Restoration after wildfires in Vale do Sousa, Portugal.
A proposal and test of a participatory multi-criteria approach

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Abstract

This thesis aims to gain insights into the selection and evaluation of criteria and sub-criteria for prioritizing critical areas for restoration through engagement with experts from the Instituto Superior de Agronomia (ISA) at the University of Lisbon and consultation with an expert from the Centre de Ciència i Tecnologia Forestal de Catalunya (CTFC). For that purpose, this thesis considers both the burned area in in Vale do Sousa, a Living Lab within the FIRE-RES project, and a participatory approach involving experts in the academia. This research evolves a Multi-Criteria Decision Analysis (MCDA) approach to elicit criteria and sub-criteria to be considered when defining the areas within wildfire perimeters where restoration is more pressing. This approach allows the integration of diverse opinions and criteria, which are weighted based on their importance to inform restoration actions in burned areas. The process includes defining the metrics for each criterion and sub-criterion during stakeholder interactions. These metrics will help identify priority areas to be ecologically restored, based on stakeholder´s preferences elicited by the MCDA approach. 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. Firstly, the information gathered namely the one that reflects stakeholder´s preferences and weights associated each criterion and sub-criteria is normalized into the same scale. Afterwards, it is combined to generate individual maps of priorities for each criterion. Finally, a prioritization map is developed that categorizes areas by restoration priority levels, from lowest to highest. This map is an influential tool for the effectiveness of restoration decision-making processes, emphasizing regions where restoration will have the most substantial impact.

Keywords: restoration, participatory, multi-criteria decision analysis (MCDA), Analytic Hierarchy Process (AHP), Geographic Information Systems (GIS).

Resumo

Esta tese tem como objetivo obter informação sobre a seleção e avaliação de critérios e subcritérios para priorizar áreas críticas para restauro, especificamente através do envolvimento com especialistas do Instituto Superior de Agronomia (ISA) da Universidade de Lisboa e um especialista do Centre de Ciència i Tecnologia Forestal de Catalunya (CTFC). A interação simula um processo participativo com especialistas da academia, que será posteriormente aplicado com partes interessadas no terreno. Além

disso, esta interação permitirá construir a abordagem participativa a partir da experiência dos investigadores nesta área. A área de estudo, parte de uma ZIF (Zona de Intervenção Florestal) e do projeto FIRE-RES, requer que as decisões sejam tomadas de forma colaborativa com todas as partes envolvidas. Para lidar com esta complexidade, propõe-se a utilização de Análise de Decisão Multicritério (MCDA). Este método permite a integração de diversas opiniões e critérios, que são ponderados com base na sua importância para fundamentar ações de restauro em áreas queimadas. O processo inclui a definição de métricas para cada critério e subcritério durante as interações com os stakeholders. Essas métricas serão utilizadas para definir áreas prioritárias para o restauro ecológico, com base numa abordagem participativa que considera as preferências dos intervenientes. O Processo de Análise Hierárquica (AHP) é utilizado dentro de um ambiente de Sistema de Informação Geográfica (SIG), que fornece uma estrutura espacial explícita que concilia múltiplas preferências. A informação recolhida nas etapas iniciais deste trabalho, assim como a integração da componente participativa para obter as preferências dos stakeholders e os pesos de importância para cada critério e subcritério, é normalizada na mesma escala e combinada para gerar mapas individuais de prioridades para cada critério e, por fim, um mapa de priorização que categoriza as áreas de acordo com os níveis de prioridade de restauro, do mais baixo ao mais alto.

Palavras-chave: restauro, participativo, análise de decisão multicritério (MCDA), Processo Análitico Hierárquico (AHP), Sistemas de Informação Geográfica (SIG).

Resumo alargado

Nas últimas décadas, os incêndios florestais tornaram-se um grande problema na região mediterrânica, incluindo Portugal. Estes incêndios afetam gravemente os ecossistemas florestais, alterando a vegetação, as propriedades do solo e os ciclos biogeoquímicos, ao mesmo tempo que causam perdas económicas significativas. Os ecossistemas mediterrâneos, naturalmente diversos e moldados tanto por fatores ambientais como pela atividade humana, são propensos a incêndios florestais devido à abundância de materiais inflamáveis e aos baixos níveis de humidade. Embora muitas espécies se tenham adaptado para prosperar nestes ambientes propensos a incêndios, as crescentes frequência e intensidade dos fogos estão a causar danos socioeconomicos e ecológicos generalizados.

Portugal enfrenta um elevado risco de incêndios florestais devido às mudanças demográficas, ao abandono de áreas agrícolas e florestais e à fragmentação da propriedade da terra, o que dificulta a gestão florestal eficaz e à escala da paisagem bem como os esforços de prevenção de incêndios. Este trabalho centra-se na avaliação da resiliência da paisagem pós-incêndio e no planeamento da melhor alocação de recursos para a recuperação florestal no Vale do Sousa, em Portugal, com ênfase na priorização das áreas mais necessitadas de restauro. Salienta a complexidade dos esforços de restauro devido ao envolvimento de múltiplos intervenientes, incluindo proprietários privados, tornando o consenso uma realidade desafiante.

Numa primeira etapa, e após uma discussão prévia com os co orientadores com vista a definir uma proposta de critérios e subcritérios a considerar para efeito de identificar àreas ardidas onde o restauro é prioritário, organizou-se uma sessão presencial com peritos para discutir e desenvolver aquela proposta. Neste contexto, para o efeito de atribuir valores de utilidade àqueles critérios e sub-critérios, foi utilizado um esquema de priorização binário (prioridade mínima e máxima). Este devido à sua simplicidade e à dimensão da área em análise permitiu uma avaliação direta que foi intuitiva e facilmente compreendida pelos participantes. Em fases posteriores, a importância destes critérios foi determinada através de comparações par a par, levando à criação de um mapa de priorização com base em dados espaciais detalhados.

Para a ponderação dos critérios e sub-critérios, foi enviado um inquérito online aos participantes devido à sua flexibilidade para compilar as respostas. A plataforma gratuita "Google Forms" foi utilizada pela sua facilidade de uso em vários dispositivos. De acordo com os valores de utilidade atribuídos a cada critério e subcritério durante a sessão de grupo, toda a informação foi normalizada antes da adição de pesos para cada critério e subcritério. Por fim, foram gerados mapas individuais de acordo com cada critério, atribuindo uma classe de prioridade de tratamento a cada célula raster em cada perímetro de área ardida.

Um resultado crítico desta pesquisa é um mapa de priorização, que categoriza as áreas conforme a sua necessidade de restauro, oferecendo um guia claro para os futuros esforços de recuperação de áreas ardidas. O mapa é criado utilizando dados espaciais e é projetado para facilitar a compreensão por todos os intervenientes. A tese está metodicamente estruturada, com secções sobre a área de estudo, metodologia, resultados e discussão, culminando em conclusões e recomendações. Esta estrutura assegura uma abordagem abrangente para compreender e enfrentar os desafios do restauro ecológico de áreas ardidas.

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AFVS - Associação Florestal do Vale do Sousa

AHP – Analytical Hierarchical Process

CBD - Convention on Biological Diversity

CI – Consistency Index

CR – Consistency Ratio

dNBR - differenced Normalized Burn Ratio

EWE - Extremely Wildfire Events

NGO´s - Non-Governmental Organizations

FG – Focus Group

GIS - Geographical Information Systems

Ha – Hectares

ISA - Instituto Superior de Agronomía

ICNF - Instituto da Conservação da Natureza e das Florestas

MCDA – Multiple Criteria decision Analysis

LUCL – Land Use and Land Cover Classification

RUSLE - Revised Universal Soil Loss Equation

SGD´s - Sustainable Development Goals

S-MCDA - Spatial Multicriteria Decision Analysis

SMART - Simple Multi-Attribute Rating Technique

USGS - United States Geological Survey

UNCCD - United Nations Convention to Combat Desertification

ZIF - Zona de Intervenção Florestal

1. INTRODUCTION

Forest fires in the Mediterranean region

The escalation of forest fires in the Mediterranean region over recent decades, including Portugal, has become a pressing concern, with burned areas totaling approximately 3.8 million hectares between 1975 and 2007, equivalent to 40% of the country's landmass (Marques et al., 2011). Forest fires impact the structure and species composition of forest vegetation, alter soil properties, influence forest succession, and affect biogeochemical cycles (Alayan, 2022). Additionally, they lead to significant economic losses stemming from the substantial resources expended in fire suppression and prevention, the associated costs related to the loss of non-market public services, and the depreciation of commercial value in damaged wood products (Alayan, 2022).

Severe fire incidents are events that are not uncommon on a global scale. They constitute unique and severe fire episodes causing catastrophic damages in terms of human casualties, economic losses or both (San-Miguel-Ayanz et al., 2013). As portrayed by San-Miguel-Ayanz et al (2013), megafires can be driven by critical weather conditions, which deviate from typical patterns, emerging as exceptional and critical occurrences. In Portugal and Spain, approximately 97% of wildfires are attributed to human origins (DGRF, 2006). A report from the Portuguese Forest Services (DGRF, 2006) highlights the breakdown of human-caused fires, 49% were intentionally caused, 27% were due to negligence and 11% were accidental. Lightning ignitions accounted for only around 3% of all fires between 2000 and 2005, underscoring their negligible impact compared to human-driven causes in this area (DGRF 2006).

Consequently, only a minor fraction of fires evades initial suppression efforts and subsequent firefighting operations. In terms of restoration, large fires differ from small fires, because small fires, typically result in localized damage and require relatively minimal restoration efforts. In contrast, megafires, characterized by their catastrophic scale and severity, inflict widespread devastation, including significant ecological and economic impacts. A study in Portugal showcases that post-fire vegetation recovery is strongly influenced by fire intensity and environmental factors such as drought (Bastos, 2011). Vegetation that suffers less damage from fires tends to recover more quickly, as seen in areas dominated by *Pinus pinaster*, a resilient species capable of regenerating after moderate disturbances (Bastos, 2011). However, severe droughts, like those experienced in 2003 and 2005, significantly impede recovery by adding stress to already damaged ecosystems (Bastos, 2011).

Mediterranean ecosystems are characterized by a spatial heterogeneity due to the natural factors and human intervention (Poirazidis et al., 2012). Additionally, due to the abundance of highly flammable materials combined with low moisture levels, wildfires are a natural part of Mediterranean ecosystems. Wildfires have predominantly shaped the current landscape mosaic, as extensively explored in post-fire regeneration studies (Pausas et al., 2004), while various species have adapted to thrive in this fire-prone environment (Trabaud, 1987).

However, the escalating frequency and severity of wildfires in recent decades are affecting the ecosystem in multiple ways (Ruiz-Gallardo et al. 2004). The threat of wildfire is especially pronounced in Portugal which has one of the highest fire risk rankings in the European continent, due to shifting demographics, changes in land use with more agricultural and forested areas being unattended, and fragmented land ownership that discourages investment in forest management and fire planning (Beighley & Hyde, 2018).

Extremely Wildfire Events (EWE) entail coupled processes, resulting in rapid, intense, and unpredictable fire behavior that often exceeds the technical constraints of control, accompanied by extreme rates of propagation (Tedim et al., 2018). The severity of the situation is exemplified by the worst year in the last decade, 2017, which witnessed around 540,000 hectares burned, 117 fatalities, and fire fronts with rates of spread rarely seen in literature (Carmo et al., 2022). Forest fire risks in Portugal, are driven by a combination of demographic, land use, and ownership factors (FRC, 2018). Population shifting from rural to urban areas have left many agricultural and forested lands unattended, leading to increased fuel loads (FRC, 2018). Despite significant investment in firefighting resources, the trend of annual burned area over the past four decades shows a persistent and heightened level of fire activity, reflecting the challenges in addressing these underlying issues.

Post-fire ecological resilience and recovery planning focus on evaluating the immediate impacts of wildfires (The Nature Conservancy, 2022). Restoring ecosystems holds a prominent position on the global agenda, as evidenced by the 2050 vision of the Convention on Biological Diversity, the United Nations Convention to Combat Desertification (UNCCD), the 2030 Agenda for Sustainable Development (the Sustainable Development Goals), and the UN Decade for Restoration (European Comission, 2022).

Restoring forests after a fire involves a deliberate effort to return the forest ecosystem to its ecological integrity and resilience (Uprety et al., 2022). According to the “Resistance-Resilience” framework, resilience refers to the properties of resistance, recovery, and reorganization in ecosystem restoration (Hodgson et al. 2015).

The “Resistance-Resilience” framework distinguishes between the concepts of resistance and resilience in how systems respond to disturbances. Resistance refers to a system's ability to remain unchanged or resist alteration when confronted by disturbances (Derose & Long, 2014). In contrast, resilience describes a system's capacity to absorb disturbances, reorganize, and recover while undergoing change, maintaining its core functions, structure, and identity (Derose & Long, 2014).

While resistance focuses on minimizing immediate impacts and avoiding change, resilience involves adapting to and recovering from disturbances. This distinction is critical in forest management, especially in the context of climate change, where strategies aim to preserve ecological goods and services by fostering both resistances to avoid undesired changes and resilience to recover from inevitable disturbance (Derose & Long, 2014).

According to the Nature Restoration Law (2024), restoration efforts for ecosystems have been inadequate to date. A major obstacle has been the insufficient commitment and political prioritization of restoration, resulting in limited funding and resources dedicated to these activities. This challenge is also evident in Portugal, where multiple interests can significantly affect restoration efforts due to the complex landscape of land ownership.

Decision making tools to support post-fire restoration

Decision-making tools, particularly those employing Multi Criteria Decision Analysis (MCDA), can facilitate comprehensive evaluation of criteria with the incorporation of stakeholder’s perspectives (e.g., Cervelli et al. 2022). A recent study by Borges et al. (2017) proposed a combination of participatory workshops and MCDA, which aims to develop and negotiate targets for ecosystem service provision and in the design of the management plan.

Additionally, Marques et al. (2021) utilized participatory techniques and tools, including cognitive mapping to identify criteria and sub-criteria to assess forest management alternatives. In this study, they considered the multiplicity of wide-ranging criteria such as income, soil erosion and wildfire risk (Marques et al., 2021). Furthermore, these authors evolved further a multi-criteria questionnaire incorporating the AHP for criteria weighting through pairwise comparisons, a Simple Multi-Attribute Rating Technique (SMART) for rating attributes, and a Delphi survey to gather stakeholders' opinions.

Rodríguez (2023), conducted a study in Vale do Sousa, aimed to design a network of managed areas to enhance the security, efficiency, and effectiveness of wildfire suppression efforts, particularly in extreme wildfire events. The methodology employed combined a participatory Multi-Criteria Decision Analysis (MCDA) with a GIS-based Analytic Hierarchy Process (AHP), resulting in maps that prioritized management areas.

In ecosystem restoration initiatives, the selection of metrics for different indicators plays a key role in enhancing the efficacy and goals of the program (Convertino et al., 2013). In this context, it is common to involve several individuals with different opinions in the evaluation of weights of importance and metrics (Saaty, 2008). The process of selecting metrics requires consideration of several factors such as environmental, socioeconomic and stakeholder concerns (Convertino et al., 2013). Often, given the constraint of financial resources it becomes a challenge to balance the significance of various concerns (Convertino et al., 2013).

According to Saaty (2008), tangible and intangible factors are crucial in decision-making processes. The Analytic Hierarchy Process (AHP) models consist of creating a hierarchy with three levels: the primary goal of the decision occupies the top level, followed by a second level containing the criteria used to evaluate the alternatives situated in the third level (Saaty & Kearns, 1985). When the AHP method is applied in a participatory process, it is frequently required to consolidate the preference scores into a single set that represents the entire group (Saaty, 2008). Saaty (2008) advocates the geometric mean as the most appropriate method for aggregating individual preferences in group decision-making within the AHP methodology. The geometric mean satisfies the reciprocal property essential to AHP, ensuring that the aggregated pairwise comparison matrix retains its consistency and validity for further processing.

The AHP method has been applied to address various environmental management challenges, as evidenced by studies like Linkov and Moberg (2011). The AHP's approach involves subjective pairwise comparisons of criteria, as opposed to using value functions and normalized weights (Convertino et al., 2013). In the study developed by Guo et al. (2020), MCDA was applied to determine the restoration constraints from industrial sites and mines with respect to damaged land. The authors classified the levels of restoration into four levels: extremely high, high, medium, and low. At a second phase, AHP was applied to determine the weight of indicators included in the evaluation. Similarly, Orsi and Geneletti (2010), conducted an assessment to ensure the success of reforestation efforts, by setting thresholds which serve as criteria for determining the priority of different sites.

Objectives and expected outcomes

The main idea of this thesis work is to gain insights for the selection and evaluation of criteria and sub-criteria to prioritize post-fire areas that are critical to restore. These insights are provided by the involvement of a group of experts affiliated with the Instituto Superior de Agronomia (ISA) at the University of Lisbon. This step goes beyond simulating a participatory approach and testing the use of a participatory approach with experts in the academia, it is also fundamental for gathering valuable insights and expertise to refine the process. By engaging with experts, the thesis benefits from their knowledge for defining criteria and sub-criteria as well as for assigning weights to the to prioritize the restauration in post-fire areas. In later stages, this information will be input to support the development of participatory processes with other stakeholders in Vale do Sousa, but not within the scope of this thesis.

To define the restoration prioritization areas for this study, a set of criteria will be agreed by consensus with all members of the expert panel. To achieve this, a multi criteria evaluation approach is proposed, as it offers a framework for integrating various opinions and evaluation criteria, weighting them based on their significance. Furthermore, the participatory approach will encompass the definition of metrics for each criterion and sub-criteria by the expert panel, the normalization of the data with their respective weights of importance according to each expert´s preferences. For this work, the aggregation of individual judgments into a single representative judgment for the group is a critical step under the MCDA framework.

The Analytic Hierarchy Process (AHP) embedded within a GIS environment will address the importance of having a spatially explicit and ecosystem-driver approach that may reconcile expert’s multiple preferences. This aggregated information will be used to generate a map delineating areas categorized by levels of restoration prioritization (from the lowest priority areas to the highest), facilitating the comprehension of the study's objectives and providing a foundational framework for engagement. The spatial data was adjusted in 30x30 raster format, ensuring the same extent for all layers and a common spatial reference.

Each level of prioritization for restoration will be presented in a final map, including the merged information of the selected criteria and sub-criteria. The final restoration prioritization map is a critical decision-making tool that integrates diverse criteria and sub-criteria relevant to ecosystem restoration. This map intends to highlight high priority regions where restoration can have the most substantial impact, due to the presence of vulnerable conditions of the soil and vegetation conditions, as well as the presence of social areas.

2. MATERIALS AND METHODS

2.1. The Vale do Sousa case study area

The case study area is Vale do Sousa, located in north-western Portugal, 50km east of Porto, on both banks of the Douro River. It extends over an area of 28,940 ha, and 14,320 ha correspond to the Zonas de Intervenção Florestal (ZIF) areas, separated by the Douro River: *Entre-Douro-e-Sousa* (north of the Douro River) and *Paiva* (south of the Douro River) (Figure 1).

The ZIF areas, are a collaborative forest management area, that exhibit tenure diversity stemming from the involvement of various ownership types, such as industrial private forestland, industry, and community/municipalities (Borges et al., 2017). When referring to "industrial private forestland", the term describes privately-owned forest areas managed primarily by industrial entities or companies. The governance structure of ZIFs is characterized by a management board comprising representatives from forest owners' associations, and usually their meetings involve the participation of different stakeholders like Non-Governmental Organizations (NGOs) or forest services (Borges et al., 2017).

This association, in collaboration with ISA (Instituto Superior de Agronomia, ULisboa), has a history of involvement in various projects related to forest management planning and currently focuses on wildfire management. Specifically, this dissertation is part of the FIRE-RES project, which addresses wildfires in Vale do Sousa.

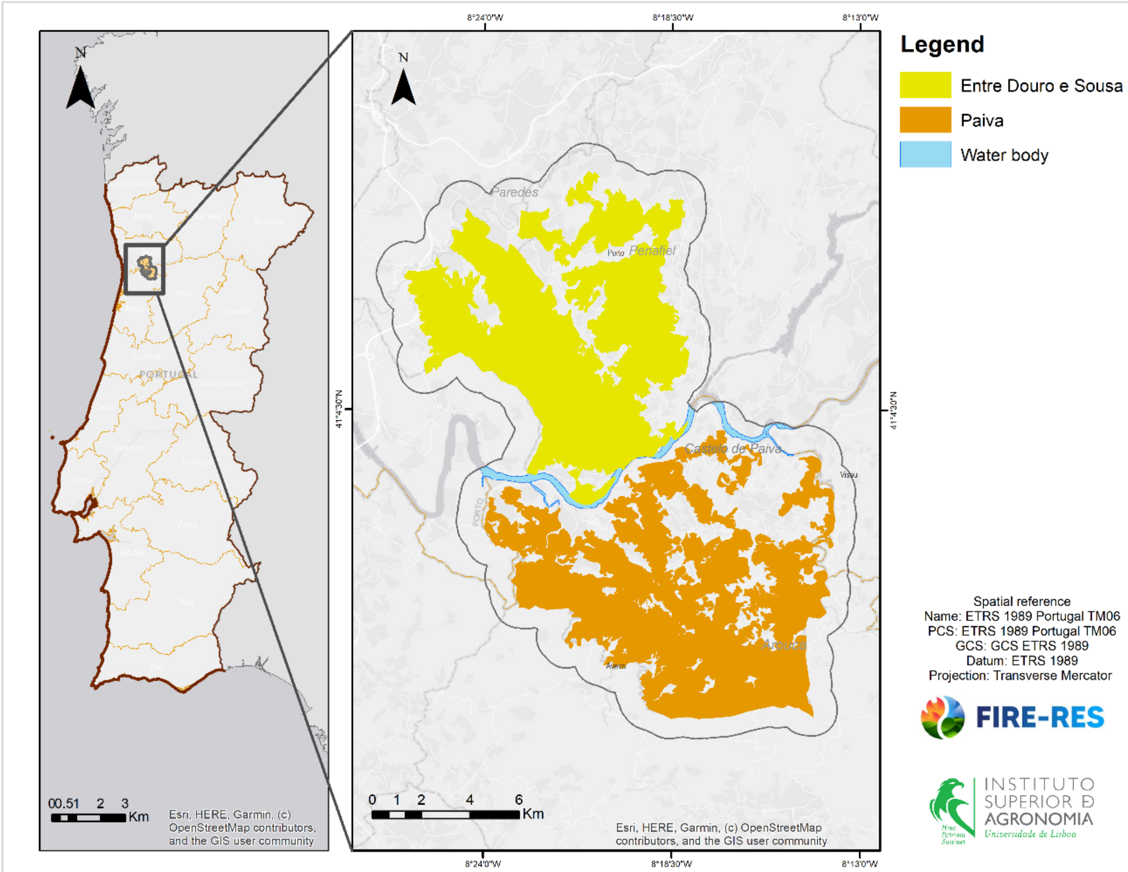

Figure 1. Forest Intervention Areas (ZIFs) in Vale do Sousa.

2.2 Vegetation and land use

The Vale do Sousa landscape is a diverse land use mosaic, where land tenure is heterogeneous (Borges et al., 2017). *Eucalyptus globulus* dominates the landscape, covering more than half (51.80%) of the total area (Figure 2). This high percentage is indicative of large-scale commercial forestry or plantations. Agriculture represents the second-largest land use class, covering 16% of the total area. Next, building areas cover just over 8% of the landscape, which indicates a moderate level of urban development and human settlement.

The rest of land use cover corresponds to non-riparian vegetation (7.5%), shrubland (6.79%), maritime pine (4.09%), riparian vegetation (2.76%), water bodies (2.34%), and bareland (0.63%). 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). Eucalypt is known for its high flammability due to its leaves containing high levels of flammable compounds in their leaves, making crown ignition and combustion easier than in species that do not have these compounds (Miller, 2001; Nunes et al., 2005).

Maritime pine (Pinus pinaster) could also be found in the study area both in pure and mixed stands. This species is the main pine tree in Portugal and is primarily considered a good source of timber production (Garcia-Gonzalo et al., 2011). Like the eucalyptus, the pines of Portugal are usually adapted to survive after a wildfire, however the major disadvantage of maritime pine is its susceptibility to fire, because of the highly flammable resinous needles and wood which is prone to easy ignition, fast and complete combustion and high heat release (CABI, 2024).

In the case of the non-riparian species, there are species such as pedunculated oak (*Quercus robur*), cork oak (*Quercus suber*), chestnut (*Castanea sativa*) and strawberry tree (*Arbutus unedo)* deemed by stakeholders as promising alternatives to diversify the mosaic (e.g., Borges et al. 2017; Marques et al. 2021; Ferreira et al. 2023).

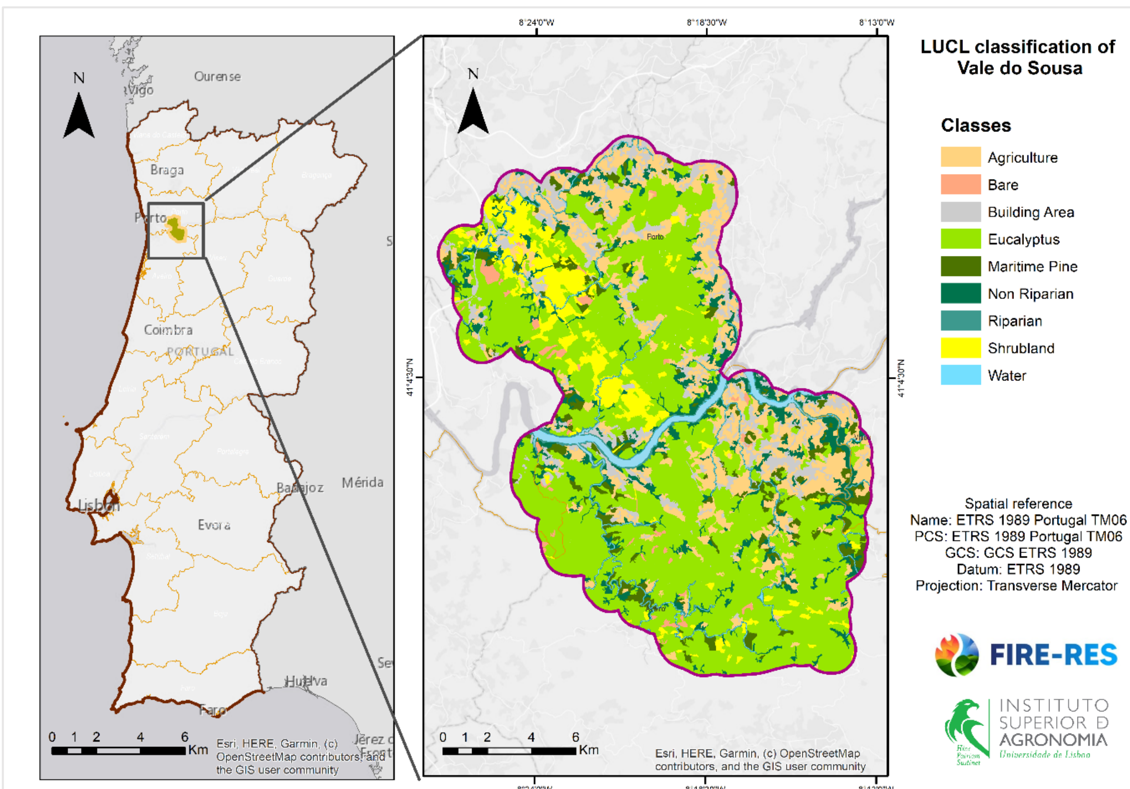

Figure 2. Land Use and Land Cover (LUCL) classification of Vale do Sousa. Source: FIRE-RES project 2024.

The significance of forests in the region, combined with predominantly private ownership and the small-scale, fragmented distribution of properties, motivated landowners to establish the “Associação Florestal do Vale do Sousa” (AFVS) 29 years ago. The AFVS is responsible for the development and implementation of the forest management plan of the ZIFs in Vale do Sousa.

2.3 Climate and topography

Portugal has a Mediterranean climate characterized by warm and dry summers and cool and wet winters (Carvalho et al., 2014). The rural region has a Mediterranean climate with an Atlantic influence, with an average precipitation of 1,240 mm but unevenly distributed throughout the year, with three very dry months (June, July and August) and three very humid months (October, November and December). Furthermore, eight of Portugal's 10 warmest years on record have been recorded in the last 20 years (Carvalho et al., 2014).

According to Soares et al. (2015), Portugal is one of the countries with the largest spatial precipitation gradients, from the northwestern region, which is directly affected by the passage of Atlantic storms, to the drier southern regions. Elevation at Vale do Sousa ranges from 20 to 710 m in the South and to 400 m in the North. Its topography is very uneven, and slopes can be very steep. Soils are mostly poor, well drained, and thin. This rural region has a Mediterranean climate with an Atlantic influence, and the soils present are mostly Umbric Leptosols and Leptic Regosols, developed over schist and granite bedrocks (IUSS Working Group WRB, 2015).

2.4 Wildfire activities

In Portugal, two notable extreme weather events occurred: one in mid-June, with temperatures soaring up to 40ºC and relative humidity dropping below 20%, and another in mid-October. Both events resulted in extensive damage, with over 500 thousand hectares scorched, and at least 112 lives lost in forest fires. In the year 2017, Portugal experienced the most severe instances of Extremely Wildfire Events (EWE) in its recorded history. The year ranked as the second warmest, marked by an extended drought, particularly a dry period from April to December, heightening the fire risk (Zeferino, 2020). The image below shows the forest fire perimeters from 2016 to 2022 that affected the Vale do Sousa region.

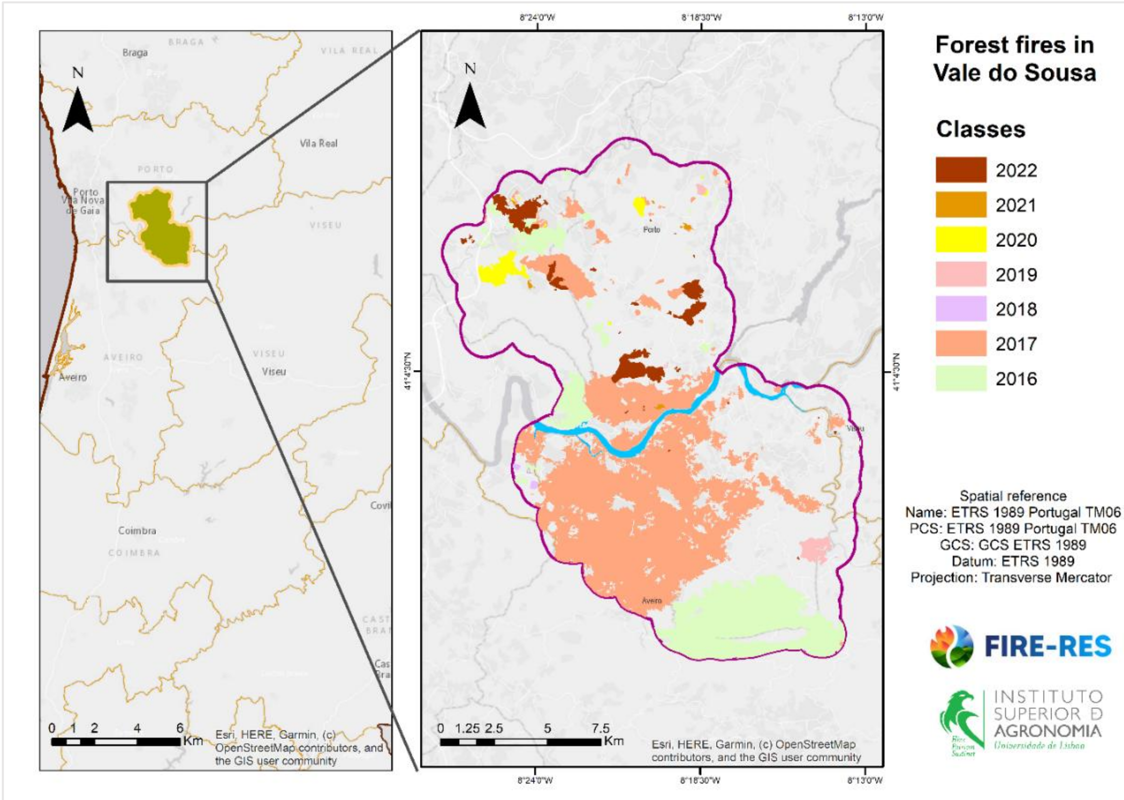

Figure 3. Forest fires perimeters (2016 – 2022). Source: Instituto da Conservação da Natureza e das Florestas (ICNF).

The surge in wildfire frequency has markedly influenced the decisions of forest owners in the area regarding their management strategies. There is an increasing preference for short rotation eucalypt stands, primarily driven by the prospect of reduced income loss in the event of a wildfire. Moreover, forest owners are less inclined to favor species with longer rotations, such as maritime pine and chestnut, due to heightened concerns regarding wildfire risks.

It is important to consider that perspectives on species conversion are undergoing a transformation among stakeholders, particularly when forest owners are provided compensation for economic losses and potential payments for the ecosystem services they provide. This shift underscores a notable transformation in forest management practices, prompted by the escalating threat of wildfires and a collective acknowledgment of the imperative for sustainable approaches.

2.5 Methods

In essence, the aim on this study, is based in restoration prioritization efforts following a wildfire event in the study area. The steps for completing the work are as follows:

2.5.1 Identification of burned areas affected by large fires and small-scale fires in Vale do Sousa

Firstly, this study involved the meticulous identification of yearly burned areas influenced by both large-scale and small-scale fires within the Vale do Sousa region (Figure 4). In this case, restoration prioritization based on burned areas, allows for the targeted allocation of restoration strategies to mitigate the severe ecological degradation and enhance the resilience of the affected area.

Information about the topography, geography and the remote sensing data on pre-fire vegetation helps to understand the post-fire vegetation evaluation (Poirazidis et al., 2012). This, in addition to identifying the burned areas, this step involves an examination of the characteristics of each burned area including information about land use and the type of species present, to gain valuable insights across the landscape.

An important aspect of this study involved further characterizing the wildfire perimeters to enhance the accuracy of post-fire landscape assessments. This characterization included analyzing key factors such as soil properties and topographic features, both of which are essential in estimating erosion risks using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). By incorporating detailed information on soil type, texture, and slope variability, this analysis allowed for a more refined estimation of erosion vulnerability within the wildfire perimeters.

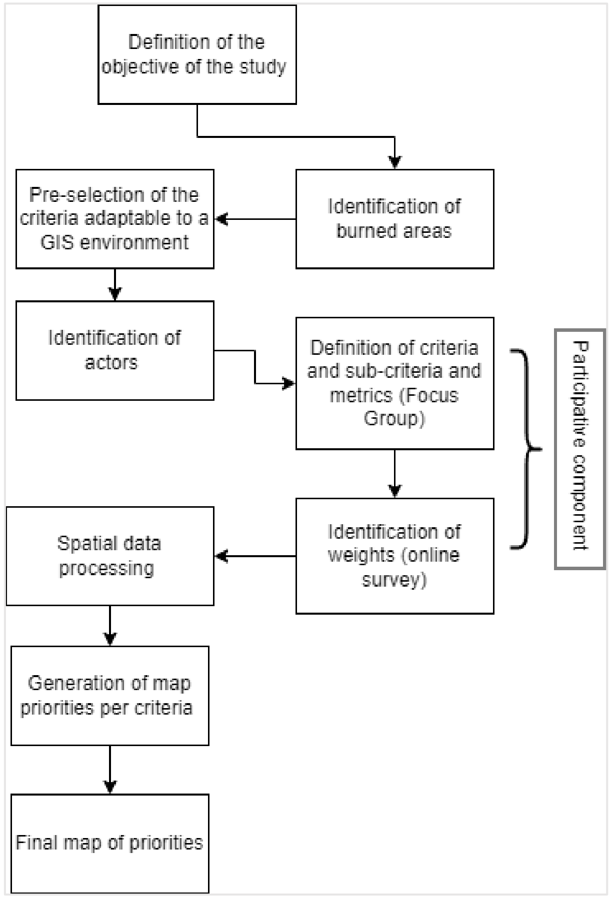

Figure 4. Flow diagram of steps to accomplish the main objective of the study.

The sections "Definition of Criteria and Sub-Criteria and Metrics" and "Identification of Weights Online" are the participatory components of this study which integrates stakeholder´s concerns from the study area (Figure 4). This approach ensures that the restoration prioritization reflects local needs and perspectives.

2.5.2 Pre-selection of criteria and sub-criteria adaptable to a GIS environment (Figure 4)

A set of pre-selected criteria can facilitate stakeholder engagement by providing a common framework for discussion and evaluation. The set of criteria may include factors or threats that exist or are amplified in the post-fire setting. The sub-criteria derive their relevance from specific characteristics related to their main criteria, referred to as a multicriteria analysis in a spatial context where each element of the decision problem has spatial dimensions.

A first approach regarding the criteria and sub-criteria was derived from best practices identified in the literature. This information was then contrasted through consultation with experts with heterogeneous backgrounds, predominantly researchers belonging to ISA, and researchers at the University of Lleida from the Department of Forestry and Agricultural Science and Engineering.

The approach of this study relies on a GIS environment, meaning that the MCDA relies on data can be systematically gathered and structured in a way that aligns with the analytical capabilities of GIS. The goal of this evaluation was to identify emergency conditions for critical values that are found to be at risk from imminent post-fire threats, and to recommend general response actions to reduce the risk and mitigate post-fire impacts to critical values.

2.5.3 Establishment of an expert panel (ISA and FIRE-RES partners)

Following the identification of data available and adaptable to a GIS environment, the next phase focused on listing a panel of participants that hold knowledge on restoration strategies and similar areas of study. A vital component of the thesis, which is the participatory approach, requires mapping of the different types of stakeholders that are present in a determined area.

The main goal of this step is to create a reliable group, ensuring a comprehensive and well-informed decision-making process. After the mapping of potential participants within ISA and affiliated organizations, each person was contacted individually, to invite them to a group discussion to talk about the relevance of the pre-selection of criteria and sub-criteria. This first contact was a week prior to the presential meeting.

An informative document (Annex 2) was generated and sent to each participant as well, containing information that was collected in relation to the case study, along with the description and visualization of the pre-selection of the criteria and sub-criteria considered relevant to the scope of this study. The goal of this informative document is to have a shared understanding of the methodology, and the study´s goal of defining priority areas for restoration within the perimeter of the selected burned areas.

By facilitating a discussion among participants with remarkable knowledge about the importance of considering different criteria, participants can discuss and justify their preferences, leading to a more transparent and agreed-upon decision. Furthermore, the prioritisation issue is a rather common topic of conservation science when economic resources are limited (Orsi & Geneletti, 2010).

2.5.4 Definition of criteria, sub-criteria and corresponding metrics (FG)

The methodology for defining the criteria and sub-criteria to be considered, as well as the corresponding metrics, involves a Focus Group (FG) session (Figure 4). According to literature, Focus Group sessions are a common qualitative method for delving into different topics, and are closely linked to the rise of participatory research (Nyumba et al., 2018).

This session was convened in person to facilitate active participation and discussion among stakeholders. Leading the session was the lead researcher, who served as the facilitator. This role was not only to moderate the discussion but also to ensure that the conversation remained in track, and that the session´s objectives were met. To support this, the meeting room was equipped with a round table to create an inclusive atmosphere, and with a projector which served as a key tool for presenting relevant data, visual aids, and discussion prompts.

The primary objective of this step is to agree on a set of criteria and sub-criteria relevant to the study's goal of defining priority areas for restoration, but also to discuss the relative importance of each indicator in the context of localizing ecologically critical areas that are important to restore. Participants were asked the question: which criteria should be considered to select a site for forest restoration?

The following activities were undertaken: first an introduction to the study goals with an emphasis on the importance of validating and identifying the main criteria and sub criteria. Next, each of the indicators were presented one by one, to ask the experts whether they thought this information was coherent with the context of the study. Lastly, through a facilitated discussion among experts the group reached an agreement on a final set of criteria and sub criteria, including suggestions on how to display the information.

During the second part of the session, participants were encouraged to contribute their insights and perspectives to enrich the discussion about the metrics that determine the priority level for restoration preferences in the study area. While some metrics are informed by existing literature, opinion of participants are required in finalizing these metrics (Convertino et al., 2013).

Each criterion and sub-criteria hold values in between the maximum threshold (that were determined during the group session) and the maximum existing value in that area, and inversely for the lower threshold. In this case, most of the thresholds are mainly provided by the output from the data for each burned area. To assign utility values to the criteria and sub-criteria, participants were asked to evaluate the range of values for each criterion and designate the corresponding minimum and maximum priority levels.

This enables a straightforward assessment that may be intuitive and easily understood by the participants. In later stages, the importance of each criterion is determined using pairwise comparisons, leading to the creation of a prioritization map based on detailed spatial data. The FG session served as the basis for generating a spatially explicit map considering the preferences of stakeholders, and their weights of importance with is determined in the next step of the methodology.

2.5.5 Identification of weights for the criteria and sub-criteria

According to Saaty (2008), tangible and intangible factors are crucial in decision-making processes, that require a careful evaluation of their measurements in relation to the decision maker's objectives. For this work, the AHP method applied, as it is suitable for participatory planning and provides a methodical way of carefully considering various factors, ensuring a balance between the quality of judgements of each decision-maker (Saaty, 2008). The weighting of criteria is based on the ranking of criteria in terms of the impact they should have of the selection of priority areas for management (Saaty, 2008).

For the weighting of criteria, an online survey was sent to the participants from the Focus Group (Annex 4), due to its flexibility to compile the answers, in relation to the criteria and sub-criteria that is critical to focus on for prioritization of areas. The free platform “Google Forms” was used due to its ease of use across various devices. Each participant received an online survey after three weeks after the FG session, so that they could indicate the weighting of importance according to their perception and the goal of the study.

Considering that a criterion may have different relative importance in a decision process, stakeholders were asked to define defined the criteria´s weights in the context of the Pairwise Comparison Method, developed by Saaty (1980), based on a continuous scale. The value 1 indicates that two criteria are “equally important” and the value 9 implies that one criterion is “extremely” more important than the other (Table 1).

Table 1. Fundamental scale of the Hierarchical Analysis Process (AHP). Based on Saaty (1987)

Intensity of importance	Definition	Explanation
1	Equal importance	Both activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment moderately favor one activity over the other
5	Essential or strong importance	Experience and judgment strongly favor one activity over the other
7	Very strong importance or demonstrated importance	One activity is strongly favored over the other
9	Extreme importance	The evidence favors one activity over the other of the highest possible order of affirmation
2,4,6,8	Intermediate values between scale values	When a middle ground is necessary

The set of all the judgments made from each stakeholder forms a matrix called "pairwise comparison matrix", in which the set of elements is compared with itself (Elineema, 2002). After constructing the matrix of paired comparisons, what is called the priority of each of the elements that are compared is calculated. In this step, each preference should be consistent as possible with the goals of the study (Pequeño-Ledezma et al., 2016). To evaluate consistency, it is fundamental to normalize the weights for each criterion and sub-criteria.

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). After the normalization of weights, the Consistency Index (CI) can be calculated using the following equation (eq. 1) as given by Saaty (1987):

$$CI = \lambda - n / n - 1$$

Where CI is the Consistency Index, n is the number of factors being compared in the matrix and lambda max is the highest eigenvalue of the pairwise comparison matrix (Saaty, 1987).

For this study, the Consistency Ratio (CR) was calculated for the weights assigned to the criteria from each participant, to verify if there were any outliers in the analysis to recalculate the weights before proceeding to the final stage. The CR is a normalized version of the CI, which compares the CI to the average consistency index of randomly generated comparison matrices of the same size. According to Rao (2007), a Consistency Ratio (CR) above 0.1 indicates inconsistency in weighting responses and suggests contradictions among pairwise comparisons.

2.5.6 Generation of the prioritization map for restoration

The preparation of data is essential for generating individual maps of prioritization, and the final map of prioritization. The working environment from ArcMap software allows to collect and process the spatial data, as well as the arrangements regarding the resolution and coordinate system. The information gathered during the first stages of this work, were compiled with the new input data elicited during the FG session and processed afterwards.

According to the utility values assigned for each criterion and sub-criteria during the FG session, the first step consists in the normalization of data which is a prerequisite for applying weights when generating the priority individual maps, to compare different variables located the different levels of the hierarchy model (Krsnik et al., 2024).

Individual maps according to each criterion were generated, assigning a class of priority for treatment to each raster cell for each burned area. In this case, the values were normalized into a common scale, being 1 the maximum priority and 0 the nonpriority. The tools in ArcMap used to generate individual maps are “Raster Calculator”, “Weighted Sum” and “Reclassify”.

In spatial decision-making, not all criteria are equally important, which is why the FG session was fundamental to determine the weights of importance of each criterion and sub-criteria. The “Weighted Sum” tool allows to assign weights to each criterion based on their relative importance (Eq. 2). In other words, this tool helps to aggregate these criteria, ensuring that more important criteria have a greater influence on the final output. This results in a composite map that integrates all the criteria into an interpretable layer.

After obtaining the raster priority maps for each group, the final priority map was computed by combining the criteria priority maps using the same procedure as before.

$$X(i) = X(ia) * W(ia) + X(ib) * W(ib) + X(ic) * W(ic) + \ldots + X(in) * W(in) \quad \text{(Eq. 2)}$$

Xi = Layer for the criteria group i
X (ia) = Layer of the attribute serving as input for the composition of Xi
W (ia) = Weight if the sub-criteria “a”

$$M(i) = (Xi - low(i)) / up(i) - low(i)$$

M (i) = map for the criteria group I
Xi = Criteria i layer before the normalization
Low(i) and up(i) = Lowers and upper values Xi

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. Using equal intervals ensures that these classes are the same and reflect the underlying data distribution. The 4 categories represent different levels of priority, making it easier to distinguish between areas that require immediate action versus those that are less critical.

Lastly, the geoprocessing to get the final prioritization map required the combination of the criteria priority maps, following the same steps as before.

3. RESULTS AND DISCUSSION

3.1 Identification of burned areas

The source of yearly burned areas was retrieved from the “Instituto da Conservação da Natureza e das Florestas” (ICNF), which is an institution in charge of the management of natural and forestry heritage in Portugal, involving territorial development actors in nature conservation and forest management (ICNF, 2024).

Two different cases for burned areas have been selected in Vale do Sousa, located in north-western Portugal, 50km east of Porto, on both banks of the Douro River. One is a continuous burned area that occurred in 2017, which affected 5,500 hectares approximately, and the second scenario are small and scattered burned areas in 2022 (total area corresponding to 635 hectares approximately) (Figure 5).

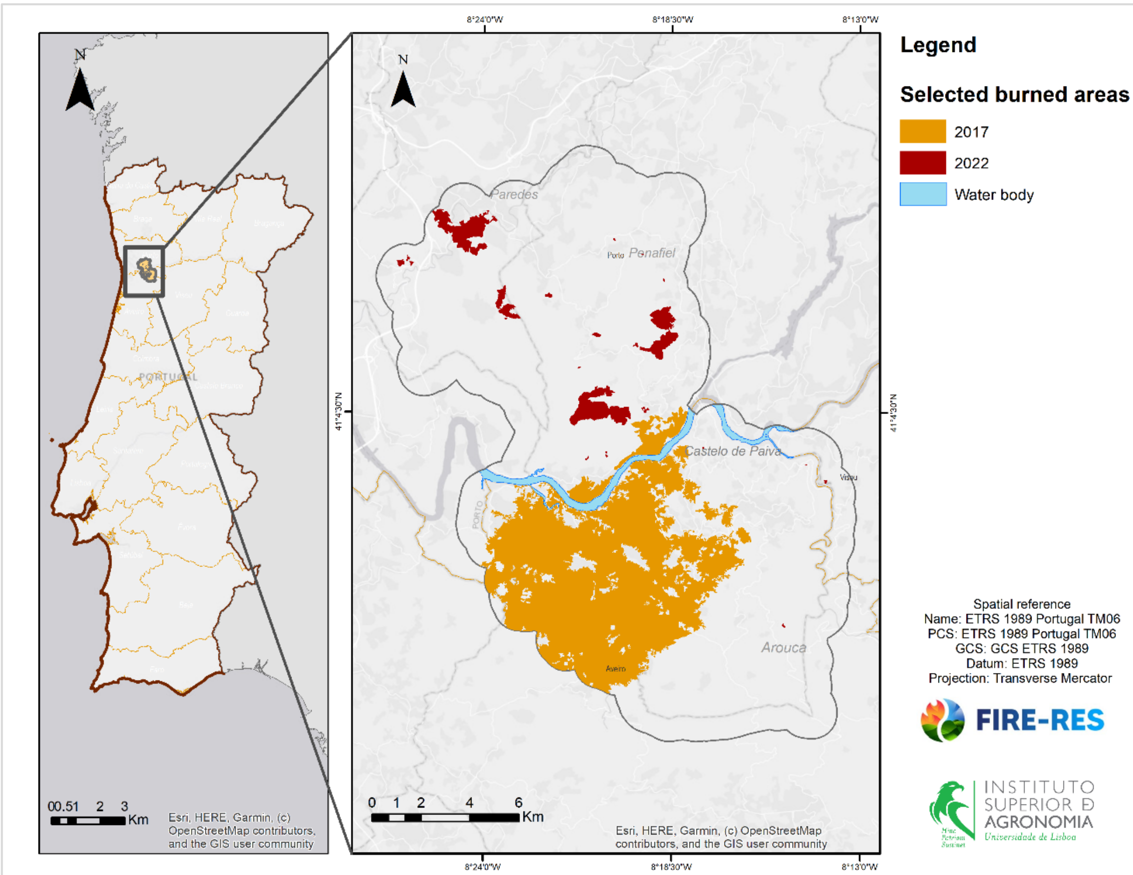

Figure 5. Burned areas for 2017 and 2022. Source: ICNF (2024).

For this study, restoration prioritization based on the forest fire perimeters, allows a targeted allocation of resources to mitigate the ecological degradation. Restoration prioritization may also be influenced whether it was a large-scale fire or small scale, which is why there are two different scenarios to analyze their current state.

3.2 Pre-selection of criteria

The two criteria that were considered relevant to consider that an area is a priority for post-fire restoration are: the erosive potential and the natural recovery capacity of the vegetation. Within these two criteria, a series of sub-criteria and/or indicators have been established for operational work (Table 2) and have been processed using spatial data. The following table presents the main attempt made in this direction.

Table 2. Pre-selection of criteria and sub-criteria.

Criteria	Sub-criteria
Soil erosion	Soil erodibility
	Topographic effect
	Vegetation cover
	Fire severity
Natural recovery capacity of the vegetation	Regrowth potential of species present
	Fire severity

Over the years, scientists have discovered that soil impacts, as opposed to vegetation impacts, are the most crucial indicators of potential post-fire watershed effects and recovery (USAID/USFS, 2022). Erosion rates are influenced by factors such as climate, topography, soil properties, and the amount of surface cover.

Soil erosion is described as the overall long-term equilibrium of sediment detachment and transportation from its initial position, entailing the destruction of soil structure, depletion of nutrients, and reduction in water retention capacity (FAO, 2019). By using the RUSLE (Revised Universal Soil Loss Equation) and its factors, we can estimate which areas represent higher erosion potential (Renard et al., 1997).

A study summarizes how fire influenced by human activity, impacts soil properties both directly and indirectly (Santín & Doerr, 2016). Direct effects occur through heat and combustion processes, while indirect effects arise from alterations in vegetation cover and increased soil redistribution due to accelerated erosion after fires (Santín & Doerr, 2016). For example, heat transfer from burning biomass and necromass above ground, as well as the combustion of organic matter within the soil, results in significant changes to soil properties (Santín & Doerr, 2016)

Furthermore, post-fire soil changes often occur indirectly and gradually, with significant consequences. The loss of protective vegetation and litter, combined with weakened soil structure and increased water repellency in some cases, leads to more rainfall directly impacting the soil surface (Shakesby & Doerr, 2006).

Among the RUSLE factors, it is the soil erodibility (K factor), the topographic effect (LS factor) and the vegetation cover (C factor) that were considered for this assessment.

The soil erodibility factor (Figure 6) was estimated according to Constantino and Coutinho (2001), and the equation includes the soil´s properties, which represents the vulnerability to soil to erosion, transportability of the sediment, and the amount and rate of runoff given a particular rainfall input (USDA, 2001).

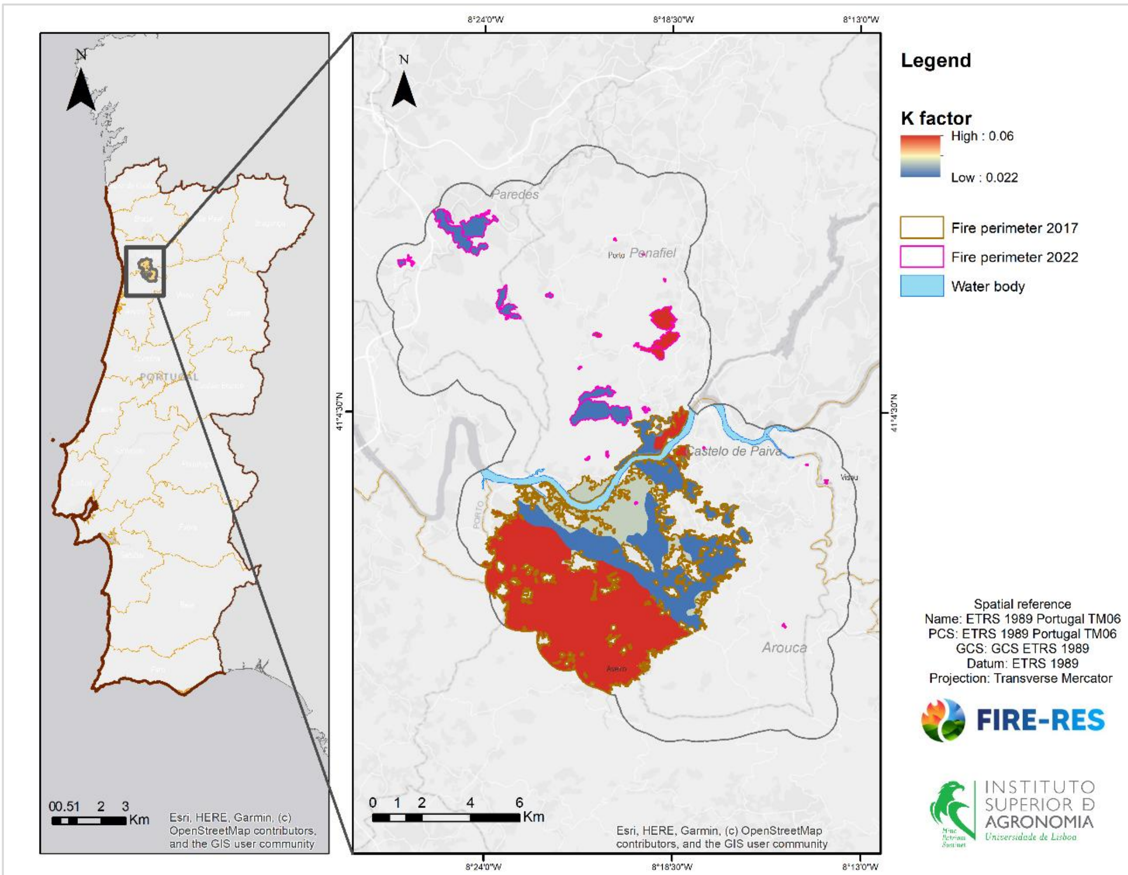

Figure 6. Soil erodibility (K factor) for the burned areas 2017 and 2022. Own elaboration based on cartography provided by the Direção-Geral do Território (DGT).

On the other hand, the effects of the topographic factor on soil loss are represented by the L and S factor, which can be considered as a single topographic factor. Both factors are dimensionless and indicate how the erosion potential of a specific slope compares to a standard reference plot (22.13 meters long, 9% steep) (McCool et al., 1997). Both have been obtained through geoprocessing, following the equations set by Desmet and Govers (1996) and McCool et al. (1997) (Figure 7).

With advances in GIS technology, determining the LS-factor using upslope contributing area or flow accumulation and slope has become popular. The usage of DEMs enable accurate calculation of the LS-factor in topographically complex landscapes (Desmet & Govers, 1996).

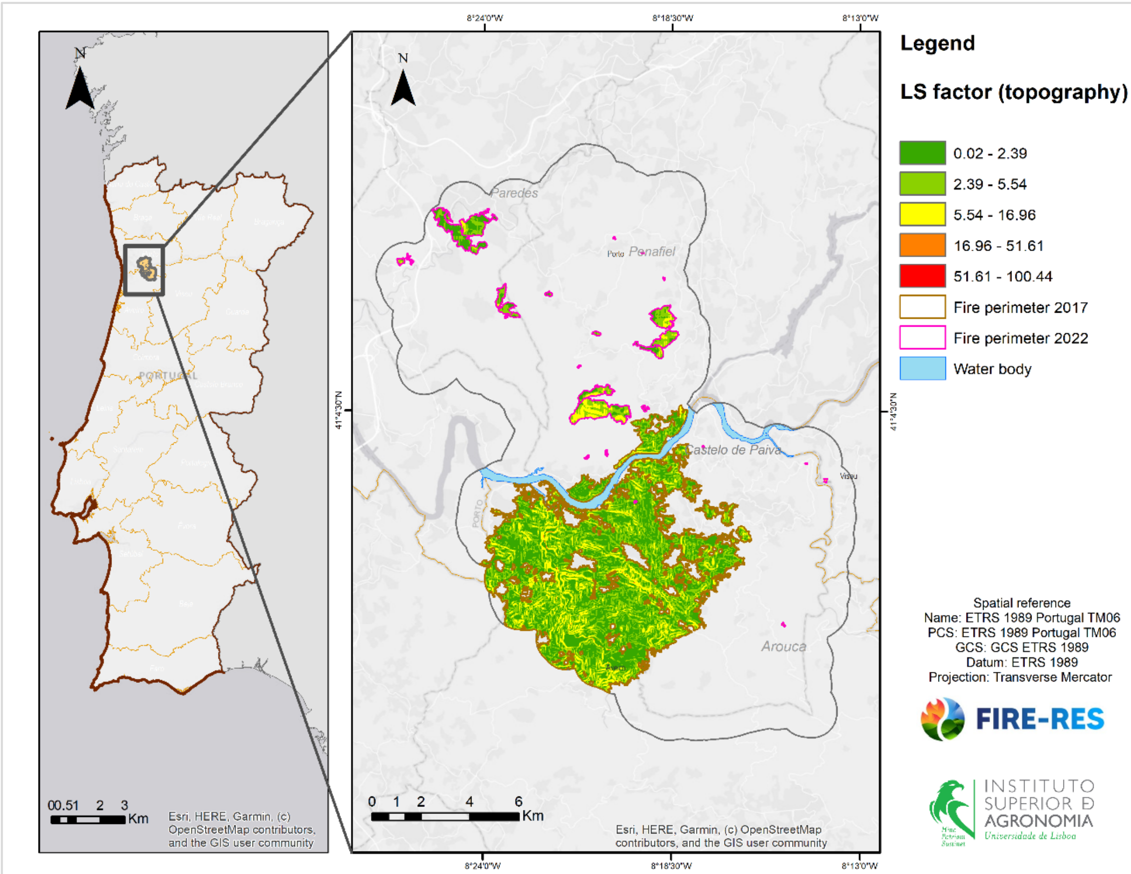

Figure 7. LS factor for the burned areas of 2017 and 2022. Own elaboration.

The cover management (C factor) is included as a function of tree canopy cover density (Annex 1) (Rodrigues et al. 2020), reflecting on 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 8). The implementation of practices in the soil has an impact on the canopy cover, meaning that the cover management values are not static.

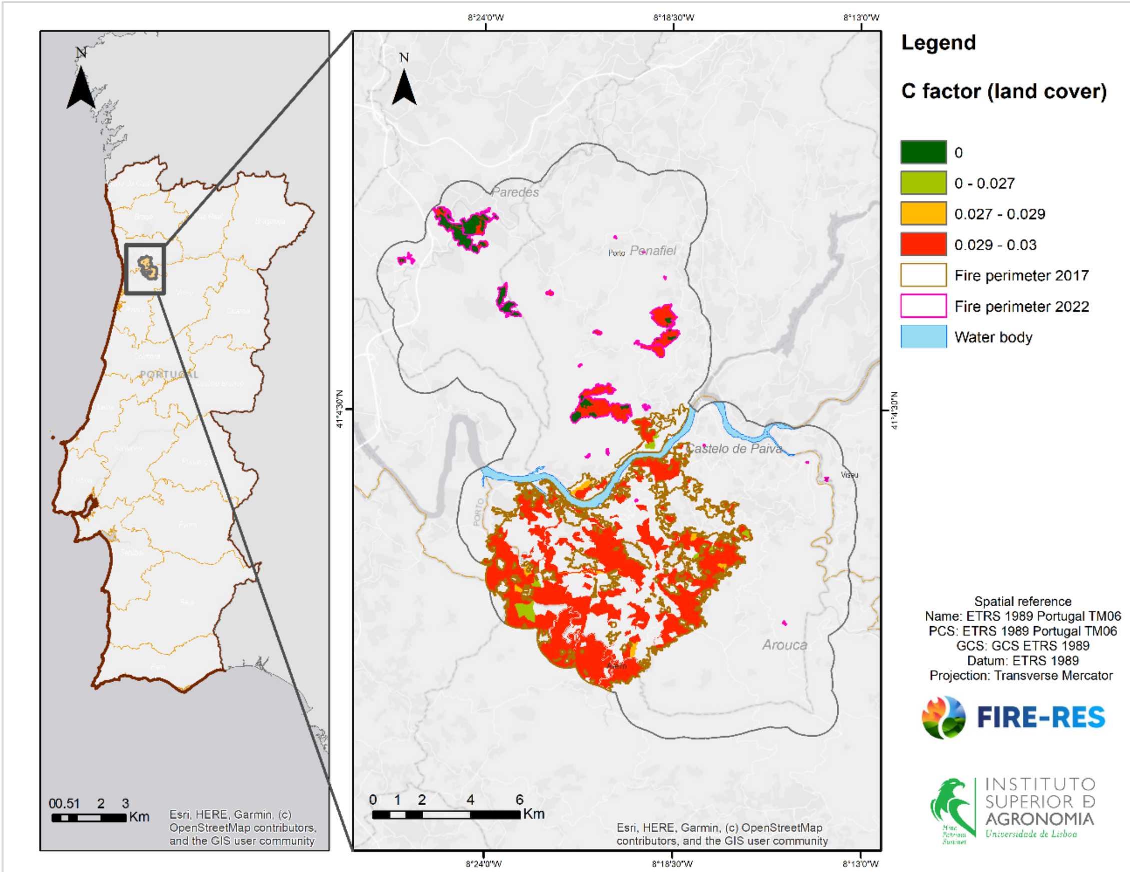

Figure 8. C factor for the burned areas of 2017 and 2022. Source: Rodrigues et al. (2020).

Another sub-criterion considered under soil erosion, is fire severity (Figure 9). Under the context of soil erosion, fire severity impacts soil both above and below the surface. Aboveground, it removes protective vegetation and litter, while belowground, the heat pulse consumes soil organic matter, alters clay structure, and degrades soil texture. These changes reduce porosity and infiltration capacity, exacerbating erosion and runoff.

According to literature, the dNBR (Differenced Normalized Burn Ratio) is an index used to assess fire severity by comparing pre-fire and post-fire satellite imagery. The NBR captures some of these effects indirectly via the amount and type of combustion residues that the fire leaves at the surface. The pre-fire imagery is usually taken several months to a year before the fire event, while the post-fire imagery is typically acquired within a few weeks to a few months after the fire, depending on cloud cover and satellite availability.

The index can generally be applied to any forest type to assess fire severity, but its effectiveness and the interpretation of results can vary based on vegetation characteristics, climate, and topography. The index uses satellite imagery to compare pre-fire and post-fire conditions, so it is capable of detecting changes in vegetation and surface conditions across a broad range of ecosystems.

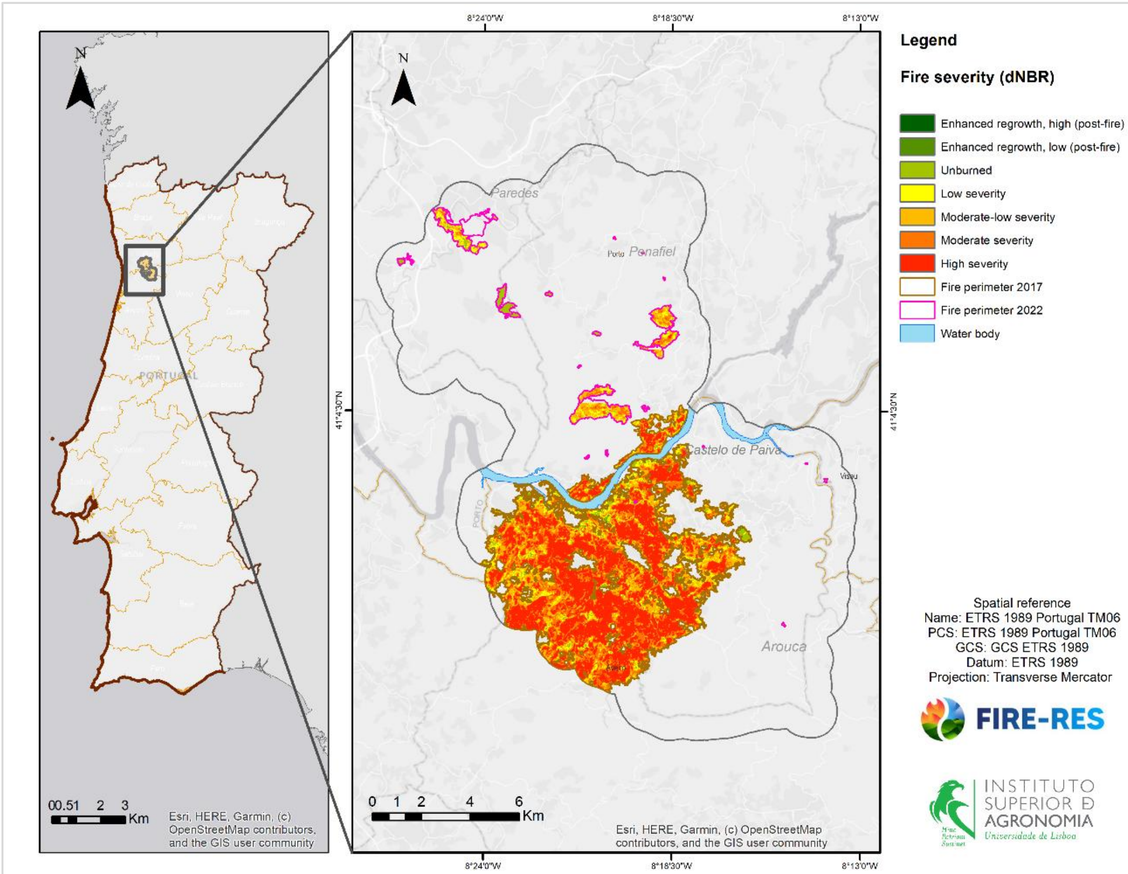

Figure 9. Fire severity (dNBR) for the burned areas. Provided by Pere Joan Gelabert.

The continuous fire of 2017 occurred from the 15th to 19th of October, and the pre fire image was obtained two weeks before. The post fire image was retrieved approximately 15 to 30 days after. For the scattered fires of 2022, the satellite images were taken between two to three weeks before the fire and between 15 to 30 days for the post fire image.

Fire severity data can assist in multiple ways, for instance the development of post-fire emergency rehabilitation and restoration plans. They can be used to estimate not only fire severity on the ground, but also to estimate the probability of future downstream impacts due to flooding, landslides, and soil erosion.

Table 3. 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

The criteria “Natural recovery capacity of the vegetation” is proposed as a key factor in post-fire restoration prioritization due to its impact on ecological resilience, resource allocation, biodiversity conservation, and long-term sustainability. As mentioned previously, Portugal experiences a high incidence of wildfires, which significantly impacts its diverse vegetation types. Vegetation with a high natural recovery capacity can help stabilize soils, reduce erosion, and facilitate the return of native species, which are vital for a long-term health and sustainability of the ecosystem.

The type of species present after a wildfire (Figure 10) is an indicator of resprouting capabilities of a species in an area after a fire occurs. Understanding how fire affects tree species is valuable for making decisions, favouring those that are more fire-resistant in the Mediterranean basin. In the context of post-fire recovery, "resprouting species" are plants that can grow back from their roots or stems after being burned by a fire (Catry et al., 2010).

This means they have a good chance of surviving and recovering even if the above-ground part of the plant is damaged or destroyed. On the other hand, "non-resprouting species" are plants that cannot grow back after a wildfire happens. However, it is important to note that these species may still regenerate via seed germination, leveraging their ability to establish new growth from seeds deposited in the soil or dispersed after a fire event.

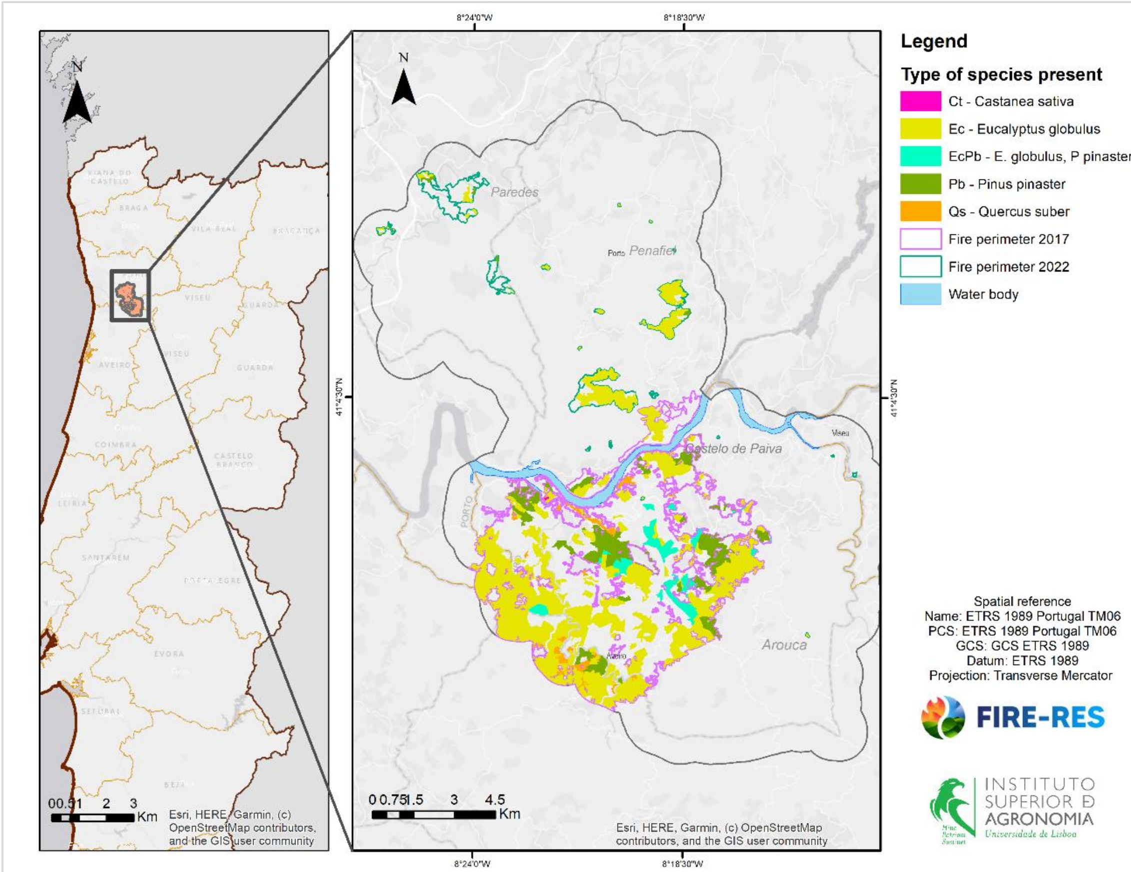

Figure 10. Type of species present in the burned areas of 2017 and 2022. Own elaboration based on the LiDAR flight data collection. Ct stands for *Castanea sativa*, Ec for *Eucalyptus globulus* stands, Pb for *Pinus pinaster*, Qs for *Quercus suber* and Rp for riparian species. Riparian species live along the banks of rivers, streams and other bodies of fresh water.

In summary, the type of species present in the fire perimeters will provide useful information about the resprouting capabilities of each species after a wildfire according to bibliography, and the discussion with participants to determine which species should be more or less important for restoration priorities according to this characteristic.

Fire severity is a transversal criterion because it conditions both a) soil erosion b) natural recovery capacity of the vegetation, which is why fire severity is included here as well, but with a different perspective (Figure 9). Using fire severity for assessing the natural recovery capacity of vegetation, can provide an indication of the extent of damage and potential for regrowth of species. High dNBR values indicate severe damage where vegetation and soil structures are heavily affected, whereas low dNBR values indicate less damage.

3.3 Identification of actors

During this phase, 9 professionals were considered for this project, targeting a group size between 8 to 10. The group comprised primarily researchers at ISA and ForestWise which is a private organization that works closely with ISA. In the end, 8 experts confirmed their participation, though one individual was unable to attend the FG session.

3.4 Elicitation of criteria and sub-criteria, and their corresponding metrics (FG)

This step was conducted during the FG session held on the 18th of July 2024 at the Forestry Building from ISA. The small size of the group and the pre-existing affinity among participants fostered an environment conducive to open discussion.

As mentioned previously, this step is divided in two sections. The first section consisted in the presentation of pre-selected criteria and sub-criteria in separated slides, including the sources of information. The informative document was printed out and provided to them as well. During this first part, the participants were well informed of the context of this study, and the importance of engaging with local stakeholders. As an outcome, the participants shared the importance of how to improve the display of each map so that the information can be more intuitive when interacting with stakeholders.

Despite this work focused on prioritizing areas that are ecologically critical to restore, as an outcome from the group discussion, the criteria of Proximity to Social Areas (Figure 11) was identified as crucial for prioritization of restoration after wildfires. This point of view displays that during a heterogeneous group there are other factors that are bounded to be considered, especially due to the local conditions (social, economical, among others). In summary, considering the proximity to social areas in decision-making aligns with the fundamental principles of public safety and risk mitigation.

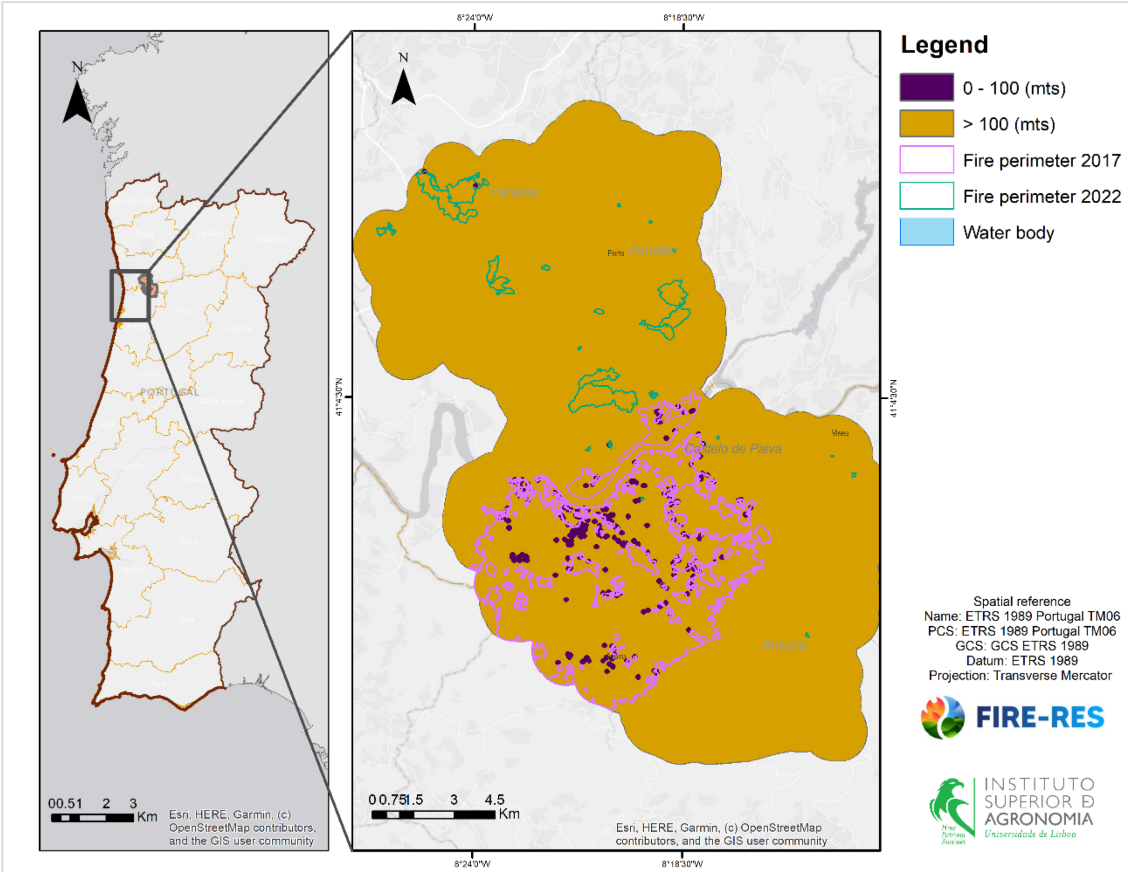

Figure 11. Criteria of “Proximity to Social Areas” within the burned areas for 2017 and 2022.

Regarding the criteria “Natural Recovery Capacity of the Vegetation”, it was suggested during the session to reformulate the sub-criteria “Type of species present” because it was important to consider the resprouting capabilities of each species, compared with the level of severity. The table below shows the final elicitation of criteria and sub-criteria.

Table 4. Elected criteria and sub-criteria, their attributed codes and units.

Criteria	Sub-criteria	Code	Units
Soil erosion	Soil erodibility (K factor)	S1	$Mg \cdot ha^{-1} MJ \cdot mm^{-1}$
	Topographic effect (LS factor)	S2	Dimensionless
	Vegetation cover (C factor)	S3	Dimensionless
	Fire severity	S4	Dimensionless
Natural recovery capacity of the vegetation	Regrowth potential	N1	%
	Fire severity	N2	Dimensionless
Proximity to social areas	Non applicable	P1	Mts

The sub-criteria defined are divided into broader groups, except for “Proximity to social areas”, which is an accepted and valid criterion to add to this work. In total there are 7 measurable sub-criteria, adaptable to a GIS environment, of which S1, S2, S3 and S4 correspond to the criteria of Soil erosion, and N1 and N2 correspond to the criteria of Natural recovery capacity of the vegetation.

In the case of the criteria of “Proximity to social areas”, without sub-criteria, the broader criteria will be evaluated directly against the other two main criteria in the AHP method. Even though having sub-criteria allow for a more detailed breakdown, during the FG session there were no other information that was considered important to include under this criterion. However, it is possible to consider this aspect for future applications of the methodology.

For the second part of the FG, the definition of utility values for the criteria and sub-criteria was a crucial step in the research process, aimed to design collaboratively the threshold that discern low or high utility for each criterion and sub-criterion. During the interaction with experts, a yes/no approach was described to categorize the data in two broad classes (high priority and low priority), reflecting a binary perspective in decision-making. These dichotomous decisions are then converted into a continuous scale (0–1) for prioritization purposes, aligning with the requirements of a hierarchical model and weighted overlay processes.

Table 5. Established threshold values for assigning utility functions.

Criteria	Sub-criteria (code)	Minimum and maximum range values	Utility values
Soil erosion	Soil erodibility (K factor)	0.022 to 0.6	0 = 0 to 0.022 1 = 0.022 >
	Topographic effect (LS factor)	0.02 to 100.44	0 = 0.02 to 49 1 = 50 >
	Vegetation cover (C factor)	0 to 0.029	0 = 0 to 0.026 1 = 0.027 - 0.029
	Fire severity	-365 to 1,559	0= -365 to +270 1= > +270
Natural recovery capacity of the vegetation	Regrowth potential	0 to 100	0 = 50 to 100 1 = 0 to 50
	Fire severity	-365 to 1,559	0= -365 to +270 1= >= 270
Proximity to social areas	Non applicable	0 to 9,027	0 = 101 to 9,027 1 = 0 to 100

Note: The utility value 0 correspond to the lowest priority, and utility value 1 corresponds to the highest priority values for restoration.

Lastly during the FG session, it was important to determine collectively, which of the species present in the study area were more capable to resprout or not due to their specific characteristics and presence in the study area. The pairwise comparison approach was used to rank the species (mixed and pure) according to their resprouting capabilities (Table 6).

In the context of analyzing the resprouting capacity of various species in comparation with the fire severity values, the group decided to exclude riparian species in the analysis, meaning those that grow along the edges of bodies of water such as rivers, lakes, and streams. Essentially, riparian species have lower exposure to fire compared to species that grow in drier areas. The high soil moisture and proximity to water create microenvironments that significantly reduce the likelihood of fires in these zones.

Table 6. Rank of species according to their resprouting capabilities.

Species	*Castanea sativa*	*Eucalyptus sp.*	*Eucaliptus sp, Pinus pinea*	*Pinus pinea*	*Quercus suber*	Total
Castanea sativa		0	0	1	0	1
Eucalyptus sp.	1		1	1	1	4
Eucalyptus sp, Pinus pinea	1	0		1	0	2
Pinus pinea	0	0	0		0	0
Quercus suber	1	0	0	1		2

After the FG session, this sub-criterion was adjusted to "Regrowth potential (%)" (Annex 6), considering an approximate value of resprouting according to literature. In this case, the utility values indicate a higher prioritization of species that present difficulties to resprout such as pines, cork oak and chestnut due to their vulnerable conditions and competition with exotic species. On the other hand, the lowest priority was assigned to the eucalyptus stands, because this species has strong resprouting capabilities regardless of the severity of the fire.

This was an interesting approach step to discuss why some species should be prioritized more than others regarding the objective of the study, and the scope of FIRE-RES project, which is to turn a degraded landscape into a resilient landscape.

3.5 Identification of weights for the criteria and sub-criteria

The weights designate the relative importance of each criterion for the allocation of the areas have a higher priority to be restored, and areas that are less critical to focus on. Regarding the results, 8 experts responded to the online survey, being one of them an expert that did not attend the FG meeting but was involved in this thesis work since the beginning.

The Consistency Ratio (CR) was calculated for each participant to observe any outliers, and if needed remove the participants to proceed with the calculation of weights for each criterion and sub-criteria (Table 7). For the criteria Natural Recovery Capacity of the Vegetation, the CR was 0 for all participants, because only 2 sub-criteria have been compared for that group.

Consistency checks, such as the CR, are essential when multiple comparisons are involved, which is why the CR was not calculated for NRCV since only two sub-criteria are being compared. However, this does not have to affect the reliability of our weights, if the outliers have been detected, as is the case.

Table 7. CR per participant weighting exercises and aggregation of them.

	Participant´s Consistency Ratio (CR)							
	1	2	3	4	5	6	7	8
Main criteria	0.32	0.38	0.42	0.34	0.11	0.20	0.24	0.28
Soil erosion	0.40	0.40	0.07	0.01	0.46	0.57	0.14	0.23
Average	0.36	0.39	0.25	0.17	0.28	0.39	0.19	0.26

Note: main criteria correspond to soil erosion, natural recovery capacity of the vegetation and proximity to social areas.

According to Rao (2007), a CR exceeding 0.1 indicates inconsistency in the weighting responses, suggesting that the answers may contain contradictions in the pairwise comparisons. For this study, outliers were not found as they presented similar values between each other. However, they were above the suggested value of 0.1 for consistent values. If the criteria being compared are closely related or perceived as equally important, it can inherently lead to inconsistencies.

The general similarity in responses across participants suggests that the inconsistencies may stem from the reasons outlined above rather than a fundamental flaw in the weighting process. The 8 participants were included in the next stages since they presented similar CR values, and no outliers were found (Table 7).

According to the criteria´s main group weights, proximity to social areas is the most important criteria with 44%, next soil erosion with 32% and lastly the criteria Natural Recovery Capacity of the Vegetation (NRCV) with 24% (Figure 11). This analysis, implies that for the criteria of social areas will dominate the final prioritization map, corresponding to infrastructure and communities located in Vale do Sousa.

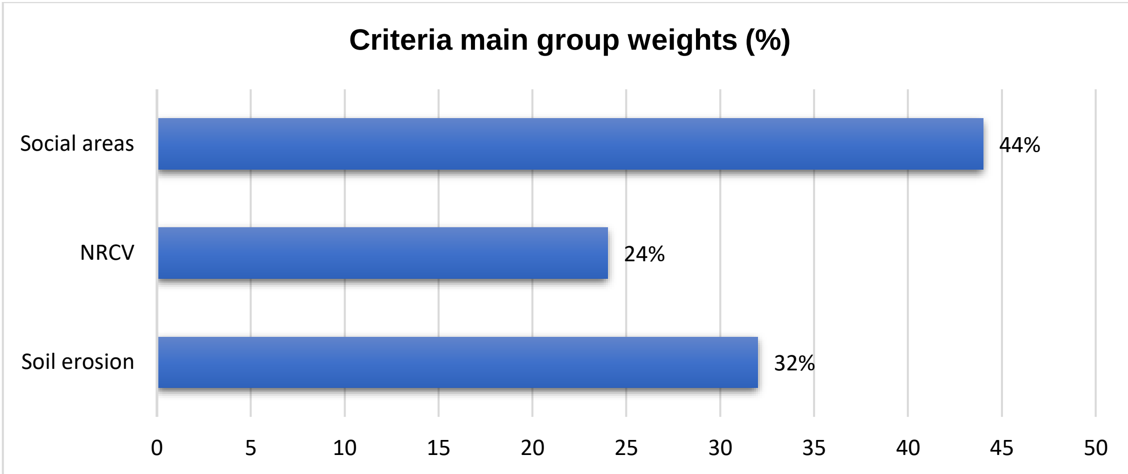

Figure 12. Weights distribution among the 3 criteria groups. Note: NRCV stands for "Natural recovery capacity of the vegetation"

Soil erosion is the next most critical criteria. Areas that are prone to soil erosion will be considered very important, but their influence on the final map will be less than proximity to social areas. However, they will still significantly impact where prioritization occurs, specially for areas that present higher topographic values, and low canopy cover values in the burned areas.

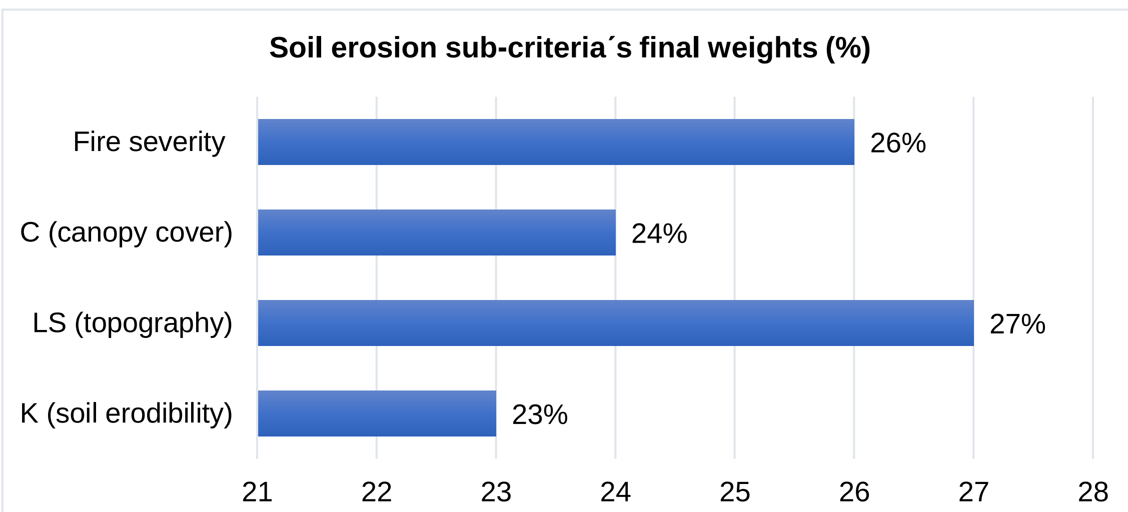

Figure 13. Soil erosion sub-criteria final weights.

Next, for the criteria of NRCV with the lowest weight, will have the least influence on the map (Figure 13). It reflects the ability of an area to naturally recover from a wildfire. While still important, the lower weight means it will modify the prioritization map less than the other criteria.

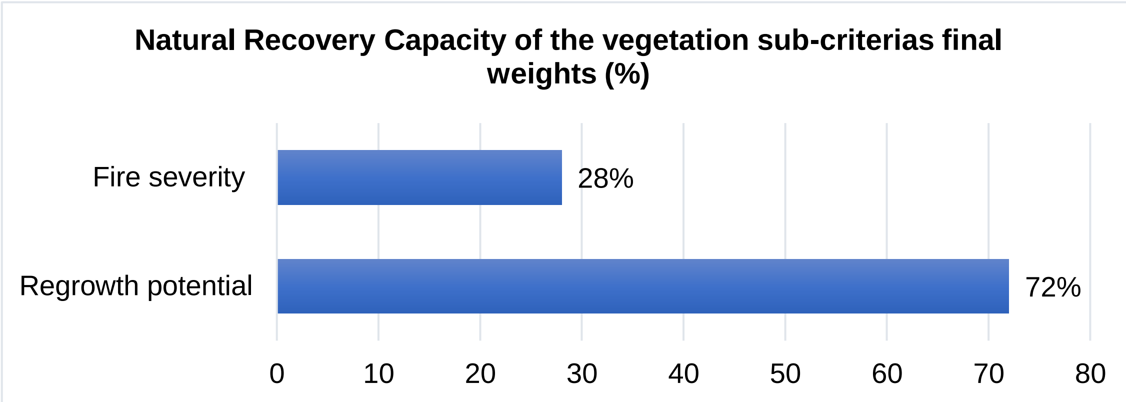

Figure 14. Natural Recovery Capacity of the Vegetation sub-criteria final weights.

3.6 Generation of priority maps per criteria

The maps for each criteria group were generated by combining the relevant spatial data layers available information for each sub-criterion and applying the appropriate weights to them. Four classes of priority for management were assigned with equal intervals, enabling a clear comparison across different areas. The resulting maps provide a visual representation of these priorities, as shown in the following figures (Figure 14 and Figure 15).

The soil erosion map highlights the areas most vulnerable to erosion by integrating several sub-criteria, with the topographic factor and the fire severity emerging as the most influential in determining priority zones. High severity fires are especially problematic as the can strip the land if its vegetation cover, leaving the soil bare and vulnerable. Therefore, areas that have experienced medium and high-severity fires are identified as top priorities on the erosion map, necessitating immediate attention for erosion control measures.

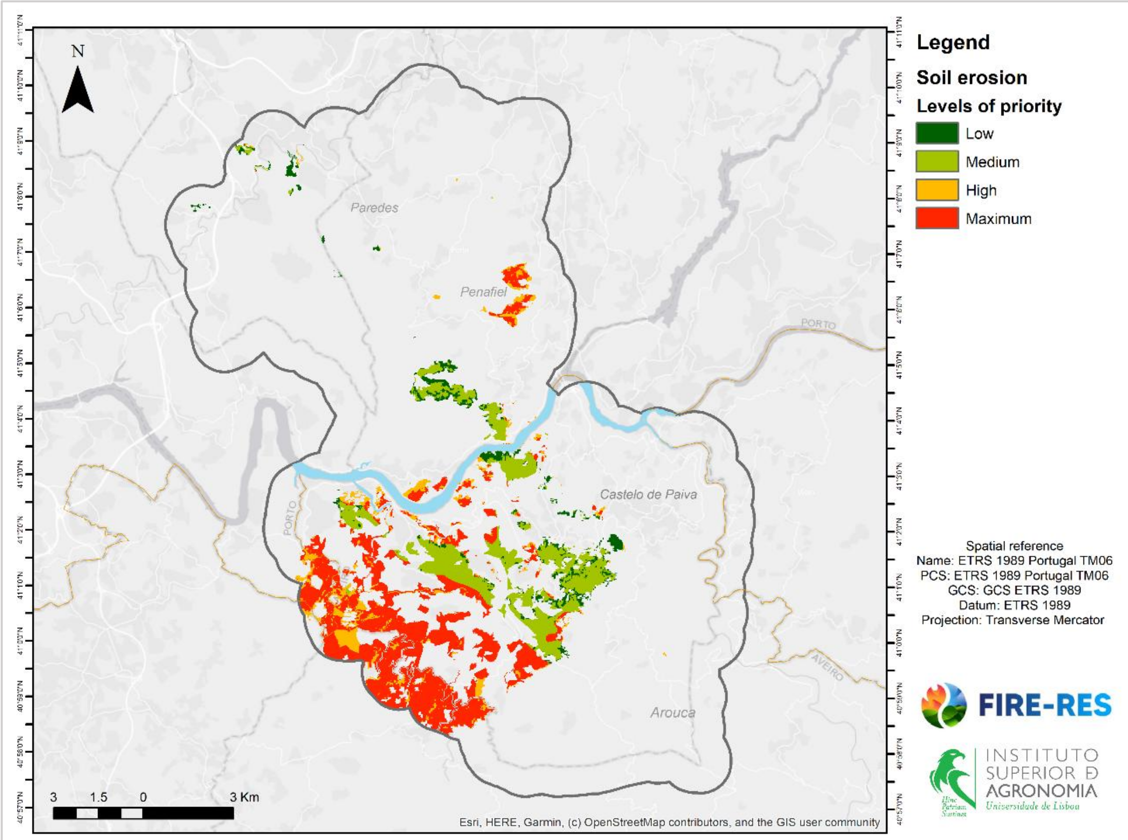

Figure 15. Map of the criterion Soil Erosion.

Continuing with the analysis, the maximum priority management areas based on soil erosion risk are those that combine multiple risk factors: high fire severity, exposure to direct sunlight, and steep slopes. Steep slopes accelerate water runoff, which can quickly carry away unprotected soil, while exposure to sunlight, particularly in areas with minimal vegetation cover, dries out the soil, making it even more prone to erosion. The situation is exacerbated in regions with anthropogenic soils—soils that have been significantly altered by human activity. These soils are often more fragile and less resilient than natural soils, making them more vulnerable to erosion, particularly after a disturbance like a wildfire.

For the following criterion (NRCV), it plays a crucial role in ecosystem management after a wildfire. Vegetation with a high natural recovery capacity is essential for stabilizing soils, reducing soil erosion and supporting the return of native or nonnative species. Within this criterion, two sub-criteria were identified: the regrowth potential and the severity of the wildfire.

The weight of importance was allocated with greater emphasis on the regrowth potential, given its direct influence on the ecosystem's resilience. Fire severity was also considered, but with a lower weight, recognizing its role in impacting recovery potential.

The resulting map highlights areas where natural recovery is expected to be more important, guiding management efforts to prioritize regions that can benefit from minimal intervention, as well as areas where past fire damage has significantly influenced recovery prospects.

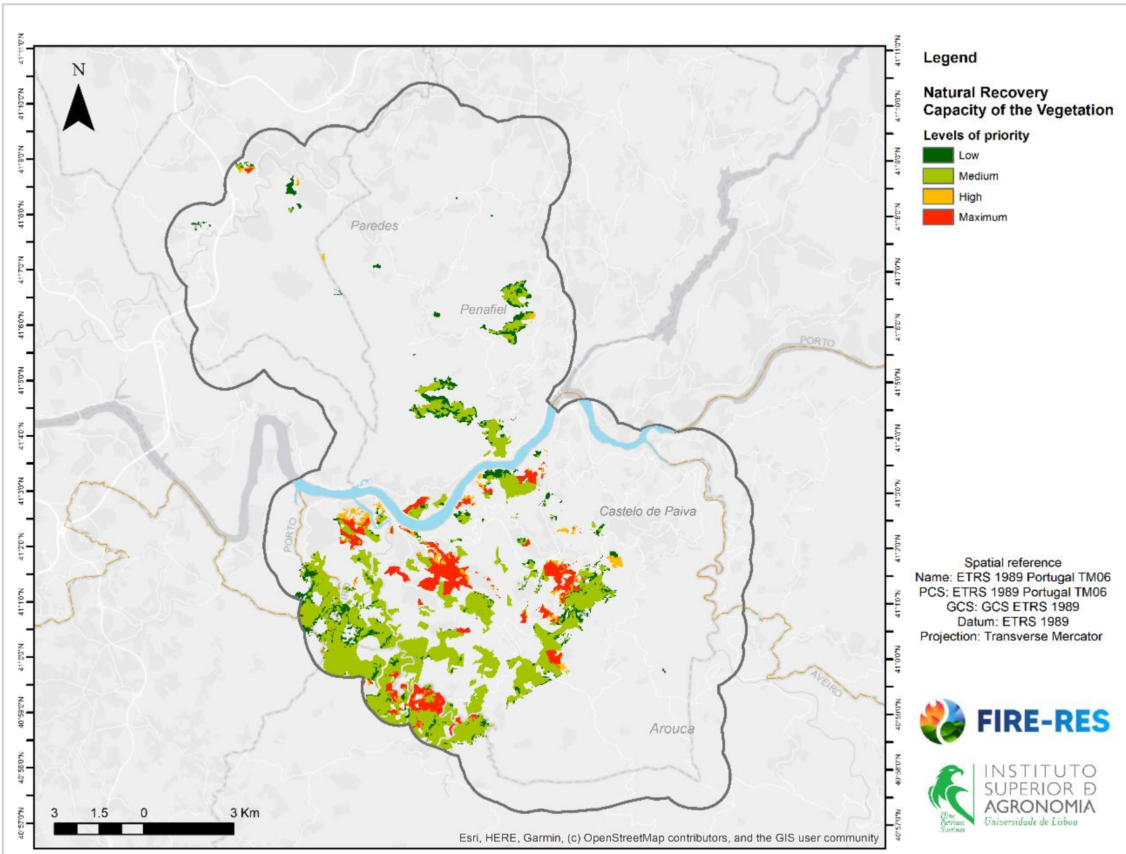

Figure 16. Map of the criterion Natural Recovery Capacity of the Vegetation (NRCV).

3.7 Final prioritization map

The final map was developed by synthesizing three key criteria: a) soil erosion, b) natural recovery capacity of the vegetation, and c) proximity to social areas (Figure 16). The highest weight corresponds to social areas, meaning this is the most critical factor for prioritization management, due to the importance of safeguarding human lives and settlements.

Next in importance is the criterion of Soil Erosion, which was also given substantial weight due to its significant implications for environmental stability and long-term land use. Therefore, the map prioritizes regions with high erosion risk values, especially those that coincide with social areas, to mitigate the potential for severe environmental and socio-economic consequences

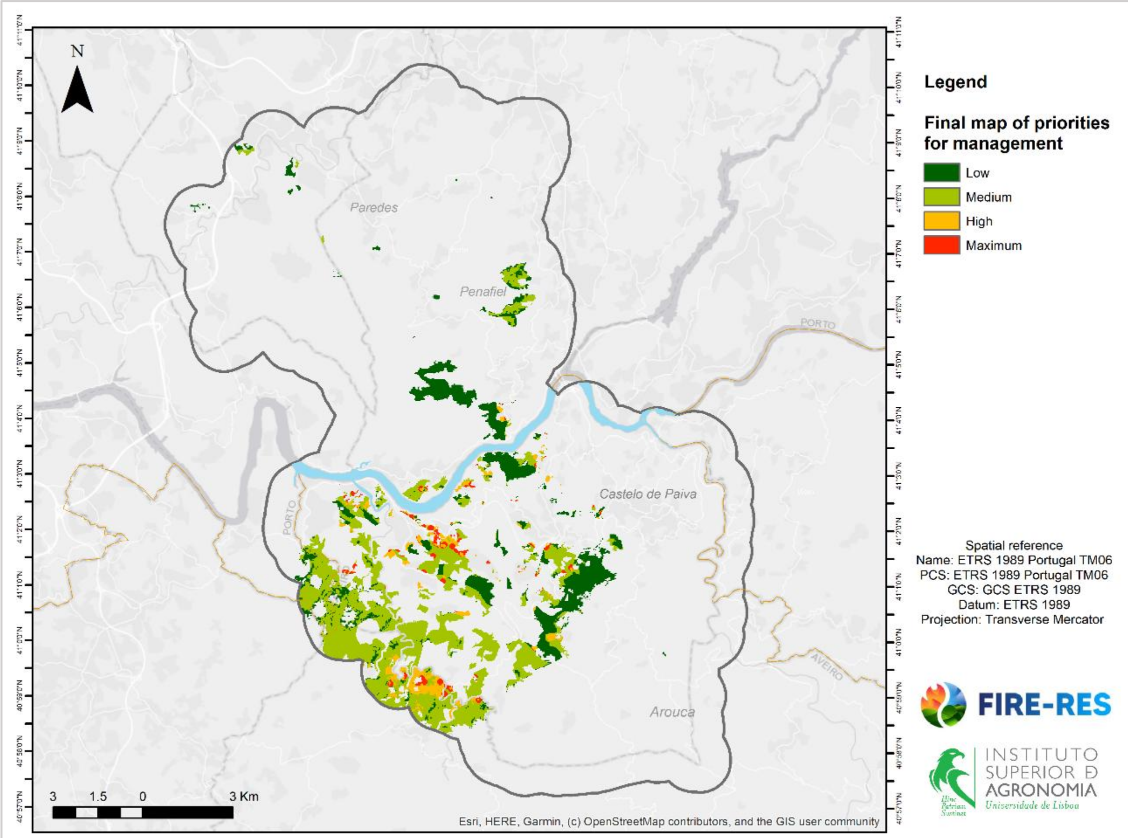

Figure 17. Final map of priorities for management

This map demonstrates maximum priority zones, where proximity to social areas overlap with significant erosion risks, indicating locations where human settlements are also affected by environmental degradation. These areas are critical for restoration management actions, such as erosion control measures, infrastructure reinforcement and community preparedness.

The division of priority classes in the final prioritization map was derived directly from the combination of weights assigned to each criterion and the normalization of the spatial data layers. These weights were informed by responses from the focus group, where participants ranked the importance of social areas, soil erosion, and natural recovery capacity of vegetation. The resulting prioritization reflects the interplay of these inputs, creating a map that visually represents areas of high and low priority based on the assigned criterion.

For the case of low priority areas, these are likely those where the natural recovery capacity is high, and there is minimal risk to proximity social areas or significant erosion. These regions can be managed with a more hands-off approach, allowing natural processed to maintain or restore ecological balance over time.

Table 8. Area of the priority levels of restoration according to each council present (ha).

Administrative units	Low	Medium	High	Very high	Total
Arouca	26.98	483.03	92.34	9.39	611.74
Castelo de Paiva	567.20	1,025.77	98.66	52.18	1,743.81
Gondomar	35.04	145.63	0.00	0.00	180.67
Paredes	23.03	8.41	0.09	0.18	31.71
Penafiel	250.08	115.06	7.07	3.16	375.37
Santa Maria da Feira	6.26	8.62	0.00	0.00	14.88
Total	908.58	1,786.52	198.17	64.91	2,958.18

Table 8 presents a breakdown of the areas designated for restoration across five administrative units (councils), in term of priority levels: low, medium, high, very high. The total area designated as low priority is 908.58 ha, which constitutes a significant portion of the overall area. This indicates that these areas may have less immediate ecological concern or may be more resilience, possibly due to better vegetation cover or lower fire severity.

The medium priority corresponds to 1,786.52 ha, highlighting many areas that require attention but do not necessarily face the most severe ecological threats. For the high priority, it corresponds a total of 198.17 and this information suggests urgent restoration actions due to significant ecological degradation.

The very high priority areas correspond to 64.91 ha, which are the most critical, indicating zones that may be severely impacted and require immediate intervention to restore ecological function, due to the combination of the three main criteria, especially the proximity to social areas.

3.7 Continuous large fire of 2017: spatial and ecological dynamics

The 2017 fire, covering approximately 8,000 hectares in Vale do Sousa, was characterized by high severity and continuous spread across the landscape, significantly altering the region's ecology and vegetation structure. The selected continuous burned patch area for this study (approximately 5,000 hectares), there were different land use types, such as agriculture, building areas, eucalyptus globulus stands, maritime pine, non riparian and shrubland.

Eucalyptus globulus is the most dominant forest type across the entire burned area (Annex 8), especially in Castelo de Paiva, where it covers 3862.18 ha (67.21% of the total area). Smaller areas of Eucalyptus are present in Arouca (195.74 ha, 3.41%) and Penafiel (167.35 ha, 2.91%). Maritime pine is present in all councils, but its highest concentration is in Castelo de Paiva, with 445.84 ha (7.76%). Other councils such as Arouca (102.93 ha, 1.79%) and Gondomar (21.27 ha, 0.37%) also have smaller areas of maritime pine. Non-riparian areas are also distributed across councils, with the largest amounts found in Arouca (173.48 ha, 3.02%) and Penafiel (80.71 ha, 1.40%). Smaller areas are found in Castelo de Paiva (178.93 ha, 3.11%) and Gondomar (1.98 ha, 0.03%).

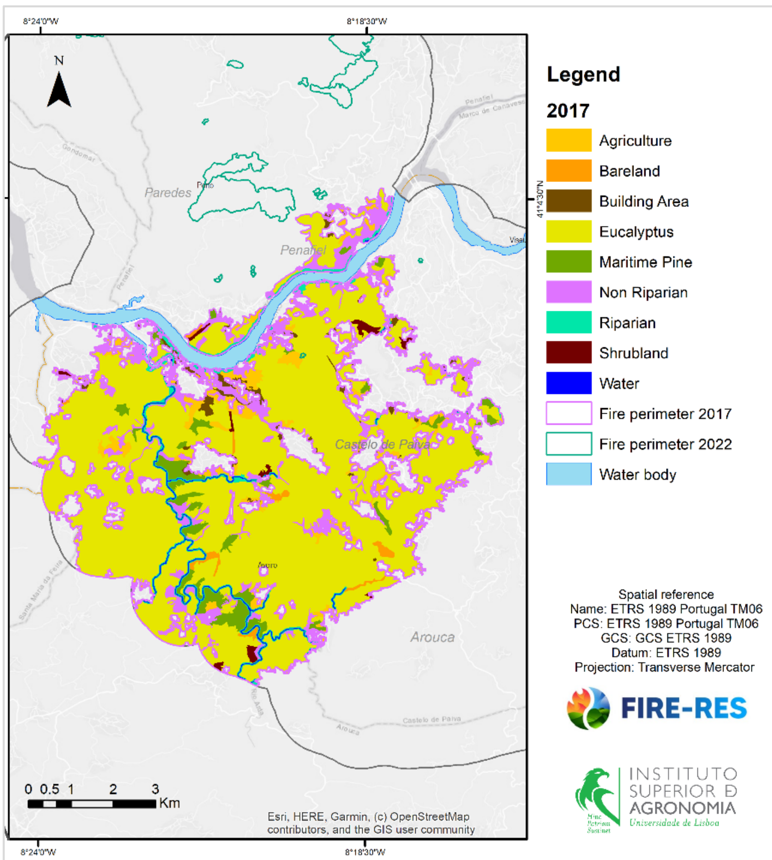

Figure 18. Burned land use areas in 2017. Source: FireRES project, 2024.

Eucalyptus globulus and maritime pine are species known for their flammability, particularly Eucalyptus globulus, which creates conditions for fast-spreading, high-severity fires due to the species' ability to ignite easily and spread flames through the canopy and litter layer (Moreira et al, 2010).

The scenario of 2017 recorded the highest levels of fire severity in the region, with significant damage to the soil and vegetation (Lucas-Borja et al., 2022). High-severity fires tend to kill most of the vegetation in their path, including tree canopies, and disrupt the seedbank, leading to long-term ecological degradation if not managed properly (Lucas-Borja et al., 2022). It is implied that the significant ecological damage might require intensive interventions, in this case for erosion control in heavily burned and sloped areas, soil stabilization where organic material has been lost and reforestation with native species to prevent invasive species from dominating.

In the case of large-scale fires, it is important to evaluate if the native vegetation and ecological balance have been heavily impacted, which might suggest active restoration to reintroduce native species and prevent the dominance of fast-resprouting exotics. For this study, the highest priority areas are a combination of proximity to social areas and high soil erosion, which suggests that restoration interventions are the highest priority where human settlements overlap with significant erosion risks. Given the scale and intensity of the fire in 2017, restoration efforts are suggested to focus on soil stabilization and erosion control in the short term. In the longer term, reforestation with native species is critical to restoring ecosystem functionality.

According to literature, the devastating fires of 2017 were fueled by a combination of extreme weather conditions (Novo et al., 2022), including prolonged drought and severe winds associated with mesoscale weather systems. While meteorology was clearly a key factor, the precise ways in which these conditions interacted with fire fronts remain a topic of further study (Novo et al., 2022). Understanding these dynamics is essential for improving fire management and response strategies, particularly in the face of increasingly frequent extreme weather events due to climate change.

3.8 Scattered fires in 2022: spatial and ecological dynamics

The 2022 fire scenario involved smaller, scattered fires across four councils (Annex 8). By examining the extent of burned areas, there were different land use types, including agriculture, eucalyptus stands, shrubland, and non-riparian areas. Regarding the forest land use type, eucalyptus stands, and non riparian species were burned in each council, except Cinfães where only agriculture areas were burned for 2022.

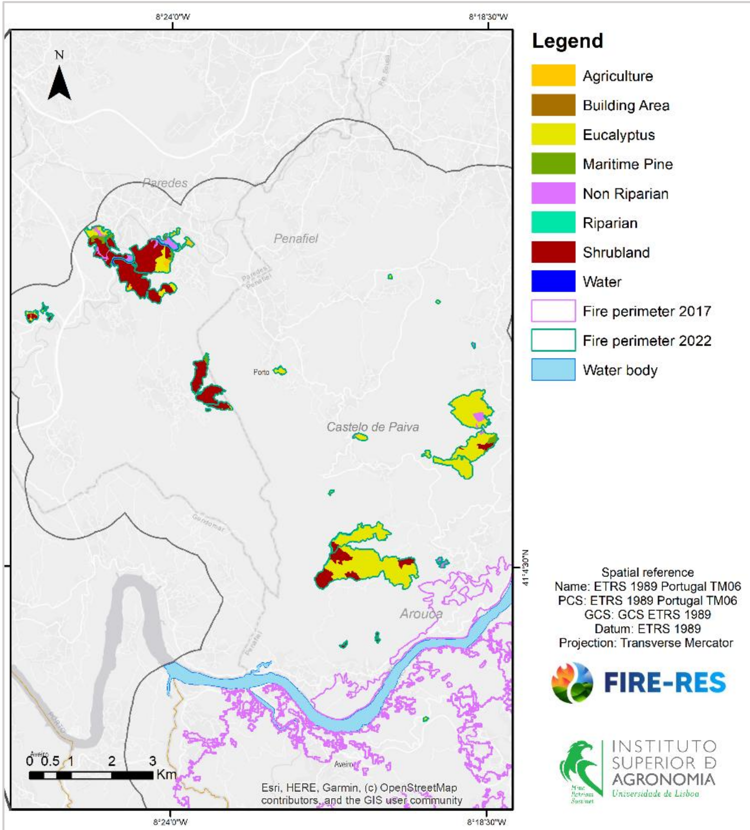

Figure 19. Burned land use areas in 2022. Source: FireRES project, 2024.

Penafiel showed the highest burned areas, with a total of 351.26 hectares burned, representing 55.25% of the total area studied. The dominant land cover burned in Penafiel was building areas, which accounts for 63.67% of the burned area in this council, then agriculture (6.92%) and then eucalyptus stands (5.07%). In the case of the council of Paredes, building areas presented the highest percentage of burned areas (33.44%), next shrublands (8.25%) and lastly eucalyptus stands (2.32%).

The burned areas in 2022, which were mainly near building zones and scattered, can be linked to several factors. Fires near building areas are often a result of human activity, either through negligence or accidental causes (Parente et al., 2018). The presence of more human activity in these areas naturally increases the risk of fire ignition. Additionally, building areas typically receive faster fire suppression responses to protect property and lives, which helps contain fires before they grow large. The combination of rapid firefighting efforts and fragmented land use likely contributed to the scattered pattern and lower severity of fires in 2022.

4. CONCLUSIONS AND RECOMMENDATIONS

A comprehensive set of criteria and sub-criteria were proposed to accomplish the study's goal of defining priority areas for restoration within the perimeter of selected burned areas, so that in later stages, local stakeholders can make use of this information to locate resources in those areas that present lower recovery potential and/or greater vulnerability to erosive phenomena.

While the dNBR index is applicable to different forest types, its thresholds (used to define burn severity levels) may need to be adapted or refined for specific types of vegetation. For example, fire-adapted species may exhibit more rapid recovery, whereas slow-growing species (such as in temperate or boreal forests) may show slower recovery post-fire, influencing how burn severity is assessed.

Fire severity is a transversal criterion because it conditions both soil erosion and natural recovery capacity of the vegetation. In other words, using the information provided from fire severity satellite images can be considered differently depending on the criterion being evaluated. For example, when assessing soil erosion, high fire severity indicates a greater risk of erosion due to the loss of vegetation cover, and on the other hand, when evaluating the natural recovery capacity of the vegetation, high fire severity suggests slower or more challenging recovery. In both cases, high dNBR values indicate severe damage where vegetation and soil structures are heavily affected, whereas low dNBR values indicate less damage.

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, and prioritizing the enhancement of native resprouts, this work can support the long-term recovery of plant communities. It is encouraged to work directly with each of the councils present in Vale do Sousa.

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. It is implied that this slower recovery underscores the need for focused restoration efforts on native flora, as they play a critical role in maintaining the ecological integrity of these areas. Areas with reduced canopy cover attracted the most attention as well, as the combination of low canopy cover and high fire severity further exacerbates the risk of soil erosion and limits the availability of seed sources for natural regeneration.

While the CR values were above the 0.1 threshold, the general similarity in responses across participants suggests that the inconsistencies may stem from the small sample size, or participants might have found it challenging to make consistent pairwise comparisons, rather than a fundamental flaw in the weighting process. It is recommended to refine the sample size or improve the survey clarity to minimize inconsistencies. In future applications, alternative methods such as the Weighted Product Method (WPM), hierarchical aggregation, or other non-compensatory approaches will be considered to address the challenges associated with perfect compensation.

The participatory nature of the approach ensured that the criteria addressed both ecological concerns, reflecting the shared priorities of stakeholders. However, during the interaction, the criterion of social areas was considered important as well. For future applications of this work, is it important to emphasize the goal of the work, and the criterion of social areas would be relevant only insofar as it helps prioritize areas where intervention is critical to mitigating risks to human lives and infrastructure.

During the process of developing the final restoration priority map, various ecological and social layers were integrated, each weighted according to its relevance to restoration objectives. However, the inclusion of the canopy cover layer led to the partial loss of spatial information in certain areas, that contained information about other land cover types that were not forest related. While this limitation reduced the total coverage of burned areas, the overall framework still provides valuable insights into restoration priorities.

Community members should be encouraged to participate in monitoring efforts and share observations about post-fire regeneration. This local knowledge can help improve understanding of resprouting behaviors and inform future restoration strategies. Furthermore, it is recommended to raise awareness among community members in Portugal about the complexities and uncertainties surrounding the resprouting capabilities of native trees after fire events, as it is crucial to have a common understanding of the ability of native trees to regenerate through resprouting after a fire.

It is encouraged to implement a long-term monitoring project in fire-affected areas to fill the existing knowledge gaps, to track vegetation changes over time, and provide valuable data for future restoration efforts. For Portugal, there is reliable information available on the short-term development of vegetation, including species that can regenerate vegetatively and those that cannot, as well as species that do and do not rely on fire-stimulated recruitment (Moreira et al., 2010).

It is recommended to conduct a comprehensive assessment of soil conditions and burn severity in the Vale do Sousa region, prioritizing areas with high to moderate fire severity areas. Particular attention should be given to drainage zones located upstream of critical infrastructure, such as villages, to mitigate potential post-fire erosion and flooding risks.

For future references in restoration actions and indicators to determine vulnerable or critical areas to restore, it is highly recommended to revise the Municipal Plan of Defense of Forest Against Fires" for each affected area. The main objective of this actions plans, is to produce a working tool, at the municipality level, that allows the implementation of provisions and which serves as an instrument for all entities that are part of the Forest Fire Defense System (DFCI).

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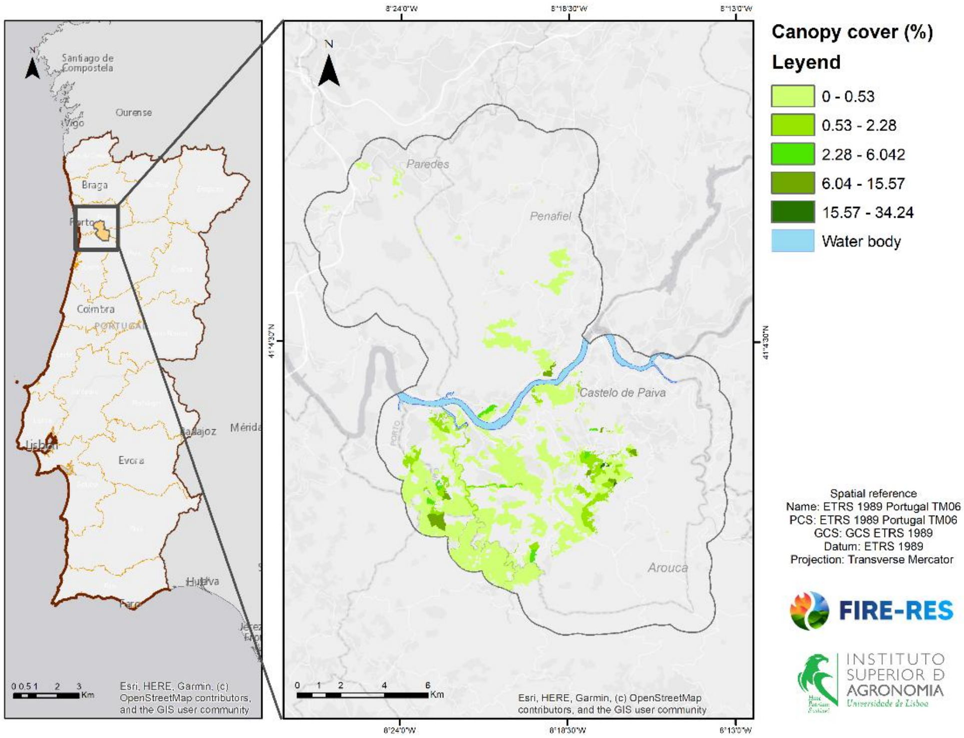
7. ANNEXES

Annex 1. Canopy cover map for the burned areas of 2017 and 2022.



Annex 2. Informative document generated before the Focus Group session.

FIRE-RES

U LISBOA | UNIVERSIDADE DE LISBOA

INSTITUTO SUPERIOR DE AGRONOMIA

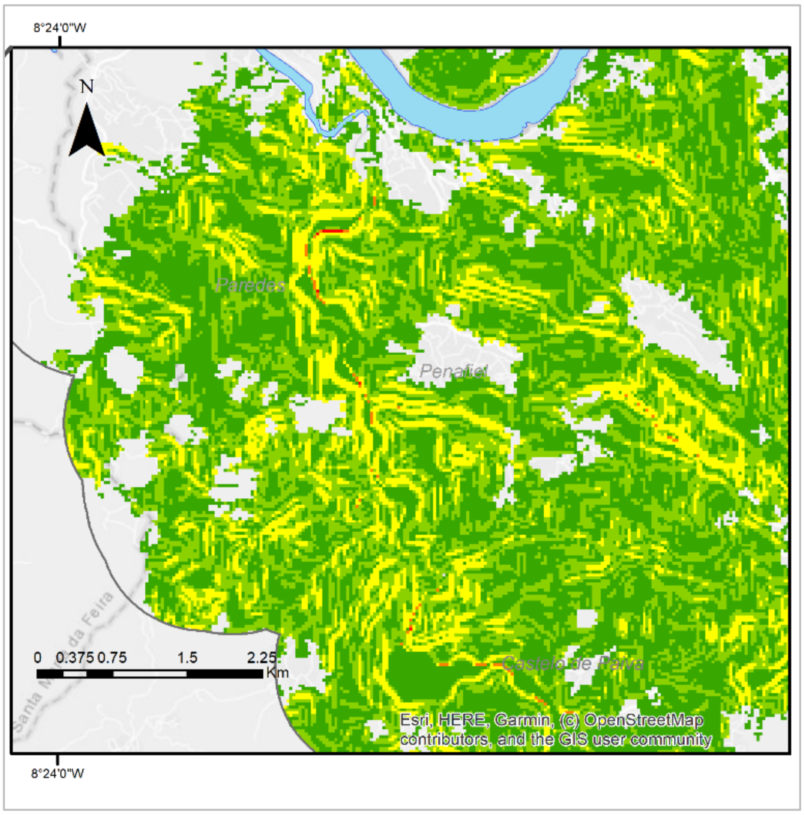
INFORMATIVE DOCUMENT ON I.A 2.6

RESTORATION AFTER WILDFIRES IN VALE DO SOUSA, PORTUGAL. A PARTICIPATORY MULTI-CRITERIA APPROACH FOR DECISION MAKING

Sara Casados

12/07/2024

Annex 3. Zooming of the LS values that are color red and orange (high steep and slope).



Annex 4. First part of the online survey for defining the weights of importance.

FIRE-RES

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.

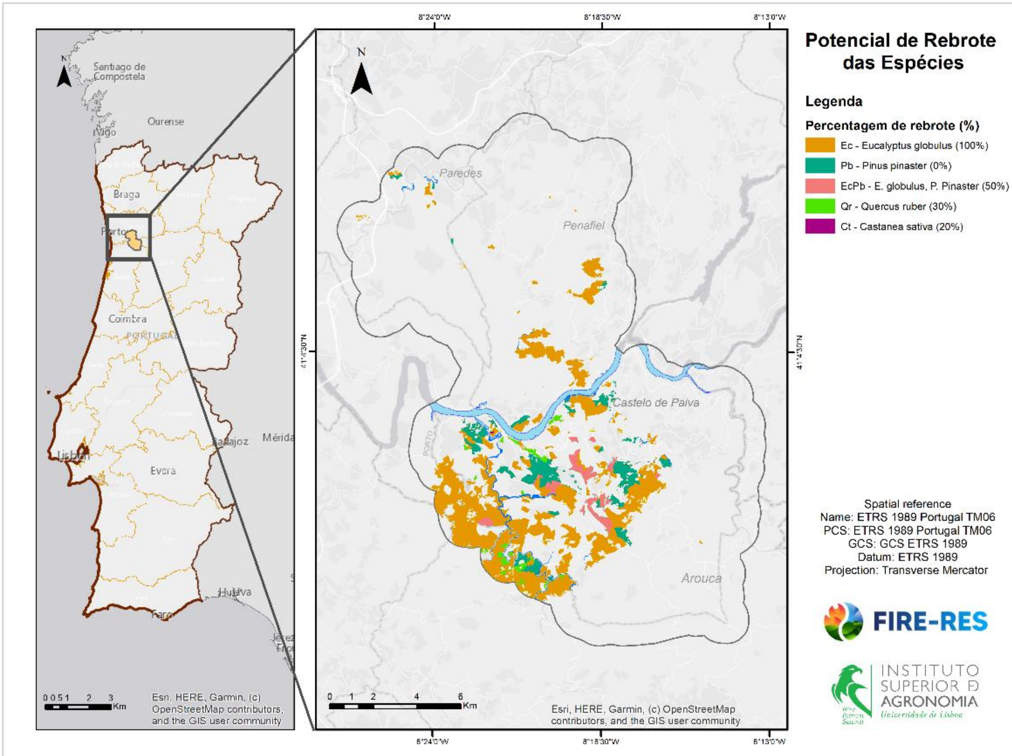
The objective of this survey is to compare by pairs different criteria, and sub-criteria within each criteria. The pairwise comparison method, involves evaluating two items at a time to determine which one is preferred or more important based on a specific criterion. This method simplifies decision-making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

Below you may find the general definition for each criteria and subcriteria:

Annex 5. Sub-criteria “Regrowth potential of species after a wildfire”.



Annex 6. Total extent for each priority management unit for restoration actions, for 2017 and 2022.

Levels of priority management	Area (ha)
Low	908.74
Medium	1,787.35
High	198.24
Maximum	64.91
Total	**2,959.24**

Annex 7. Total coverage of the burned inventory in 2017, for each council. Source: ICNF, 2015.

Council	Coverage (ha)	Coverage (%)
Arouca	**493.26**	**8.58**
Agriculture	11.30	0.20
Building area	3.08	0.05
Eucalyptus globulus	195.74	3.41
Maritime pine	102.93	1.79
Non riparian	173.48	3.02
Shrubland	6.73	0.12
Castelo de Paiva	**4,884.39**	**85.00**
Agriculture	214.17	3.73

Building area	100.29	1.75
Eucalyptus globulus	3,862.18	67.21
Maritime pine	445.84	7.76
Non riparian	178.93	3.11
Shrubland	82.98	1.44
Gondomar	**52.54**	**0.91**
Agriculture	18.98	0.33
Building area	0.29	0.01
Maritime pine	21.27	0.37
Non riparian	1.98	0.03
Shrubland	10.02	0.17
Penafiel	**311.33**	**5.42**
Agriculture	19.21	0.33
Building area	7.14	0.12
Eucalyptus globulus	167.35	2.91
Maritime pine	11.25	0.20
Non riparian	80.71	1.40
Shrubland	25.67	0.45
Santa Maria da Feira	**4.58**	**0.08**
Shrubland	4.58	0.08
Total	**5,746.10**	**100.00**

Annex 8. Total coverage of the burned inventory in 2022, for each council. Source: FireRES project, 2024.

Council	Coverage (ha)	Coverage (%)
Castelo de Paiva	**3.14**	**0.49**
Agriculture	1.52	0.24
Eucalyptus	1.15	0.18
Non Riparian	0.47	0.07
Cinfães	**1.54**	**0.24**
Agriculture	1.54	0.24
Paredes	**279.79**	**44.01**
Building Area	212.57	33.44
Eucalyptus	14.77	2.32
Shrubland	52.45	8.25
Penafiel	**351.26**	**55.25**
Agriculture	44.01	6.92
Building Area	223.66	35.18
Eucalyptus	32.24	5.07
Non Riparian	4.38	0.69
Shrubland	46.98	7.39
Total	**635.73**	**100.00**

Annex 9. Conservation areas in Vale do Sousa. Source: ICNF (2024).