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Improving societal resilience through a GIS-based approach to manage road transport networks under wildfire hazards

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ABSTRACT

Climate change is causing an increase in the frequency and intensity of wildfires, demonstrating that our capacity to respond to them is insufficient. Therefore, it is necessary to reconsider wildfire management policies, practices, and decision-support tools, extending beyond emergency measures. This study presents the extension of a GIS-based methodology for fire analysis, providing decision-making support for the implementation of new fire-related policies for road transportation infrastructure. It represents a novel contribution that facilitates the transition towards proactive wildfire policies. The framework is demonstrated to support informed decision-making, addressing both reactive actions, i.e., emergency response, and the evaluation of proactive adaptation measures at a system level. The results suggest that landscape management policies can play an important role in improving the resilience of road networks to wildfires.

Introduction

Most communities have built considerable resilience to wildfires over time. However, increasing human encroachment on the natural environment and the impacts of climate change are testing our ability to respond to wildfires worldwide. While wildfires were once concentrated in certain areas, such as the Mediterranean region of Europe, the risk is now spreading to central and northern Europe. This shift is evident in countries like Ireland, Sweden, and the Netherlands, which are already experiencing these unexpected events. Climate change is a key factor contributing to the increased propensity and intensity of wildfires [6, 23]. Consequently, the fire season extends beyond the traditional summer months, occurring more frequently and impacting various regions each year. The emergence of a new generation of wildfires characterized by extreme behavior has been recently acknowledged.

Recognizing the surge in extreme wildfires, many countries have substantially enhanced their wildfire management practices, i.e., planning, prevention, and suppression of fires to safeguard society. The primary focus has been on strengthening emergency preparedness and response capacities. For instance, initiatives like the EU Civil Protection Mechanism in the European Union have invested significant efforts in coordinating wildfire suppression [14]. In this perspective, land-based transport infrastructure plays a crucial role in wildfire management, as society depends on it for evacuation and accessibility to emergency facilities during and after emergency scenarios. Therefore, there are several improvements in fire monitoring (e.g., the European Forest Fire Information System, EFFIS, or [11]), early warnings (e.g., [9]), and evacuations (e.g., [7,16,22]). However, the escalating frequency and severity of wildfires have revealed limitations in emergency response [19]. Extreme wildfires strain resources and hinder effective containment, prompting the need for a comprehensive approach beyond emergency measures [5]. Thus, it is necessary to change the paradigm and assume that it will be impossible to eliminate wildfire risk and that we must learn to live with it [10,15,20]. This highlights the significance of prioritizing adaptation and proactive prevention in wildfire management. Recognizing the limited benefits and substantial investments related to emergency response, there is significant potential in adopting proactive adaptation policies and practices to strengthen society's resilience. Proactive adaptation policies refer to efforts to minimize susceptibility to wildfires by adapting land-use plans, i.e., landscape management, fuel management, ecosystem protection, and forest adaptation, as well as constructing buildings with enhanced fire resistance.[13].

There are several limitations to realizing a paradigm shift towards

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these resilience-oriented policies, including a limited understanding of the new regimen of extreme weather events (EWE) and the absence of efficient tools to support the implementation of these policies. Consequently, there are two primary challenges in the current state of addressing wildfire resilience in transportation networks; (I) there has been limited effort to quantify the preparedness capacity of these networks for wildfire impacts; (II) Despite efforts towards climate-change mitigation by orienting transport planning policies towards the reduction of GHG emissions (e.g., [2,3]), and some attempts to consider climate-change adaptation (e.g., [1,18]); there is a notable absence of frameworks for evaluating policies aimed at enhancing the resilience of road transport networks to wildfires, especially at the system level and in alignment with the characteristics of proactive adaptation measures. The first issue has been addressed in the GIS-based fire analysis methodology, GIS-FA, proposed by Arango et al. [4], which evaluates the exposure and criticality of road transportation infrastructure to different wildfire hazards. Building upon that work, the present study aims to overcome Issue (II) by implementing the GIS-FA for resilient policy assessment at the road system level and thus, promoting more resilient wildfire management.

In this sense, the primary contribution lies in the application of the GIS-FA methodology as an effective decision-making support tool for evaluating adaptation policies and strategies. This tool enables the examination of the relevance of policies related to emergency response during wildfires (reactive measures) and policies towards enhancing wildfire coping capacity (proactive adaptation measures). Specifically, the tool is able to assess the effectiveness of grey, green, and soft adaptation measures. Grey measures involve physical infrastructure and engineering solutions, green measures focus on natural and ecological strategies, and soft measures encompass behavioral changes. This assessment is achieved by considering physical, environmental, and social factors and their interactions at the system level. In this context, the proposed methodology supports the creation of policies to prevent, adapt, and cooperate to combat wildfires and improve management across Europe and worldwide.

The framework considers different wildfire categories, enabling the evaluation of policy benefits for both normal and extreme wildfires, and providing a comprehensive understanding of the advantages in terms of exposure reduction, resource allocation, and overall system resilience. The application of the framework is given in a case study in the Portuguese region of Leiria. The modeling process and visualization of results are automated using a Geographic Information System (GIS). In this way, the relevant information is provided to stakeholders (e.g., emergency first responders, infrastructure managers, and policymakers) in a timely and usable manner, during regular operations as well as during emergency scenarios, allowing a more efficient decision-making process.

The rest of the document is organized as follows. Section 2 presents the methodology description, applied to the case study in Section 3. The results are presented in Section 4, the discussion of results from the policy point of view in Section 5, and some conclusions are drawn in Section 6.

GIS-FA methodology

The GIS-FA methodology is based on exposure and criticality analyses encompassing factors linked to EWE causes and consequences. For the sake of clarification, the wildfire hazard is understood as the inherent source of damage. The concept of exposure is employed instead of vulnerability based on evidence suggesting that extreme hazard risk is more influenced by exposure than vulnerability [21]. Exposure is defined as the extent to which an organization and/or stakeholder is subject to an event and vulnerability as the intrinsic properties of something resulting in susceptibility to a risk source that can lead to an event with a consequence [8]. In the context of road networks, exposure pertains to the degree to which an asset is susceptible to an event depending on its geographical location. Meanwhile, vulnerability is related to factors like pavement properties, which are normally uniform throughout the network. Therefore, the concept of vulnerability loses relevance. Criticality quantifies the impact of not being able to use a specific road segment, i.e., with more critical roads leading to more severe consequences. Both concepts, normally associated with risk, are adopted from a resilience perspective, i.e., with a broader approach that emphasizes the system's ability to cope with the unexpected.

The causes are determined at the asset level utilizing the FIRe Arrival Time (FIRAT), an exposure metric that considers seven diverse types of wildfire behaviour, including EWE., It provides an exposure mapping in terms of average time (expressed in minutes) for a random fire to reach each asset (i.e., road). The FIRAT is calculated based on the Ratio of Spread (ROS) and the Equivalent Fire Distance (EFD). ROS, the fire propagation rate associated with a burning source, is one of the most characteristic parameters of wildfire behaviour and is easily related to distance. EFD is the equivalent distance between a certain asset and all nearby burning sources and fire extinguishers (hereinafter referred to as sources and barriers) that cause or change the level of fire exposure. The computation of EFD involves a homogenization process using a reference source, to allow the aggregation of the distances corresponding to all sources/barriers based on a ROS ratio. Since the framework is resilience-based, the ignition point is irrelevant, i.e., it is expected that any random wildfire will occur regardless of the reasons that cause it.

Through the criticality approach with an emphasis on social dimensions, the wildfire consequences on a road traffic network are quantified at the system level. This analysis considers (I) the road traffic network's topological properties, to assess connection based on nodes and links' locations and configurations; and (II) the traffic demand and network performance in terms of travel time cost. Criticality analysis measures the increase in total travel time caused by the disruption of different components of the road traffic network (i.e., links) when affected by wildfires. The links are disrupted one at a time. To evaluate the corresponding travel times, the approach uses a stochastic user equilibrium model as a traffic assignment model (see [24]), which implies a biased perception of users who do not have a perfect knowledge of the situation and other users' responses. The results allow the identification and classification of the network links based on their importance within the network. For instance, a road with either high demand or low redundancy can be identified as a critical one, whereas roads with several alternative options or barely used will be ranked as low criticality.

The exposure and criticality analyses are normalized between 0 and 1 using the maximum and minimum obtained values. Then, following a risk-inspired approach, exposure and criticality values are multiplied to obtain the priority level for the intervention of each link. The general framework steps are presented in Table 1. The reader is referred to Arango et al. [4] for a detailed description of the methodology.

The GIS-FA framework facilitates the assessment of different policies (green, grey, and soft adaptations) impacting environmental, social, or physical aspects, which are incorporated into the exposure and criticality analysis through fire and traffic conditions, respectively. In that sense, adaptation measures aimed at reducing exposure are reflected in the FIRAT classification, and traffic-related adaptation measures are reflected in the criticality ranking. The priority level for intervention serves to indicate where to intervene and to objectively evaluate the effectiveness of different adaptations. The schematic representation of the approach is depicted in Fig. 1, which is based on the GIS-FA methodology proposed by Arango et al. [4] and is extended to allow policy evaluation.

Case study

GIS-FA methodology is applied to the municipality of Pedrógão Grande located in the Leiria District, Central Region of Portugal. This area was one of the most affected by the wildfires that occurred in 2017.

Table 1
Methodology steps based on resilience for road transport systems affected by wildfires.

Exposure analysis	Criticality analysis
1. Inputs definition. Studied asset (e.g., road); fire propagation sources, reference source, existing barriers and the wildfire classification of Tedim et al. [17].	**1. Inputs definition.** Traffic network topology (nodes, links, links length), road characteristics (lanes and road type), Origin-Destination (OD) pairs, routes, and OD traffic demand.
2. ROS values identification for the different sources and barriers (i), considering the source and zone characteristics.	**2. Fitting** the assignment traffic model with real traffic data.
3. ROS ratio estimation. $W_i = ROS_{ref}/ROS_i$, Where ROS_{ref} is the ROS of the reference source and ROS_i the ROS of each source and barrier (i).	3. Estimate the **reference total travel** cost (no damage scenario).
4. Distances calculation. d_i measure between fire propagation sources/barriers to the studied asset.	**4. One-at-the-time analysis**, reducing a percentage of each link's initial capacity and estimating the associated total travel cost.
5. EFD calculation. $EFD = W_i \cdot d_i$ d_i real distances from the sources and barriers to the asset.	5. Calculate the **relative increment** of travel cost regarding the reference cost.
6. FIRAT estimation. $FIRAT = EFD/ROS_{FC-i}$ *EFD*: Equivalent Fire Distance (after homogenization process) and ROS_{FC-i} is the ROS associated with each fire type according to Tedim et al. [17].	**6. Criticality Ranking.**
Priority level for intervention = Exposure*Criticality	

The case study with the respective transport network is shown in Fig. 2. The transport network is mainly composed of primary networks and is defined by 45 nodes (blue-shadowed) and 118 links. Red shadowed nodes are origin and destination (OD) nodes.

The process is followed as specified in Table 1, assuming as the asset of study the road network's links. The fire propagation and barrier sources were defined using available information from Open Street Maps in QGIS, a free and Open-Source Software, along with land cover data from DGT (2018), also Open-Source. Thus, the considered fire propagation sources are the land cover (i.e., forest type, agriculture, pastures, sports) and the sources that could directly affect the asset or considerably increase the fire's speed in the event of an explosion, such as gas stations, power plants, and substations, industrial, commercial, and residential buildings. The considered barriers are wasteland (i.e., gravel pits, arid deserts, dunes, and rocky outcrops), land covered by open water bodies (i.e., lakes and the highest order rivers), and the existence of firefighter's brigades and other large water bodies (i.e., swimming pools) that can serve as backup for firefighters. ROS values are assigned according to the values given by Arango et al. [4], assuming grassland as the reference source.

The inputs needed for the traffic model, that is the network topology including nodes' coordinates and links' length, and traffic information, including link free-flow speed and AADT (average annual daily traffic) were provided by the Portuguese public company '*Infraestruturas de Portugal. S.A*'. The information is used to tune the traffic model assuming the C-logit Stochastic User Equilibrium model proposed by Zhou, Chen, and Bekhor [24] and the BPR function (as in [12]). Through a process of error minimization between the observed and modelled data, the link flow patterns associated with 113 routes and a total of 25 OD pairs are obtained. In the criticality study, the traffic model under normal conditions, i.e., without damage scenario, is considered as a reference and then used in the one-at-the-time analysis. For this, the degradation introduced to each link considers a remaining capacity of 1% of the initial capacity to study the influence on the network's overall travel time. For more details about methodology and procedure, see Arango et al. [4].

Results

Fig. 3 shows the results of the exposure assessment, which consists of Fire Arrival Time (FIRAT) maps associated with two different wildfire categories. FIRAT maps contain information about the time it takes for a random fire to reach each road, depending on the propagation capacity of the surrounding sources. Therefore, this time can be considered as the available response time before the fire reaches the roads.

These maps can serve for emergency planning. They cover a range of fire categories, from normal fires (categories 1 to 4) to extreme wildfire events (categories 5 to 7) based on the EFD. Each wildfire category is associated with a different response time. This time decreases with the increasing wildfire category. E.g., Roads 56 and 57 have between 30 and 100 min for response before the fire reaches the roads under fire Category 1, whereas under Category 6, the response time is less than 5 min. Significant changes under the two wildfire categories can also be appreciated in Road 49, see Fig. 3 blue circles. Consequently, moving from one fire category to another significantly affects the number of safe roads available for any type of response under a wildfire event. For instance, under fire category 1, there are 9 roads highly affected with less than 5 min for a response, meanwhile, in fire category 6 it increases to 49 roads. The new links falling into the group with a FIRAT<5 mins when changing the fire category are highlighted with a thicker red line. Other exposure variations are identified in Fig. 3 a and b which compare fire categories 1 and 6.

Criticality analysis classifies links into 4 categories from low (<0.3) to extreme criticality (0.8 – 1.0), see criticality map in Fig. 4. In this

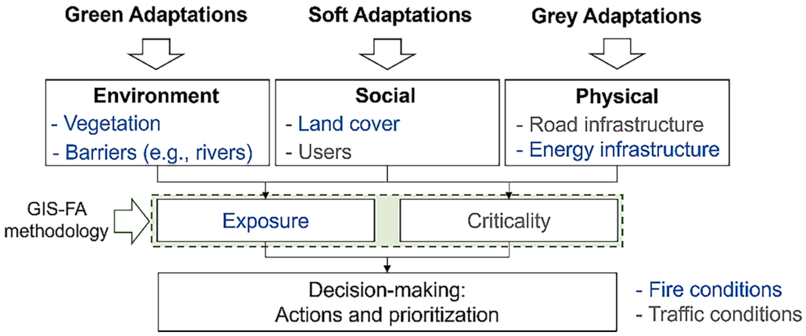

Fig. 1. GIS-FA Framework to Support Decision-Making in Adaptation Policies.

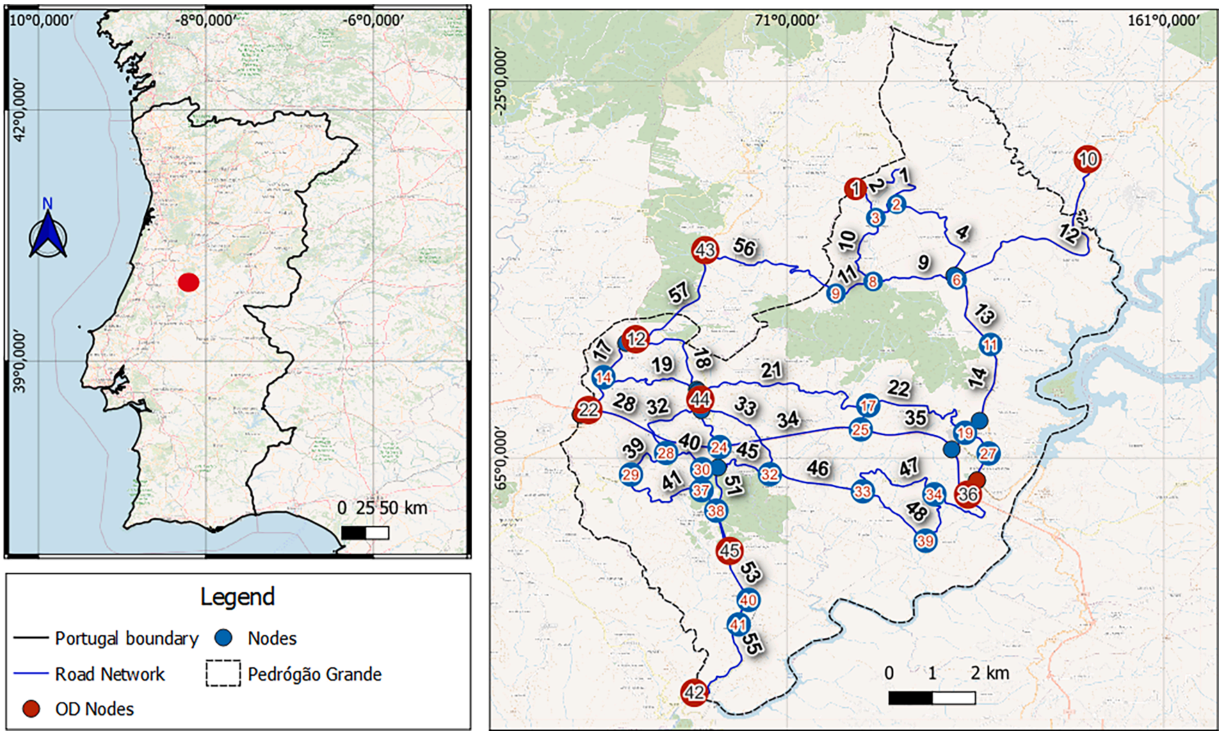

Fig. 2. Pedrógão Grande Case study - traffic network, Source of background: Open Street Maps.

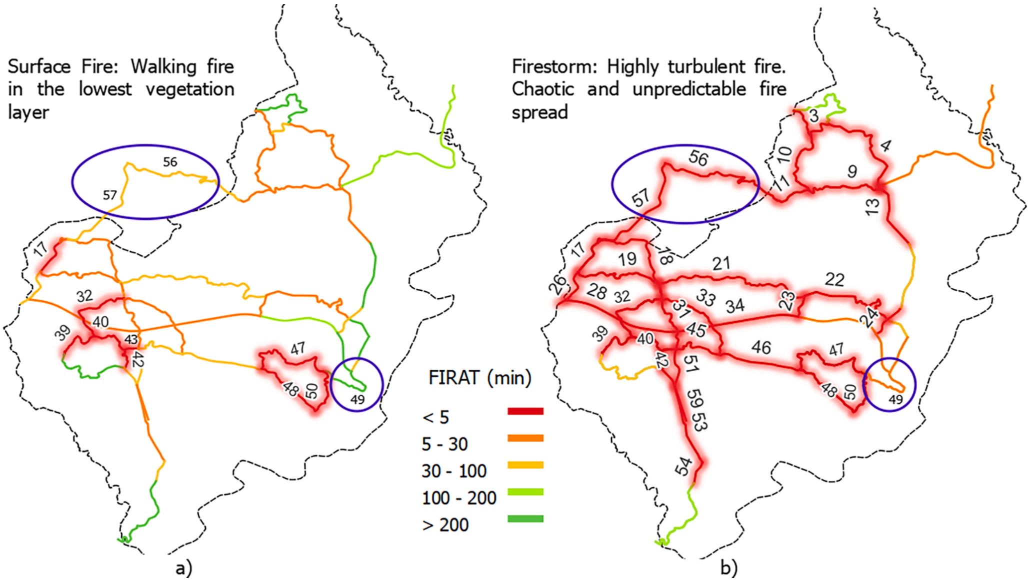

Fig. 3. Fire Approach Time – FIRAT (mins) for Pedrógão Grande traffic network (in minutes), a) Fire category 1, b) Fire category 6.

sense, 25 % of the links are of low criticality, 50 % are of medium criticality, 7 % are of high criticality, and 18 % are of extreme criticality, i.e., the most important roads into the network in terms of connectivity and number of users.

After combining exposure and criticality, a ranking of the most critical and exposed links in the network is obtained. This is represented by the priority level for the intervention map, as shown in Fig. 5. The classification ranges from Low (<0.25) to Extreme priority (>0.75). Considering their location (fire propagation sources nearby), connection, and traffic demand, links such as 93, 34, 72, 86, 57, 13, 71, and 12 are identified as of extreme priority, i.e., against any random fire, normal or EWE, these will be the most affected roads. These links are shaded in Fig. 5. They conform to a central corridor that splits the region into two, that is, the southern zone links mostly with low and medium priority levels, and the northern zone with links that require higher priority. Also, the southern roads present lower priority levels than those in the northern area. There are roads, such as 34–93, with a very high priority level for intervention due to their high exposure and criticality values. Reducing either the exposure level, the criticality, or both will decrease the wildfire risk in the entire network. Conversely, cases like road 50, which has high exposure but low criticality, result in a low priority level for intervention, as it is not a heavily used road. In these cases, the potential damage from a wildfire will be limited and have a local effect; therefore, intervening on those roads is not a priority.

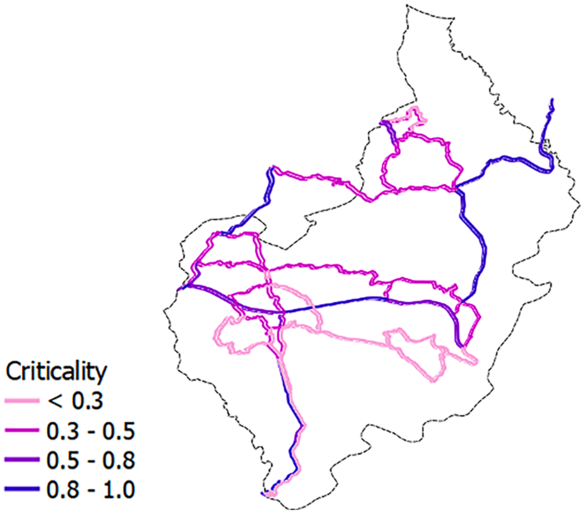

Fig. 4. Links criticality for Pedrógão Grande traffic network.

Discussion from the policy point of view

The previous section indicates where to intervene according to the maps of exposure, criticality, and priority level for intervention. From this information, it is possible to support decision-making in wildfire management at two stages, reactive and proactive actions. The first aims at enhancing immediate crisis response, such as suppression and evacuation activities, while the latter encompasses all preparedness measures undertaken before any event occurs, to minimize the impact of potential damages. The FIRAT maps are useful for improving emergency response as they provide information on the evacuation time associated with the ongoing and potential future fire categories. For example, in the case study, the central and northwest zones are suggested as the first areas to be evacuated due to their lowest response time before the fire reaches them. A timed evacuation response reduces the chances of having important roads being compromised by the fire. The unavailability of critical roads can result in the loss of connectivity in the traffic network, limiting further evacuation and suppression actions.

Concerning the proactive actions, the tool can inform about (I) the investment and resource prioritization by using the priority level for the intervention map. This implies that with limited resources, efforts can be concentrated on the highest-priority roads. For instance, in the case study, the investment should be prioritized around the central and eastern areas of the study zone, mainly links such as 2, 12–71, 57–106, 34–93 (highlighted in blue in Fig. 5); and (II) the evaluation of the policies' effectiveness. Policies can shift towards more proactive actions, reducing reliance on suppression activities, which are reactive in nature. Examples of such proactive measures include investing in the reduction of the criticality of links, such as the construction of alternative roads and managing and maintaining vegetation to reduce exposure.

In this section, an investment for vegetation management is analyzed in terms of exposure reduction. Measures would be aimed at maintaining the cleanliness of forests and crops, guaranteeing a limited fuel load. In addition, the inclusion and combination of more restrictive vegetation in areas with vegetation associated with high values of exposure, i.e., those that allow rapid fire advances, such as invasive species, eucalyptus (plantation), and maritime pine (plantation), could be considered. Given these assumptions, Fig. 6 shows the comparison in FIRAT under wildfire category 1 for the current exposure and the case where environmental policies are introduced. The vegetation intervention to obtain such a reduction in exposure is shown in Fig. 6b, with a light green shaded area.

In the analysed case, the policy implementation is constrained by available resources and stakeholder criteria. Although this policy significantly reduces the exposure of important roads, its implementation would require considerable efforts to intervene in a large area of vegetation. Therefore, it may be more convenient to apply this adaptation measure only to the area surrounding the links identified as a priority. Identifying optimal locations for intervention areas to achieve the

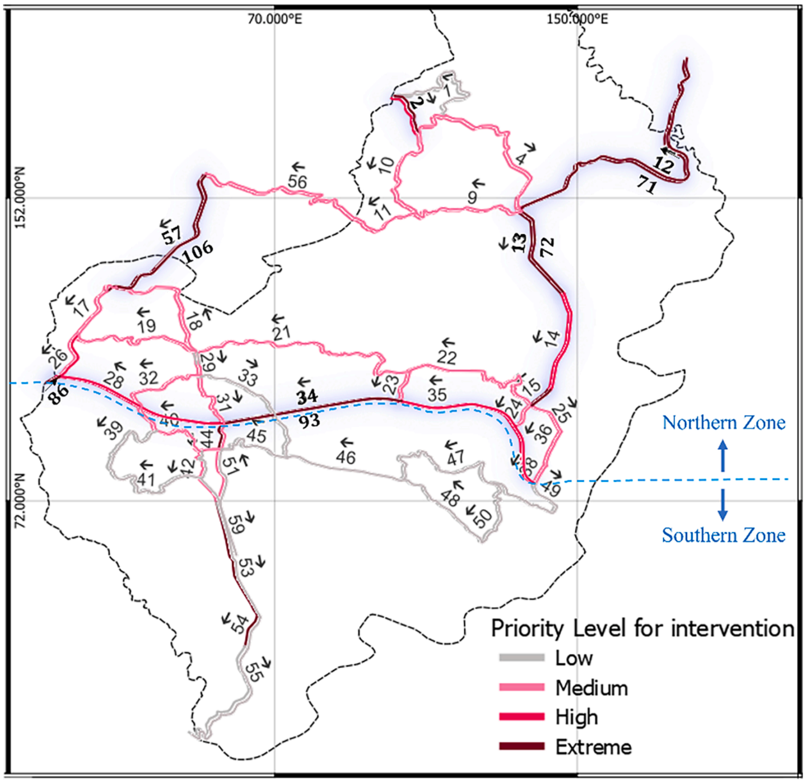

Fig. 5. Priority Level for the intervention of the links for the Pedrógão Grande traffic network.

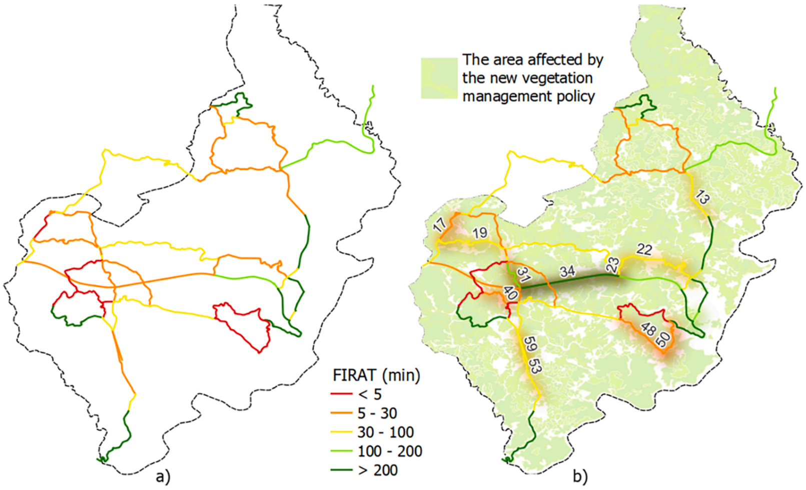

Fig. 6. FIRAT (in mins) for Pedrógão Grande traffic network, comparison wildfire category 1 a) present case and b) introducing vegetation management policies.

desired exposure reduction will be addressed in future studies. Alternative solutions can be found by evaluating other types of adaptation measures such as firebreaks or the combination of different green, gray, and soft measures. Nevertheless, the GIS-FA tool can be useful in assisting stakeholders in these decisions.

Conclusions

The new wildfire regime places in doubt the suitability of the existing wildfire management. Under this scenario, there is a need for tools to support decision-making regarding policies to increase resilience to wildfires. To cover this gap, this paper shows the potential of the GIS Fire Assessment tool to support decision-making in two relevant aspects of wildfire management, reactive and proactive actions.

The tool employs a resilience-based approach to assess system-level policies, encompassing the management of both the built and natural environments. This tool can guide policymakers regarding proactive adaptation policies to prepare systems for potential events. In essence, the tool assists in determining where to intervene, the priority order for intervention, and the impacts of various adaptation measures on reducing wildfire risk. For instance, effective vegetation management (a green adaptation measure) can reduce the exposure of critical roads, thereby enhancing the system’s resilience to wildfires. Nevertheless, combining green measures with different soft (e.g., traffic management) and grey measures (e.g., fire station construction) is considered to be more cost-effective. Identifying an optimal solution can be facilitated using the tool, although this will be addressed in future studies. One limitation of the proposed approach is its omission of feasibility and cost considerations for the recommended solutions. Real-world decision-making often hinges on the availability of resources and the economic feasibility of proposed actions. Ignoring these factors may result in the selection of strategies that, while effective in theory, may not be viable or sustainable in practice.

Finally, it is highlighted that although the methodology has been applied to a road network, it can be used to assess other types of critical infrastructure systems through the proper definition of sources, barriers, and criticality assessment.

CRediT authorship contribution statement

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

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 the Foundation for Science and Technology.

Data availability

Data will be made available on request.

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