Effectiveness Assessment of Adaptation Measures to Build Wildfire Resilience of Road Networks

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Effectiveness Assessment of Adaptation to Build Resilient Road Networks to Wildfires

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ABSTRACT: Wildfires have become a source of concern for society due to the increase in frequency, intensity, and unpredictability. This has caused serious impacts all over the world, even in areas where this type of problem did not occur before. Studies on the adaptation of critical infrastructure have been conducted to reduce the impacts of this type of hazard influenced by climate change. However, there are currently no tools to evaluate adaptation measures and their influence on the resilience of transport infrastructure to wildfires. Therefore, this paper proposes the application of a simplified methodology to assess the priority level in interventions on bridge networks and the effectiveness of different adaptation measures. The methodology is applied to a case study in Portugal. In that sense, the results show that adaptation measures such as changing vegetation management policy and implementing wildfire spread barriers effectively reduce the exposure of bridges. Therefore, this tool can be very useful for stakeholders and practitioners supporting wildfire management in terms of adaptation measures.

1. INTRODUCTION

Society's concern towards wildfires is growing because dealing with and attempting to minimize their severe impacts have become more and more challenging over the last decade. It reflects that the resilience developed by society is insufficient to face the new wildfire regime caused by climate change. Given that climate change is expected to favor more intense and extreme wildfires, the need to anticipate and adequately counteract the social, eco-environmental, economic, and cost impacts is paramount. For a long time, efforts to fight climate change have focused mainly on mitigation measures. These measures refer to reducing the causes of climate change, such as reducing carbon emissions. Given the relative failure of the mitigation policies observed so far, important efforts are paid towards adaptation or preventive actions, which focus on coping with the consequences of climate change. In that sense, adaptation measures increase the resilience of infrastructures and thereby minimize the impacts of upcoming events (Vajjarapu and Verma 2021).

Road networks are vital, as they are one of the primaries means of transportation (Adey et al. 2021). However, also one of the most exposed systems to natural hazards due to its spatial distribution. One of the critical components of road networks are bridges. Any damage to these assets can generate traffic disruption causing large economic losses. Research efforts have focused on proposing adaptation measures related to reconditioning of existing infrastructure, materials improvement, and maintenance (e.g., Schweikert et al. 2014), for several climatic stress factors (e.g., Bollinger et al. 2014; Regmi and Hanaoka 2011), for different critical infrastructures (e.g., Quinn et al. 2018), Hallegatte 2009; Rowan et al. 2013). Despite the important body of knowledge on climate change adaptation existing in scientific literature, there are several limitations in this field. The first limitation is that most of these frameworks are based on cost as the main (if not the only) criterion to select the adaptation measures. Second, they do not account for the high level of uncertainty associated with climate change. In relation to wildfires, the new extreme wildfire events that behave in an unknown and thus, unpredictable manner, bring challenges in the identification of limits and effectiveness of the measurements (Arango, Sousa, and Matos 2021). Therefore, there are no available tools to assess the effectiveness of different measures to improve the resilience of road networks to wildfires.

In this paper, the methodology proposed by Arango et al. (2023) is extended to evaluate different adaptation measures and their ability to improve wildfire resilience.

Arango et al. (2023) determine the exposure level of traffic networks affected by wildfires and combine it with the criticality level of the different roads of the network to determine the priority level for intervention. In this paper, the methodology is applied to the bridges belonging to a road network. Then, several adaptation measures are evaluated in their capacity to reduce the exposure level of the bridges. Therefore, the novel contribution of this work is the application of the methodology to assess the effectiveness of different adaptation measures. The methodology allows considering normal and extreme wildfire regimes. It deals with the uncertainty associated with wildfires by introducing exposure level rather than occurrence probability. Also, other sources of unpredictability, such as the ignition point are overcome using the bridges' exposure.

The methodology is applied to a case study in the Leiria region (Portugal). The priority level of each bridge within the network is obtained and different adaptation measures to reduce exposure and criticality are evaluated. This is an effective, quantitative, and easy-to-apply tool to assess the influence of different adaptation measures. This information can be useful to support decision-making on the resilience of the road network to wildfires. The rest of the paper is organized as follows, Section 2 briefly describes the methodology, the risk components, and its ability to assess different adaptation options. Its application to a case study in Portugal is shown in Section 3 and the results are discussed in Section 4. This is followed by the conclusions in Section 5.

2. METHODOLOGY

The proposed methodology ranks the priority level of intervention of infrastructure assets, in this case, bridges. To this end, the exposure and criticality of the assets are considered. Exposure is measured in terms of FIRe Arrival Time (FIRAT). FIRAT is an exposure metric that considers seven types of wildfire behavior, providing an exposure classification map for a portfolio of assets.

The wildfires can be classified according to their spread capacity, from normal wildfires, with a characteristic ratio of spread (ROS) of 15 m/min to extreme wildfires with ROS=300 m/min (see Table 1). In addition to the fire category, the ROS depends on the type of burning sources and barriers (e.g., rivers) the fire encounters. Diverse sources and barriers with different ROS can be transformed into a reference burning source.

Table 1: Wildfire category according to Tedim et al. (2018)

Normal wildfires		**Extreme Wildfires**	
Fire Category	ROS (m/min)	Fire Category	ROS (m/min)
1	5 - 15	5	150-250
2	15-30	6	250-300
3	20-50	7	>300
4	50 - 100		

For instance, as shown in Figure 1, if it is taken grassland as a reference, and a eucalyptus plantation placed 2 km away from the asset is equivalent to grassland at 4 km, given that the ratio of the spread of the plantation is half the grasslands. Thus, the equivalent fire distance, (EFD) of the eucalyptus plantation is 4 km.

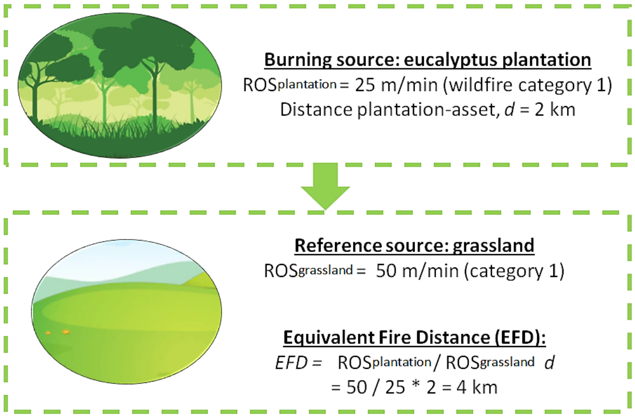

Figure 1: Calculation of the equivalent fire distance, EFD.

Expressing all the sources and barriers nearby the studied asset in terms of their EFDs allows their aggregation. Consequently, using the ROS of the reference source for each wildfire category, the time that a random wildfire would take to reach a given asset, that is, the FIRAT, can be obtained.

The evaluation of the criticality provides the relevance of each asset at a network level. With this aim, the topological properties of the network and traffic demand are considered to determine the impact that a bridge damage or failure would have in terms of increased travel time. It provides a ranking of assets based on the relative increase in travel time. For more details on the formulation applied to roads, see Arango et al. (2023).

This framework can support decision-making during critical scenarios through exposure maps, help prioritize resource investment and maintenance through the priority level maps and evaluate the effectiveness of adaptation actions.

2.1. Uncertainty associated with wildfire hazards.

Wildfires can be characterized by their location, intensity, magnitude, and frequency. The location or ignition point of a fire is associated with several sources derived from volcanic, climatic, and meteorological and anthropogenic characteristics. Disregarding the volcanic activity that occurs in specific areas, lightning is the most common natural source of wildfires. Within a region with the same meteorological conditions, the probability of a lightning strike can be assumed as randomly distributed over space. On the other hand, in Mediterranean Europe, the wildfires in the last decade are mostly related to human factors. For example, 98% of forest fires in the last 30 years in Portugal are mostly due to delivered actions, negligence, accident, or carelessness (Beighley and Hyde, 2018; Parente et al. 2018). The probability of occurrence of an ignition point over the physical space caused by human actions entails a large uncertainty. Therefore, estimating fire ignition points, both natural and man-made, is a complex task. In general, models assume random ignition points with no other probabilistic considerations. The described methodology assumes a uniform probability distribution of the occurrence of an ignition point over space.

Regarding intensity and frequency, the atmospheric conditions that promote ignitions, such as low relative humidity, high temperatures, and strong winds are exhibiting new behavioral patterns. That is, wildfires, normally attributed to the summer season, are now occurring in different seasons, such as spring and autumn. The new weather conditions result in events of unexpected magnitude and frequency. The proposed methodology provides exposure maps associated with different wildfire intensities. Determining the frequency of the events will help assess the cost-benefit of the different adaptation actions.

2.2. Assessment of the effectiveness of adaptation measures

Adaptation measures are defined as an adjustment to natural or human systems to respond to the effects of climate events, providing the capacity to moderate the impacts (IPCC 2014). In this case, they are those measures that can reduce the exposure and criticality of the assets. Actions to reduce the exposure level include but are not limited to enhancing infrastructure, structures, and buildings to be safer and more resistant to extreme conditions, vegetation management, and the creation of more wildfire barriers, such as wastelands. Meanwhile, considering alternative road construction, diverting traffic during wildfire events, and increasing capacity may reduce the assets' criticality.

3. APPLICATION

This methodology is applied to a bridge network in Portugal, specifically in the Pedrógão Grande municipality (Leiria District). Internationally known for the damaging fires that occurred in 2017. The network consists of 24 bridges, classified as 13 culverts, 6 overpasses, 2 underpasses, and 2 viaducts. This information is summarized in Figure 2, as well as the most relevant fire propagation sources and barriers. Within the burning sources, it is considered the land cover (i.e., forest type, agriculture, pastures, sports), gas stations, power plants, substations; industrial, commercial, and residential buildings, among others. The barriers include aspects such as wasteland (e.g., gravel pits, and rocky outcrops), land covered by open water bodies (e.g., lakes or rivers), and firefighter stations. This information is obtained from the Open-Source, Open Street Maps in QGIS software. The ROS of the burning sources and barriers is collected based on the literature and validated with experts in the area. Details about the considered ROS may be obtained in Arango et al. (2023).

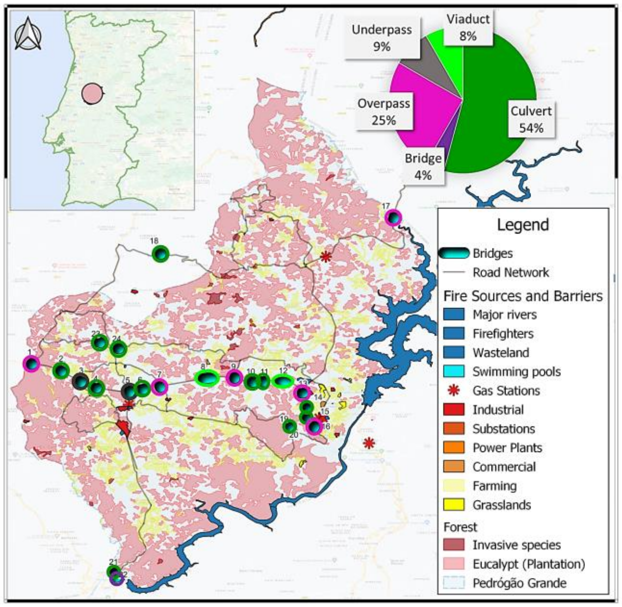

Figure 2: Pedrógão Grande Case study - Bridges network. Identification of wildfire sources and barriers. Background source: Google Maps.

For each bridge, the EFD is computed. Then, considering the ROS associated with each wildfire category as given in Table 1, the FIRAT for each bridge is obtained, as plotted in the exposure maps. The exposure maps are provided for each of the seven wildfire categories. For instance, Figure 3 a and b show the difference between the exposure of the bridge network for a wildfire category 1 (normal) and 6 (extreme), respectively. Bridges 3 and 20 are the most exposed ones because even for a low wildfire the FIRAT time is less than 5 minutes. For wildfire category 6 almost all the bridges have less than 30 min for the fire to reach them, except for bridges 21 and 22 which have more than 100 mins.

The criticality is calculated by accounting for the traffic information. Traffic data including network topology, road characteristics, and AADT are introduced in a stochastic traffic assignment model, yielding the total travel time associated with the users in the network. Then, one at a time, each bridge is removed from the network and the new total time is evaluated.

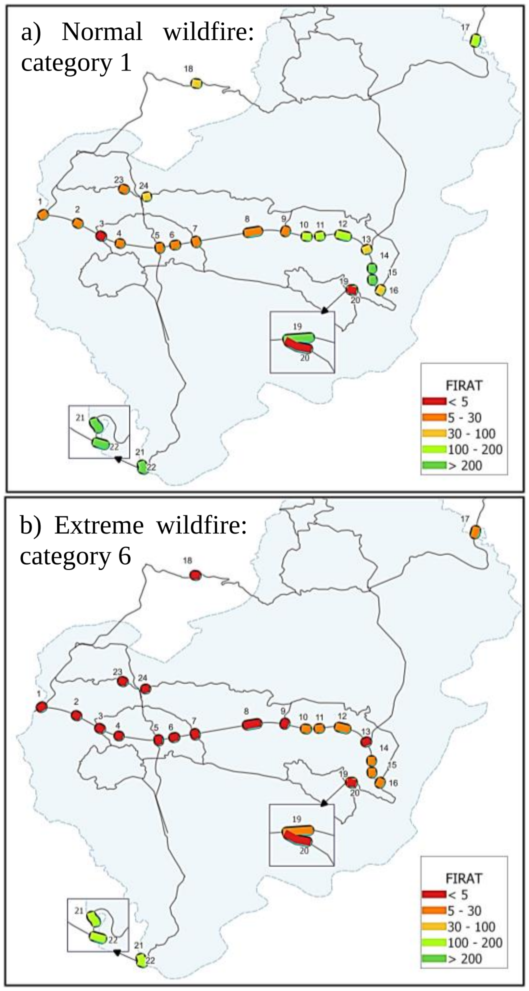

Figure 3: Exposure maps for the bridge network of Pedrógão Grande. FIRAT (in minutes) for a) normal wildfire category 1 and b) extreme wildfire category 6.

Those bridges on roads with more traffic or with few alternative roads will result in the largest time increase when removed from the network. In that manner, the most critical bridges are identified. In terms of criticality, the most critical bridges are bridges 5 to 8, i.e., those that are vital for the traffic network functionality. The criticality map for the bridges is provided in Figure 4. Finally, the priority level, which combines both exposure and criticality is obtained as shown in Figure 5.

The bridges requiring the highest priority are bridges 1, 5-9, and 17, while bridges 19 to 22 have a low priority level. Bridges 5 to 8 are highly exposed and critical, so the priority level is high.

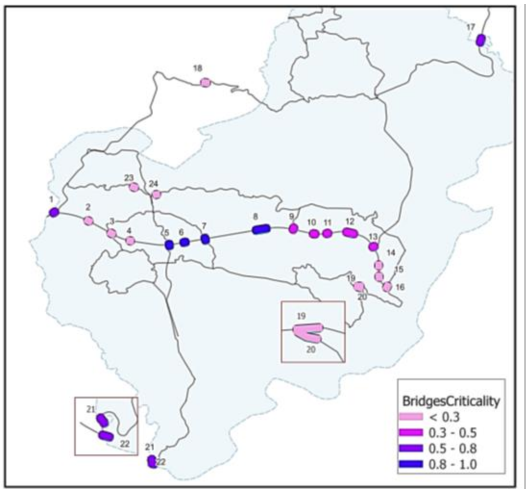

Figure 4: Criticality map for the bridge network of Pedrógão Grande.

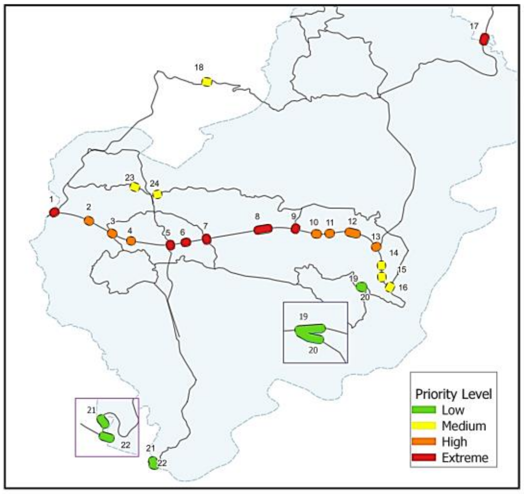

Figure 5: The priority level of Pedrógão Grande Case study - Bridges network.

However, a good example of the importance of combining both aspects (exposure and criticality) is bridge 20, which has a high exposure but is little used by users, resulting in a low priority level. Another example is bridge 17, which has low exposure but very high criticality due to the number of users associated with it, resulting in a high priority level.

4. DISCUSSION OF RESULTS

This section shows how the efficiency of different adaptation measures can be assessed using the framework. The adaptation measures exemplified in this case are related to exposure reduction.

In the first place, a change in vegetation management policy is assessed. This type of measure can involve anything from weed removal to vegetation replacement to reduce wildfire advance. To exemplify this measure, it is considered the replacement of high-exposure vegetation that allows a rapid-fire advance, such as invasive species, Eucalypt (plantation), maritime pine (plantation), stone pine (plantation), grasslands, and shrublands by more restrictive vegetation, i.e., chestnuts and hardwoods trees. In terms of the methodology, this implies modifying the ROS for the vegetation to be replaced and assigning the ROS of a hardwood tree (i.e., trees that burn slowly and can be planted according to regional conditions). With this assumption, the exposure of the bridge network is re-estimated. Figure 6 shows in light green the area of vegetation to be modified.

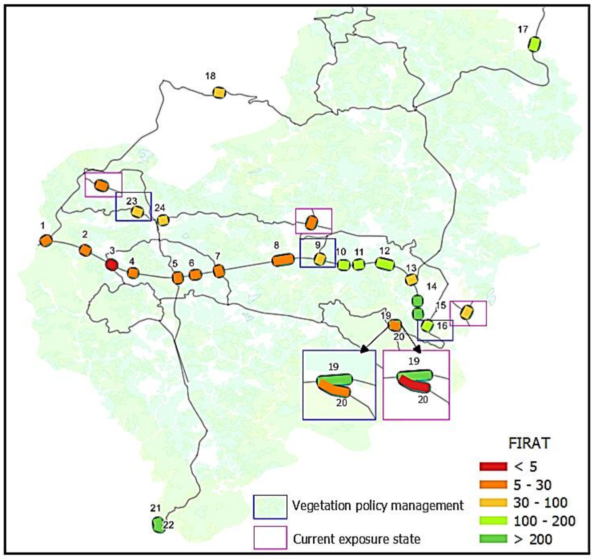

Figure 6: New FIRAT values (exposure map) for category 1, influenced by vegetation management policy.

This area can be contrasted with the current situation in Figure 2 (pink area), in which almost the entire study area is composed of high-exposure vegetation. Figure 6 also shows how the change in vegetation policy would reduce exposure for some of the bridges. For example, bridge 20 goes from having 5 minutes of FIRAT to having from 5 to 30 minutes. Bridge 16 goes from having 30 to 100 minutes of FIRAT to 100 to 200 minutes. Zoom boxes in Figure 6 mark the most significant changes in the exposure of the bridges.

On the other hand, the reduction of the exposure level is evaluated after implementing a firebreak barrier. A firebreak is generally defined as a set of actions on vegetation that aims to reduce the fuel load and therefore the advance of the fire. Firebreaks can be natural, such as rivers, or manmade, such as permanent bare ground, i.e., the eradication of vegetation in strips or areas (see Figure 7). It can also be a barrier of fire-resistant vegetation or a combination of resistant vegetation and bare soil to slow the fire spread.

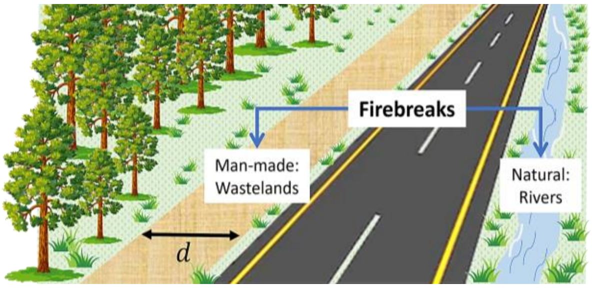

Figure 7. Example of the construction of barriers against the advance of the fire, firebreak

In this case, bare ground strips of different widths (d) and their influence on exposure reduction will be evaluated. In that sense, Junta de Andalucia (2010) establishes that the firebreak width should meet any of the following conditions. I) two and a half times the dominant height of the trees and, at least 15 m in the proximity of wooded areas. II) 10 m when the road is close to shrub or bush vegetation. III) 5 m in areas of herbaceous vegetation.

Texas A&M Forest Service recommends that the strips should be approximately 3 meters wide, or more (TAMFS 2017). Therefore, widths of 10, 20, and 50 m are proposed, the latter as a very restrictive case. In this example, the barriers are applied from bridge 5 to bridge 9, which are high-priority bridges in terms of exposure and criticality. As a result, Figure 8 shows how the FIRAT changes with increasing barrier width. The example is shown for fire categories 1 and 6.

For a wildfire cat. 1 and a 10 m firebreak width, the FIRAT of the bridges would increase from 7.9 min to 8.8 min, i.e., a relative increase of 11.4%. While with a 50 m wide firebreak, the FIRAT would increase by 62%, i.e., to 12.8 min. It is notable how the FIRAT increases as the firebreak width increases for minor wildfires. Meanwhile, for extreme fires, such as wildfire cat 6, the FIRAT does not increase substantially. It only increases by 0.24 min with a 50 m width barrier. Visually it would not be noticeable on the exposure map because the increase is less than 30 minutes.

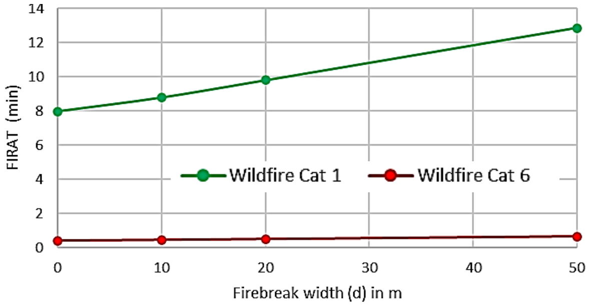

Figure 8: FIRAT increases due to different firebreak widths (d). d=0 represents the current situation of exposure

These firebreak strips intend to prevent fire from reaching the roads directly. However, factors such as wind can easily carry flames in the event of extreme fires across those considered widths (firestorms). Additionally, there is the smoke factor that can be deadly in some cases because it is highly toxic. Fire smoke can reduce the sense of orientation and the ability to perceive changes in fire behavior, causing traffic accidents (Wetterberg, Ronchi, and Wahlqvist 2021). The 2017 fire in this area of Pedrógão Grande, caused more than 40 people to lose their lives trapped on the roads due to the flames and smoke (CTI 2017). In South Africa, there are about nine traffic fatalities per year due to dense smoke from the uncontrolled burning of native fynbos (fine shrubs) (Tedim et al. 2020).

On the other hand, although Junta de Andalucía (2010) mentions that well-designed firebreaks can also provide habitat for wildlife, this type of measure can have counterproductive effects in ecological terms that have not been evaluated. Modifying the vegetation type or eradicating vegetation, may affect small ecosystems, which in the long term may not be sustainable. However, the analysis of the impacts of the application of these policies is not included in the scope of this work.

Other types of barriers, such as the construction of artificial lakes and the combination of barriers, can be evaluated in the same way. It is also possible to evaluate any type of measure that can reduce the ROS from any of the sources considered. It is even possible to consider measures that reduce criticality. For example, the consideration of alternative routes and maintenance actions that are directly reflected in the assignment of users and travel time. It means that the methodology is effective for evaluating different types of adaptation measures as well as their impact on exposure and criticality reduction.

5. CONCLUSIONS

The described methodology addresses the need for wildfire management tools. It shows the effectiveness of different adaptation measures, such as changes in vegetation policy and implementation of barriers. The first measure does not cause a great impact on exposure reduction, on the contrary, it would require great efforts for its implementation, since it implies changing the vegetation of a very large area. Therefore, it is not a very effective adaptation measure. As for firebreaks, they can be considered an effective alternative, but may not be sufficient to deal with extreme wildfires. Therefore, a solution to reduce the risk associated with wildfires could be the combination of several adaptation measures. Future works will address the problem from the point of view of the optimal design of adaptation measures.

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