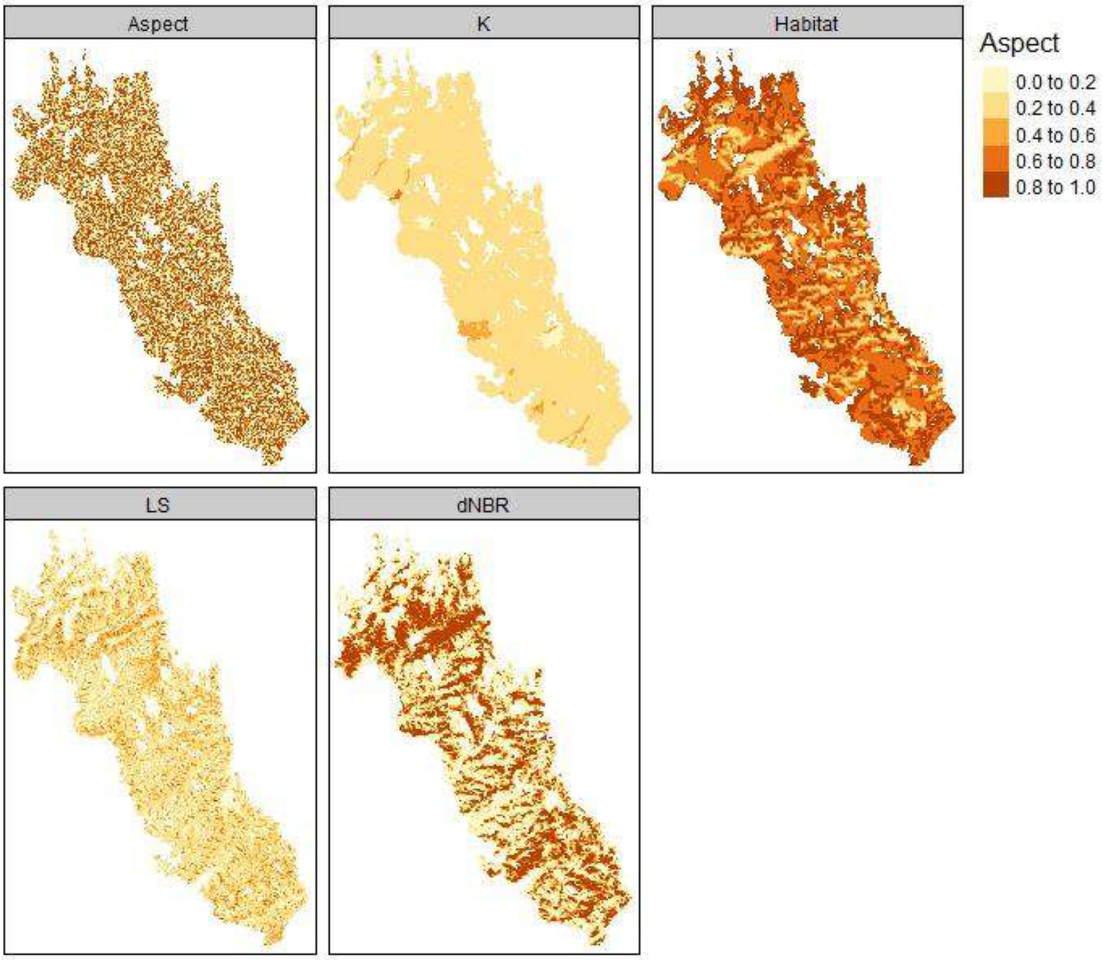


Figure 28. Spatial distribution maps of the factors chosen for the restoration priority exercise

Results of the erosion and natural recovery of the vegetation criteria are presented in Figure 29.

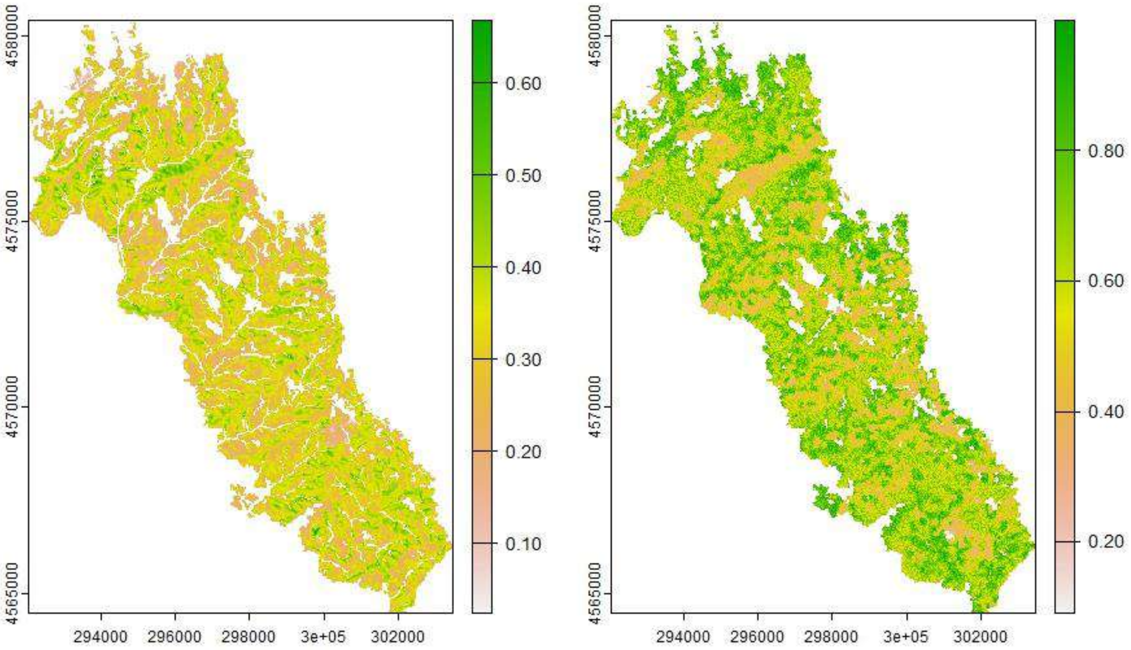


Figure 29. Map of priority areas for post-fire restoration according to soil erosion criterion (left) and vegetation capacity for natural recovery criterion (right)

The prioritization exercise in the selected fire shows that the areas of highest restoration priority are distributed throughout the fire affected area (Figure 30).

The larger areas, located in the northern zone of the fire, usually coincide with areas of higher LS factor value combined with a lower presence of resprouting species and higher severities. The southern zone of the fire, which presents greater susceptibility to erosion and concentrates areas with higher severities, presents a greater potential for natural recovery due to the relative dominance of resprouting communities.

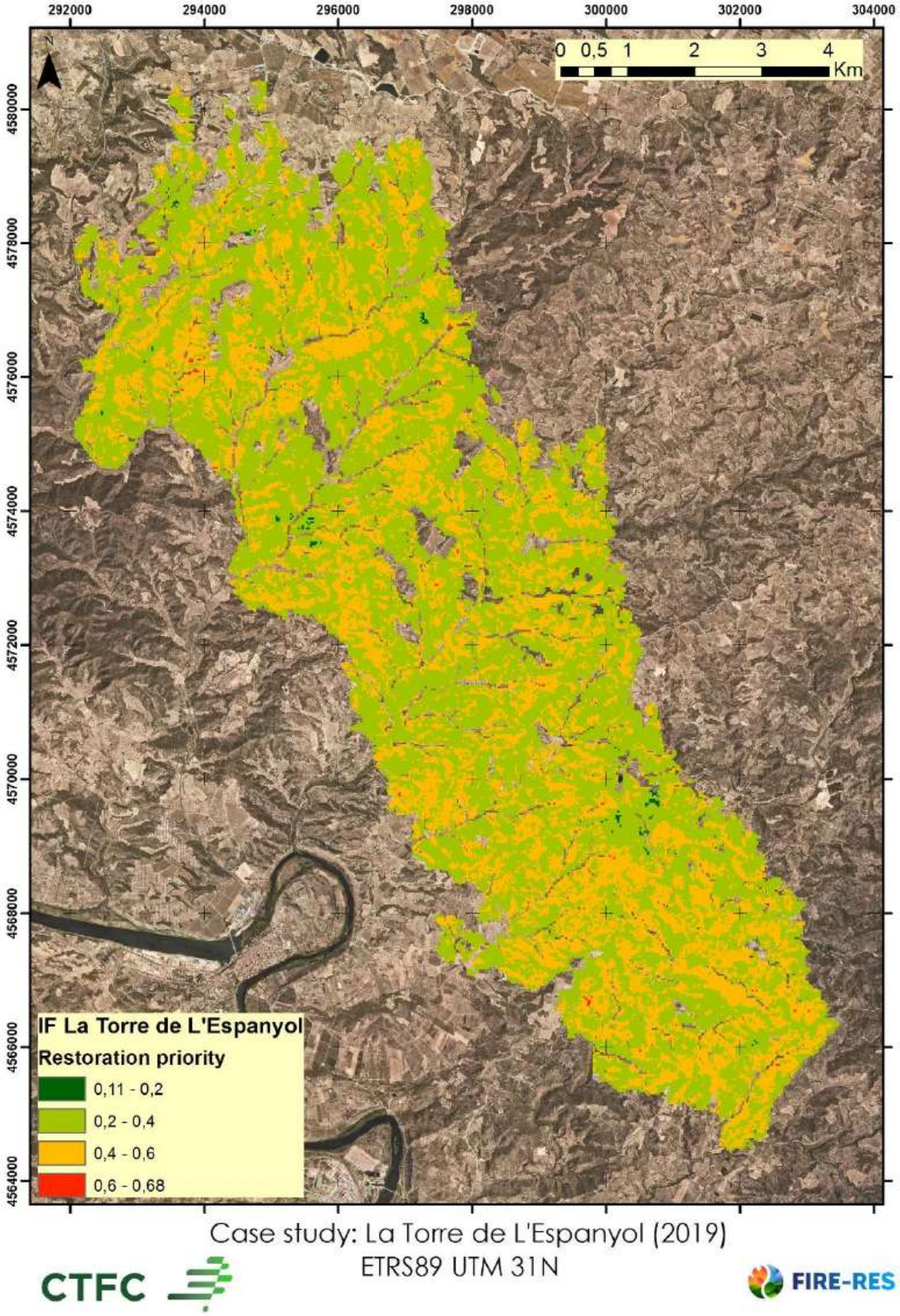
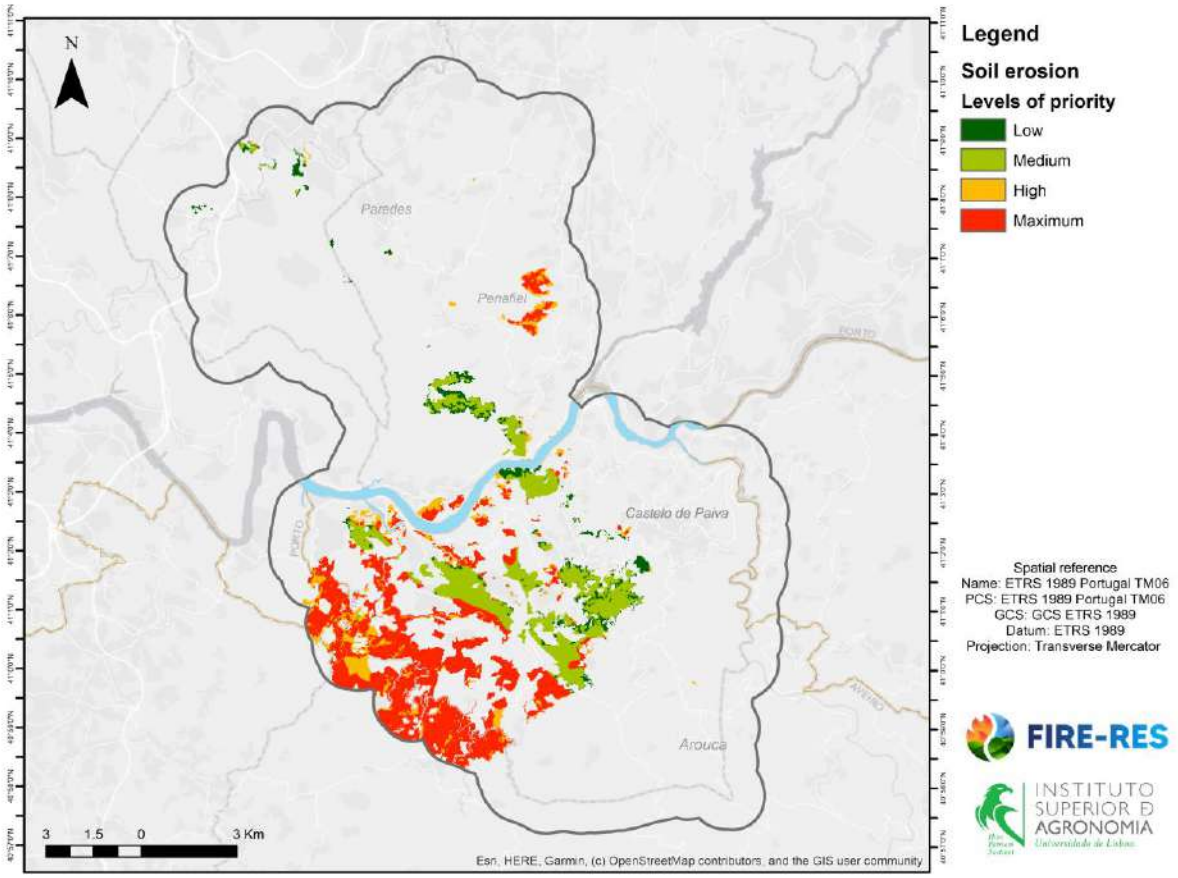


Figure 30. Resulting map of the application of the developed methodology via expert criteria for the case study La Torre de L'Espanyol EWE.

3.2. Portugal Living Lab

The maps for each criteria group were created by combining the relevant spatial data layers for each sub-criterion and applying the appropriate weights. Four priority levels for management were assigned using equal intervals (low, medium, high, maximum), allowing for a clear comparison across different areas.

The soil erosion map (Figure 31) identifies the most erosion-prone areas by integrating multiple sub-criteria, with topographic factors and fire severity emerging as the most influential in determining priority zones. Areas assigned the highest priority for management based on soil erosion risk are those where multiple risk factors converge: high fire severity, direct sunlight exposure, and steep slopes. Steep slopes accelerate water runoff, rapidly displacing unprotected soil; prolonged sunlight exposure, especially in areas with minimal vegetation cover, dries out the soil, further increasing its susceptibility to erosion. This issue is particularly severe in regions with anthropogenic soils (i.e., those significantly altered by human activity).



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Figure 31. Map of soil erosion criterion.

For the natural recovery capacity of the vegetation map (Figure 32), greater emphasis was placed on regrowth potential, given its direct influence on ecosystem resilience. Fire severity was also considered, albeit with a lower weight, acknowledging its impact on recovery potential. The resulting map identifies areas where natural recovery is expected to be limited, guiding management efforts to prioritize regions that would benefit most from intervention.

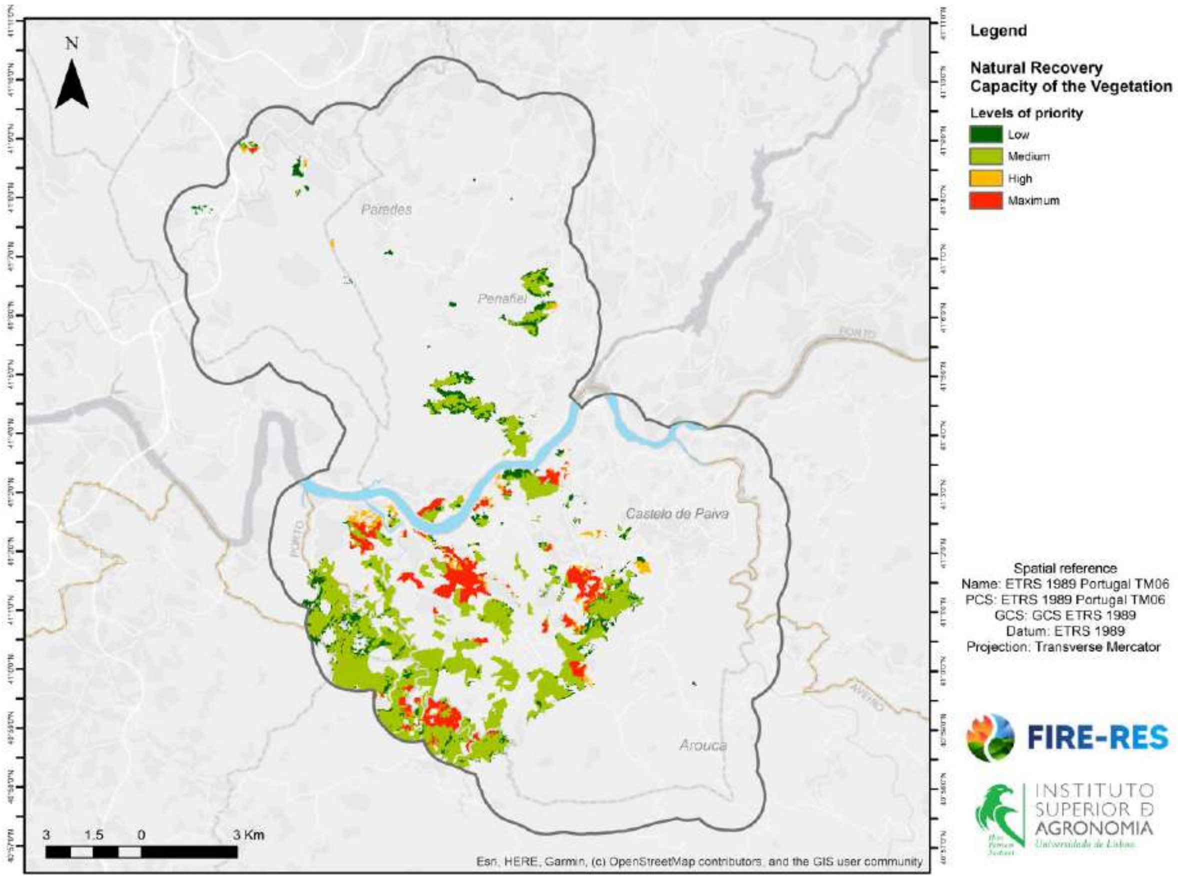


Figure 32. Map of natural recovery capacity of the vegetation criterion.

The final map (Figure 33) was created by integrating three key criteria: soil erosion, the natural recovery capacity of vegetation, and proximity to social areas. This map highlights maximum priority zones, where significant erosion risks coincide with proximity to social areas, indicating locations where human settlements are directly affected by environmental degradation. These areas are critical for targeted restoration efforts, including erosion control measures, infrastructure reinforcement, and community preparedness.

Conversely, low-priority areas are likely those with high natural recovery capacity and minimal risk to nearby social areas or significant erosion. These regions can be managed with a more passive approach, allowing natural processes to sustain or restore ecological balance over time.

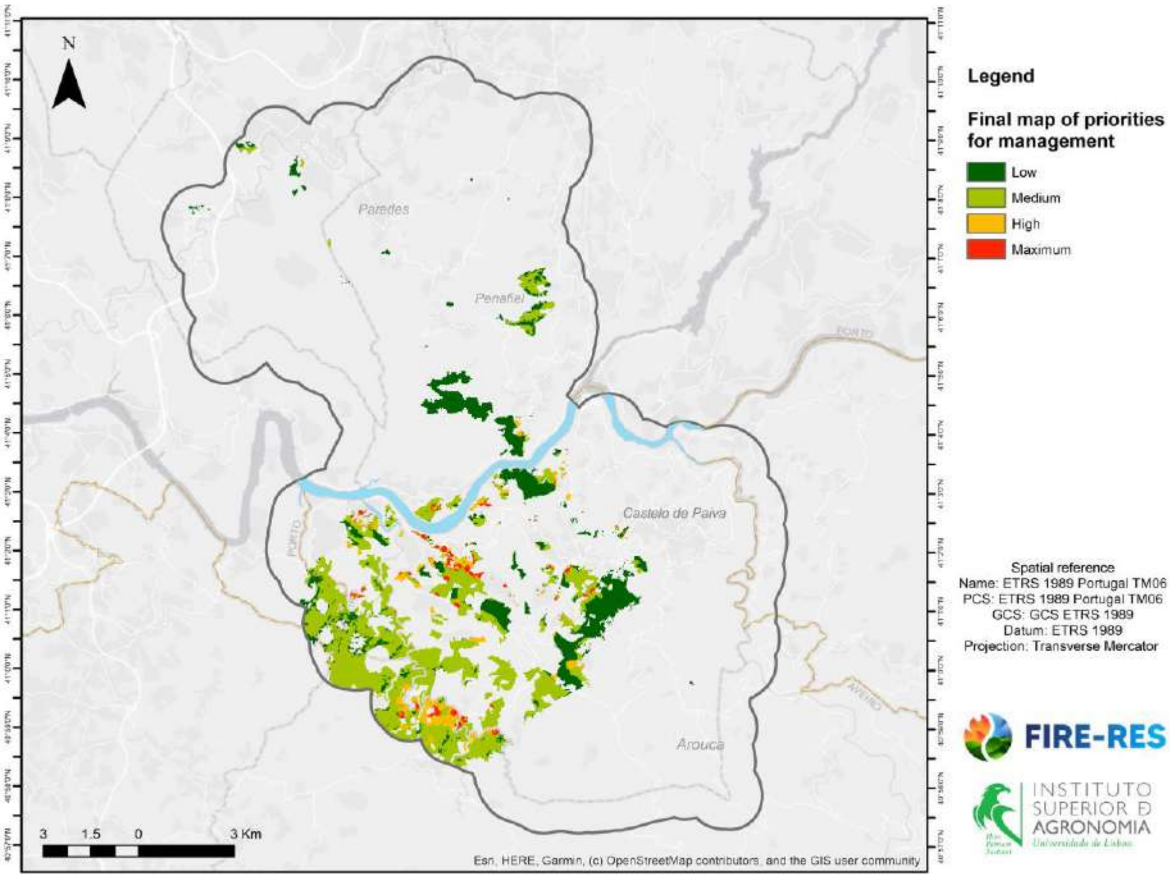


Figure 33. Final priority restoration map of Lisbon Living Lab.

3.3. Gran Canaria Living Lab

Once the different base layers were pre-processed, they were combined to obtain the final map for prioritising restoration areas. Figure 34 shows the workflow diagram followed on the integration process.

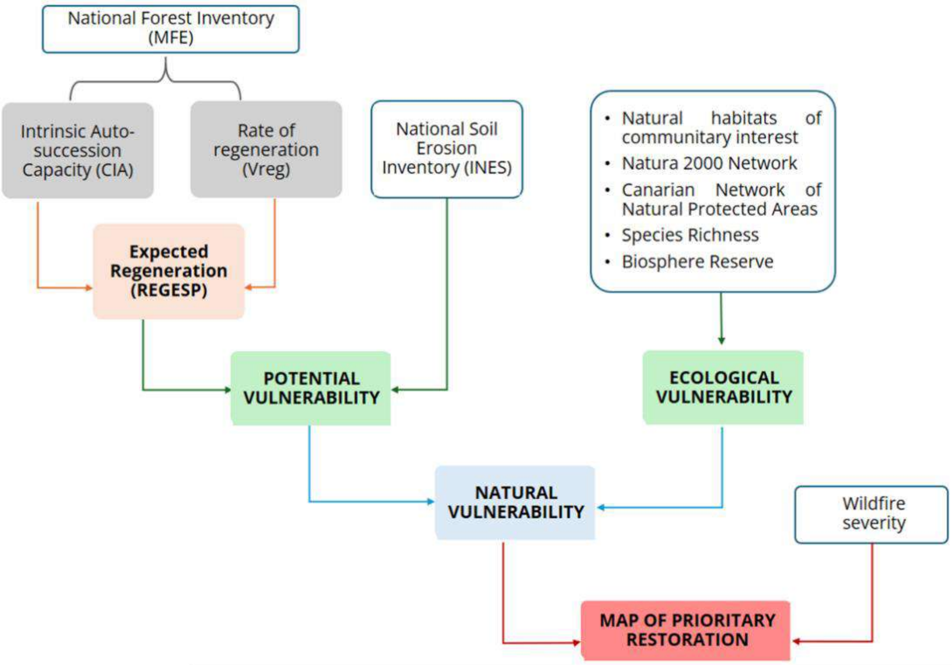


Figure 34. Flow diagram to calculate de prioritisation map. White and grey boxes represent the input layers.

As illustrated in Figure 34, obtaining the prioritization map requires the calculation of several intermediate layers. These intermediate steps are detailed below.

1. **Expected regeneration or potential regeneration capacity**: Calculated by integrating the intrinsic self-succession capacity and regeneration rate layers. This integration is performed through a qualitative assessment based on the information presented in Table 8. As expected, the lowest values of potential regeneration capacity correspond to areas dominated by non-native conifer species or xerophilous shrub communities (Figure 35).

Table 8. Criteria followed to calculate the expected regeneration using regeneration rate and Intrinsic auto-succession capacity.

Intrinsic auto-succession capacity	Regeneration rate			
	High (3)	Medium (2)	Low (1)	Not applicable (0)
High (3)	High	Medium	Low	Not applicable
Medium (2)	High	Medium	Low	Not applicable
Low (1)	Low	Low	Low	Not applicable
Not applicable (0)	Not applicable	Not applicable	Not applicable	Not applicable

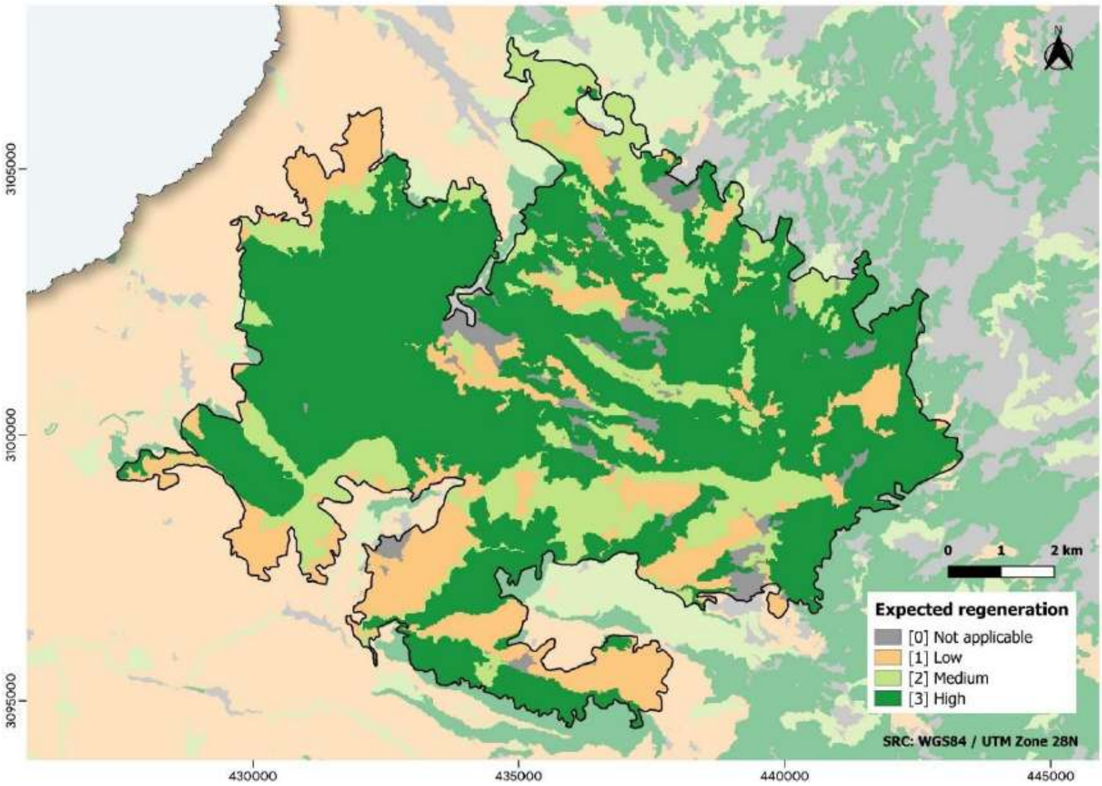


Figure 35. Expected regeneration distribution in the case study area. Not applicable values refer to agricultural land or urbanised areas

2. **Potential vulnerability**: Calculated by integrating the expected regeneration and Potential Soil Erosion layers. This integration is performed through a qualitative assessment based on the information presented in Table 9. Given that potential soil erosion is quite homogeneous throughout the wildfire perimeter, the higher potential vulnerability values correspond to those areas where the expected regeneration of vegetation is low (Figure 36).

Table 9. Criteria followed to calculate the potential vulnerability using expected regeneration and potential soil erosion.

Expected regeneration	**Potential soil erosion**			
	Low (1)	Medium (2)	High (3)	Very high (4)
High (3)	Low	Medium	High	High
Medium (2)	Medium	Medium	High	Very high
Low (1)	High	High	Very high	Very high

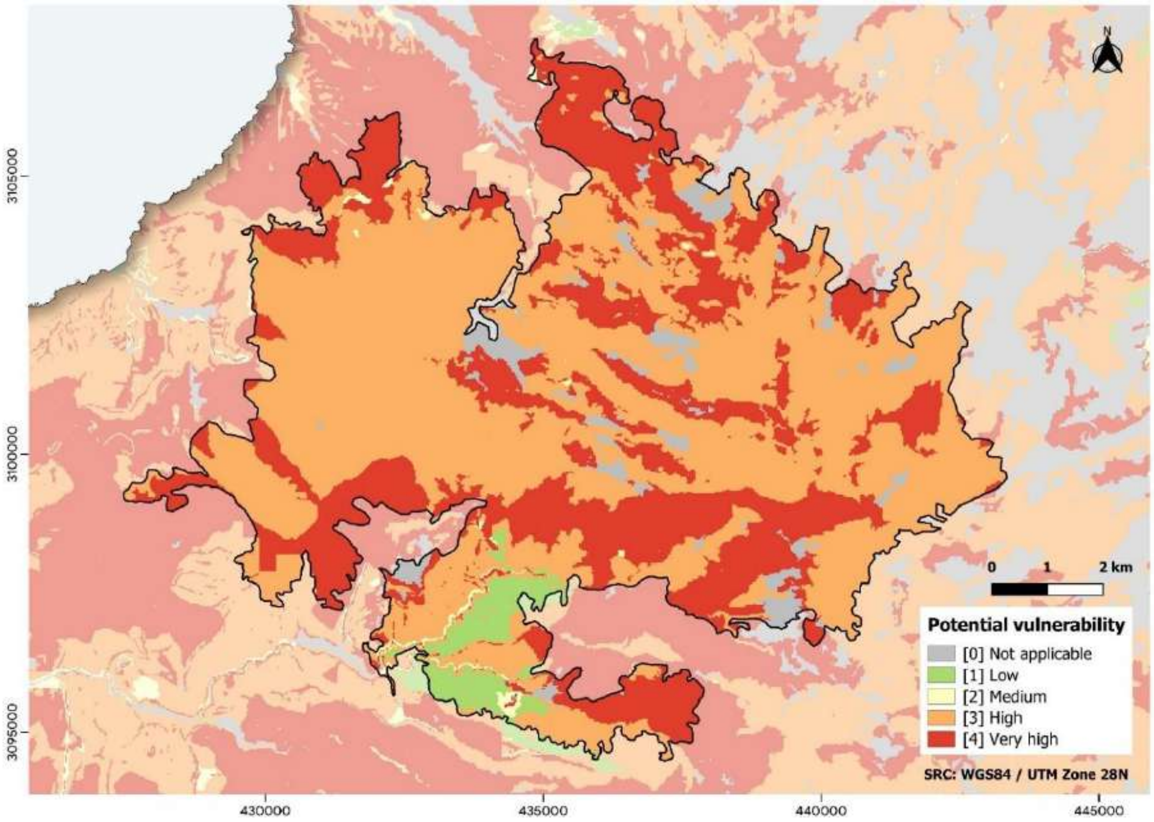


Figure 36. Potential vulnerability distribution in the case study area.

3. **Ecological vulnerability**: Calculated by integrating the layers of Protected Natural Areas, Natura 2000 Network, Habitats of Communitary Interest, Biosphere Reserve, and Species Richness. This integration resulted in values ranging from 0 to 200, which were afterwards categorised according to the criteria presented in Table 10. According to Figure 37, the highest ecological vulnerability values are found in areas where multiple protection designations overlap and/or where the highest levels of restriction apply.

Table 10. Classification values of the output raster for Ecological vulnerability

Raster value	Ecological vulnerability
0	Not applicable
1	Low (0-25)
2	Medium (25-75)
3	High (75-150)
4	Very high (150-200)

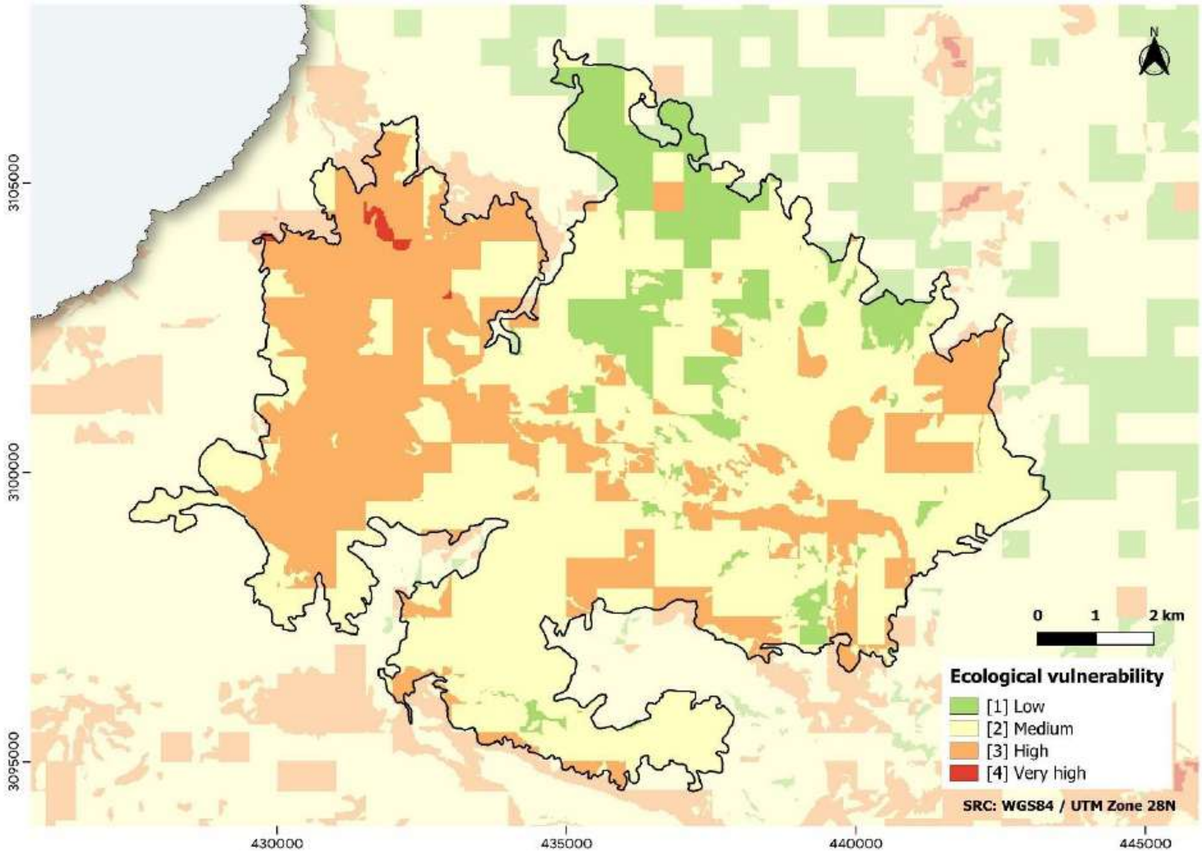


Figure 37. Ecological vulnerability distribution in the case study area

4. **Natural vulnerability**: Derived from the integration of the Potential Vulnerability and Ecological Vulnerability layers. Potential Vulnerability assesses the likelihood of an affected area's capacity to return to its pre-fire state, while Ecological Vulnerability evaluates the immediate ecological damage and losses incurred by the fire, particularly concerning flora and fauna. Consequently, the Natural Vulnerability layer reflects both the overall environmental quality and the ecosystem's challenges in recovering to the pre-fire condition. The resulting layer was categorised according to the standards outlined in Table 11. Thus, the highest values correspond to those areas with low vegetation regeneration capacity and higher protection levels (Figure 38).

Table 11. Criteria followed to calculate the natural vulnerability using ecological and potential vulnerabilities.

Potential vulnerability	Ecological vulnerability			
	Low (1)	Medium (2)	High (3)	Very high (4)
Low (1)	Low	Medium	Medium	High
Medium (2)	Medium	Medium	High	High
High (3)	Medium	High	High	Very high
Very high (4)	High	High	Very high	Very high

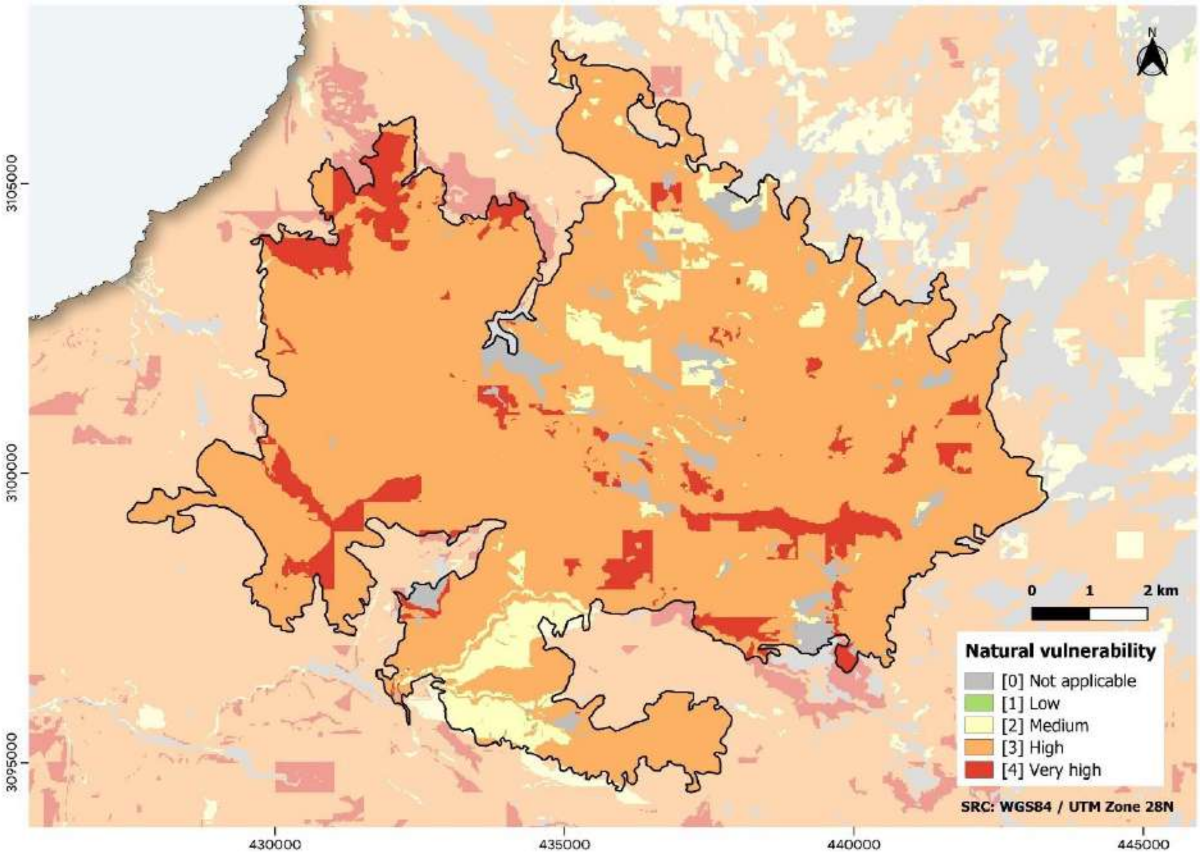


Figure 38. Natural vulnerability distribution in the case study area.

The **final priority restoration map** was calculated by integrating the natural vulnerability and fire severity layers. The categorisation was performed according to the provisions set out in Table 12.

Table 12. Criteria followed to calculate the priority restoration map by combining natural vulnerability and wildfire severity

Wildfire severity	**Natural vulnerability**			
	Low (1)	Medium (2)	High (3)	Very high (4)
Low (1)	Low	Medium	High	High
Medium (2)	Medium	Medium	High	Very high
High (3)	High	High	Very high	Extreme (5)

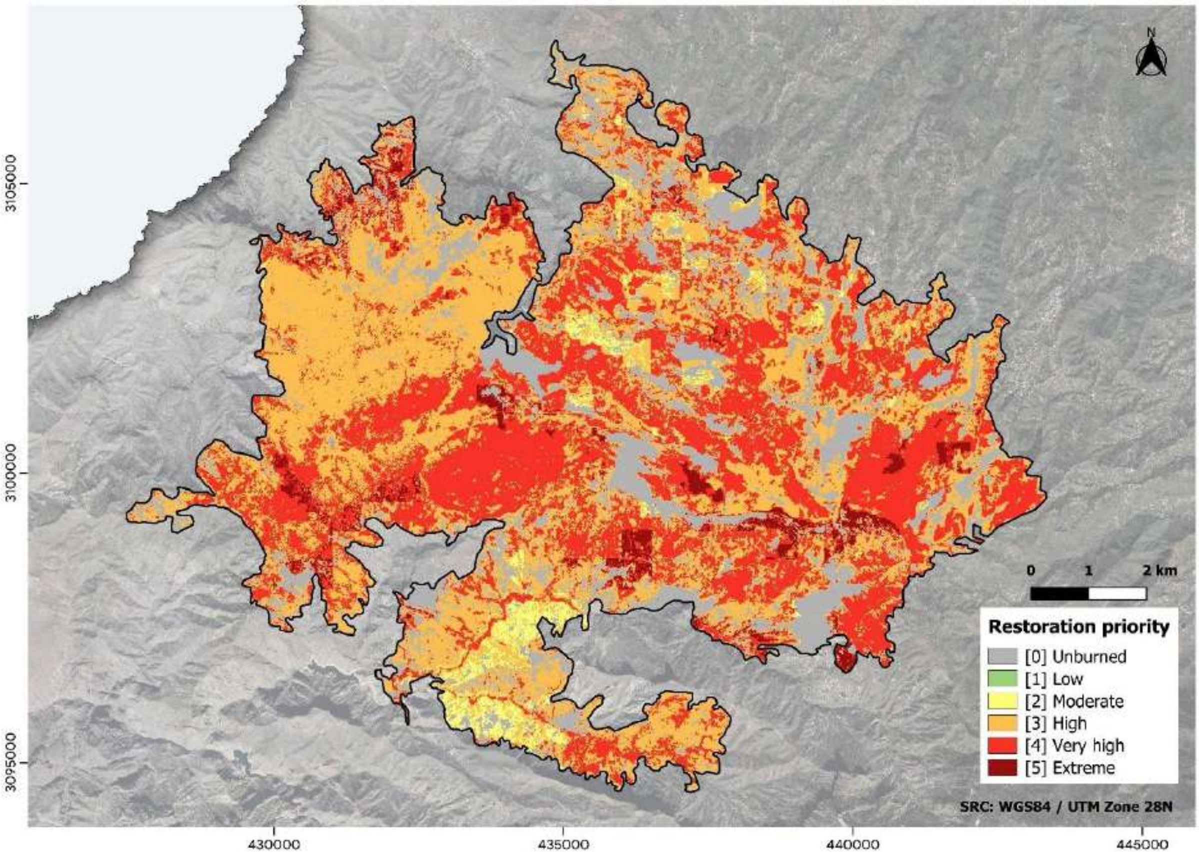


Figure 39. Resulting map of priority areas for post-fire restoration of the case study of Valleseco and Artenara wildfires.

The final prioritization map shown in Figure 39 reveals that 95% of the total area affected by the wildfires has a high or higher restoration priority, with high priority being the most represented (42%). This outcome is largely due to the significance of the potential soil erosion layer, which identifies most of the burned area as being under a high erosion risk, regardless of fire severity. Given the impracticality of implementing corrective measures over such an extensive area, it is considered more feasible to focus attention on areas categorised with extreme risk, primarily located in the eastern region and scattered in the north-west and south-west parts.

In order to assess the viability of the methodology, these results were compared with field data. Thus, in November 2024, five years after the wildfires, several locations with different priority categories were visited. These visited areas are shown in Figure 40 and summarised below:

A) **High-severity zone dominated by *Pinus radiata***, a non-native species lacking fire-adapted strategies. Currently, many dead standing trees are still visible. However, it is worth noting that, after five years, both *Pinus canariensis* individuals and native shrub cover show good recovery. Since some signs of fire damage are still visible, this zone has been correctly classified with extreme priority on the priority map. Post-fire restoration strategies here should have focused on removing dead non-native pines to promote native vegetation and further accelerate recovery process.

B) **High-severity zone dominated by *Pinus canariensis***. In this location, the fire spread primarily through crown fire. Unlike the previous location, most Canarian pine individuals resprouted, achieving nearly full recovery five years after the wildfires. This zone is classified with very high priority.

C) **Low-severity zone dominated by *Pinus canariensis***. Here, the wildfire spread through surface fire without significantly affecting tree crowns. The difference in the appearance of the crowns of this stand compared to the stand in image B is notable; due to the high burned-crown percentage and the subsequent resprouting activity, tree crowns are smaller in this location. This zone is classified with a high level of priority, mainly due to the weight of the potential soil erosion factor, as previously mentioned.

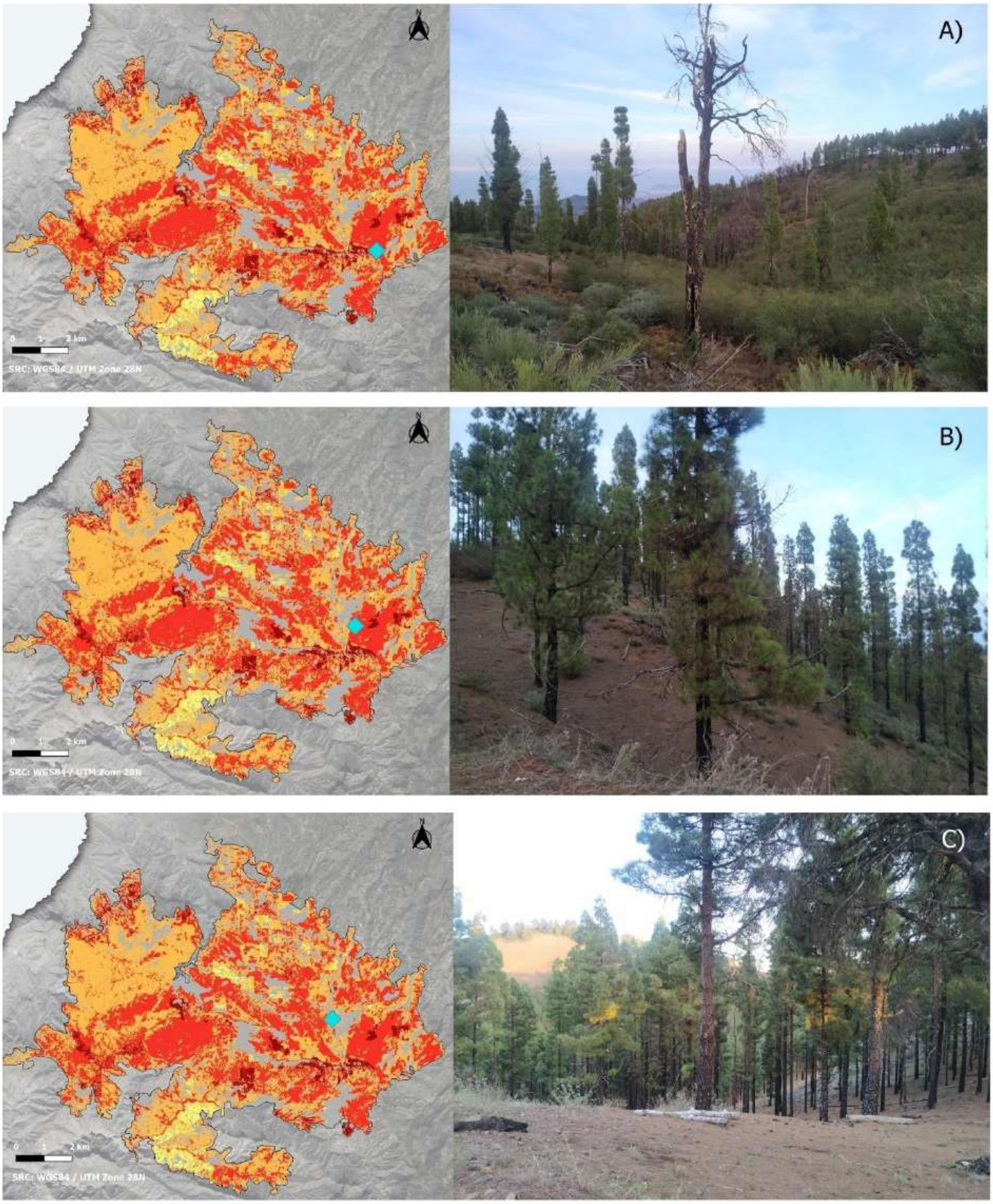


Figure 40. Regeneration status of several locations affected by Valleseco and Artenara wildfires 6 years later. A) Pinus radiata stand in high fire severity. B) Pinus canariensis stand in low high fire severity. C) Pinus canariensis stand in low fire severity (note the difference in canopy shape in comparison with B). Blue dots indicate the location of the pictures. Source: own source, pictures taken in November 2024.

4. Discussion

4.1. Case studies

4.1.1. Catalonia Living Lab

Experts ranked the soil erosion criterion as the most critical factor influencing post-fire restoration, as vegetation cannot regrow without soil. Soil physical characteristics, such as erodibility and slope length, were given higher importance than fire severity in the assessment. Regarding the natural recovery potential of vegetation, the greatest weight was placed on the resprouting ability of pre-fire vegetation. In the case study of the La Torre de l'Espanyol wildfire, after applying the described methodology and combining the information from both criteria, a few small patches distributed throughout the burned perimeter were identified as having the highest priority for restoration (Figure 30). Most of the fire perimeter was classified into one of the two middle categories, with the lowest category assigned to a few very small patches. By identifying the areas at highest risk, targeted post-fire management strategies can be more effectively designed and implemented.

Experts rated fire severity as of low importance, although it was included in the two criteria used (erosion and vegetation recovery) and some studies consider it among the most important factors for post-fire recovery (Blanco-Rodríguez et al., 2023). Our methodology could be underestimating the effect of unburned vegetation islands within the fire perimeter. These vegetation islands are areas where severity is null or very low, and where generally it is not necessary to act (or at least not urgently). On the other hand, these unburned vegetation islands function as fire refugia, acting as dispersal nuclei for ecosystem recovery (Morelli et al., 2016), as they represent seed reservoirs necessary for species that need mature adult individuals to regenerate (Pimont et al., 2011). Similarly, due to the complexity of assessing the impact of anthropogenic elements (e.g., abandoned crop terraces), on the actual slope length within the L factor, this factor may have been overestimated.

The restoration priority may also include other social conditioning factors that are not considered in this Living Lab. For example, it has been observed that local communities living near or within the perimeter of a fire often prioritize the restoration of areas close to their homes, both because of the potential impacts associated with unprotected soil (flooding, clogging of reservoirs, impacts on infrastructure) and because of their connection with the forest areas nearby their homes (Ryan & Hamin, 2008). The presence of protected areas, or poles of economic activity, are also criteria that other studies have considered priority areas for restoration (Cervelli et al., 2022). These variables have been considered, however, in the Portuguese Living Lab, introducing possible improvements to our methodology.

The next steps in the Catalan Living Lab include comparing and validating the methodology used to identify priority areas for restoration using the Tasseled Cap Brightness (TCB) index, that is known to be well related with the cover of the soil by vegetation. Additionally, it is expected to develop a tool to help technical staff responsible for restoring burned areas in Catalonia quickly identify priority intervention zones within days of a fire.

4.1.2. Portugal Living Lab

The participatory nature of the approach ensured that the criteria addressed both ecological and social concerns. According to the results of this study, the most critical zones to restore present a combination of severe soil degradation, low canopy cover density, anthropogenic soils and medium to high fire severity values, which are close to infrastructures and social areas. By focusing on critical areas with poor soil conditions, severe fire impacts, and reduced canopy cover, while prioritizing the enhancement of native resprouts, this work can effectively support the long-term recovery of plant communities. Fire severity was considered a transversal criterion because it conditions both soil erosion and natural recovery capacity of the vegetation. That is, the interpretation of fire severity data from satellite images may vary depending on the specific criterion being assessed

During the FG session, the experts expressed significant concern about regions dominated by non-resprouters, as these areas typically require more intensive and long-term restoration efforts due to their limited capacity for natural recovery after a fire. Although this study prioritizes ecologically critical areas for restoration, FG discussions emphasized the importance of the "proximity to social areas" criterion in post-wildfire restoration. This reflects the influence of local social and economic factors in decision-making. Ultimately, integrating this criterion enhances public safety and supports effective risk mitigation.

4.1.3. Gran Canaria Living Lab

This methodology was developed with the objective of generating a simple tool that provided an approximate first identification of priority restoration zones. For this reason and, to simplify the data processing to the maximum, only environmental factors were considered. However, with this simplification, the importance of certain factors such as aspect and the spatial rainfall distribution (given the highly irregular spatial rainfall pattern in Gran Canaria, which ranges from 60 mm/year in the southern coastal strip to 740 mm/year in the highest altitudes; Luque Sollheim et al., 2024) could be underestimated. These factors, influence the moisture conditions in the territory and, indirectly, the vegetation's regenerative capacity.

Regarding other factors not considered either, the preliminary methodology developed by the Government of the Canary Islands on which this is based, includes social and economic factors such as the population's level of exposure, the presence of critical infrastructure, or the estimation of the loss of economic value of the services affected by the fire as an assessment of economic vulnerability. Integrating this information could enhance prioritisation efforts by considering the broader implications associated with wildfire incidents.

All in all, the two primary challenges to ecosystem recovery after a fire are the regeneration capacity of plant species and soil loss. On the positive side, Canarian vegetation is generally well-adapted to fire, with many species employing sprouting strategies that facilitate rapid recovery, enabling nearly complete vegetation coverage within just a few years (Höllermann, 2000). However, soil loss remains a significant concern in these ecosystems, particularly due to the soil typology and the steep terrain typical of Gran Canaria and other mountainous islands of the Canarian archipelago. Extreme erosive processes can impact not only the productivity of the soils in the area and the maintenance of vegetation cover but also have serious downstream effects due to the amount of material that can potentially be mobilised.

In fact, the Government of the Canary Islands allocated 1.9 million EUR for environmental restoration in areas affected by the Valleseco wildfire (Gobierno de Canarias, 2021). The project, initiated in June 2020 and concluded in the summer of 2021, included erosion monitoring in two representative burned areas: one dominated by *Pinus canariensis* with gentle slopes and the other by *Pinus radiata* with steep slopes. The results showed that erosion rates in the first two years exceeded the tolerable limits of soil loss (0.3 – 1.4 T/ha per year), with higher rates in the Pinus radiata stand. This was attributed to the slow recovery of vegetation cover in both areas, which took nearly two years to reach 40%. In the Pinus canariensis stand, the delay was related to a lack of rainfall, while in the Pinus radiata area, it was due to the inability of the species to resprout and the limited seed bank. Additionally, erosion control treatments using wood chip and pine needle covers were tested, which significantly reduced annual erosion rates (Neris Tomé J., 2021). Consequently, restoration efforts in these areas must prioritise not only the recovery of vegetation but above all, the prevention of excessive soil loss, with measures that have an immediate effect and maintain their effectiveness in the medium term to allow for the recovery of vegetation and soil.

4.2. Post-fire restoration techniques

Once priority restoration areas have been identified, a restoration action plan that defines the specific post-fire management strategies to undertake needs to be designed. These interventions are the first line of defence with the aim of protecting the soil to minimize erosion and reduce surface runoff. They are called emergency stabilisation measures and can be classified into hillslope measures and channel measures (Lucas-Borja, 2021).

4.2.1. Hillslope measures

Mulch application: There are several types of mulch to spread over the soil surface after a wildfire, including debris (bark, litter, and chopped branches), agricultural straw, hydromulch, and wood chip. Mulching with debris and organic material is effective in steep slopes with low plant cover, as it prevents rain splash, surface flow, and soil crusting and compaction. This enhances infiltration, which is particularly important at the end of summer when high intensity rainfalls increase the risk of erosion (Vallejo et al., 2012). Wood-based mulches are more expensive than agricultural straw mulches due to high production and transportation costs. However, the most expensive option is hydromulch, a wet slurry, with or without seeds, based on fibre mulches and soil stabilizers that, when mixed with water and applied to the soil, forms a protective matrix that reduces soil erosion by binding loose soil and ash, protecting downstream water quality and promoting plant growth (Napper, 2006).

Hillslope barriers: They are designed to slow runoff, avoid sediment movement, and increase water infiltration (Lucas-Borja et al., 2021). Hillslope barriers can be constructed from different types of materials, depending on the type of area burned (e.g., forest, shrublands…):

- **Log erosion barriers**: It consists of felling and laying burned trees on the ground along the contour lines of the slope. Implemented in forested areas, this method helps prevent erosion by reducing slope length (Napper, 2006).
- **Contour-felled log debris barriers**: It consists of felling and laying branches and burned canopy trees on the ground along the contour lines of the slope to provide soil cover and protect it against erosion.
- **Fiber rolls**: They are prefabricated rolls made up of rice straw and wrapped into degradable plastic or jute netting. They help reduce erosion by shortening slope length and are used when log-erosion barriers are not feasible due to a lack of trees.
- **Silt fences**: Consist of geotextile fabric that traps sediment. They are rarely used.

Figure 41. Mixed barriers made with burned logs and debris (Collado Mediano, Madrid). Photo: Sergio de Frutos

Figure 42. Contour-felled log debris barriers (Navas del Rey, Madrid). Photo: Sergio de Frutos

Soil scarification and seeding: Involves the preparation of the seedbed for seeding and improving water infiltration by lightly disturbing the soil surface to create roughness (Napper, 2006).

Sowing with native species: This involves seeding to restore native plant communities and recover vegetation cover, which helps protect the soil from erosion. The approach used depends on the post-fire regeneration strategy of the dominant species in the area (no fire related traits, post-fire colonizers, seeders, resprouters) (Mauri & Pons, 2019).

4.2.2. Channel measures

Check-dams: Structures built in ravines, drainage channels, or gullies, perpendicular to the flow of water that are designed to reduce the speed of surface water flow, act as a barrier to retain sediments and facilitate natural regeneration upstream. They can be constructed with straw, timber, or rocks, depending on the availability of materials.

Figure 43. Dry masonry check-dam (Hellín, Albacete). Photo: Sergio de Frutos

Active reforestation is usually done by forest and local administrations, yet in many cases assisted natural restoration is more efficient and cost-effective, as most fire-adapted species have developed regeneration strategies that allow them to recover efficiently after fire (Vallejo et al., 2012).

The effectiveness of all these treatments depends on fire severity, the design of the structure, and the season of construction (Lucas-Borja, 2021). The type of post-fire treatment implemented influences soil quality in terms of the physical (e.g., texture, infiltration capacity), chemical (e.g., organic carbon and nutrients), and microbiological (e.g., fungi presence, respiration) properties of the burnt soil for at least five years following the wildfire (Gómez-Sánchez et al., 2019) and will determine its development and future plant and ecosystem function recovery, including the seeder-to-resprouter and woody-to-non-woody species ratio of the system (Lucas-Borja, 2021).

Grazing animals can trample vulnerable soil and feed on regenerating plants, potentially limiting the post-fire regeneration capacity of the ecosystem. Thus, measures should be implemented to prevent herbivory in the most fragile post-fire areas (Vallejo et al., 2012).

Despite not being a restoration action itself, salvage logging (i.e., harvesting of commercially valuable dead or damaged trees) after fire can affect plant diversity months after the wildfire (Lucas-Borja, 2021). While salvage logging offers economic benefits, its application is controversial as it may have negative ecological impacts depending on local site conditions, including alterations in nutrient cycling, carbon sequestration, tree regeneration and increased risk of subsequent disturbances (Leverkus et al., 2018). After a wildfire, soil is very sensitive to mechanical operations, and short-term salvage logging may contribute more to soil erosion that the wildfire, depending on the erodibility of the soil and topography of the site. On vulnerable soils, logging operations should avoid log dragging, as it may cause even more erosion than the fire itself (Vallejo et al., 2012). Moreover, when conducting salvage logging, the harvesting technique implemented is crucial: stem-only or whole-tree harvesting. Stem-only harvesting leaves more organic matter on site; branches should be left in piles, where they act as erosion barriers in combination with logs. If whole-tree harvesting is used, it is recommended to keep at least the branches from every fifth tree to retain some organic matter on site (Mauri & Pons, 2019). Additionally, retaining some snags is important for biodiversity purposes (Vallejo et al., 2012). Preserving snags and standing burned trees in clumps can help protect vulnerable soils, retain sediments transported by surface runoff from burned area to water streams, and support biodiversity (Mauri & Pons, 2019).

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