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DOI
10.1016/j.ijdrr.2025.105371

Publication date
2025

Document Version
Final published version

Published in
International Journal of Disaster Risk Reduction

Citation (APA)
Arango, E., Nogal, M., Sousa, H. S., Matos, J. C., & Stewart, M. G. (2025). Wildfire preparedness: Optimal adaptation measures for strengthening road transport resilience. *International Journal of Disaster Risk Reduction*, *121*, Article 105371. https://doi.org/10.1016/j.ijdrr.2025.105371

International Journal of Disaster Risk Reduction 121 (2025) 105371

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

Wildfire preparedness: Optimal adaptation measures for strengthening road transport resilience

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ARTICLE INFO

Keywords:
Resilience
Preparedness
Optimal adaptation
Road network infrastructure
Wildfire hazards

ABSTRACT

This paper addresses the growing need to shift wildfire management strategies from suppression to greater preparedness and adaptation in response to increasingly frequent and intense wildfire events. Traditional approaches prioritize suppression actions, but this study emphasizes the combined role of adaptation measures and suppression efforts in enhancing resilience to wildfires. While suppression tackles immediate threats, adaptation aims to reduce long-term vulnerabilities and enhance resilience to future wildfire risks. The European Union has made significant efforts to promote fire-resistant territories, but gaps persist in adaptation knowledge and preparedness. To address this, the study demonstrates the effectiveness of a resilient-preparedness framework to analyze the systemic impact of adaptation measures. Subsequently, the framework is extended to identify the most cost-effective combination of measures to enhance system resilience. The methodology employs a genetic multi-objective algorithm to identify the most effective set of adaptation measures across various wildfire intensities and dimensions of resilience, including physical, operational, and social aspects. By integrating grey, green, and soft adaptation measures, the methodology contributes to understanding how to enhance the wildfire resilience of road networks. Overall, it serves as a decision-support tool to guide initiatives under the EU Green Deal and improve wildfire management strategies.

1. Introduction

Increasingly frequent and intense wildfires, attributed to climate change and land use modifications [1,2], are causing serious societal impacts. Recent wildfires in Los Angeles (2025), Hawaii, Greece, and Canada (2023) exemplify the potential magnitude of the damage under the new wildfire regime [3–5]. The urgency to address wildfires from a perspective beyond suppression becomes increasingly apparent when considering projections indicating an escalation of these events in the upcoming years [6,7].

Effective wildfire management should integrate proactive, reactive and learning approaches [8]. Reactive actions imply responding to events after they occur, such as suppression efforts, i.e., extinguishing the flames. Proactive actions aim to prevent, protect and detect fire occurrences and reduce their impacts. The learning process, tied to adaptation, lies in its ability to introduce changes in natural or human systems by learning from each new experience and adjusting strategies accordingly. Although (climate change) adaptation is primarily associated with the learning stage, mainly because it involves previously unexperienced phenomena, it

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https://doi.org/10.1016/j.ijdrr.2025.105371
Received 2 August 2024; Received in revised form 3 March 2025; Accepted 4 March 2025

has the potential to enhance proactive and reactive measures, thereby providing the capacity to minimize the impacts of climate events [9].

However, the prevailing wildfire management strategy, centered on reactive strategies (i.e., suppression) and emergency management, is unsustainable in the long term [10,11]. This has become especially evident over the past decade of wildfires [12,13]. In addition, the problem of wildfires has traditionally been studied from the risk-based perspective (e.g., [14–17]). However, risk-based approaches have several limitations in addressing the wildfire challenge, as they rely on known and measurable threats and are incapable of capturing extreme wildfire events (EWE), as discussed in [18]. Therefore, a resilience perspective, focused on preparing for, absorbing, recovering from and adapting to actual or potential adverse events, is essential to effectively manage wildfire challenges. Consequently, there is a pressing need to move towards proactive strategies and adaptation as essential approaches to co-exist with these events [19]. As a result, adaptation has become globally recognized as the key to strengthening resilience in the face of this escalating threat [13,20,21].

In terms of wildfire adaptation, the European Union has made significant efforts to promote fire-resistant territories by integrating various activities encompassing land use and planned fuel treatments [11,22]. According to [23], there are at least 38 projects promoting fuel management initiatives for wildfire risk prevention in the Mediterranean region. The scientific community also focuses on wildfire adaptation, conducting studies on land management-based wildfire prevention (e.g., [24,25]), ecological measures for wildfire mitigation (e.g., [26]), and the assessment of adaptation costs for building retrofitting (e.g., [27]), and power infrastructure (e.g., [28]). Methodologies such as those proposed by [29,30] are suggested as possible tools to support the evaluation of adaptation measures in this context. Meanwhile, quantitative-qualitative models (e.g., [31]) are reported to evaluate interventions.

Despite this notable progress, significant knowledge and implementation gaps remain in proactive strategies and adaptation. Reports such as [13] highlight the insufficient capacity to cope with climate impacts, while studies like [32] identify the challenges in effectively implementing adaptation strategies. A key barrier to proactive strategies is the lack of understanding regarding the potential effectiveness of various adaptation plans, policies, and measures. Moreover, there is a pressing need for tools that can assess the effectiveness of adaptation strategies in enhancing resilience at a systemic level and across multiple dimensions. The United Nations Environment Program (UNEP) and the European Union have also recognized this gap [21].

To address these challenges, [33] proposed a GIS-based methodology that evaluates the effectiveness of adaptation measures in reducing wildfire exposure, accounting for uncertainties related to EWE. While the GIS-based methodology is effective for analyzing exposure reduction, it is not able to capture how different adaptation measures increase resilience across multiple dimensions. To address this gap, [34] incorporate the GIS-based methodology into a resilience assessment framework. However, the framework is not able to systematically introduce and compare different adaptation measures.

Therefore, this paper makes two key contributions. (i) The first novel contribution is the extension of the existing resilience framework to systematically assess a variety of adaptation measures at the system level, taking into account their geographical location. To systematically assess adaptation measures, it is necessary to expand the exposure measures within the GIS-based methodology. Specifically, the framework evaluates green, grey, and soft adaptation measures. Grey measures include physical infrastructure interventions (e.g., road construction, building upgrades); green measures involve natural and ecological strategies (e.g., vegetation mosaics, fuel strip management); and soft measures focus on non-structural actions, including social and behavioral changes (e.g., public education, awareness campaigns). A more detailed description of these adaptation measures is provided in Section 2. While the resilience framework is capable of assessing all three types of adaptation measures, this paper places particular emphasis on green and soft measures, as they remain under-explored in the existing literature. Grey measures have been the focus of several studies (e.g., [35]) due to the availability of multiple models that simulate infrastructure behavior. Nevertheless, comprehensive frameworks for the evaluation of green and soft adaptation measures remain underdeveloped, representing a critical gap that this study aims to address.

(ii) The second contribution of this study is the integration of a multi-objective optimization approach to identify the most cost-effective combination of adaptation measures. Building on the extended resilience framework to systematically evaluate adaptation measures, this approach determines both the optimal set of strategies to enhance system resilience and their optimal geographical locations for implementation. By incorporating this optimization technique, the study provides decision-makers with a tool for efficient resource allocation, carefully balancing the trade-offs between resilience improvements and the costs of different adaptation measures.

The methodology evaluates key system functionalities across resilience dimensions. The physical domain is addressed by safety and connectivity functionalities, focusing on network infrastructure. The operational domain is covered by reliability and efficiency, reflecting system performance and traveler preferences. The social domain is captured by the road transport demand and land use. These functionalities are assessed under varying wildfire conditions. Additionally, it considers natural and man-made environmental factors by incorporating the GIS-based methodology. Dynamic thresholds are used to specify the acceptable loss of performance associated with different wildfire intensities. As the focus is on the effectiveness of adaptation measures, the analysis emphasizes the system's ability to cope with disruptive events rather than the recovery process. The methodology, applied to road networks, enables the evaluation of grey, green, and soft adaptation measures to enhance their wildfire resilience across various fire intensities, including EWE.

The rest of the document is organized as follows: Section 2 discusses the adaptation measures in the context of wildfires and road networks. Section 3 describes the foundation frameworks and the optimization-based methodology, followed by the demonstration of its application in Section 4, in which the road network in the Leiria Region, Portugal is studied. Section 5 presents the discussion, concluding with a presentation of the main insights in Section 6.

2. Adaptation measures in wildfire management

Adaptation to climate change refers to the process of introducing modifications in response to actual or anticipated climate impacts. It is not a one-time emergency response, but rather a series of proactive measures [13]. These measures aim to reduce vulnerability and exposure to climate hazards (e.g., drought, wildfires) while enhancing resilience to their effects. Such adjustments may involve changes in infrastructure, behavior, or policies to address both current and future climate risks, minimizing potential damage from extreme weather events and related hazards [9]. In essence, these strategies aim to enhance the resilience of systems, encompassing natural ecosystems and built environments. There are different ways to classify adaptations; [36] presents some examples. However, this paper adopts the classification by the European Environment Agency, which categorizes adaptation into grey, green, and soft measures [37]. They correspond, respectively, to infrastructure-based, ecosystem-based, and policy, legal, social, and financial measures.

In the context of road networks, examples of grey measures include the construction of alternative roads, enhancing buildings (e.g., water curtains and fire resistant materials), or relocation or adaptation of high-exposure sources (e.g., petrol stations). Green measures, which encompass natural and ecological strategies, may involve various land management options. For instance, protect heritage trees [38] or implement fuel strip management as a firebreak, using wastelands and rivers around roads and buildings. Meanwhile, soft measures that account for non-structural, social, and behavioral changes can include the implementation of flexible lanes, and signage to facilitate evacuation; educational sensitization; or traffic management. While the road network is the primary infrastructure under consideration in this study, adaptation evaluation encompasses the entire system, including other infrastructure systems (e.g., power supply), the surrounding environment, and social factors.

Their geographical distribution is considered when assessing the measures' effectiveness, and each location represents a different adaptation strategy. Thus, green, grey and soft adaptations are applied in either mosaics (i.e., spatial), strips (i.e., longitudinal), or undefined geographically distributed.

Vegetation mosaics involve strategically placing low-fire-exposure areas within a landscape surrounding or interrupting high-fire-exposure zones. This deliberate arrangement aims to create breaks in fuel continuity, protecting against wildfires. To reduce wildfire exposure, the vegetation mosaic strategy encompasses different adaptation measures. For instance, clearing weeds and invasive species, protecting heritage trees, and maintaining crops can be implemented within this strategy that targets surrounding zones.

Fuel strip management helps prevent low-intensity fires from directly reaching the roads. It is useful because many wildfires start along roads or railways, spreading to important farmland and grazing areas. This strategy can involve different types of firebreaks of various widths, either natural (e.g., rivers) or human-made, using methods such as mowing, plowing, or controlled burns to clear the strips.

Undefined geographically distributed measures include educational sensitization that empowers individuals and communities to make informed decisions and protect themselves and their property from wildfire events. They can be proactive and reactive actions such as preventing controlled burn management, informing people about evacuation procedures, recognizing early warning signs, and identifying shelters or safe routes.

The following section details how the evaluation of these adaptation strategies and measures can be incorporated into a resilience framework.

3. Methodology: Optimal adaptation strategy to increase resilience

In this section, a brief overview of the frameworks underlying the methodology is provided, namely, the GIS-FA (GIS-based tool for Fire Analysis) and the preparedness resilience assessment. Readers interested in detailed information on resilience assessment and the GIS-FA frameworks are referred to [18,34], respectively. Afterwards, the novel contribution of this work is presented, that is, (i) systematically evaluate adaptation measures through resilience assessment and (ii) an optimization model to identify the best combination of adaptation measures to increase resilience.

3.1. GIS-FA tool

The GIS-FA tool assesses the exposure level of a road measured in terms of the arrival time of a random fire (FIRAT) of a given intensity to reach the road. The methodology considers the nearest propagation sources and barriers $l \in \{1 \cdots L\}$ around the asset under study. All sources and barriers are aggregated considering their ratio of spread (ROS) in terms of a reference source by calculating the Equivalent Fire Distance (EFD). This enables the assessment of exposure to different fire intensity categories, ranging from normal to extreme wildfires. The steps for the FIRAT calculation are summarized as follows:

1. *Inputs definition*: Studied asset (i.e., road), fire propagation sources (e.g., eucalyptus plantations), barriers (e.g., wetlands), reference source (e.g., grasslands), wildfire classification according to [39], and ROS values for the different sources and barriers, considering the source and zone characteristics.
2. *ROS ratio estimation*: for all sources and barriers l, $W_l = ROS_{ref}/ROS_l$, where ROS_{ref} is the ROS of the reference source and ROS_l is the ROS of each source and barrier.
3. *Distances calculation*: for each road i and all sources and barriers l, the distance $d_{i,l}$ between the centroid of the studied asset and the closest point of each fire propagation source and barrier.

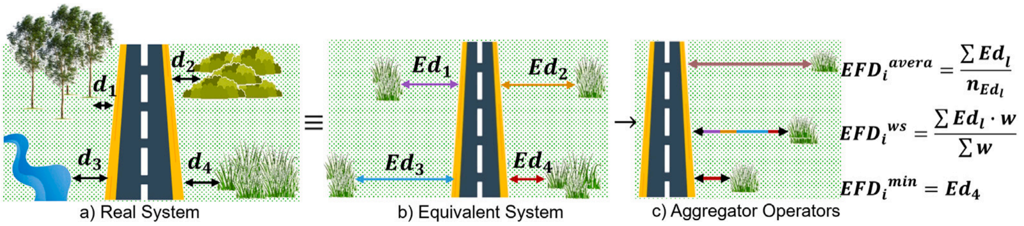


Fig. 1. Different aggregation operators for EFD assessment. (a) Real system: 4 sources/barriers at different distances to the analyzed road. (b) Equivalent system: distances expressed in terms of the reference source (Ed_l). (c) Aggregation operators: The obtained equivalent distances Ed_l are aggregated using the average, weighted sum and minimum operators, resulting in the Equivalent Fire Distance (EFD_i) for the road i.

4. *EFD (Equivalent Fire Distance) calculation*: for each road i, $EFD_i = \wedge_{l \in S} W_l d_{i,l}$, with $\wedge_{l \in S}$ being an operator that aggregates the different distances weighted by the ROS ratios. They are aggregated based on a given criterion.
5. *FIRAT estimation*: for each road i and wildfire category c, $FIRAT_i = EFD_i / ROS_c$, where ROS_c is the ROS associated with the reference source under the seven different fire categories defined in [39].

Regarding the aggregation operator $\wedge$ used to combine various surrounding sources and barriers in Step 4, previous works (e.g., [18,40]) propose the use of the average aggregator. However, this paper discusses the impact of the $\wedge$ selection. More precisely, the use of the minimum, mean and weighted sum operators on the equivalent distances, as depicted in Fig. 1.

To demonstrate the impact of the different operators on the EFD assessment, an example in Table 1 is discussed. This example assumes a reference system (Scenario A) with three sources (grasslands, Eucalypt plantation, and a river) surrounding a road. In Scenario B, the Eucalypt plantation located at 5 m from the road is replaced by shrubs. The scenario shows the operators' ability to capture the introduction of new fire-spread sources near the road. Compared to Scenario A, an increase in exposure is expected because shrubs spread fire faster than the eucalyptus plantation. Consequently, a small reduction in the EFD is expected. Among the three operators, only the weighted sum operator reflects a reduction. The minimum and the average operators lack sufficient sensitivity. Scenario C assesses the ability of the operators to capture the introduction of barriers; in this case, a 3-m-wide firebreak strip located 3 m from the road. For this case, a reduction in exposure and thus an increase in EFD, is expected compared to Scenario A. The three operators, min, average, and weighted sum, capture this change with relative EFD increases of 67%, 7%, and 84%, respectively. The reader can explore additional scenarios in Appendix A - Table A.1.

The minimum operator focuses on the sources causing the highest exposure in the vicinity of the studied road. Thus, this operator is insensitive to adaptation measures aimed at sources other than the most critical. In this research work, the minimum operator is not considered as the objective is to evaluate adaptation measures across large areas, focusing on their compound effects across the entire system. The average operator offers a global perspective by smoothing out fluctuations and extremes in ROS values. It treats all sources and barriers equally, calculating their collective impact based on average distances. This operator facilitates the assessment of general exposure, as evidenced in previous studies [18,33]. However, it may fail to effectively capture changes in fuel conditions or the introduction of adaptation measures.

In contrast, the weighted sum operator is formulated to prioritize immediate exposure by assigning weights as the inverse of the source distances ($1/d_l$). This approach effectively assesses exposure levels based on proximity to fire propagation sources, providing a more suitable method to assess the geographic location of adaptation measures relative to the study target. In this research work, the weighted sum aggregator is employed to capture the effects of adaptation measures. Note that other weight functions, such as linear or radical functions of distance, can also be used. However, this study does not explore the effectiveness of alternative operators. Future research will examine them and their impact on both exposure assessment and optimization outcomes for adaptation strategies.

3.2. Resilience assessment framework at preparedness stage

Resilience is assessed using the framework introduced by [34]. This framework assesses road networks resilience by emphasizing anticipatory and coping capacity, i.e., addressing preparedness for varying wildfire intensities. These different intensities correspond to the seven wildfire categories mentioned in Section 3.1 whose characteristics are provided in [39]. The frequency of different wildfire intensities is not considered in the resilience calculation. Instead, the focus is on reducing road exposure. It is noted that resilience does not equal recovery; while recovery is an important component of resilience, the system's ability to prepare for and respond to disruptions is also relevant in resilience assessment. A detailed discussion regarding the distinction between resilience and recovery can be found in [34]. Given the emergent nature of EWE, where suppression strategies are increasingly ineffective, wildfire resilience assessment should emphasizes the capacity to cope with disruptive events rather than focusing on the recovery process. The key elements of the framework include the consideration of different hazard intensities, multiple network functionalities with different levels of importance, and dynamic thresholds associated with the hazard intensity and functionality importance.

The framework evaluates the performance of a traffic network across various functionalities, including safety, connectivity, reliability, and efficiency. While wildfires may not physically damage road infrastructure, they can result in unacceptable delays,

Table 1
Aggregation operators analysis.

Source	ROS (m/min)	$d_{i,l}$ (m)	Ed$_l$ (m)	EFD_i min (m)	EFD_i aver. (m)	EFD_i ws (m)
A. Initial system						
Grassland	50	20	20	6	410	78
Eucalypt plantation	25	8	16			
Eucalypt plantation	25	5	10			
Eucalypt plantation	25	3	6			
River	1	40	2000			
B. Including a new high fire propagation source at 35 m in Scenario A. It is expected to increase exposure and thus reduce EFD.						
Grassland	50	20	20	6 (0%)	410 (0%)	77 (−1%)
Eucalypt plantation	25	8	16			
Shrubs	35	5	7			
Eucalypt plantation	25	3	6			
River	1	40	2000			
C. Including a new barrier in Scenario A - firebreak at 3 m. It is expected to reduce exposure and thus increase EFD.						
Grassland	50	20	20	10 (67%)	439 (7%)	143 (84%)
Eucalypt plantation	25	8	16			
Eucalypt plantation	25	5	10			
Firebreak (3 m width)	1	3	150			
River	1	40	2000			

Notation: ROS: ratio of spread of the source. d: real distance between the target (e.g., a road) and the source. Ed_l: equivalent distance of each source l, considering grassland as a reference source. EFD_i *min*, *aver*., and *ws* represent the Equivalent Fire Distance considering the minimum, average, and weighted sum aggregation operators, respectively.

Table 2
Equations for functionalities assessment, from [34].

Functionality	At link or OD level $\forall i \in \mathcal{N} \quad \forall pq \in \mathcal{PQ}, \quad \forall c \in C$	At the system level $\forall c \in C$
Safety (S)	$S_{i,c} = \begin{cases} 0 & if\ FIRAT_{i,c} \leq t_i \\ 1 & if\ FIRAT_{i,c} > t_i \end{cases}$	$S_c = \frac{1}{\lvert\mathcal{N}\rvert} \sum_{i \in \mathcal{N}} S_{i,c}$
Connectivity (C)	$C_{pq,c} = \begin{cases} 1 & if\ \mathcal{R}_{pq,c} = \emptyset \\ 0 & if\ \mathcal{R}_{pq,c} \neq \emptyset \end{cases}$	$C_c = \frac{\sum_{pq \in \mathcal{PQ}} C_{pq,c}}{\sum_{pq \in \mathcal{PQ}} \lvert\mathcal{R}_{pq,0}\rvert}$
Reliability (RL)	$RL_{pq,c} = \frac{\min_{r \in \mathcal{R}_{pq,0}} \{\tau_r\}}{\min_{r \in \mathcal{R}_{pq,c}} \{\tau_{r,c}\}}$	$RL_c = \frac{1}{\lvert\mathcal{PQ}\rvert} \sum_{pq \in \mathcal{PQ}} R_{pq,c}$
Efficiency (E)	$E_{pq,c} = \frac{d^g_{pq}}{\lvert\mathcal{R}_{pq,c}\rvert} \frac{\sum_{r \in \mathcal{R}_{pq,c}} \frac{X_r}{d_r}}{\sum_{r \in \mathcal{R}_{pq,c}} X_r}$	$E_c = \frac{1}{\lvert\mathcal{PQ}\rvert} \sum_{pq \in \mathcal{PQ}} E_{pq,c}$

Notation. i: link, i.e., continuous segment of the road with similar physical and traffic characteristics. $\mathcal{N}$: set of links. $FIRAT_{i,c}$: fire arrival time to link i under fire category c. t_i: travel time of the link i. $\mathcal{R}_{pq,c}$: set of available routes connecting the OD pair pq under wildfire category c. Sub-index 0 means normal conditions. τ_r: travel time associated with route r. d^g_{pq}: geometric distance. d_r: route length. X_r: total users of route r.

sometimes involving long detours, make some areas unreachable, and even affect the users' well being, depending on the wildfire conditions. In order to capture these aspects of different nature, these functionalities have been chosen. The calculation of the functionalities are summarized in Table 2. Note that, (i) each functionality is initially evaluated at the link level, i, or the origin–destination (OD) level, pq, and subsequently at the system level; (ii) the exposure measure (FIRAT) is introduced to evaluate the performance of the functionalities. The functionalities are formulated hierarchically to ensure consistency and continuity. In the sense that a road that is not safe (i.e., subject to a very close fire) directly affects network connectivity; connectivity disruption impacts travel time reliability; and a disconnected origin–destination with no routes will result in zero efficiency.

Based on the functionality assessment, the performance matrix of the network, PM, is calculated for $\mathcal{M}$ functionalities and C hazard levels as follows:

$$PM = [f_{j,c}], \qquad \forall j \in \mathcal{M}, \quad \forall c \in C$$

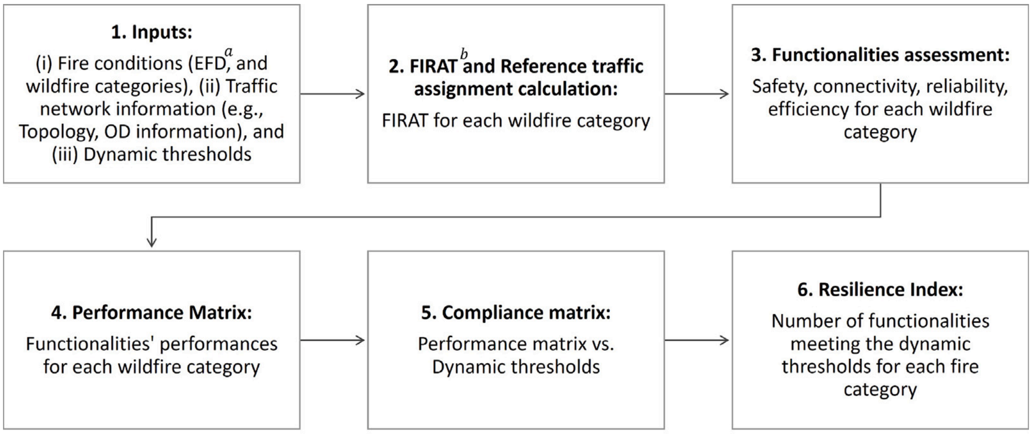
where the matrix components are denoted as $f_{j,c}$ for functionality j and fire category c. For instance, $j = 1$ is Safety.

In addition, the performance of each functionality is compared against dynamic thresholds to determine whether the loss of performance is acceptable under the analyzed wildfire conditions. Therefore, the dynamic thresholds are defined for different hazard intensities and the significance of the functionalities within the network. This comparison yields the network's capacity to handle different hazard intensities and the corresponding resilience index. The dynamic thresholds associated with functionality j and wildfire category c are denoted as $threshold_{j,c}$. They can take values ranging from 0 to 1 (0%–100%), where 0 means accepting the complete loss of the given functionality. The result of this comparison is captured by the compliance matrix, $g_{j,c}$, which is defined as follows;

$$g_{j,c} = \begin{cases} 0 & if\ f_{j,c} < threshold_{j,c} \\ 1 & if\ f_{j,c} \geq threshold_{j,c} \end{cases}, \qquad j = 1 \dots M, c = 1 \dots C$$

	$Hazard\ 1$	$\cdots$	$Hazard\ C$	Partial Res. per funct.
Functionality j=1	$g_{1,1}$	$\cdots$	$g_{1,C}$	$\frac{1}{C}\sum_{c=1}^{C} g_{1,c}$
$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
Functionality $j = M$	$g_{M,1}$	$\cdots$	$g_{M,C}$	$\frac{1}{C}\sum_{c=1}^{C} g_{M,c}$
Partial Res. per hazard	$\frac{1}{M}\sum_{j=1}^{M} g_{j,1}$	$\cdots$	$\frac{1}{M}\sum_{j=1}^{M} g_{j,C}$	$R = \frac{1}{MC}\sum_{j=1}^{M}\sum_{c=1}^{C} g_{j,c}$

Fig. 2. Resilience index calculation.



a) EFD: Equivalent Fire Distance b) FIRAT: FIRe Arrival Time

Fig. 3. Methodology for resilience assessment of a traffic network affected by wildfires.

Dynamic thresholds differ from static thresholds by adjusting the minimum performance requirements based on the hazard intensity. Unlike risk approaches, non-compliance with these thresholds does not necessarily imply system failure.

The resilience index, R is calculated as the average of all compliance scores in the matrix, representing the overall performance across multiple functionalities and hazard levels. Fig. 2 illustrates the R calculation.

The steps of the resilience assessment methodology are depicted in Fig. 3. For more detailed information about the formulation and specific applications, readers are referred to [34].

3.3. Modeling adaptation measures and the impact on resilience

As seen in Section 3.2, the resilience index depends on the fire and traffic conditions. The different adaptation strategies, distributed in mosaic, strip, or geographically undefined, as described in Section 2, can influence one of these factors through; (i) the ratio of fire spread (ROS) of unique or several sources of wildfire propagation to varying degrees; or (ii) the traffic, affecting the number of users and travel time. The effect of the measures affecting ROS is captured by the GIS-FA tool in terms of the exposure level (i.e., fire conditions), whereas the traffic model captures those influencing traffic. Additionally, the effectiveness of the adaptation measures can be assessed for different wildfire intensities due to the capabilities of the GIS-FA tool.

Fig. 4 illustrates the integrated framework. It describes how the different adaptation measures (i.e., grey, green, and soft) are introduced into the resilience assessment. This is a sequential process in which the adaptation measures directly influence various framework domains (i.e., environmental, social, and physical). These, in turn, induce changes in both fire and traffic conditions, which are the bases for the resilience framework (see Step 2 of Fig. 3). These changes subsequently impact the performance of the system functionalities, ultimately determining the resilience level. The contribution of each adaptation strategy can be determined when compared with a baseline scenario. It is highlighted that each functionality relates to different resilience domains. For instance, safety and connectivity represent the physical domain, since they include the network infrastructure and other physical components of the traffic network. Reliability and efficiency are related to the operational domain, which considers traffic management, and the social domain involving transport demand.

3.4. Optimization of the adaptation strategy

Evaluating the effectiveness of individual and combined adaptation measures and their variations is a complex task involving a large number of combinations. In this sense, an optimization model presents a good solution for systematically analyzing different scenarios, and identifying optimal combinations of measures, by maximizing the resulting effectiveness while considering various constraints.

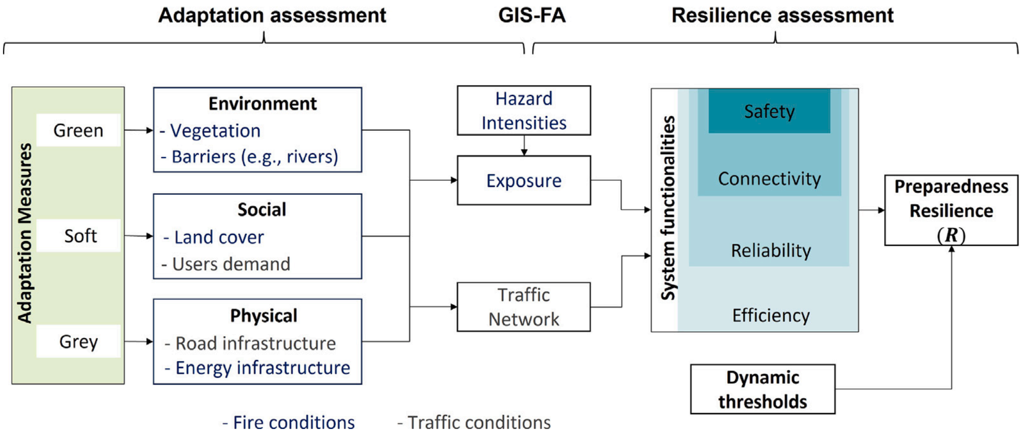


Fig. 4. Framework for assessing the capacity of adaptation measures in improving resilience. *GIS-FA* (GIS-based Fire Analysis) based on [18] and *Resilience assessment* based on [34]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this context, it is assumed that the area under study is divided into Z zones, that is, $z \in \{1 \dots Z\}$. The subdivision of zones can be done by considering the road network topology or administrative boundaries. The studied traffic network contains N links, where each link represents a single direction of a road. For example, a two-lane road corresponds to two links. Road segmentation into links can be based on changes in road characteristics, intersections, and points of entry or exit for users. Measures in mosaics and strips are introduced using the defined zones and links. Moreover, measures with undefined geographical distribution are captured at the traffic level. Traffic is distributed through the network to allocate a given traffic demand from the origin–destination (OD) pair υ_{pq} $(pq \in \{1 \dots PQ\})$. Therefore, the traffic demand for the link i is expressed as υ_i.

The proposed optimization model aims to identify the optimal adaptation strategy to enhance the transportation network's resilience while minimizing costs. The optimal adaptation strategy will contain a combination of adaptation measures in mosaic, strips, and geographically undefined, that is $\boldsymbol{X} = [X_z; X_i; X_{pq}]$, respectively. Therefore, the decision variable $\boldsymbol{X}$ with dimension $Z + N + PQ$, takes values from 0, meaning no adaptation measure associated with the corresponding mosaic, strip, or OD, to the maximum number of adaptation measures applicable at each mosaic, strip, or OD. For instance, if 3 possible adaptation measure types are considered for zone $z = 1$, that is, vegetation cleaning, replacement, and combination, then X_1 can take the values $\{0, 1, 2, 3\}$.

The measures distributed in a mosaic pattern are associated with a reduction in the ROS value, ROS_z for zone z; the measures in strips are defined through the width of the firebreak b_i along road i, and undefined distributed is captured by a demand change, υ_{pq} for users of OD pq. Note that the impact of a given adaptation strategy must be analyzed at each road. All changes distributed in mosaic and firebreak affect all roads, but the influence of firebreaks benefits the associated road to a greater extent. The traffic condition change affects every road at the system level.

The multi-objective optimization can be expressed as in Eq. (1).

$$\min_{\mathbf{x}}\{C(\mathbf{x}); -\Delta R(\mathbf{x})\} \tag{1}$$

where C refers to the cost of implementing the adaptation strategy and ΔR represents the corresponding relative increment in resilience, expressed as in Eq. (2),

$$\Delta R(\mathbf{x}) = \frac{R\left(\mathrm{ROS}_z(\mathbf{x}_z), b_i(\mathbf{x}_i), \upsilon_{pq}(\mathbf{x}_{pq})\right) - R_0}{R_0} \times 100 \tag{2}$$

where R_0 is the system's resilience before applying any adaptation measures used as the baseline scenario, and $R(\mathbf{x})$ represents the resilience of the system when adaptation strategy $\mathbf{x}$ is applied.

The optimization problem is constrained by the condition that the cumulative effect of different adaptation measures at the mosaic level does not result in ROS values smaller than a minimum threshold, denoted as ROS_{min}. This restriction ensures that the remaining values after ROS reductions are not negative, which would lack physical meaning. However, this threshold can be interpreted as the ROS of low-spreading vegetation, as it is unrealistic to assume that the ROS could be zero, especially considering the challenges of maintaining such mosaic management conditions. This condition is expressed as

$$\mathrm{ROS}_{l,0,z} - ROS_z \geq ROS_{min} \quad \forall l = \{1 \dots L\}, z = \{1 \dots Z\} \tag{3}$$

where $ROS_{l,0,z}$ represents the existing ROS value of each source l without any adaptation 0 in each zone z. Note that the variation of the traffic demand is introduced through a ratio, thus, no negative demand values are possible.

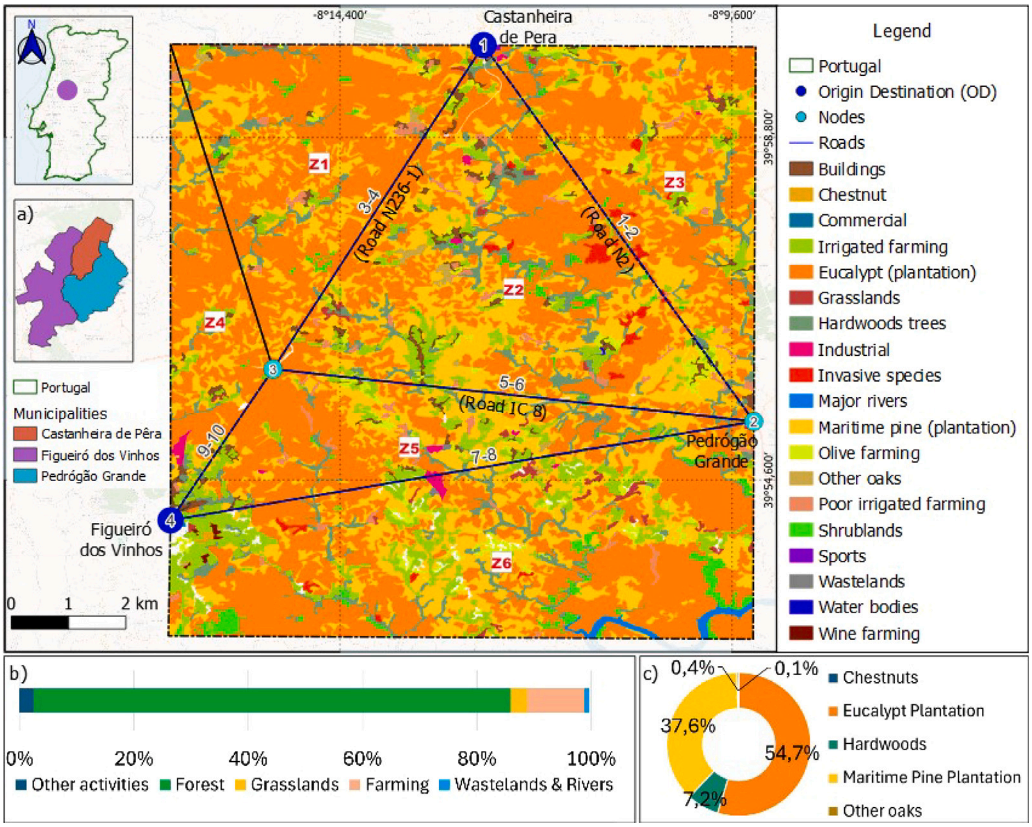


Fig. 5. Portuguese Road Network case study. (a) Municipalities involved in the case study; (b) Land cover composition; (c) Forest cover classification. The ID Z corresponds to the zone subdivision.

4. Application to the portuguese case study

The presented methodology is applied to the case study located in the Leiria region of Portugal, among the municipalities of Pedrógão Grande, Figueiró dos Vinhos, and Castanheira de Pera (as shown in Fig. 5a).

These areas were severely impacted during the extreme wildfires in Portugal in 2017, resulting in 67 casualties. Nearly half of the fatalities occurred on one road, specifically, the initial section of road 3–4 northbound, as shown in Fig. 5, where flames and smoke trapped drivers fleeing from the wildfire [41]. This emphasizes the increased importance of road networks during such events and highlights the need for preparedness plans.

The area under study is detailed in Fig. 5. The primary roads crucial for connecting the three municipalities have been included in the analysis.

4.1. Traffic network

For illustrative purposes, a simplified road network has been used, preserving key topological characteristics such as main nodes, road length, capacity, and demand. This simplified road network comprises 5 road segments, 10 directional links, 4 nodes, and 2 OD pairs (1-4 and 4-1). Despite its simplicity, the network presents redundancy, offering multiple alternatives for transit between the OD pairs. Traffic information was provided by *Infraestruturas de Portugal S.A.*, namely, road length, free-flow speed, traffic flow, capacity, and OD demand for each origin–destination pair. The C-logit Stochastic User Equilibrium (SUE) model proposed by [42] is used for traffic assignment. Details of the traffic model are provided in [18].

4.2. Environmental wildfire conditions

The land cover composition for the study area, as illustrated in Fig. 5, reveals that the forested zone constitutes 83%, farming occupies 10%, and grasslands cover 3%. Further details of the land cover analysis are presented in Fig. 5b. Notably, eucalyptus and maritime pine plantations account for 92% of forest cover, making them highly exposed due to their rapid fire-spreading characteristics compared to other species in the region. Fig. 5c outlines the specific forest cover classification.

Following the steps for FIRAT calculation outlined in Section 3, wildfires are categorized based on their ROS using the classification proposed in [39], which consists of seven categories. The first four categories represent normal wildfires with a ROS between 15 and 100 m/min, while the last three denote extreme wildfires with ROS exceeding 150 m/min. The ROS is influenced by element types encountered by the fire, including both sources of spread (e.g., shrub masses) and barriers (e.g., rivers). All diverse sources and barriers with varying ROS values near the asset under study are aggregated and expressed in terms of EFD based on a reference source. For example, considering grassland (ROS = 50 m/min) as a reference, shrublands with ROS = 25 m/min located 2 km from an asset are considered equivalent to grasslands located 4 km away. This yields the FIRAT for a wildfire reaching a specific asset based on the ROS of the reference source for each category.

Sources and barriers are considered from geographical information concerning land use and occupancy within the region, accessible Open Data provided by DGT [43]. The ROS values for all sources and barriers were obtained from [18], where detailed FIRAT formulation information can be found.

4.3. Adaptation measures

Following the methodology explained in Section 3, the adaptation measures considered are as follows: Vegetation Mosaics encompasses (i) vegetation clearing, which involves the removal of weeds, dry crops, or grasslands that can contribute to the rapid spread of fires; (ii) combining fire-resistant vegetation in areas with high exposure. Fire-resistant vegetation is strategically introduced to create fuel breaks, reducing the capability of wildfires to spread; (iii) vegetation replacement, intentional removal of trees, shrubs, and any vegetation prone to high fire exposure, such as eucalyptus plantations, and replacing them with fire-resistant species.

To evaluate the vegetation mosaics, the case study has been divided into six zones delineated by the roads and nodes depicted in Fig. 5. However, other types of subdivisions can be implemented. Each adaptation measure encompassed in this strategy – vegetation clearing, combination, and replacement – can reduce the ROS of the different sources. Specifically, they are assumed to reduce ROS by 5, 10, and 15 m/min, respectively, within the affected mosaic.

Regarding fuel strip management, they are placed along the sides of roads with different strip widths. Here, firebreak strip widths of 3, 10, and 20 m are considered. It is noted that according to Portuguese Decree-Law 17/2009, 10-m-wide firebreak strips are mandatory. However, non-compliance with this regulation was observed after the 2017 fire in this area, according to the forensic report [41]. Thus, studying strip widths of 3 and 20 m in addition to the mandatory 10-m width allows for a comprehensive analysis of different scenarios. The 3-m width represents a narrower strip that may be a cheaper solution yet suitable for specific terrain or vegetation types. On the other hand, the 20-m width represents a wider strip that could provide enhanced protection against spreading wildfires but may incur higher costs or have practical limitations in implementation. By examining a range of widths, the study can assess trade-offs between effectiveness, cost, and feasibility to inform decision-making and policy recommendations regarding firebreak strip design and implementation.

Awareness campaigns are assumed to instruct network users to avoid the most exposed roads during wildfires. That implies that under wildfire alert, users will be informed before using the traffic network, helping to avoid unnecessary roads that are currently or expected to be affected by fire. Informed users will result in a demand reduction of 25%, 50%, and 100% per OD pair, with 100% meaning that the route is closed. Demand reduction is the result of a number of informed users who do not use the network. During wildfire events, people may be evacuated by air, advised to stay at home, or directed to designated shelters. In all these cases, transportation demand decreases. Uncoordinated closures, as seen in incidents such as the Pedrógão Grande wildfire, can lead to severe consequences. Therefore, implementing awareness and education programs helps encourage road users to act in accordance with emergency protocols. The adaptation measures presented in this study focus on these proactive perspective, aiming to improve community response through pre-planning and sensitization efforts.

These models collectively influence resilience calculations through various functionalities. Table 3 summarizes the considered adaptation measures. The model includes a ‘Business As Usual’ (BAU) option for each adaptation approach, used to describe a scenario where no changes are made, meaning that no adaptation measures are implemented. This provides flexibility and serves as a baseline for comparison, allowing for the evaluation of various measures’ potential benefits or impacts. Consequently, given the three types of adaptation measures plus the BAU option for each of the zones, strips, and OD pairs, the number of possible combinations rises to $4^{(Z+N+PQ)} = 4^{6+10+2} = 68.7 \times 10^9$.

A minimum ROS value, ROS_{min}, is set to 7 m/min, as shown in Eq. (3). This value reflects that even low-exposure vegetation exhibits a non-zero ROS value. Thus, the ROS_{min} value of hardwood is assumed in this case. Alternative ROS_{min} values can be considered for this analysis. The sensitivity analysis of this parameter is provided in Appendix C.

4.4. Adaptation costs

The adaptation costs span 5 years, aligning with the typical duration of the mayoral term at the municipal level in Portugal. Cost values have been extracted from Portuguese project information, comprising the initial investment and the maintenance cost. Initial investments are projected for the year 2023, while maintenance costs for the subsequent four years are computed with a 2% discount rate, reflecting the country’s average over the last 20 years [44]. Table 4 summarizes the costs of each adaptation measure, whereas Table B.1 in Appendix B provides details of each cost along with their respective references.

Table 5 provides the areas and road distances associated with each zone and road, obtained with QGIS free software. Note that D_i corresponds to the real road length.

Table 3
Characterization of adaptations applied in the case study. BAU: Business As Usual.

Adaptation strategy	#	Adaptation measures	Apply to:	Decision parameter	Units	Range
Vegetation mosaics	1	BAU	Zones (z)	ROS variation (ROS_z)	m/min	0
	2	Veg. cleaning				5
	3	Combine veg.				10
	4	Veg. replacement				15
Fuel strips management	5	BAU	Along road (i)	Strip width (b_i)	m	0
	6	Firebreak strips				3
	7					10
	8					20
Educational sensitization	9	BAU	OD (pq)	Demand variation (v_{pq})	%	0
	10	25% Reduction				25
	11	50% Reduction				50
	12	Route closure				100

Table 4
Total cost of adaptation measures, including 4-year maintenance at 2% discount rate.

Adaptation measure	Initial investment at 2023	4-Year maintenance	Total costs	Unit
Cleaning	155.3	653.1	808.4	10^3 €/km^2
Combine veg.	394.7	596.5	991.2	10^3 €/km^2
Veg. replacement	461.9	952.0	1419.8	10^3 €/km^2
Firebreak strips				
3 m	0.5	1.1	1.6	10^3 €/km
10 m	1.7	3.5	5.2	10^3 €/km
20 m	3.4	7.1	10.4	10^3 €/km
Demand reduction 25%	220.5	25.7	246.2	10^3 €
Demand reduction 50%	439.7	77.2	516.9	10^3 €
Route closure per day	903.0	102.9[a]	1005.9	10^3 €

[a] The maintenance cost refers to the educational campaigns.

Table 5
Areas, A_z, and roads length, D_i, of the case study.

Index (z or i)	1	2	3	4	5	6
A_z (km^2)	20.11	33.02	20.17	9.67	15.45	38.55
D_i (km)	17.662	9.525	9.105	20.865	4.403	

Table 6
Thresholds associated with different functionalities for the case study.

	Fire category, c						
Functionality	1	2	3	4	5	6	7
Safety	1	1	1	1	1	1	1
Connectivity	1	1	1	0.5	0.5	0.2	0.2
Reliability	1	1	0.8	0.6	0.5	0.4	0.2
Efficiency	1	0.8	0.6	0.4	0.2	0.2	0.1

4.5. Resilience assessment

The roads have been represented in a simplified manner by linking several segments into a single road. Consequently, the safety functionality is evaluated based on the travel time required to reach the first exit from the node, rather than the time needed to transit the entire road. This approach is adopted due to the considerable length of the simplify roads.

On the other hand, the dynamic thresholds considered in the analyzed case for the 7 wildfire categories are indicated in Table 6. For more detail regarding dynamic threshold definitions, see Section 3.2 and more detail in [34].

Resilience increment is assessed using Eq. (2). The multi-objective problem in Eq. (1) has been solved using a Genetic Algorithm, employing the 'gamultiobj' function from the MATLAB Global Optimization Toolbox. This approach yields the corresponding Pareto front, which represents the set of optimal solutions where increases in resilience come at the expense of the increase in cost.

4.6. Results

The output of the multi-objective optimization is represented by the Pareto front shown in Fig. 6.

It provides the six best adaptation strategies, where each point represents the associated trade-off between resilience increment and adaptation costs. Each strategy accounts for different adaptation measures in different locations of the system as described in

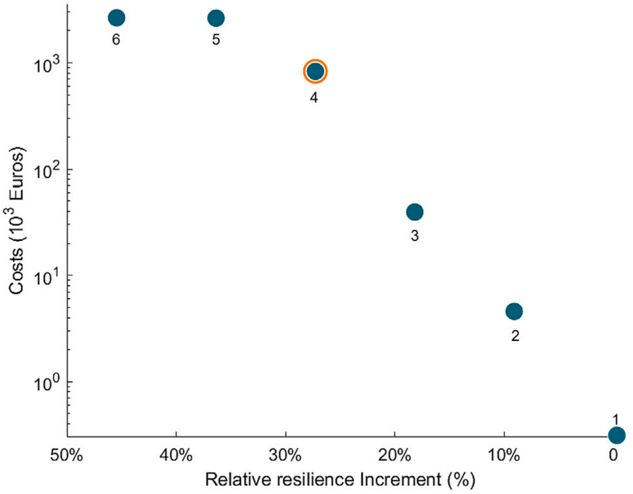


Fig. 6. Pareto Front with the optimal intervention strategies: Trade-offs between resilience increment and costs.

Table 7
Intervention of the system components (zones, roads, and OD) based on the identified optimal strategies.

Adaptation and location	Influence	Strategy					
		1	**2**	**3**	**4**	**5**	**6**
ROS zone 1	ROS reduction (m/min)	0	0	0	0	5	5
ROS zone 2		0	0	0	0	0	0
ROS zone 3		0	0	0	0	0	0
ROS zone 4		0	0	0	5	10	10
ROS zone 5		0	0	0	0	0	0
ROS zone 6		0	0	0	0	0	0
Firebreak link 1	Firebreak width (m)	0	0	0	10	10	20
Firebreak link 2		0	0	0	0	0	0
Firebreak link 3		0	0	0	0	0	0
Firebreak link 4		0	0	20	20	20	20
Firebreak link 5		0	0	0	0	0	0
Firebreak link 6		0	0	20	20	20	20
Firebreak link 7		0	0	0	0	0	0
Firebreak link 8		0	0	10	10	10	20
Firebreak link 9		0	20	20	20	20	20
Firebreak link 10		0	0	20	20	20	20
Demand OD 1	Demand reduction (% users)	0	0	0	0	0	0
Demand OD 2		0	0	0	0	0	0
Costs (10^3 Euros)		0.0	4.6	39.4	830.3	2632.8	2652.8
Resilience (%)		39.3	42.9	46.4	50.0	53.6	57.1
Resilience increment (%)		0%	9%	18%	27%	36%	45%

Table 7. Zero value means no adaptation is suggested for that component and location. Note that Strategy 1 corresponds to BAU scenario, i.e., no adaptation. Achieving higher resilience incurs higher adaptation costs. For instance, increasing resilience in 45% corresponds to an investment of 2.7 million euros in the following 5 years (see Strategy 6). Conversely, Strategy 1 indicates no improvement in resilience, resulting in no additional costs. Intermediate points, such as Strategy 2, represent a lower resilience increment (9% compared to the initial resilience) but at a reduced cost compared to Strategy 3.

Table 7 suggests that Zones 1 and 4 are the key areas for enhancing resilience. Zone 4 consistently requires mosaic interventions, particularly through cleaning and vegetation replacement (Strategies 4, 5, and 6). Zone 1 also exhibits notable potential for improvement, especially in Strategies 5 and 6, suggesting vegetation cleaning, i.e., a 5 m/min reduction in ROS. Therefore, these zones are crucial to improve system resilience and should be prioritized for adaptation.

On the other hand, several firebreaks are suggested to improve resilience in each of the adaptation strategies, highlighting the critical links for each road and their contribution to system resilience. The final segment of Road N236-1 is one of the most important roads, with its links (9 and 10) consistently suggesting the need for a 20-m-wide firebreak. This highlights its importance in enhancing resilience. In contrast, only one side of the rest of the roads are identified in the adaptation strategies, such as Links 4, 6, and 8, with firebreak widths ranging from 10 to 20 m under Strategies 3 to 6. Road N2 shows minimal intervention, limited to Link 1 in Strategies 3–6. These results emphasize the prioritization of critical links to maximize resilience benefits while ensuring efficient resource allocation. Further discussion on firebreak effectiveness will be provided in Section 5.

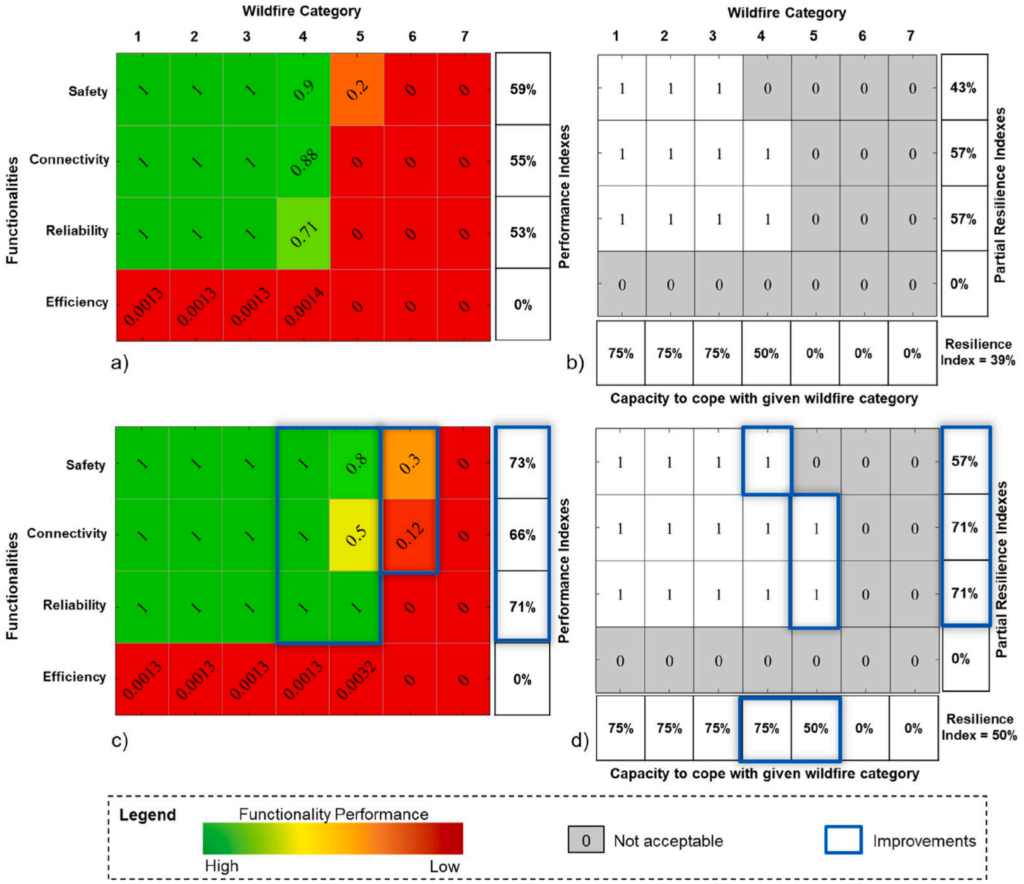


Fig. 7. Comparison of system resilience: (a) Initial performance and (b) resilience without adaptation, R_0. (c) Performance and (d) resilience after adaptation measures, $R(x)$, following Strategy 4. Blue boxes highlight the changes in both scenarios. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In the case of the OD demand reduction, they are not considered in the optimal combination of adaptation strategies. Despite the area's high exposure, roads in this region are relatively short, enabling users to quickly and safely find alternative routes. Therefore, it is more beneficial to focus on reducing exposure in nearby zones, also for cost-related reasons. However, for longer routes with limited or no alternative routes available, such as those in Canada and Australia, proactively closing of roads could be an effective adaptation strategy to enhance resilience.

These adaptation strategies enhance network functionalities leading to increased compliance with dynamic thresholds. This can be appreciated in Fig. 7, which compares the road network's performance before and after adaptation using as an example the optimal Strategy 4. Fig. 7(a) and (c) represent the performance matrices without and with adaptation, respectively. In both cases, the performance degrade as wildfire intensity increases. However, the adapted scenario demonstrates improved performance.

The adaptation strategy significantly enhances performance, particularly for wildfire categories 4 to 6, which represent extreme intensities. The relative improvements in overall safety, connectivity, and reliability are 24%, 20%, and 34%, respectively. Similarly, Fig. 7(b) and (d) compare compliance matrices before and after adaptation. The improvements in the partial resilience index, shown in the last column, and the system's capacity to cope with various fire intensities, shown in the last row, are both highlighted with blue boxes. Specifically, there is a notable improvement starting from wildfire category 4, where the coping capacity increases from 50% to 75%, and for wildfire category 5, where the capacity increases from 0% to 50%. The most noticeable changes concerning the partial resilience indexes are safety, connectivity and reliability. Safety increases compliance from 43% to 57%. Note that improving safety is more difficult because the thresholds are stricter. Finally, it can be seen that the system resilience would improve from 39% to 50% when applying adaptation Strategy 4.

5. Discussion with a focus on decision-making support

The information provided by this methodology offers important support to stakeholders involved in wildfire management and adaptation. For instance, the Pareto front serves as a practical tool, providing stakeholders with a comprehensive perspective of the trade-offs of different optimal strategies. This enables them to identify strategies that strike the best balance between increasing

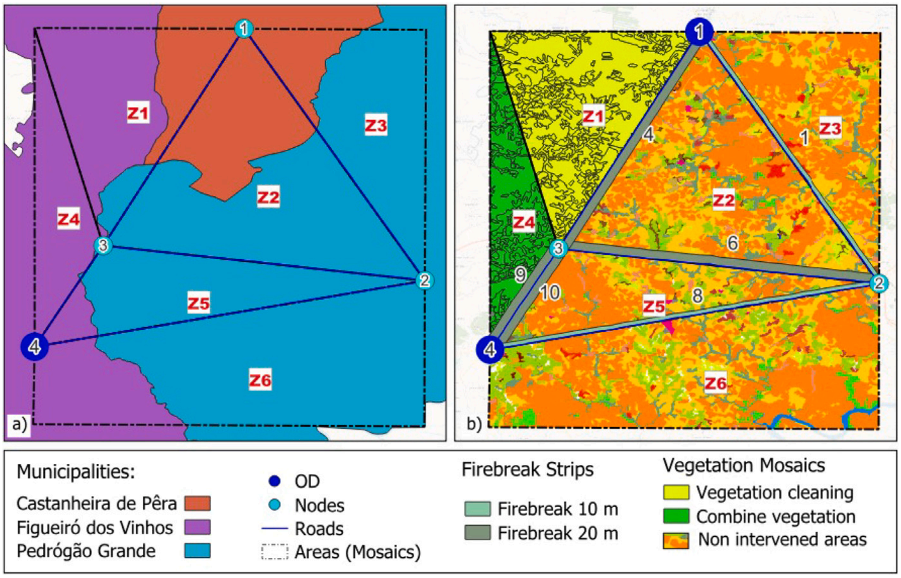


Fig. 8. Land and road management based on optimal adaptation Strategy 5. (a) Municipalities responsibilities. (b) Location of adaptation measures.

resilience and managing costs. The selection of a specific option depends on stakeholder criteria, influenced by their interests and resource availability.

When discussing system adaptation, various stakeholders, such as land and road infrastructure managers, are involved. Hence, it is crucial to identify their respective responsibilities. This methodology facilitates the identification of stakeholder responsibilities. This will be exemplified based on Strategy 5 shown on the Pareto front in Fig. 6.

The availability of resources to adapt the land and road infrastructure may be linked to administrative divisions, such as municipalities. Fig. 8 illustrates the responsibilities of each municipality regarding these aspects. For instance, the analyzed strategy suggests applying mosaic vegetation adaptation in Zones 1 and 4. Mosaic in Zone 1 involves stakeholders from the three municipalities, while Zone 4 involves stakeholders from one municipality. Involving more stakeholders can increase the complexity of adaptation management.

In cases where the resources and execution of adaptation measures depend on municipalities, coordination is essential. Non-compliance by any party may adversely affect others. For instance, if Castanheira de Pera does not take care of the vegetation actions in Zone 1, the fire could spread throughout the entire area and reach Road N236-1 faster. Achieving increased resilience hinges on all parties fulfilling their commitments to the full set of adaptation measures. Failure to comply with any measure prevents achieving the desired resilience level. Thus, managing forest interventions requires a good understanding of forest ecosystem dynamics as well as stakeholder engagement and cooperation [25].

It is worth noting that 3-m-wide fuel strips are not selected by any of the optimal strategies to increase resilience. Firebreaks are widely recognized as an important measure for wildfire prevention, particularly along roads where many fires originate, as they can significantly reduce the number of ignitions caused by traffic passing through them [45]. Therefore, the wider the firebreak the more effective. Studies such as [46] show that 30-m-wide firebreaks can reduce burn probability by up to 27%, while [47] showed that 120-m-wide firebreaks reduce the average burn probability by 31%. Additionally, firebreaks are useful for supporting suppression efforts (e.g., [48,49]). However, the effectiveness of narrower firebreaks, such as Portugal's mandatory 10-m-wide road firebreaks, may be limited, particularly given that 98% of wildfires in Portugal are attributed to arson [50].

It is important to mention that, vegetation mosaics and firebreak strips do not offer complete safety for individuals or vehicles caught in a fire, nor can they completely stop the spread of wildfires [45]. For instance, the effectiveness of firebreaks varies with fire intensity. [46] report that under high seasonal severity rating scenarios, wildfire risk remained significant even with optimal fuel treatments (30-m-wide firebreaks, prescribed burning, and fuel thinning). These results align with the conclusions presented in this study, as the adaptation measures do not enhance system performance under the most extreme wildfire intensities, wildfire category 6 and 7 (see Fig. 7).

The administration of the road network in the area of study falls under the responsibility of the Portuguese public company *Infraestruturas de Portugal*. Thus, road network management companies oversee firebreak strips, which requires agreement and cooperation between municipalities and road infrastructure management companies in the adaptation plan. According to Portuguese law, all roads are required to have firebreaks, and proper land management practices must be implemented for all vegetation. However, the associated costs can be challenging. This study demonstrates that achieving resilience and minimizing costs does not necessarily require adapting all aspects. However, if budget constraints are not a concern, firebreak strips can serve additional purposes, such as preventing ignitions and during emergencies.

5.1. Flexibility of the framework under diverse wildfire and network contexts.

The GIS-based methodology is flexible and can be applied to any type of sources and barriers, as long as the distance from the source or barrier to the asset under study and their respective ROS are available. In [18], different ROS values are presented for various sources and barriers, including diverse land covers such as forests, farming areas, grasslands, and sports fields, as well as gas stations, power facilities, industrial and commercial areas, or buildings. Since the data used are spatial open data, such as those from OpenStreetMap (OSM), this approach facilitates widespread application and accessibility. The methodology's capacity to capture diverse wildfire conditions has been demonstrated in other case studies. For example, it was applied to a cross-border case study in Portugal–Spain, effectively capturing regional differences, as shown in [8]. The resilience framework, in turn, has been tested on various network types, see [34].

The complete optimization methodology is adaptable to any region by subdividing the study area into targeted zones. For this case study, the subdivision of areas for vegetation mosaics has been based on the road network, considering nodes and roads. However, alternative divisions could be implemented according to stakeholders' needs. For instance, divisions could be made at the municipal level to facilitate the identification of responsibilities. The GIS-FA tool has previously been used to identify stakeholders' responsibilities in a cross-border case study between Spain and Portugal [8].

Moreover, the optimization problem can be adapted by adding new constraints to accommodate the diverse needs of stakeholders. For example, a constraint might specify a minimum budget allocation for certain adaptation measures. Also, forcing interventions in specific zones or roads where adaptation is required. The latter could be determined based on road criticality, measuring the importance of a road within the transport network. These constraints ensure that the optimization process considers financial limitations and allocates resources accordingly, thereby aligning with the practical constraints and objectives of stakeholders involved in decision-making.

On the other hand, applying green adaptation measures has certain challenges, which include the maintenance of these strips, the potential environmental impacts of regular clearing, and the need for coordination among various stakeholders to ensure effectiveness. In this case, the ecological and social costs associated with the adaptations have not been considered in the optimization problem. However, there is potential to include them as additional objectives to be optimized. Ecological issues exist stemming from green adaptations, such as habitat loss due to vegetation replacement of firebreak strips. These issues have not been thoroughly examined in this work. Nonetheless, it is imperative to address these concerns from the outset when designing such measures. This will therefore be analyzed in future work. By integrating ecological and social considerations into the optimization process, adaptation strategies can be ensured to enhance resilience and minimize adverse impacts on ecosystems and communities.

In addition, other types of adaptation measures can be analyzed, or the effectiveness of adaptation can be compared across different measures, such as grey versus green adaptations. The methodology is flexible enough to include all these types of modifications. In either case, the key to effective adaptation is the combination of different measures. Nonetheless, it is imperative to be aware that fuel management alone does not eliminate the need for efficient fire suppression efforts. Enhancing preparedness and resilience levels will not be effective unless there is a proficient firefighting force ready to respond quickly and effectively. If firefighting is unable to capitalize on the slow spread of fire facilitated by fuel management strategies, the risk of escalating fires remains significant. Even with appropriate adaptation, there may still be instances in which adverse weather conditions allow fires to escalate beyond control.

In this regard, the methodology can also aid in emergency management by identifying areas with minimal exposure and providing the functionality of the transport system under varying fire intensities through the use of FIRAT maps. These maps provide information on the action time before the fire reaches the roads for different wildfire categories, with applications found in [8,40]. This information can effectively assist in establishing shelters and devising evacuation routes and plans.

6. Conclusions

To address the increasingly severe wildfires of recent decades, a fundamental shift is needed in societal perceptions and wildfire management practices, fostering a more sustainable coexistence with fire. This entails greater acceptance and implementation of adaptation strategies to enhance resilience to wildfires. However, the concepts of adaptation and resilience are relatively new in wildfire management, and there is a lack of tools to assess the impact of adaptation measures effectively.

This study demonstrates the effectiveness of a resilience preparedness framework in evaluating the systemic impact of different adaptation measures (i.e., green, grey, soft). The novel framework identifies the most cost-effective strategy to enhance system resilience and guides optimal implementation locations. Demonstrated in a real case study, it serves as a decision-making tool in the management of wildfires and infrastructure, offering stakeholders a variety of optimal strategies aligned with their objectives and constraints. Moreover, integrating dynamic thresholds into the resilience framework offers a way to accommodate stakeholders' diverse interests regarding their tolerance for system functionality loss in varying wildfire intensities. The study also explores different uses of aggregation operators from [18]'s GIS-FA methodology to support wildfire management. The framework was applied to a Portuguese case study in the Leiria region. The conclusions are case-specific; that is, the results presented here are derived from this case study, and other cases should be analyzed individually. However, the methodology is flexible and can support the study of different fire and system conditions.

Adaptation should be approached at the system level involving various stakeholders, beyond the common approach of focusing on fire suppression. The findings suggest that collaboration among municipalities, wildfire, and road infrastructure management entities is essential for successful adaptation implementation and overall resilience enhancement.

Although Portuguese legislation mandates firebreak management on all roads and proper land management, achieving resilience increases and cost minimization does not necessarily require total system adaptation. Instead, strategic selection and a combination of measures can effectively enhance the resilience of the system while managing costs.

Furthermore, effective fire suppression efforts are crucial alongside adaptive measures such as fuel management strategies. Improved preparedness and resilience must be complemented by a responsive firefighting force capable of mitigating fire spread and minimizing damage. The tool's ability to identify areas of lower exposure and assess road system functionality under varying fire intensities supports emergency management by facilitating shelter and evacuation planning. The tool's ability to evaluate and choose the most effective adaptation measures, as well as its support for emergency management, could greatly aid in achieving and fulfilling the goals of the European Union's Green Deal regarding adaptation.

Finally, while ecological and social costs are not currently integrated into the optimization processes, their consideration in future studies is likely to lead to more sustainable wildfire management strategies. Another future study involves estimating the increase in resilience in economic terms to allow comparison with adaptation costs.

CRediT authorship contribution statement

Erica Arango: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Maria Nogal:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Hélder S. Sousa:** Writing – review & editing, Supervision, Funding acquisition. **José C. Matos:** Writing – review & editing, Supervision, Funding acquisition. **Mark G. Stewart:** Writing – review & editing, Validation, Supervision, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Erica Arango reports financial support was provided by Foundation for Science and Technology (FCT), Portugal. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments and funding statement

This work was partly financed by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020 (doi.org/10.54499/UIDB/04029/2020), and under the Associate Laboratory Advanced Production and Intelligent Systems ARISE under reference LA/P/0112/2020.

This work is financed by national funds through the FCT, Foundation for Science and Technology, under grant agreement 2020.05755.BD (doi.org/10.54499/2020.05755.BD) attributed to the first author.

This work was also supported by the Dutch Research Council (NWO) and the Department of Science & Technology, India (DST), through the Merian Fund under Grant No. 482.482.302.

Appendix A. Scenario analysis of exposure and EFD

See Table A.1.

Appendix B. Adaptation measures costs. Detailed costs for each adaptation measure for the year 2022, differentiated between implementation and maintenance cost

See Table B.1.

Appendix C. Sensitivity analysis

In this section, the sensitivity of the results to two parameters is discussed, namely, the discount rates and value of ROS_{min}.

First, the optimization is conducted to assess the impact of varying discount rates (1%, 2%, 3%, and 5%) on adaptation costs, and consequently, on the cost-benefit trade-offs. The results, shown in Table C.1, indicate that the optimal strategies remain the same across the different interest rates, with only minor variations observed in the total costs associated with each strategy.

Regarding the assumed ROS_{min} value (Eq. (3)), two values are considered, namely, 0 and 7 m/min, while maintaining the same adaptation costs with a discount rate of 2%. The value of 7 m/min is based on the typical ROS rates observed in low-exposure forest types. ROS of 0 m/min is the minimum value, although it is not realistic due to the significant challenges involved in maintaining such conditions through mosaic management.

The comparison of the Pareto fronts for these two scenarios is presented in Fig. C.1. This parameter influences the optimization model's outcomes, including the selection of adaptation strategies, resilience improvements, and associated costs. For $ROS_{min} = 7$ m/min, the maximum ROS reduction for the different zones is limited, therefore, the maximum resilience increment achievable across the evaluated strategies is 45%. In contrast, when the minimum ROS is relaxed to 0 m/min, the model allows further

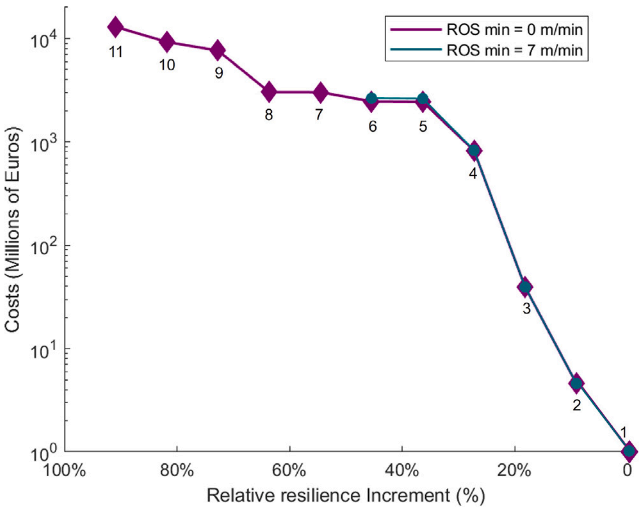


Fig. C.1. Comparison of Pareto fronts for different ROS min thresholds with constant costs.

reducing ROS, enabling resilience improvements of up to 91%. While this provides the potential for more substantial enhancements in resilience, it also results in significantly higher costs as shown in Table C.2. However, adaptation Strategies 1 to 3 are the same and Strategies 4 to 6 differ only in the width of the firebreak for Links 4 and 10.

The choice of ROS_{min} must balance practical considerations with resilience goals. Stricter thresholds aim to reflect a more conservative strategy, particularly for areas with high exposure where vegetation management is challenging. For instance, during the 2017 Pedrógão Grande wildfire, one of the sources of fire spread was poorly maintained crops with the presence of invasive species. Therefore, adopting a higher ROS_{min} value accounts for the practical limitations of poor land management, whereas a $ROS_{min} = 0$ m/min assumes ideal conditions in which vegetation-based adaptations function optimally. This sensitivity underscores the importance of calibrating ROS_{min} to local conditions and objectives in order to achieve feasible adaptation strategies.

Table A.1
Aggregation operators analysis.

Scenario	Source	ROS (m/min)	$d_{i,l}$ (m)	Ed$_l$ (m)	EFD_i aver. (m)	EFD_i ws (m)
A. Initial system	Grassland	50	20	20	410	78
	Eucalypt plantation	25	8	16		
	Eucalypt plantation	25	5	10		
	Eucalypt plantation	25	3	6		
	River	1	40	2000		
B. Including a higher fire propagation source at 3 m in Scenario A. It is expected to increase exposure and thus reduce EFD.	Grassland	50	20	20	410 (0%)	77 (−1%)
	Eucalypt plantation	25	8	16		
	Eucalypt plantation	25	5	10		
	Shrubs	35	3	4		
	River	1	40	2000		
C. Including a new barrier in Scenario A - firebreak 3 m width. It is expected to reduce exposure and thus increase EFD.	Grassland	50	20	20	439 (+7%)	143 (+83%)
	Eucalypt plantation	25	8	16		
	Eucalypt plantation	25	5	10		
	Firebreak (3 m)	1	3	150		
	River	1	40	2000		
D. Including a new barrier in Scenario A - firebreak 20 m width. It is expected to reduce exposure and thus increase EFD.	Grassland	50	20	20	564 (+38%)	274 (+251%)
	Firebreak (20 m)	1	8	400		
	Firebreak (20 m)	1	5	250		
	Firebreak (20 m)	1	3	150		
	River	1	40	2000		
E. Implementing vegetation cleaning in Scenario A, reducing ROS in e.g., 5 m/min. It is expected to reduce exposure and thus increase EFD.	Grassland	45	20	22	412 (0%)	80 (3%)
	Eucalypt plantation	20	8	20		
	Eucalypt plantation	20	5	13		
	Eucalypt plantation	20	3	8		
	River	1	40	2000		
F. Implementing vegetation to reduce ROS in e.g., 15m/min. It is expected to reduce exposure and thus increase EFD.	Grassland	35	20	29	422 (+3%)	91 (+17%)
	Eucalypt plantation	10	8	40		
	Eucalypt plantation	10	5	25		
	Eucalypt plantation	10	3	15		
	River	1	40	2000		
G. Including combined adaptation measures in Scenario A, vegetation cleaning (5 m/min) and firebreak 20 m width. It is expected to reduce exposure and thus increase EFD.	Grassland	45	20	22	564 (+38%)	274 (+251%)
	Firebreak 20 m	1	8	400		
	Firebreak 20 m	1	5	250		
	Firebreak 20 m	1	3	150		
	River	1	40	2000		

Table B.1
Adaptation measures — Detail costs. FV: Future value, cost brought forward to 2022.

Adaptation	Type of investment	Intervention	Year	Value	Units	REF	
Cleaning	Initial investment & Maintenance	Clearing undergrowth with a brush cutter or harrow: Continuous plowing, or Ditch and hill, or Plantation watering	2022	62.100	€/km^2	[51]	pag 31 C1a
		Control of woody invasive — cutting and brushing (includes product)		90.200	€/km^2		pag 36 L8a
				152.300	€/km^2		
Combine veg.	Initial investment	Clearing undergrowth with a motorized brush cutter and digging holes with an auger	2022	190.800	€/km^2	[51]	pag 31 C1a
		Installation of soil-improving crops with land preparation. Weeding and ridging		27.000	€/km^2		pag 34 k2
		Chestnut tree planting/sowing, fertilizing, mulching, and materials		169.200	€/km^2		pag 33 H3
				387.000	€/km^2		
	Maintenance	Control of woody invasives	2022	50.000	€/km^2	[51]	E1a
		Weeding and hilling (only eligible for broadleaves)		27.000	€/km2		K1
		Clearing undergrowth with a brush cutter or harrow: Continuous plowing, or Ditch and hill, or Plantation watering		62.100	€/km^2		pag 31 C1a
				139.100	€/km^2		
Veg. replacement	Initial investment	Reducing excessive density (young stands): Forest stands between 3000 and 7000 trees/ha	2022	60.100	€/km^2	[51]	pag 35 L4
		Formative pruning		58.500	€/km^2		pag 35 L2
		Clearing undergrowth with Destruction of eucalyptus stumps and ditch and hillock		102.800	€/km^2		pag 32 D3a
		Soil treatment: fertilization		12.200	€/km^2		pag 35 k4
		Chestnut tree planting/sowing, fertilizing, mulching, and materials		169.200	€/km^2		pag 33 H3
		Control of woody invasive		50.000	€/km^2		pag 35 L7a
				452.800	€/km^2		
	Maintenance	Control of woody invasive	2022	50.000	€/km^2	[51]	E1a
		Clearing undergrowth with a brush cutter or harrow: Continuous plowing, or Ditch and hill, or Plantation watering		62.100	€/km^2		pag 31 C1a
		Weeding/Pruning		52.800	€/km^2		L1
		Formative pruning		58.500	€/km^2		L2
				223.400	€/km^2		
Firebreak strips	Initial investment	Fuel management strips for municipal road networks	FV(2008) at 2022	**164.95**	€/km^2	[52]	Pag 2 – 11
	maintenance	(assumed as half of the initial price)	2022	**82.47**	€/km^2		

(*continued on next page*)

Table B.1 (*continued*).

Reduction of 25%	Initial investment	Simple temporary signaling kit (24 h)	FV (2016) at 2022	1.098,49	€	[53]	pag 10
		Temporary traffic restrictions (per section of road or intersection)	2022	115,90	€	[54]	pag 4 5.2.4
		Campaign (25% total cost)	2022	214.948,84	€		
				216.163,24	€		
	Maintenance	2 awareness-raising actions per year (2 h each)	2022	**6.000**	€		
Reduction of 50%	Initial investment	Simple temporary signaling kit (24 h)	FV (2016) at 2022	1.098,49	€	[53]	pag 10
		Temporary traffic restrictions (per section of road or intersection)	2022	115,90	€	[54]	pag 4 5.2.4
		Campaign (50% total cost)	2022	429.897,69	€		
				431.112,08	€		
	Maintenance	3 awareness-raising actions per year (4 h each)	2022	**18.000**	€		
						link	
Route closure	Initial investment	Surveillance actions in critical periods/areas	2022	290,0	€		pag 82
		4 awareness-raising actions per year (4 h each)	2022	24.000	€	[55]	pag 72
		Development and production of the forest fire prevention campaign	FV (2007) at 2022	859.795,38	€	[56]	pag 4
		Simple temporary signaling kit (24 h)	FV (2016) at 2022	1.098,49	€	[53]	pag 10
		Temporary traffic restrictions (per section of road or intersection)	2022	115,90	€	[54]	pag 4 5.2.4
				885.299,77	€		
	Maintenance	4 awareness-raising actions per year (4 h each)	2022	**24.000**	€		

Table C.1
Impact of discount rate variations on optimal adaptation strategies.

Location	Influence	Strategy					
		1	**2**	**3**	**4**	**5**	**6**
Zone 1	ROS reduction (m/min)	0	0	0	0	5	5
Zone 2		0	0	0	0	0	0
Zone 3		0	0	0	0	0	0
Zone 4		0	0	0	5	10	10
Zone 5		0	0	0	0	0	0
Zone 6		0	0	0	0	0	0
Link 1	Firebreak width (m)	0	0	0	10	10	20
Link 2		0	0	0	0	0	0
Link 3		0	0	0	0	0	0
Link 4		0	0	20	20	20	20
Link 5		0	0	0	0	0	0
Link 6		0	0	20	20	20	20
Link 7		0	0	0	0	0	0
Link 8		0	0	10	10	10	20
Link 9		0	20	20	20	20	20
Link 10		0	0	20	20	20	20
OD 1	Demand reduction (% users)	0	0	0	0	0	0
OD 2		0	0	0	0	0	0
Resilience increment (%)		0%	9%	18%	27%	36%	45%
Costs (10^3 Euros) for different discount rates	1%	0.00	4.5	38.6	806.4	2560.8	2580.4
	2%	0.00	4.6	39.4	830.3	2632.8	2652.8
	3%	0.00	4.7	40.6	855.5	2707.4	2727.8
	5%	0.00	5.0	42.9	907.4	2868.0	2883.5

Table C.2
Optimal adaptation strategies with $ROS_{\min}$ threshold of 0 m/min and a discount rate of 2%.

Location	Adaptation Influence	Strategy										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Zone 1	ROS reduction (m/min)	0	0	0	0	5	5	10	10	0	5	10
Zone 2		0	0	0	0	0	0	0	0	0	0	5
Zone 3		0	0	0	0	0	0	0	0	10	10	10
Zone 4		0	0	0	5	5	5	10	10	10	10	10
Zone 5		0	0	0	0	0	0	0	0	10	10	10
Zone 6		0	0	0	0	0	0	0	0	5	5	10
Link 1	Firebreak width (m)	0	0	0	10	10	20	10	20	0	3	3
Link 2		0	0	0	0	0	0	20	20	20	3	0
Link 3		0	0	0	0	0	0	20	20	20	3	10
Link 4		0	0	20	20	10	10	0	0	20	20	10
Link 5		0	0	0	0	0	0	0	0	20	10	0
Link 6		0	0	20	20	20	20	20	20	0	3	0
Link 7		0	0	0	0	0	0	0	0	0	20	3
Link 8		0	0	10	10	10	20	20	20	0	3	3
Link 9		0	20	20	20	20	20	20	20	20	10	3
Link 10		0	0	20	0	0	0	0	0	10	10	10
OD 1	Demand reduction (% users)	0	0	0	0	0	0	0	0	0	0	0
OD 2		0	0	0	0	0	0	0	0	0	0	0
Costs (M euros)		0.0	0.005	0.039	0.827	2.447	2.467	3.025	3.034	7.660	9.284	12.995
Resilience (%)		39,3	42,9	46,4	50,0	53,6	57.1	60.7	64.3	67.9	71.4	75.0
Resilience increment (%)		0%	9%	18%	27%	36%	45%	55%	64%	73%	82%	91%

Data availability

Data will be made available on request.

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