Climate Risk Management 44 (2024) 100595

Contents lists available at ScienceDirect

Climate Risk Management

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

Enhancing infrastructure resilience in wildfire management to face extreme events: Insights from the Iberian Peninsula

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A R T I C L E I N F O

Keywords:
Wildfire management
Resilience
Iberian Peninsula
Cross-border policies
GIS-based tool

A B S T R A C T

Factors such as human activity and climate change are contributing to an increase in the frequency and intensity of wildfires. This problem has challenged society's knowledge, response capacity, and resilience, revealing its inadequacy to cope with the new wildfire regime characterized by extreme wildfire events (EWE). Policies on wildfire management mainly focus on suppression and managing emergencies, which may be insufficient to reduce EWE's incidence and cope with its impact. Consequently, there is a lack of tools to support decision-making in wildfire management in other important aspects, such as prevention and protection. This study examines global wildfire policies specifically in the Iberian Peninsula (Portugal and Spain), including cross-border policies. A GIS-based tool to evaluate different normal and extreme wildfire management policies is applied to a cross-border case study, paying attention to the impact on critical land-based transport systems. A relevant outcome of the tool application is that suppression must be complemented with other wildfire management strategies in the analyzed area. The gained insights can help stakeholders to improve decision-making in wildfire management to successfully address EWE.

1. Introduction

Climate change is causing significant changes in the frequency, intensity, and duration of wildfire events around the world. Consequently, we are experiencing a new regimen of wildfires, characterized by uncontrollable behavior that burns through large areas, resulting in severe and unexpected impacts, i.e., destroying homes, wildlife, and natural resources as never before. For instance, the Australian bushfires of 2020 destroyed over 10 million hectares of forest and caused dozens of fatalities (BBC, 2020). Over the last 20 years, wildfires in the European Union have cost more than €55 billion (Gonzalez, 2021; EC, 2018), significantly affecting the Southern Member States, such as Spain and Portugal. In 2017, wildfires severely affected the municipality of Pedrógão Grande in Portugal, causing the deaths of 65 people. It resulted in over €523 million in direct costs, with an estimated total social cost of €613 million (CTI, 2017). The wildfire of 2023 in Maui, Hawaii, stands as one of the deadliest catastrophes in the United States, claiming approximately 100 lives. Furthermore, it resulted in the displacement of nearly 6.000 people, with an estimated $5.5 billion required

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https://doi.org/10.1016/j.crm.2024.100595
Received 15 May 2023; Received in revised form 26 February 2024; Accepted 27 February 2024
Available online 11 March 2024
2212-0963/

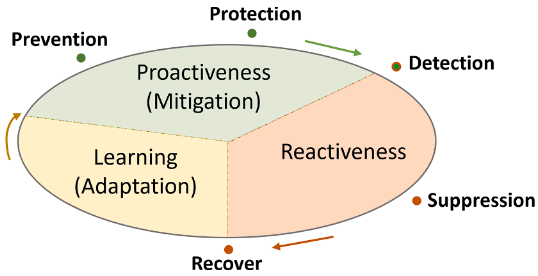


Fig. 1. The holistic view of wildfire management based on resilience.

for the repair of damaged areas in West Maui (Hassan and Betts, 2023). In this context, the existing wildfire policies are facing increasing pressure, and their adequacy is being questioned in light of the new conditions induced by climate change and inadequate land and forest management. The latter is critical in the Iberian Peninsula due to the land abandonment (Duane et al., 2021).

For the sake of clarity, in this paper, Extreme Wildfire Events (EWE) are defined following Tedim et al. (2018), as fires with exceptionally high values in critical aspects, such as intensity and rate of spread, leading to unpredictable behavior. These pose significant challenges to suppression efforts and result in significant societal costs.

Effective wildfire management is a complex multifaceted process that integrates proactive and reactive approaches. Reactiveness involves responding to fires with a focus on extinguishing them rather than addressing their underlying causes. In contrast, proactiveness encompasses actions aimed at preventing fire occurrences and impacts (Mourao and Martinho, 2019). These approaches encompass various strategies, such as prevention, protection, detection, suppression, and recovery strategies. Prevention aims to reduce the risk of wildfires by addressing the root causes, such as reducing fuel loads, managing forests, and implementing fire-safe building codes. Protection involves mitigating the potential damage from wildfires by creating defensible spaces around homes and communities and developing evacuation plans for residents. Detection is also an important aspect of wildfire management, as early warning systems can provide crucial information about the location, size, and potential impact of a fire. Rapid response is critical and suppression policies and resources such as firefighters, helicopters, and equipment are critical to this effort. Once a wildfire has been contained, recovery policies are necessary to help communities and ecosystems rebuild and heal. This includes supporting displaced residents, restoring damaged infrastructure, and rehabilitating affected ecosystems. Effective wildfire management requires a comprehensive and integrated approach that encompasses the five strategies from a resilience perspective. Fig. 1 presents a global view of wildfire management based on resilience theory. This framework aligns with the Integrated Fire Management framework proposed in the European Commission report (EC, 2018). One notable difference lies in the incorporation of the learning process within the holistic vision presented here. Note that mitigation is implicit in prevention and protection strategies. While adaptation is primarily associated with the learning process, it can also be implemented at any of the other stages.

Although wildfire management should include the five strategies, the main focus of wildfire-related policies is suppression and emergency management (Fernandes et al., 2020; Leone et al., 2020; Rossi et al., 2022). This approach has been adequate for normal wildfires, i.e., fires that do not fall under the classification of EWE which are more controllable. However, as fires become EWE, i.e., more intense, and faster spreading, suppression capacity is overwhelmed (Fernandes et al., 2016; Moreira et al., 2020).

Wildfire management and policies are generally approached from the perspective of risk management and suppression (Noble and Paveglio, 2020). Countless methods of all kinds have been developed to study the wildfire problem and support decision and policy making. For instance, qualitative methods attempt to incorporate the different factors related to the complexity of the fire phenomenon (Asori et al., 2020; Schultz et al., 2021). The quantitative methods include but are not limited to, statistics-based models that correlate various types of data (e.g., Costafreda-Aumedes et al., 2017; Alcasena et al., 2021). Data analysis and simulation tools to extract information from large databases are used by Wang et al. (2017); McNamee et al. (2022), logistic models or random forest algorithms are applied by Galizia and Rodrigues (2019); Salis et al. (2021); whereas Naderpour et al. (2021) implement automatic learning methods. These methods are based on historical records and forecasts, usually data intensive. Since EWE are characterized by unexpected behavior, and increasingly exceed expectations in terms of intensity, frequency, and magnitude, using past data to predict EWE may not be suitable (Pinto et al., 2018). The uncertainty associated with the new wildfire regime makes predicting its behavior extremely difficult. Therefore, risk estimation and the consequent decision-making are subjected to larger uncertainty. On the other hand, many of these methods are scenario-based, often becoming highly categorical for specific scenarios. Generalizing results to other scenarios and conditions requires careful consideration. Consequently, these methods are unable to properly capture the effects of the new generation of EWE (Arango et al., 2023a).

In conclusion, risk assessment relies on accurate and updated hazard information. Thus, wildfire management is based on known and measurable data. This approach is successful in suppressing wildfires and protecting society in highly predictable scenarios (Castellnou et al., 2019) but not facing EWE. Therefore, experts suggest shifting the paradigm from suppression to prevention and adopting a resilient approach (IPCC, 2022; Ganteaume et al., 2021; Moreira et al., 2020). It results in several studies aiming to increase the resilience of wildfire emergency response, (e.g., Talebi et al., 2022; Sakellariou et al., 2023; Castellnou et al., 2019); and others to promote the transition towards more resilient landscapes, as Duane et al. (2022). However, there are some limitations to be covered such as the lack of available tools to support the implementation of proactive strategies around prevention and protection. These tools are key to improving policies. Existing tools generally focus on supporting only one of the phases of wildfire management, either reactive (e.g., Andrade and Hulse, 2023) or proactive (e.g., Song et al., 2023; Subramaniam et al., 2023). However, from a resilience-based perspective, policies should aim at finding a sustainable balance between reactivity and proactivity in the long term.

To overcome the lack of available tools, Arango et al. (2023a) propose a GIS-based fire analysis tool, GIS-FA, to quantify the exposure level to wildfires of infrastructure or buildings, based on natural and man-made environmental conditions. This tool also overcomes the described limitations of the risk-based models. Furthermore, it allows assessing different strategies in their capacity to reduce wildfire impact, including normal and extreme wildfires (Arango et al., 2024).

The novelty of this paper lies in showcasing how to enhance decision-making in resilient wildfire management in transboundary contexts. Despite the importance of cross-border collaboration for defending communities against the increased risk of wildfires, this subject is little analyzed. This has been achieved by leveraging the capabilities of the GIS-FA tool. The paper highlights the unique ability of this tool to effectively address fire management in situations involving multiple borders, thus marking a significant advance in integrated fire management in border areas. It not only identifies and overcomes limitations in individual country-level fire policies but also promotes bilateral cooperation, optimizing management and emphasizing joint actions to address common challenges in resilience and safety in cross-border areas. This facilitates a balanced approach between reactive and proactive measures, supporting long-term decision-making and emergency planning. This paper presents a discussion on the policies and strategies addressed in wildfire management, putting under scrutiny the prevention and protection capacity of communities and approaches to manage the problem of the new fire regime. Special attention is paid to wildfire management policies in the Iberian Peninsula (Portugal and Spain), analyzing a cross-border case study. It shows an example of cross-border cooperation of countries with vast experience in wildfire management but yet little experience in EWE. In this context, the land-based transportation system is analyzed given its critical role in the different phases of wildfire management. The GIS-FA tool is used for this purpose providing interesting insights on the challenges of cross-border cooperation and potential consequences of centering the efforts on suppression under EWE. The discussion presented in this work can help to find the keys to future wildfire management and research.

The rest of the document is organized as follows. In Section 2, policies and practices related to wildfire management are analyzed at the international level with a particular focus on the Iberian Peninsula. Then, the GIS-FA tool is explained in Section 3. In Section 4 the cross-border case study is presented, whereas the discussion around the limitations of the cross-border cooperation and insights from the case study are presented in Section 5. Finally, some conclusions are drawn in Section 6.

2. Review of policies on wildfire management

2.1. A global approach based on suppression

This section reviews the existing policies on wildfire management, paying attention to those countries with more experience in fire fighting. The United States had a policy of total fire suppression until the year 2000. Then, they approved the National Fire Plan (NWCG, 2006), with a clear shift towards ecosystem adaptation, recovery, and economic assistance to rural communities (McCaffrey et al., 2015). After 2009, it was strengthened through the Federal Land Management and Land Assistance Improvement Act (WFLC, 2014). The foundation of the USA wildfire policy is risk management, which mainly incorporates fuel treatment such as firebreaks or prescribed burning. However, property and people protection, early warnings, and better management of natural resources to coexist with wildfires are poorly considered. Therefore, at present, the USA fire management mostly focuses on suppression.

Current Canadian practices are more resilience-oriented. They include zoning based on the five strategies of wildfire management. However, most resources are dedicated to the suppression phase, despite studies pointing to the need for increased protection capacity (EMPOD, 2017). In terms of prevention, they use measures such as forest area closures, burning permits, and the prohibition of fires (e.g., bonfires, fireworks, and explosive targets). Forecasts of future EWE suggest that current wildfire management policies in Canada are insufficient to address the growing wildfire threat (Tymstra et al., 2020).

In the case of Australia, due to its long history of wildfires, they have implemented more advanced management policies in terms of prevention and protection. They include the preliminary stages of training and education of communities to reduce the likelihood of fire-related losses and improved building standards to reduce vulnerability (Reynolds, 2017). People took up the focus on community safety and protection as an incentive to stay during fires to defend their properties (Whittaker et al., 2013). However, after the Black Saturday wildfires (2009), there was a shift towards early self-evacuation as the safest option for the community (McLennan et al., 2019). Despite these social and research development efforts to reduce wildfire risk, the current management program, the Enhanced Bushfire Management Program (EBMP), is more focused on supporting improved wildfire suppression and risk reduction (OEH, 2016).

European policy focuses on fire suppression too, with evacuation being the last option. However, in recent years, preventive guidelines, projects, and funding focused on fire-resistant landscapes through fuel management or preventing arson have been mainly encouraged in some of the countries in the southern part of Europe (Salis et al., 2016; EC, 2018). However, protection initiatives remain ineffective and financially under-resourced (Cardoso et al., 2018). The European Union (EU) has created a Civil Protection Mechanism to strengthen cooperation among the EU countries and participating states regarding firefighting, thus, improving response to disasters. Member States are required to make as many resources available as the Commission may request, however, they are not obliged to offer their assistance.

This reality shows that society is aware of the importance of wildfire prevention and protection, however, actual changes in wildfire management policies towards prevention and protection although significant, are insufficient and efforts continue to focus on wildfire suppression.

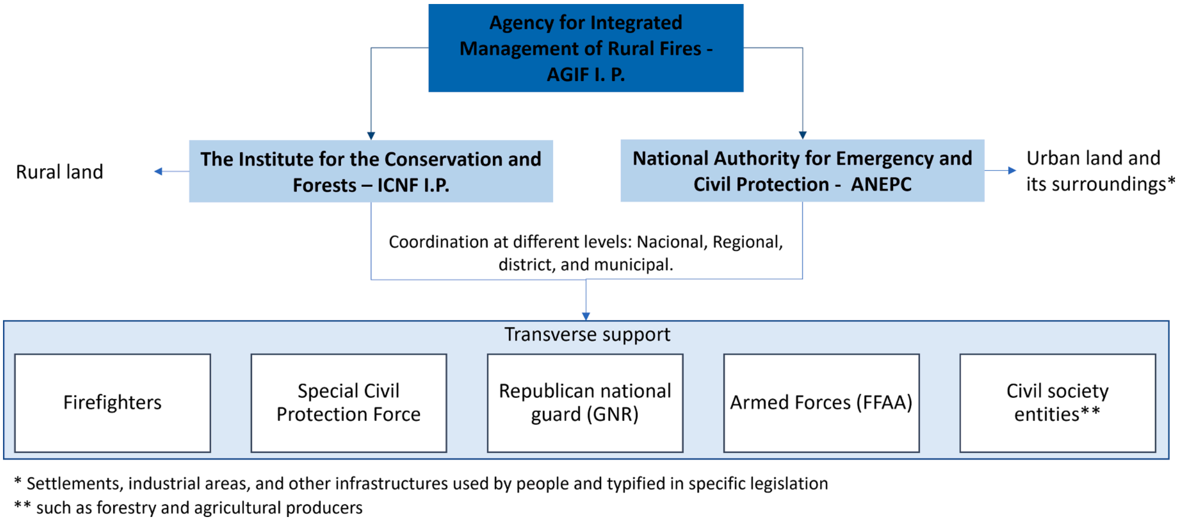


Fig. 2. Strategic coordination of the Integrated Management System for rural fires - Portugal.

2.2. *Cross-border policies: the Iberian Peninsula*

It is frequent in Europe to find fires initiated in one country that cross the border and cause serious damage in the neighboring country. Especially in the border area between Portugal and Spain, which is one of the longest land borders in Europe with about 1.200 km. Both countries have similar landscapes and orography, and most of the border territory is predominantly rural, especially in Portugal. The urban areas are poorly developed with small settlement concentrations. Moreover, given the geographical situation, they are prone to wildfires, thus, their collaboration is essential for the defense of their communities against the increased risk of large forest fires. This section describes the legislative framework related to the wildfire policies of each country and analyses their cross-border wildfire management policies and cooperation instruments. This section also serves to contextualize the case study.

2.2.1. *Wildfire legislation and policies*

Related to wildfire legislation and policies, Portugal and Spain present a similar framework. The fire management strategy is based on national legislation that governs the forest area and its management. The Portuguese policy is based on Law 76/2017 (Diario da República, 2017), *Sistema de Defesa da Floresta Contra Incêndios*, an updated of Decree-Law 124/2006. The forestry policy in Spain is based on Law 43/2003 (BOE-A-2033-21339), *Ley de Montes*. Each of the District Centres in Portugal and each regional Spanish community have legislative autonomy to establish laws and guidelines for their territory (always complying with the guidelines set at the national level). Designated government entities of each country are responsible for wildfire management throughout the national territories and their districts to support prevention and suppression tasks.

In recent decades, Portugal has been the subject of several analyses by wildfire specialists, especially after the wildfires in 2017 and 2018 (CTI, 2017; CTI, 2018). The recommendations were relatively consistent and pointed to four main domains that require enhancement: (1) preventing negligent human ignitions, (2) creating a structural fire defense system consisting of fuel management strips and reducing fuel loads in critical areas, (3) improving firefighting capabilities by implementing perimeter control tactics and comprehensive firefighting strategies, and (4) restructuring firefighting organization (Beighley and Hyde, 2018). Therefore, based on the lessons learned from the 2017 and 2018 wildfires, the Portuguese National Forest Fire Defence Plan was modified. The new plan, developed by the Agency for Integrated Rural Fire Management (AGIF) and approved by the Portuguese Congress (resolution No. 45-A/2020), contains a fuel management program for 2020–2030, that aims to reduce exposure to wildfires. Unlike its predecessor plan (the one that ruled from 2006 to 2018 whose main objective was suppression), this plan recognizes that rural fires cannot be prevented entirely, so it is necessary to prepare the society. Therefore, the plan is based on two central axes: managing rural wildfires and protecting against rural wildfires. Prevention measures mainly consist of fuel treatment mosaics or linear firebreaks designed with local stakeholders (i.e., free of waste, spontaneous scrub, and dry vegetation). These prevention measures are an important step but are still insufficient. For example, the firebreak strips were officially approved by Portuguese Decree-Law 17/2009 and the forensic report of the 2017 fire (CTI, 2017) found no evidence of fuel management for the municipality of Pedrógão Grande.

The Spanish forestry law establishes common guidelines on training in prevention and suppression. Related to fire prevention, the fragmentation of forest areas is a solution to regulate the exercise of all the activities that can increase fire risk. Another safety standard is to provide a minimum of 25-meter-wide firebreak strips for homes and buildings in forest areas. Similarly, the ditches and easement areas of roads and railways that cross forest areas shall be kept clean for a minimum width of 2 meters. It is recommended that preventive work has to be carried out throughout the year. Related to wildfire suppression, firefighting services prioritize using public infrastructures such as roads, telephone lines, airports, reservoirs, seaports, and all those necessary for the communication and supply of these services.

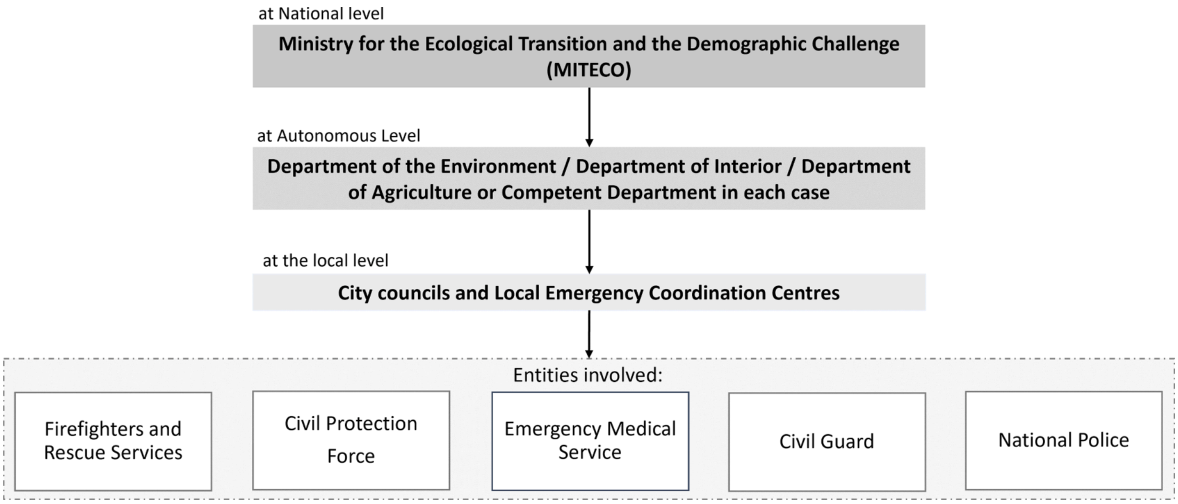


Fig. 3. Entities involved in the coordination of wildfire management emergency - Spain.

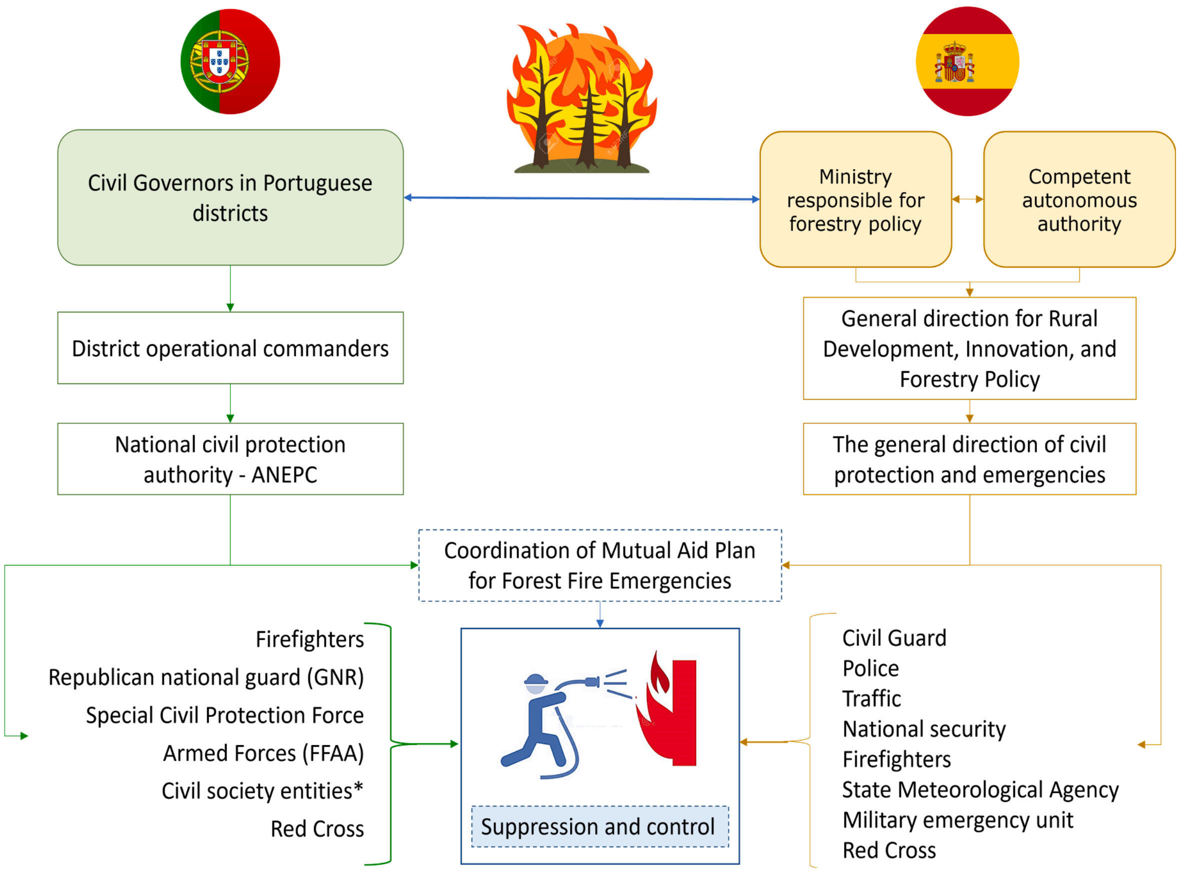


Fig. 4. Mutual Aid Plan for wildfire emergencies in border areas between Portugal – Spain.

With the advance of large wildfires, despite the increase in the investment of equipment and resources for suppression, it has not been enough to control this type of event. Therefore, initiatives have arisen to increase investment in wildfire prevention programs, i.e., the promotion of long-term preventive actions. The target is to move from a management model mainly based on specific actions and maintenance of infrastructures (such as firebreaks and water points) to a long-term value forestry and agricultural model in rural areas to create an agroforestry territory resilient to forest fires (WWF, 2021).

Therefore, both countries are guiding their efforts towards prevention with fuel-treatment measures such as agricultural zoning resilient to forest fires and creating networks of linear firebreaks (i.e., linear fuel-cutting) designed with local stakeholders. However, these plans are recent, and the implementation of these measures is very slow, with few resources that are not able to achieve an effective response.

2.2.2. Agents involved in the coordination of wildfire management

Regarding the coordination, the Agency for the Integrated Management of Rural Fires, I.P. (AGIF, I.P.), created by Decree-Law No. 12/2018, is responsible for the strategic coordination of the integrated wildfire management system (SGIFR) in Portugal. The success of this system depends on the harmonious integration of the responsibilities assigned to two main public institutions, the Institute for Conservation and Forests (ICNF, I.P.), and the National Authority for Emergency and Civil Protection (ANEPC). Both are in charge of the prevention and protection of fire risk, in rural areas and the built and industrial surroundings, respectively. These two entities count on the support of the local government, Republican National Guard (GNR), and the Armed Forces, as well as other entities from civil society, to manage wildfires from planning to recovery, that is, through planning, prevention, protection, suppression, and post-event recovery. Fig. 2 summarizes the hierarchical coordination for compliance with the Portuguese SGIFR.

With three levels of hierarchy, Spain shows similar coordination (see Fig. 3). However, each Autonomous Community manages wildfires under different directorates, examples of wildfire management in each community can be found in González and Vallejo (2023); Typsa (2023). When the fire affects different areas, the three levels (national, autonomous, and local) collaborate through the national coordination committee, which supports the entities involved in wildfire management, such as firefighters, medical services, national police, and the Civil Guard.

Because of the similarities between the management of wildfire policies and conditions, the first steps to cross-border cooperation Portugal-Spain were established in 1980. Since then, there has been a technical cooperation and mutual assistance agreement between the Portuguese and Spanish firefighting and rescue services with an additional protocol on forest fires in border areas. It was formalized through the so-called Évora protocol, signed by the two countries on March 9th, 1992 (Martín et al., 2018) and its last update was in 2019 (BOE-A-2019-12928). It aims to allow rapid intervention and mutual assistance in the event of wildfires in the border area, whenever the urgency of the situation requires. Within border areas, special attention will be given to fires that are less than 25 km from the border and whose propagation conditions (i.e., wind, topography, fuel patterns) suggest that there is a very high probability that the fire crosses the border in a short period. Fig. 4 summarizes the mutual aid plan for cross-border in Portugal - Spain.

Cross-border cooperation involves policies, legal instruments, such as bilateral agreements and treaties, as well as financing programs. Among the most important funding programs is the "Interreg" program, which has been implemented between Portugal and Spain since 1989. The current version is Interreg VI, which covers the period from 2021 to 2027 (Interreg Spain-Portugal, 2022). This program finances projects focused on (i) training and equipping the staff for cross-border suppression operations, (ii) educating the rural population about the risk of large forest fires, good preventive practices, and self-protection, and (iii) improving the coordination of the emergency action units with common elements of mobile emergency communication, among others –FIREPOCTEP (FIRE-POCTEP 2020), Interlumes (Interreg Spain-Portugal, 2019), CILIFO (Interreg, 2019), ARIEM-112 (ARIEM, 2015)–.

The Cross-Forest project (CEF, 2018) aims to develop a Digital Service Infrastructure (DSI) focused on predicting forest fire behavior and spread. It includes forest maps and forest fire spread models at the country level based on GIS datasets. This project is co-financed by the European Union's Innovation and Networks Executive Agency (INEA), through the Connecting Europe Facility (CEF). Also, the VOST platform (Sousa et al., 2018), formed by a large group of volunteers, whose objectives ranges from monitoring, collecting, and disseminating official information during emergencies of any kind on social networks, to combating the phenomenon of online disinformation that can cause a social alarm during emergencies.

It is noted that the main focus of the long-standing collaboration has been on suppression and emergency actions. On the other hand, despite the wide variety of entities and projects aiming at cross-border cooperation, further work must be done on integration, coordination, and sharing of data and experiences to make the actions more effective. For instance, to avoid overlaps and duplication of responsibilities in wildfire management in all phases. In this sense, tools to inform stakeholders and support the decision-making process can be used by both countries to identify the need for interventions and the division of responsibilities, thus improving the coordination of wildfire management. In this sense, wildfire management can be oriented towards a more holistic view based on resilience (see Fig. 1).

3. GIS-FA tool to inform policies on wildfire management

Arango et al. (2023a) propose the GIS-FA tool that allows the assessment of the priority level for the interventions of infrastructure systems in wildfire management, supporting the decision-making and prioritization of resources. The tool includes the impact of normal fires and EWE at a system level and considers inter-dependencies and redundancies between system components. It is developed from a resilience-based perspective, focusing on the system's capabilities rather than wildfire occurrence probability. The tool considers the system's exposure to different types of wildfires as a consequence of the natural environment and human activities, including those aiming at preventing and protecting the system. However, it does not consider the wildfire occurrence probability, thus, it avoids the unpredictability associated with the EWE problem.

The priority level for intervention is calculated using two criteria, the exposure of the infrastructure to wildfires and the criticality of an asset within the system. In this work, exposure assessment is highlighted as an individual tool to support decision-making. It uses an exposure metric denominated Fire Arrival Time (FIRAT), which considers the environment in its ability to spread fire under different fire conditions. As a result, an exposure map is obtained providing the average time for a random fire, either normal or EWE,

Table 1
Characteristic ROS values of grassland for the different wildfire categories according to Tedim et al. (2018).

Fire category	Normal fires				Extreme Wildfires		
	1	2	3	4	5	6	7
ROS (m/min)	5–15	15–30	20–50	50–100	150–250	250–300	>300

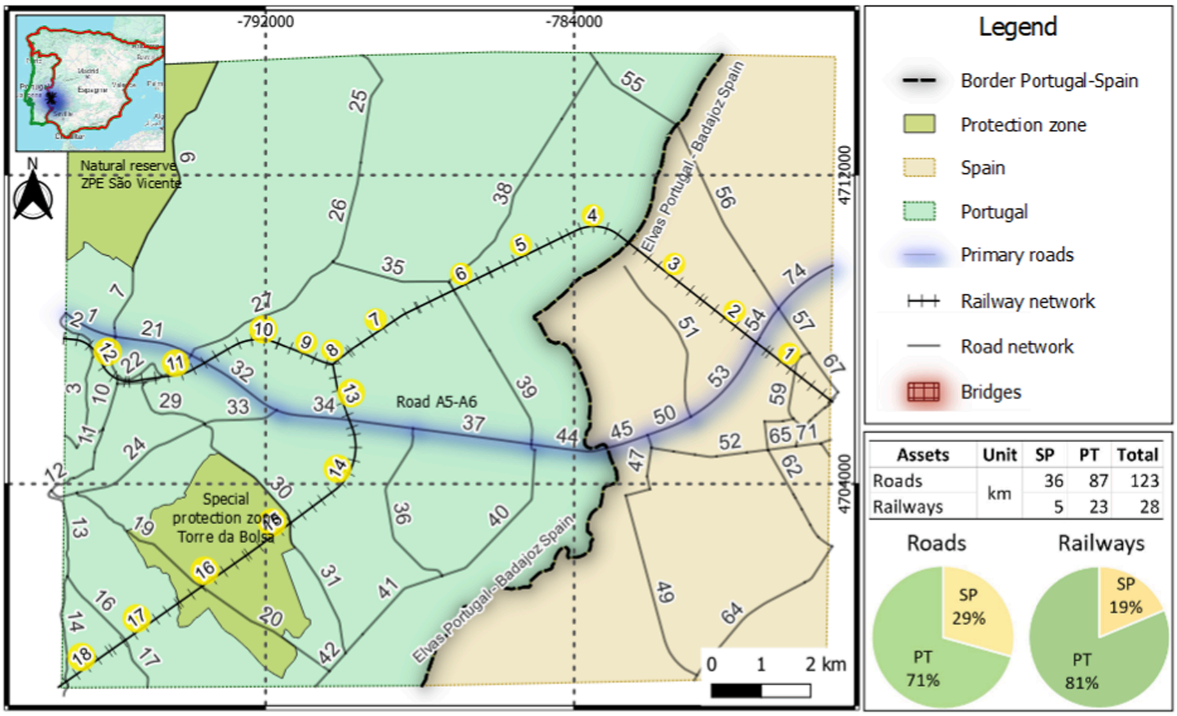


Fig. 5. Cross border case study: Elvas Portugal (PT)-Badajoz Spain (SP) transportation network. The enumeration of railway segments is listed in yellow, and road segments are listed in white.

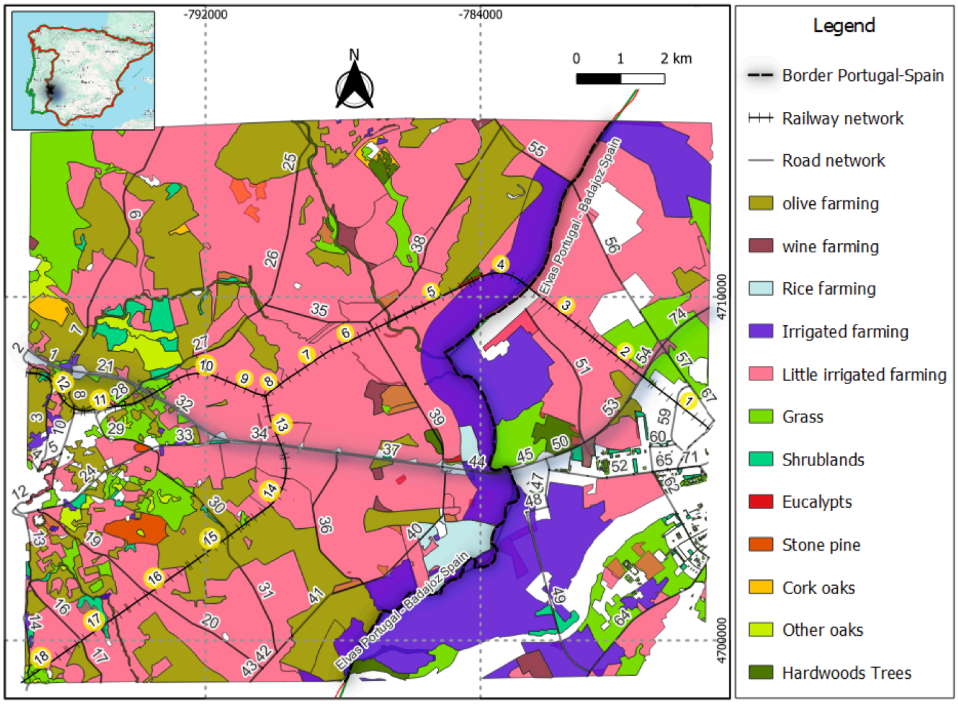
to reach a given asset of the system (e.g., roads, stations). FIRAT calculation considers the Rate of Spread (ROS) associated with different burning sources and fire barriers for a different wildfire intensity, as well as the Equivalent Fire Distance, EFD. The EFD allows the aggregation of different sources and barriers around the asset. Seven wildfire categories are included in the analysis based on the corresponding ROS values, as summarized in Table 1.

Therefore, to determine the exposure level of a given infrastructure system using this tool, the following steps have to be followed: (1) Definition of the studied system through its components or assets (e.g., buildings or roads) and fire propagation sources and barriers that can influence the exposure of the studied target. (2) Establishing the ROS values for the different burning sources and fire barriers considering their characteristics and locations. (3) Selection of one reference object from the fire propagation sources previously identified (e.g., grassland). (4) Normalization of the ROS values of the sources and barriers using the reference object. (5) Measurement of the distances between the fire propagation sources and barriers and the components or assets. The most critical distance for each source and barrier concerning each component or asset is considered. (6) Equivalent Fire Distance (EFD) is calculated as the mean value of the critical distances for each component or asset, multiplied by the normalized ROS rations. (7) FIRAT estimation, which considers the EFD and the characteristic ROS value of the reference object associated with each wildfire category (see Tedim et al., 2018).

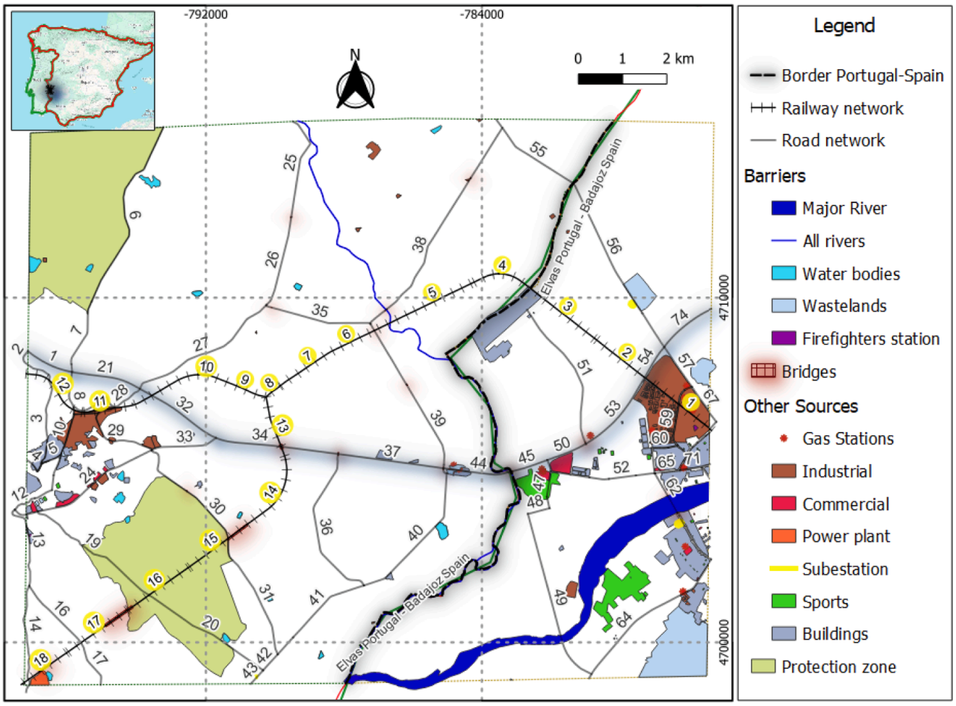
Exposure assessment introduces aspects related to the environmental conditions of the system, thus reflecting the impact of economic, social, and political activities. In this way, the social dimensions of wildfires are considered. For a more detailed description of the parameters, procedure, and results the reader is referred to Arango et al. (2023a).

4. Cross-border case study

GIS-FA tool has been presented and validated in Arango et al. (2023a) and Arango et al. (2023b), respectively. This section presents a cross-border case study using the GIS-FA tool and how it can support the decision-making process at all stages of wildfire management.



(a) Land uses that promote fire spread (i.e., sources).



(b) Land uses that hinder the fire spread (i.e., barriers) and other sources.

Fig. 6. Fire propagation sources and barriers considered for Elvas - Badajoz.

	Unit	Total	Elvas Portugal	Spain Badajoz
Population	*Habs.*	176.923	23.364	153.559
Land use				
Forest		8,8	6,5	2,3
Shrubs		4,5	1,9	2,6
Grasslands		16,4	4,8	11,6
Farming	km^2	162,9	106,6	56,3
Industrial /Commercial		3,9	1,1	2,9
Urban territory		5,2	2,7	2,5
Others		5,9	0,6	5,3

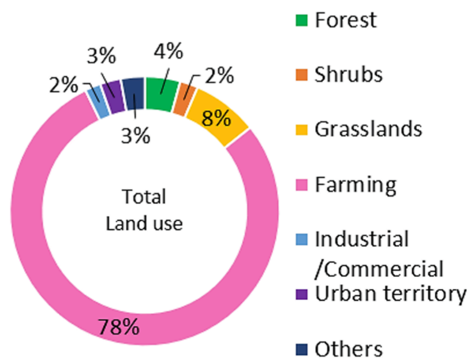


Fig. 7. Analysis of the land cover in the cross border case study: Elvas Portugal - Badajoz Spain.

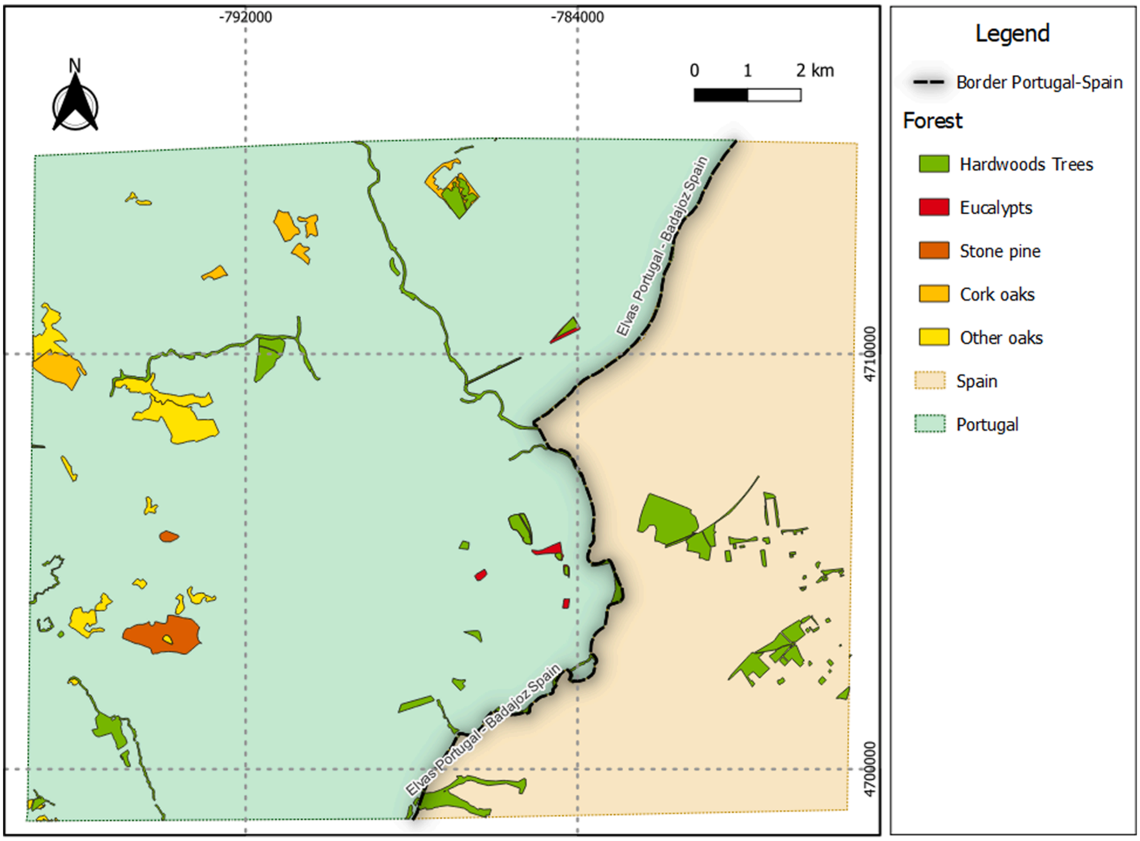


Fig. 8. Differences between the forest classification for Portugal and Spain.

4.1. Case study description

The study area is located between the Portuguese city of Elvas, in the district of Portalegre in the Alentejo region, and the Spanish city of Badajoz, the capital of the namesake province and the largest economic and commercial center of the autonomous community of Extremadura (see Fig. 5). This area was legally constituted as Euro-City Elvas-Badajoz in 2013 after the abolition of border controls by the countries and the Schengen Agreement. Since the agreement, it has become the area with the largest population within the Portuguese-Spanish border area (Castanho et al., 2017). This case study was selected due to its high fire risk probability, ranging from 60 to 70%, as indicated by information from the European Forest Fire Information System (EFFIS, 2022). Additionally, this area is crucial for land connectivity between the two countries. The area is connected by road and railway networks, as depicted in Fig. 5. The principal roads crossing the region are the A5-A6 motorway connecting the capitals of both countries, Madrid-Lisbon, which enters the region from the northeast and exits through Badajoz, in the west, in the direction of Lisbon. The railway network, which transports

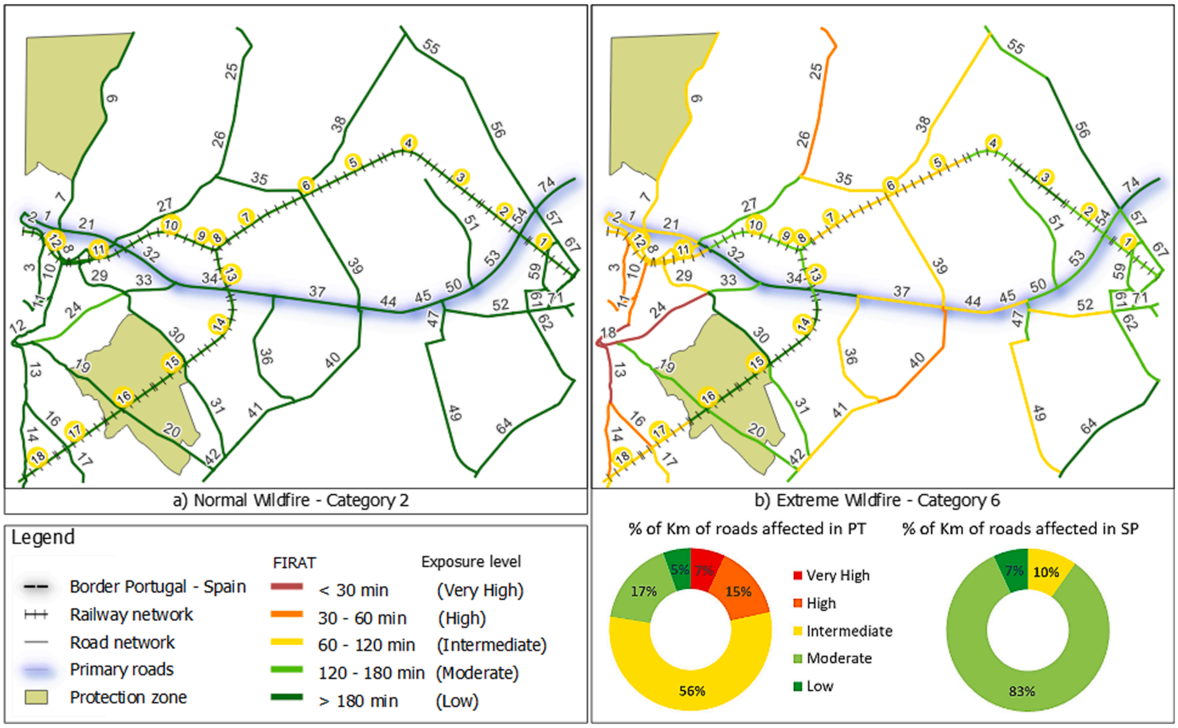


Fig. 9. Fire Approach Time – FIRAT (in minutes) for the Elvas Portugal (PT)-Badajoz Spain (SP) transport network. (a) Normal Fire Category 2, and (b) extreme Fire Category 6.

users and goods, has connections to Madrid, Lisbon, and other large cities such as Seville, Huelva, and Ciudad Real via the Madrid-Cáceres-Mérida-Badajoz-Lisbon corridors. These rail and road routes are the most direct transportation lines connecting the capitals of both countries.

4.2. Results from exposure analysis in the cross-border case study

The transportation system under study encompasses 123 km of road network and 28 km of railway network. To conduct the analysis, the roads and railways have been segmented in order to provide a more detailed exposure assessment. Both networks are split at the border level, to better support decision-making because actions rely on one of the two countries, see Fig. 5. The road network is segmented into 74 road sections according to intersections with other roads and railways. The rail network is also divided into 18 segments regarding intersections and then at equal distances, in this case, 1.7 km long.

The sources of fire spread and barriers considered are shown in Fig. 6. The area consists of wide and softly undulating plains cut by river branches. One of the most important rivers of the Iberian Peninsula, the Guadiana, flows through the zone, which is used for irrigation and electricity generation. The Portuguese area has two special-nature protection areas, San Vicente and Torre da Bolsa, as shown in Fig. 5.

Crops constitute 78% of the land cover in the case study, olives and plums being the most important crops. Grasslands constitute 8% of the land cover, and forests 4%. For the entire analysis of the land cover composition, refer to Fig. 7. Note that the predominant land cover in the case study is comprised of crops, with forested areas playing a lesser role. While forests are recognized as significant contributors to fire spread, crops can also play a substantial role. An example of this case is the Pedrógão Grande fire in Portugal in 2017, where crops, poorly managed due to invasive species, emerged as a main source of fire spread (CTI, 2017). The information on sources and barriers is obtained for QGIS, through Open Street Maps, and complemented with the land cover/use maps of each country (DGT, 2022; CNIG, 2020). The modeling process and visualization of the results are automated using the Geographic Information System (GIS).

When applying the methodology to both countries, differences in the quality of the information are apparent because the databases are not homogenized. In this case, the biggest difference is in the forest categorization, displayed in Fig. 8. The classification of forests in Portugal is given in up to 5 levels of detail (left area in green color). Compared to the Spanish forest classification, which has only one level of detail (the right area in beige color). These differences will influence the accuracy of the outputs, i.e., the exposure assessment. For instance, if a more detailed classification would reveal the presence of high-exposure species in Spain, such as eucalyptus, the exposure would be higher for those areas.

The ROS values for all sources and barriers are considered as in Arango et al. (2023a) with updates to this specific case regarding crop detail. The ROS values considered are shown in Tables A-1 and A-2 in Appendix A.

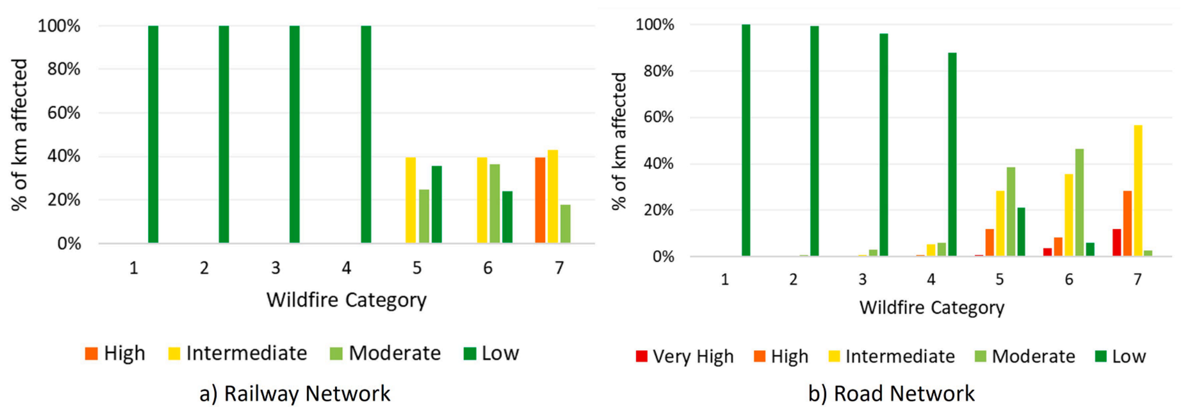


Fig. 10. Percentage of km affected for the different exposure levels according to each wildfire category of the Elvas-Badajoz transport network. a) Railway network, b) Road network.

The aggregation of the different sources and barriers is done considering the grassland ROS value as the reference source for normalization. The grassland ROS value is used for convenience following Tedim et al., (2018), which provides the classification of ROS characteristic values for different wildfire categories, as specified in Table 1. However, with the proper information, any source can be used as a reference. Then, the average value of the normalized sources and barriers is considered for evaluating the EFD. The calculated EFD and the ROS associated with the different wildfire categories are combined to obtain the exposure level of the transportation network. Fig. 9(a) shows the exposure map of the road and railway networks for a normal wildfire category (Category 2, ROS of 30 m/min). In contrast, Fig. 9(b) shows the exposure level of the networks for an extreme wildfire (Category 6) with a propagation speed of 300 m/min. Each FIRAT interval is associated with a specific exposure level; i.e., FIRAT less than 30 min corresponds to a very high exposure level. For wildfire Category 2, the level of exposure of both transport networks is mainly low for both countries. Except for Road 24, with 177 min for FIRAT or reaction time, which has a moderate exposure level. It is due to being surrounded by diverse sources of high exposure, including commercial and industrial sources (see Fig. 6b). This implies that in case of low wildfire, that would be the first road that can be reached by the fire, and consequently, it would be the main road that could be proactively intervened upon to reduce its exposure. In contrast, for wildfire Category 6, it can be observed that the transport network's exposure is higher. Especially in Elvas Portugal, for which 22% of the roads have reaction times of less than one hour, as shown in Fig. 9 (b). This short reaction time can lead to road closures severely hampering evacuation processes and consequently to high societal impacts. Meanwhile, the level of exposure of the transportation networks in Badajoz Spain is lower. This can be attributed to more barriers in the Spanish area, such as the river. As a result, most roads have moderate to intermediate levels of exposure.

Fig. 10 shows the difference in the level of exposure of the transportation networks analyzed for all wildfire categories. It is evident from the data that the railway network exhibits low exposure to normal fires (Categories 1 to 4). A high exposure level occurs in Category 7, encompassing 40% of the railway network segments. In contrast, the road network, under the same category, has 12% of its roads classified at a very high exposure level and 28% at a high level. Further details regarding exposure levels can be found in Fig. 10. Additionally, Table B-1 in Appendix B provides detailed exposure levels categorized for each country.

4.3. Discussion of results on decision-making support using the GIS-FA tool

This tool supports decision-making for medium- and long-term planning (i.e., proactively) and during emergence (i.e., reactively). For medium- and long-term planning, decision-makers should define the degree of exposure they are able to accept under specific wildfire conditions. For instance, for normal-category fires, their goal is to guarantee that none of the assets of the analyzed system has an exposure level larger than 30 min. This time may be related to the time for emergency services to reach the area. However, setting this condition for the entire system under extreme events may be unrealistic because the fire ratio of spread can be 60 times larger than normal wildfires. Therefore, for this type of wildfire intensity, the focus should be on guaranteeing some critical assets of the system, for instance, the roads of an evacuation route to safeguard civilians.

The GIS-FA tool allows the assessment of the intervention's impact on the existing exposure of the system. These interventions can aim at improving vegetation management, creating firebreaks, installing temporal fire stations during the most critical months, or any other type of infrastructure adaptation. Then, the tool can translate these interventions into geographically located sources and barriers thus, modifying the exposure of the system. To illustrate how this tool can be used to support medium- and long-term decision-making, some examples are presented below. Based on the exposure map for wildfire Category 2 (Fig. 9a), one of the actions could be investment in reducing the level of exposure of Road 24, as it is the most exposed road. Examples of actions to reduce the exposure of this road can be guaranteeing adequate maintenance of poorly irrigated crops and unattended vegetation in the surroundings. For more details on vegetation management actions see Menon and Vishnu-Menon (2022); Herbert et al. (2022); Baudena et al., (2023). From the exposure map for wildfire Category 6 (Fig. 9b), Roads 1, 21, 37, 44, and 45 could be intervened as they are part of the most important road within the studied area, which connects the capitals of both countries. Also, intervention measures could be implemented to reduce the exposure of the most affected railway sections, guaranteeing the safety of the users. The above implies a greater effort on the part of Portugal compared to Spain, as the exposure level for both railway segments and roads is higher in Portugal. Moreover, additional interventions can be considered in the Portuguese zone, for the area near Roads 17 and 9, since their exposure level implies that the special protection zone Torre da Bolsa can also be compromised. It should be clarified that these results are susceptible to a more detailed mapping of information, especially in the case of Spain.

On the other hand, the tool can support decision-making for emergency planning. In this case, since the study focuses on transport networks, it can support traffic management in terms of evacuation routes and ensure users' safety. The exposure maps of the different wildfire categories serve as a basis for this purpose, in which the main objective is ensuring users' safety by avoiding potentially disconnected areas in a wildfire event. Thus, the primary assumption is that depending on the wildfire category, the roads or railway segments with a high level of exposure will be likely closed. For instance, as one of the first routes to be affected is Road 24, evacuation routes must be defined in such a way that this road is avoided. However, the more intense the wildfire, the more difficult it is to define safe routes to reach the origin–destination pairs. As shown in Fig. 9(b) for EWE, network connectivity is compromised in different areas. At the road network level, to go from one country to another, the main route could not be used after 120 min, as fire may reach Roads 1, 21, 37, 44, and 45. Alternative routes such as the Northern route consisting of Roads 56, 55, 38, 35, 27, 21, and 1 present the same problem. It can be rightly argued that in the event of a southbound wildfire, the Northern route can be more dangerous. During an emergency, decision-makers should combine the real-time information with the exposure map corresponding to the given wildfire or larger intensity if worse conditions are expected. Even under very critical conditions and with a very intense wildfire, the entire transport network may be affected simultaneously. For this reason, the constant improvement of all means of fire suppression and evacuation cannot be neglected.

Cases such as Roads 32 and 34 should also be carefully considered for timely closure. To better explain this, look at Road 34 which is intercepted at both ends by roads with higher exposure levels. Thus, if Road 34 is not closed in time, users may be trapped in the flames and smoke (CTI, 2017 mentioned this effect in the case of Pedrógão Grande). One way to prevent users from being isolated is to improve network connectivity. For example, Road 51 has only one end (node) connected. Therefore, extending the connectivity of Road 51, for instance to Road 38, could reduce the possibility of that area becoming isolated.

In any case, increasing the redundancy of the network facilitates evacuation routes by adding alternative routes for the same origin–destination pair. For this reason, the railway network is more problematic than the road network in terms of emergency planning. Fig. 9(b) shows that any affected segments from 1 to 8 would directly affect the overall performance of the network under consideration. For extreme wildfire categories, the rail network would lose its connectivity in less than two hours, as Segments 5, 6, and 7 have higher exposure level i.e., less than 120 min of FIRAT. Consequently, evacuation and closure of the rail network must be a priority in case of wildfires.

5. Insights from the cross-border case study

Cross-border collaboration brings several challenges for the countries involved. These challenges are associated with different areas, stakeholders, and resources, which include but are not limited to:

- Governance. It represents one of the most challenging aspects of cross-border cooperation. It is because both countries have high institutional complexity and poor joint actions between the entities in charge, making articulation difficult, and creating overlapping and duplication of responsibilities. For instance, in Portugal, the national forestry authority has changed its institutional structure six times in the last twenty years and there are more than 50 derived entities engaged in the prevention and fight against wildfires (CTI, 2018). Consequently, it is not only difficult to coordinate cooperation at the national level in each country, but even more at the cross-border level.
- Infrastructure and mobility. There is a weak development of jointly managed cross-border public transport services and deficiencies in the density of railway lines, especially in areas such as Extremadura-Spain and Alentejo-Portugal. This is an obstacle to connectivity and mobility between both sides of the border. This limitation becomes more relevant when it comes to emergency management, since the lower the redundancy of the networks, the more likely it is that an area will be secluded. For instance, if the emergency plan fails and transport networks collapse, some Portuguese areas could be isolated from Spain and other parts of Europe.
- Digitalization. There are differences between the two countries regarding their connectivity and digital services, as well as the use of cloud services and Big Data, which is lower than the EU average for both countries (Interreg Spain-Portugal, 2022). An example of a digitalization issue is the difference in geographic data detail, explained in Section 4.3. This challenge is being studied by projects such as Cross-forest (CEF, 2018), which aims a combine Forest Inventory Datasets from Portugal and Spain to support forest management and forest protection.
- Hazard management. Wildfires are particularly frequent in the area, and both sides of the border present a high fire risk level. This means that the cooperation between Portugal and Spain, which only covers emergency plans, must also be extended to prevention and protection projects. In the analyzed case, the suppression capacity during EWE should guarantee response times lower than 60 min. If the capabilities of the emergency systems cannot make it possible, this implies that prevention and protection strategies must complement wildfire management, thus reducing the hazard's risk.

The countries sharing a border must implement actions to overcome these and other limitations in their cooperation. Adopting a more resilient approach is also important, paying attention to all the wildfire management strategies, from prevention to suppression

Table A-1
ROS values for spread and barrier sources – assumptions or observations, according to Arango et al. (2023a).

Spread sources	ROS (m/min)	Assumptions - Comments
Basics		
Grassland	50	All values were taken in 10% Humidity and 20 km/h Wind condition.
Shrublands	25	
Dry eucalypt forest	12	
Pine plantations	7	
Wet eucalypt forest	1	
Fire Barriers		
Wastelands	0.5	They are assumed as elements that do not spread fire, i.e., fulfill the function of a barrier.
Rivers and water bodies	1	
Swimming pools	0.5	
Firefighters	0.5	
Forest		
Invasive species	50	It is assigned the same ROS as grass due to the existence of Cortaderia Selloana, a species with high propagation speed.
Shrublands	35	This vegetation type is assumed to be large-scale plantations and therefore can increase fine flammable fuels at a landscape scale. The mean values of models built with previous information in this area were used.
Eucalypt (plantation)	25	
Maritime pine (plantation)	30	
Stone pine (plantation)	33	These values are established from the base values and expert judgment.
Cork oak	12	
Other oaks	12	
Chestnut	7	
Hardwoods trees	7	
Farming		
Poor irrigated farming	25	Farming is assumed to be combustible and therefore spread the fire.
Olive farming	15	These values are established from the base value "Poor irrigate farming" and expert judgment.
Constantly irrigated farming	10	
Wine farming	10	
Rice farming	1	
Other activities		
Gas stations	200	Assuming an average damage radius of 550 m and a 60s time to reach it.
Industrial	450	Assuming 3 km of heavy damage recorded on the Beirut (Vancouver) blast and 400s to reach that blast radius.
Subestations and Power plants	250	An average explosion radius of 250 m is assumed and 1 min is considered to reach that radius for the most critical scenario.
Commercial	170	A blast radius of 804 m according to the reference and time of 284 s is assumed.
Sports	25	Assuming that they are mostly grass fields or with green areas such as pastures.
Buildings	7.2	Assuming fire-spread mechanisms between buildings with non-combustible claddings through non-fire-rated roofs or wall openings is use a critical separation distance a broken window of 18 m and 2.5 min to reach that length.

Table A-2
Additional ROS values for spread and barrier sources – assumptions or observations.

Spread sources	ROS (m/min)	Assumptions/ Observations
Poor irrigated farming	25	It is assumed to be fuel due to the presence of weeds and poor irrigation.
Olive farming	15	Derived from the other values.
Irrigated farming (constantly irrigated)	10	They are assumed to be more careful crops regarding weeds and the constant presence of water prevents a rapid fire spread.
Wine farming	10	Derived from the other values.
Rice farming	1	It is assumed as irrigated rice crops, paddies filled with water (Kraehmer et al., 2017). It, therefore, acts more as a barrier than as a propagation source.
Water Bodies	1	It is assumed as an element that does not spread the fire. It is a barrier.

and recovery. In addition, cross-border collaboration should be done around all the strategies and not only during emergencies. For instance, differences in the level of prevention and protection may have implications in the long term for both countries. At the emergency level, any problems in the coordination of the emergency services of the two countries can have serious societal consequences. In this sense, the presented GIS-FA tool may help to identify and overcome such limitations and support decision-making at all stages of wildfire management.

6. Conclusions

Adequately addressing the new wildfire regime requires reconsidering the policies in wildfire management. The persistence of applying only reactive and short-sighted wildfire management policies results in fighting the symptoms of the problem but not the

Table B-1
Exposure level of the Elvas-Badajoz transport networks for different wildfire categories.

Country	Network	Wildfire Category →	Cat 1		Cat 2		Cat 3		Cat 4		Cat 5		Cat 6		Cat 7	
		Exposure Level ↓	km	%	km	%	km	%	km	%	km	%	km	%	km	%
Portugal	Railway	Very High														
		High													11	49%
		Intermediate									11	49%	11	49%	6,7	30%
		Moderate									3,5	15%	6,7	30%	4,9	22%
		Low	22,6	100%	22,6	100%	22,6	100%	22,6	100%	8,1	36%	4,9	22%		
Spain	Railway	Very High														
		High														
		Intermediate													5,2	100%
		Moderate									3,4	65%	3,4	65%		
		Low	5,2	100%	5,2	100%	5,2	100%	5,2	100%	1,8	35%	1,8	35%		
Portugal	Roads	Very High									0,9	1%	4,7	7%	14,8	22%
		High							0,9	1%	14,5	21%	10,0	15%	33,0	48%
		Intermediate					0,9	1%	6,4	9%	33,0	48%	38,3	56%	17,8	26%
		Moderate			0,9	1%	3,9	6%	7,5	11%	12,4	18%	11,6	17%	2,9	4%
		Low	68,5	100%	67,6	99%	63,7	93%	53,7	78%	8,4	12%	3,8	5%		
Spain	Roads	Very High														
		High													2,0	4%
		Intermediate									2	4%	5,3	10%	51,9	95%
		Moderate									35	64%	45	83%	0,5	1%
		Low	54,5	100%	54,5	100%	54,5	100%	54,5	100%	18	32%	3,7	7%		

underlying problem. There is a pressing need to evolve towards more resilient policies that are effective in combating fire problems and are sustainable in the long term. This change of vision does not imply diminishing wildfire suppression efforts, but it does require more attention and investment in other aspects such as prevention and protection. In that sense, a balance should be found between these strategies.

One of the barriers to achieving this policy shift is the lack of adequate decision-support tools for the various levels of wildfire management. Those tools should be formulated from a resilience point of view. This paper shows how the GIS-FA tool can be effectively used to support decision-making at the protection and emergency management levels. Due to its ease of application, it can be implemented for different components of the built environment including in cross-border areas. It can be applied at the asset level such as buildings, factories, and bridges, or the infrastructure level such as roads, railways, and electric networks. Also, it can help to support decision-making policies regarding land management, e.g., crops, for which some tool adjustment is necessary.

There are two main specifications of applying this tool to cross-border case studies: (i) the determination of assets or targets, such as railway and road transport, must be defined according to the boundaries of the respective countries. This is because each country makes the decisions about these assets; (ii) the accuracy of the exposure assessment depends on the quality of the database. For instance, the uncertainty of the exposure assessment for the Spanish area is higher than for the Portuguese area, due to the simplified classification of the forest. Hence, it is important that countries have standardized (or homogeneous) databases to allow the same assessment quality and better cooperation between countries. As demonstrated, the tool can support long-term decision-making, as well as emergency planning. The obtained exposition maps can be combined with real-time information, such as fire ignition points to identify the optimal evacuation routes and road closures.

The GIS-FA tool can be also used to determine the extent of the reliance on suppression activities. In the analyzed case, Fig. 9(b), suppression actions may not be sufficient to cope with EWE in either country. Both transport networks exhibit reaction times of less than 180 min. It also establishes the areas of priority and responsibility to be considered by each country.

The new wildfire management policies should be aligned at the cross-border level. Poor wildfire management in one country can affect the neighboring country because, although the fire may not reach the neighboring country, its consequences will. Therefore, cooperation between two border countries such as Portugal and Spain is essential for the defense of their population against the increased risk of extreme wildfire events. However, achieving successful coordination between two countries for the management of hazards is extremely complex. In this regard, there are several constraints ranging from digitization to governmental and administrative barriers. One of the major limitations of cross-border coordination between Portugal and Spain is that it exists only for emergency management. Therefore, it is important to extend cross-border coordination to other aspects of wildfire management such as prevention and protection.

Acknowledgements/Funding

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 attributed to the first author.

Declaration of Competing Interest

The 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.

Data availability

Data will be made available on request.

Appendix A. Input data: ROS Values

ROS values considered for the exposure analysis are given in Table A-1 according to Arango et al. (2023a). Additional ROS values are detailed in Table A-2.

Appendix B. Outputs: Exposure level of the Land Transportation System

see Table B-1

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