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EVACUARFLORESTA PROJECT: EVACUATION DECISIONS AND PLANS IN WILDFIRE SCENARIOS



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Evacuarfloresta Project - Evacuation Decisions and Plans in Wildfire Scenarios

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PREFACE

Wildfires are increasingly recognized as one of the most complex and intensifying natural hazards, exacerbated by the impacts of climate change. Their frequency and severity have escalated notably in Mediterranean and temperate regions, posing significant threats to human lives, infrastructure, and ecosystems. In Portugal, the devastating wildfires of 2017 exposed critical vulnerabilities in emergency response systems and highlighted the pressing need for a more integrated approach to wildfire risk assessment, evacuation planning, and community resilience.

Against this backdrop, effective evacuation planning, coordinated territorial management, and informed community engagement have become essential elements of wildfire risk mitigation. This book provides a comprehensive approach to these issues, drawing on the EvacuarFloresta research project (2021–2025). By combining field research, spatial modeling, and behavioral studies, the book bridges the gap between academic knowledge and practical applications, focusing on effective evacuation planning, coordinated territorial management, and informed community behavior.

The chapters align with key tasks of the project, being Chapters 1 and 2 the introduction of the research. Chapter 3 reviews Portugal's Operational Management System (Sistema de Gestão de Operações - SGO) and evacuation decision-making, comparing strategies from countries like Spain, Greece and California, with case studies from Lousã, Sertão and Coimbra. Chapter 4 examines wildfire risk perception and preventive behaviors through interviews, surveys, and data analysis, exploring how past experiences and trust in institutions shape preparedness. Chapter 5 uses GIS tools to assess wildfire risk through hazard and vulnerability maps for selected municipalities, considering factors like topography and social indicators. The study also models evacuation travel times to improve emergency planning. Chapter 6 compares fire spread simulation tools (FireStation, Wildfire Analyst, Fire Dynamics Simulator) and introduces a methodology using satellite data (VIIRS) to enhance prediction accuracy. It *also* models evacuation using AnyLogic, integrating fire dynamics and road networks. Chapter 7 presents evacuation case studies, highlighting the importance of early warnings and identifying vulnerable

populations, especially in isolated areas and tourist destinations. Chapter 8 examines legal and institutional frameworks for evacuation, proposing a methodology for maintaining databases of vulnerable individuals using tools like Google My Maps.

This book is aimed at researchers, emergency planners, and students in fields such as geography, civil protection, and urban planning. It serves as both a scientific resource and a practical guide for improving wildfire risk management, contributing to safer, more resilient communities.

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Following the conclusion of the research project activities, it is a pleasure to extend our gratitude to those institutions and individuals whose cooperation and support were instrumental in the research activities underpinning this project, namely: Câmara Municipal da Lousã, Câmara Municipal da Sertã, Câmara Municipal de Coimbra, Junta de Freguesia da Lousã e Vilarinho, Junta de Freguesia de Cernache do Bonjardim, Nespéral e Palhais, Junta de Freguesia das Torres do Mondego, Corporações de Bombeiros dos respetivos municípios, Autoridade Nacional de Emergência e Proteção Civil e Guarda Nacional Republicana.

The cooperation and availability of these entities have not only contributed to the research but *also* have been a profound personal inspiration. It is with sincere respect and gratitude that we acknowledge their significant roles in the completion of this project.

ACRONYMS AND ABBREVIATIONS

- ADAI - Associação para o Desenvolvimento da Aerodinâmica Industrial
(Association for the Development of Industrial Aerodynamics)
- ANAFRE - Associação Nacional de Freguesias (National Association of Parishes)
- ANEPC- Autoridade Nacional de Emergência e Proteção Civil (National
Authority for Emergency and Civil Protection)
- ANMP - Associação Nacional de Municípios Portugueses (National Association
of Portuguese Municipalities)
- AUC - Area under the curve
- BGRI - Geographic Base for Referencing Information
- CEIF- Centro de estudos de incêndios Florestais (Forest Fire Studies Center)
- COS - Comandante de Operações de Socorro (Rescue Operations Commander)
- CFD - Computational Fluid Dynamics
- CTI - Comissão Técnica Independente (Independent Technical Commission)
- DECIR - Dispositivo Especial de Combate a Incêndios Rurais (Special Rural
Firefighting Device)
- DGAV - Direção Geral da Alimentação e Veterinária (General Directorate for
Food and Veterinary Affairs)
- DIOPS - Dispositivo Integrado das Operações de Socorro (Integrated Rescue
Operations Device)
- DON - Diretiva Operacional Nacional (National Operational Directive)
- ENB - Escola Nacional de Bombeiros (National Fire Service School)
- FDS - Fire Dynamics Simulator
- FFSS- Forças de Segurança (Security Forces)
- FS - Fire Station
- GNR - Guarda Nacional Republicana (National Republican Guard)
- ICNF - Instituto da Conservação da Natureza e das Florestas (Institute for
Nature Conservation and Forests)

IR - Incêndios Rurais (Rural Fires)

MAE - Mean absolute error

MAPE - Mean Absolute Percentage Error

MBE - Mean bias error

MBPE - Mean Bias Percentage Error

OTI - Observatório Técnico Independente (Independent Technical Observatory)

PEA - Plano Estratégico de Acção (Strategic Action Plan)

PMEPC - Plano Municipal de Emergência de Proteção Civil (Municipal Civil Protection Emergency Plans)

PNEPC - Plano Nacional de Emergência de Proteção Civil (National Civil Protection Emergency Plans)

PNGIFR - National Plan for Integrated Rural Fire Management (Plano Nacional de Gestão Integrada de Fogos Rurais)

PSP- Polícia de Segurança Pública (Public Security Police)

ROC - Receiver operating characteristics curve

ROS - Rate of Spread

SERQ - Centro de Inovação e Competências da Floresta (Innovation and Competence Forest Centre)

SGIFR - Sistema de Gestão Integrada de Fogos Rurais (Integrated Rural Fire Management System)

SGO - Sistema de Gestão de Operações (Operational Management System)

SIOPS - Sistema Integrado de Operações de Proteção e Socorro (Integrated Protection and Rescue Operations System)

SVES - Social Vulnerability for Evacuation Support

TO - Teatro de Operações (Theater of Operations)

UF - Union of Parishes (União de Freguesias)

WFA - Wildfire Analyst

WUI - Wildland–urban interfaces areas

ZCI - Zona de concentração e Irradiação (Concentration and Deployment Zone)

Chapter 1

SUMMARY OF EVACUARFLORESTA PROJECT

The decision of who, how and when to evacuate during a wildfire is a complex mission. Evacuations during wildfires disasters can involve large and somewhat unpredictable numbers of civilians, both informed and uninformed, traveling largely in private vehicles, for instance. An evacuation should not be an immediate or nearly immediate event, but a careful planning, with a correct management and planning of the territory, a good evaluation of the risks, a proper notification, a safe and timely community response, as well as, from agencies of the national emergency system, and much more. Defining, understanding, and anticipating fire, traffic and human behaviours are also key to a safe and efficient evacuation.

Much of the focus of evacuation planning involving transportation systems, such as streets, roads and highways has been directed at well-defined large areas, e.g. coastal cities, where a possible need for evacuation might occur and might involve large numbers of people (due to a hurricane, for example). Recognition for the size of the evacuation problem and the need for advanced planning are the first greatest challenges for large areas and/or large number of people.

However, there are growing concerns for ensuring that safe evacuation of small/medium areas (like neighbourhoods and building complexes) can take place. Improving community resiliency to wildfire is also a challenging problem in the face of ongoing development in fire-prone regions. Evacuation and shelter-in-place are the primary options for reducing wildfire casualties, but it can be difficult to determine which option offers the most protection in urgent scenarios. Evacuation decisions

can be part of a blend of interventions for the general population and subpopulations with particular sensitivities and vulnerabilities. For example a given wildfire situation may require the provision of community shelters for some population subgroups and the simultaneous evacuation of other subgroups. Although guidelines and policies have been proposed in some countries to inform this decision, a formal approach to evaluating protective options would also help advance protective action theory. Protecting a community can be viewed as assigning threatened households to one of three actions: evacuation, shelter-in-refuge, or shelter-in-home. The combined challenges of a high fire risk and poor vehicle access in mountainous regions may lead authorities to consider non-traditional alternatives to complete evacuation of a region under threat. Community fire shelters might be put forward as one such alternative.

Severe wildfires may cause devastation on communities, most significantly loss of life. The safety of at-risk populations depends on accurate risk assessment and emergency planning. Evacuation modelling and simulation systems are essential tools for such planning and decision making. During a wildfire evacuation, the behaviour of people is also a key factor; what people do and when they do it.

The decision to evacuate must be made cautiously based on the specific circumstances. Therefore, the proposed research project has the following main objectives as a decision-making support for the optimal protective-action to at-risk population: i) characterization of the territory, with identification and assessment of the current demography, the real transportation networks and territorial planning/managing, which may lead to significant problems in evacuation during a wildfire event; ii) to estimate evacuation risk; iii) to predict people behaviour and type; iv) to study the impact of three scenarios for emergency planning by communities: evacuation, shelter-in-refuge, shelter in home (or partial combinations), providing insights into circumstances that favour evacuation and those that do not; v) determine the required vehicles, scheduling and routes under uncertainties in evacuee population, time windows and wildfire propagation; and vi) awareness and education of the population, using dissemination workshops and training actions, promoting the resilience of populations. During a wildfire evacuation, people's behaviour is a key factor to decide on what people do and when they do it. For mountainous regions in rural villages, the use of community shelters will be studied

as an alternative to displacement from the community. Basing on an accurate risk assessment and different wildfire scenarios and weather conditions, it will be provided current evidence about whether i) to evacuate, and if so, who, when, where to and how to evacuate, ii) to shelter at home or iii) to shelter-in-refuge in the village. Emergency planning will be included in this project for an optimal protective-action to households in an urgent wildfire scenario.

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The research units involved in the research project are:

ISISE – Institute for Sustainability and Innovation in Structural Engineering

CITTA - Centro de Investigação do Território, Transportes e Ambiente

NICIF - Núcleo de Investigação Científica de Incêndios Florestais

IJ – Instituto Jurídico da Faculdade de Direito da Universidade de Coimbra.

The partner institutions are:

SerQ – Centro de Inovação e Competências da Floresta

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Chapter 2

INTRODUCTION

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2.1. Introduction

In recent decades, researchers have observed an increasing trend in the destructiveness of wildfires around the world (Moritz *et al.*, 2014, Bowman *et al.*, 2017, Tedim *et al.*, 2020). Humanity and fire have always coexisted, but the ability to manage fire has not been achieved and could become increasingly complex due to climate change (Moritz *et al.*, 2014, Bowman *et al.*, 2009). Furthermore, it is expected that wildfire risk will become much more common in areas that are not currently classified as prone (Ronchi *et al.*, 2019).

Moreover, when wildfire enters wildland–urban interfaces (WUI) areas, where human development meets or intermingles with undeveloped wildland or vegetative fuels (FEMA, 2022) that are both fire-dependent and fire-prone, the effects on

communities can be catastrophic, causing environmental and socioeconomic devastation. Recently, major forest fires all over the world have resulted in the loss of human life and have forced people to evacuate. In 2009 in Austrália, for example, there were 173 deaths, and, in 2014 in Sweden (the Vastmanland Fire), around 1000 people were forced to evacuate, with one death recorded. In Portugal, in 2003, 2005, and 2017 (June and October), there were 21, 16, and 116 fatalities, respectively, while in 2017/18 in California, 44 deaths were recorded. In Greece (Mati) in 2018, dozens of people were surprised by fire inside their homes and cars, resulting in around 100 deaths and 187 injured (Mitsopoulos *et al.*, 2015; Guerreiro *et al.*, 2018; Guerreiro *et al.*, 2022; Palaiologou, 2019; Pastor, 2020).

Multiple investigations into deaths and injuries caused by fires around the world show that more than two thirds of those injured and more than half of those killed could have been evacuated (Hall *et al.*, 2004; Kuligowski, 2023; Qin *et al.*, 2024).

The safety of at-risk populations relies on accurate risk assessment and emergency planning. The decision of who, how, and when to evacuate is a highly complex and delicate task. Evacuations during wildfire disasters may involve large numbers of citizens, who may or may not be aware of the severity of the disaster, and who might *also* find themselves in unpredictable situations (for example, traveling in personal vehicles). Additionally, despite the intrinsic characteristics of combustion, which make it difficult to evacuate due to smoke, incandescent particles, and flames (McCaffrey, 2015), several professionals linked to the subject argue that the safest action residents can take when faced with the threat of a forest fire is to evacuate (Edgeley and Paveglio, 2015). Thus, when faced with the threat of a wildfire, evacuation is mandatory in the USA and Canada (McLennan *et al.*, 2019). In Greece, after the Mati fire in 2018, early evacuation was favoured, as was evident during the recent 2021 fire season (Zikeloglou *et al.*, 2023).

However, an evacuation exercise may not be the most appropriate response, especially in places with poor accessibility or in biophysical settings that trigger the rapid movement of flames (Cova *et al.*, 2009; Neto *et al.*, 2023). There are also some complexities associated with evacuation: notification, timing, evacuating pets and evacuating individuals who refuse to leave or who delay leaving (Carroll and Cohn, 2007). In addition, since evacuation is a contingency exercise, there are

always associated risks. The work in Haynes *et al.* (2010), which analysed fatalities in Australia in the period 1900–2008, showed, for example, that 32% of fatalities occurred during late evacuations, while only 8% occurred when people remained sheltered in a property that could be protected. Looking at the economic aspect, too, post-fire studies have shown, for example, that a significant percentage of homes are destroyed by falling incandescent particles/embers before or after the fire front passes close to or through the structure, something that could be avoided by people remaining in their homes (Cohen, 2000; Quarles *et al.*, 2010).

In this context, there are other alternatives to evacuation, such as the stay and defend strategy used in North America and Australia, for instance (Walpole *et al.*, 2020). Another alternative is to shelter in place in a specific location, which can be a dwelling or a common area, defined in advance (Stasiewicz and Paveglio, 2021). Evacuation is always complex (Cameron *et al.*, 2009; Wong *et al.*, 2020), prompting numerous studies on the subject through evacuation simulations (Intini *et al.*, 2019; Murray-Tuite and Wolshon, 2013), fire progression and evacuation simulations (Wahlqvist *et al.*, 2021), and models that make it possible to identify a threshold around communities. Once this threshold is breached by the fire, communities should be triggered for evacuation (Dennison *et al.*, 2007; Li *et al.*, 2018). To this end, various software programs have been developed to work with evacuation at different scales and with different possibilities (Beyki *et al.*, 2023). However, these models typically lack detailed features that account for the interaction between wildfire behaviour and the evacuation behaviour of WUI residents. In fact, factors such as age, sex, culture, race, impairments, occupation type (whether residents or tourists), and income influence each evacuee's decision-making process and should be considered. Moreover, proximity to wildfire hazards significantly impacts evacuees' decision and behaviour (Beyki *et al.*, 2023).

In Portugal, evacuation plans are at an early stage. Rodrigues *et al.* (2022) investigated the Pedrogão fire in 2017, wherein 66 people died and found that 65% of deaths were linked with leaving the site (fleeing/evacuating) without orders or information from the authorities. The author adds that the safety of communities, particularly in the WUIs, depends on risk assessment, planning, and qualified emergency management (Rodrigues *et al.*, 2022). This is in line with Thompson

et al. (2016) and North *et al.* (2015), who state that improving the safety and effectiveness of response to fire requires a multi-faceted approach, i.e., an effective response requires effective pre-fire planning. The work by Oliveira *et al.* (2020), carried out in a Portuguese mountain parish with a very significant history of fires and an elderly population, concluded that knowing the level of risk of each village and the time needed to reach a safe spot by different routes can help define priorities for emergency intervention. *It also* states that this information is essential to establish safety and evacuation protocols adapted to each village.

Chapter 3

OVERVIEW OF THE EMERGENCY AND EVACUATION PLANNING AND TERRITORIAL MANAGING

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3.1. Introduction

The shift in the paradigm of wildfires is an imminent reality, with an increasing frequency and severity of fires, which are now exhibiting destructive potential far beyond what was once common.

“[...] Portugal, like the Mediterranean in general, is experiencing a convergence of two long-term trends: the widespread abandonment of a rural landscape that has become economically irrelevant, coupled with a strong reluctance of the government to live with fire” (<https://nationalgeographic.pt/>, 2019).

What is now referred to as mega-fires is an increasingly present phenomenon, not only in Portugal but globally. The extreme behavior of fire is becoming more frequent, often associated with extreme climatic events, which themselves occur with increasing regularity.

According to some authors, there is no clear definition of a mega-fire, but in the context of this study, such fires are considered to have spread over vast areas, crossing property boundaries, affecting homes and infrastructure, and exhibiting destructive potential that has yet to be fully recognized, putting lives and properties at risk (Leite, 2013).

This type of phenomenon is known for being extreme and highly complex, capable of reaching significant dimensions and intensities, causing substantial environmental and socioeconomic impacts. In this regard, these fires are considered ecological disasters of high intensity, which, more than their extraordinary size, are characterized particularly by their impacts and profound transformations at the environmental, social, and economic levels (Leite, 2013).

Climatic conditions have proven to be of great importance in the development and propagation of wildfires. When specific atmospheric conditions are met, the likelihood of mega-fires occurring increases significantly, as seen in the case of Pedrogão Grande in 2017, Portugal (Viegas *et al.*, 2017).

The government structures in Portugal, following the major wildfires of 2017, recognized, particularly in Resolution of the Council of Ministers No. 157-A/2017, that “*Portugal faces a structural issue in land planning, which the phenomenon of climate change has shown to be a serious threat to the safety of populations*”.

Following this realization, several measures have been implemented with the aim of reformulating the wildfire prevention and response system. Special focus has been placed on enhancing the safety of populations, involving and holding accountable local municipalities and other local entities, as well as promoting actions aimed at improving public preparedness and resilience in the face of rural fire situations. The government’s proposals have been gradually implemented in Portugal since then.

Wildfires with extreme and unpredictable behavior worldwide are a growing and critical problem, requiring mass evacuations to protect people and ensure safety (Manzello *et al.*, 2018).

3.2. Portuguese Context

3.2.1. Operational structure – strategies associated with evacuation actions

Emergency management involves handling the period between the emergency event itself and the arrival of structured aid, aiming to safeguard the safety of people and property in the affected area while minimizing negative consequences.

In Portugal, there are several documents, legislation and operational directives, that structure the actions related to intervention in rural fire situations. The key documents relevant to this topic in Portugal are as follows:

- National Operational Directive 1 – Integrated Device for Protection and Relief Operations (Dispositivo Integrado das Operações de Proteção e Socorro);
- National Operational Directive 2 – Special Device for Rural Firefighting (Dispositivo Especial de Combate a Incêndios Rurais);
- Integrated System for Protection and Relief Operations (Decree-Law No. 72/2013, of May 31, created by Decree-Law No. 134/2006, of July 25, and amended by Decree-Law No. 114/2011, of November 30);
- Operational Management System (Sistema de Gestão de Operações - SGO) – Revised by Resolution of the Council of Ministers No. 157-A/2017, of October 21;
- National Civil Protection and Emergency Plan (Plano Nacional de Emergência e Proteção Civil - PNEPC);
- Municipal Civil Protection and Emergency Plans (Planos Municipais de Emergência e Proteção Civil - PMEPC).

Analyzing the relief structure through the previous documents, which define the strategies to be applied in Portugal, it is understood that the decision to evacuate settlements always rests with the Rescue Operations Commander (Comandante das Operações de Socorro - COS) present at the Theater of Operations (Teatro de Operações - TO). The COS, always represented by the senior member of the firefighting forces on-site, assumes responsibility for both fighting the fire and ensuring the safety of the affected populations.

The Operational Management System (Sistema de Gestão de Operações - SGO), reviewed by Dispatch No. 3317-A/2018, establishes the configuration

of the system and operation management, dividing it into three levels: Strategic, Tactical, and Maneuver. It is at the Strategic Level that the COS must develop and maintain an up-to-date Strategic Action Plan (Plano Estratégico de Ação - PEA), which gathers a set of actions aimed at anticipating the development of the incident, forecasting and maximizing combat opportunities, and empirically assessing the need for evacuation of populations. While the Tactical and Maneuver levels focus on execution operations, although evacuation-related actions are not explicitly stated in the legal framework, the operatives at these levels are key in planning evacuation actions, as they are on the ground and support the COS in decision-making through the information they provide.

Dispatch No. 3317-A/2018 also organizes the Theater of Operations (TO) according to the evolution of the fire. As the number of operatives at the TO increases, the complexity of the command post also increases proportionally to the size of the fire, as shown in Figure 1.

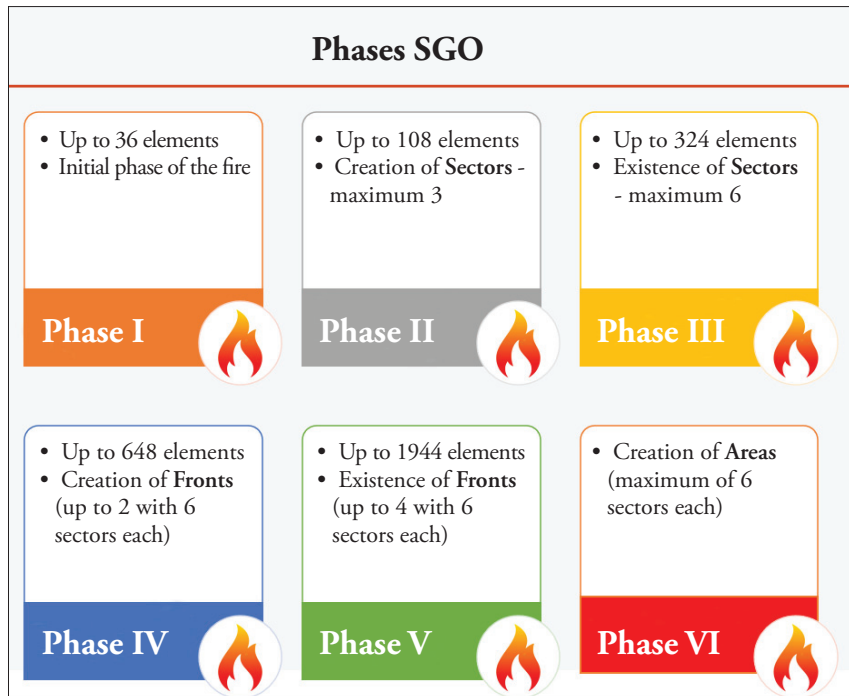


Fig. 1 - Phases of the Operations Management System (Rodrigues *et al.*, 2022).

As is widely recognized, “A devastating fire requires three coincidences: a dry period that predisposes all dead fuel to burn, dries out annual plants, and reduces the moisture of living vegetation tissues; the simultaneity of hot, dry air with strong winds or rugged terrain; and a high fuel load. Any fire that is not immediately controlled after ignition will be uncontrollable under these circumstances” (Fernandes, 2017).

To face the rapid development a fire can take, especially in areas with a high urban-forest interface, the operational structure progresses to ensure the presence of operatives on the ground to provide safety and support for the evacuation of people, such as the Sector Commander and Front Commander, as well as the creation of an operations cell responsible for “proposing evacuations not foreseen in the PEA” (Dispatch No. 3317-A/2018). Figure 2 presents the decision-making framework for the evacuation of populations during the first hours of a fire and, consequently, during phases I and II of the SGO.

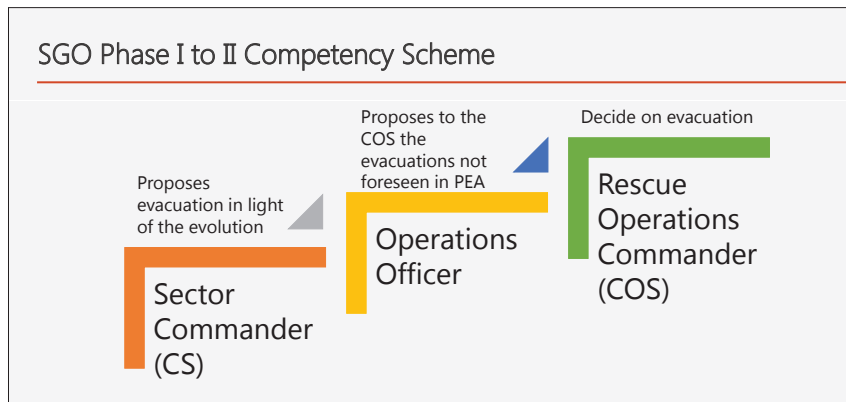


Fig. 2 - Decision-Making Framework for Evacuation (Rodrigues *et al.*, 2022).

In the subsequent phases, the framework evolves, creating Logistics and Planning cells that aim to provide a more technical approach to decision-making. The Planning cell will assess the need to evacuate settlements based on the fire’s evolution, while the Logistics cell will develop plans to support the evacuation of people in coordination with municipal civil protection services. Figure 3 schematically represents this evolution.

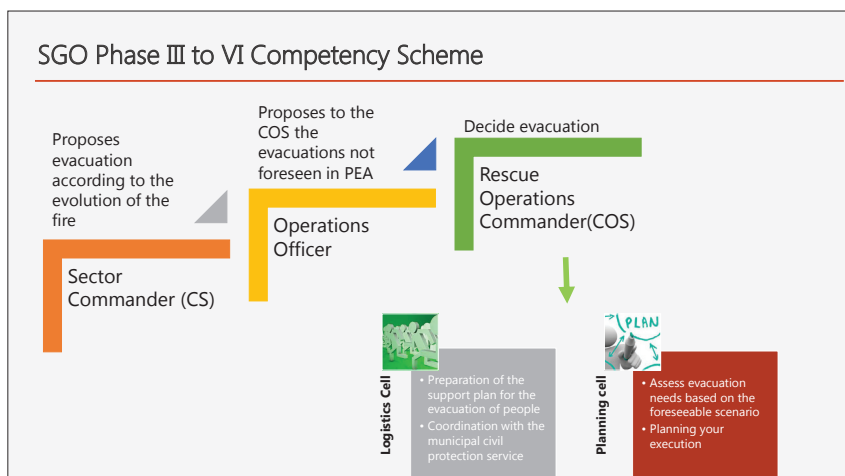


Fig. 3 - Decision-Making Framework for Evacuation – Phases III to VII of the SGO
(Rodrigues *et al.*, 2022).

In phases III and beyond, the operational command structure foresees the creation of two cells – Logistics and Planning – where an organization and planning of potential evacuation actions will be coordinated with the local Municipal Civil Protection Service, when available.

Although the legislation defines the rank of the COS for each phase of the SGO, during Phase I, it is stated that “[...] *the COS role is assumed by the leader of the first team to arrive at the site, regardless of their rank*”. Experiences from recent years of fires in Portugal have shown that fires can threaten populations during the initial hours of an incident. Thus, it is crucial and urgent to train rescue structures, from the base up, so they can recognize the need to evacuate urban settlements at the interface, to avoid unnecessary evacuations or situations where evacuation would have been necessary.

The evacuation action is identified in the operational structure as logistical operations and the safeguarding of populations. Annually, the National Authority for Emergency and Civil Protection publishes National Operational Directive No. 2 – DECIR (Special Rural Firefighting Device), which establishes the special device for rural firefighting. This document aims to “[...] *define the primary responsibilities and coordination of multiple agents with shared responsibilities in rural and periurban areas, acting to ensure the management of rural spaces and the application of efficient*

techniques and tactics for suppression, in conjunction with any related or derived risks” (ANEPC, 2020). This document annually establishes the responsibilities of each intervening entity within the Integrated System for Rural Fire Management and outlines the available resources at each phase of DECIR.

Regarding evacuation and population safety, this directive establishes confinement/evacuation as a phase of combat operations. It notes that not all fires go through this phase, summarizing that during initial or expanded attack actions, efforts should be made to concentrate populations in shelters or refuges in case of a risk of fire spreading to settlements. It further states that “[...] *when a threat to populations exceeds their self-protection capabilities, request the evacuation of settlements from the Security Forces, through the COS*” (ANEPC, 2020). In this process, the GNR (National Republican Guard) and PSP (Public Security Police) are tasked with supporting the evacuation as security forces, maintaining circulation restrictions, and opening emergency corridors for rescue operations. The armed forces, when present at the TO, should also collaborate with the authorities in this mission.

According to the National Emergency and Civil Protection Plan approved by the Resolution of the Council of Ministers No. 87/2013, of December 11, the emergency phase prioritizes, among other actions, “*Evacuation of at-risk populations, with special attention to the sick, bedridden individuals, elderly, children, disabled persons, and others in vulnerable situations*” (ANEPC, 2013). In terms of responsibilities, the national plan and the consulted district plans, contrary to what is stated in DON2-2021, indicate that it is the firefighters’ mission to participate in the primary evacuation within their areas of intervention or as reinforcement. Both at the national level and in district plans, the responsibility for coordinating evacuation actions lies with the GNR, with support tasks for evacuating populations, and the possibility of advising populations to remain in their homes if this option is identified as the best course of action. The PSP should also support the evacuation of endangered populations. These security forces face additional challenges during the evacuation process, such as the lack of information on priority individuals needing evacuation with special vehicles (e.g., ambulances) and dealing with people who, in the Portuguese context, often resist evacuation and prefer to stay in their homes to protect them, sometimes putting their lives at risk.

The “Aldeia Segura, Pessoas Seguras” program brings some innovation; although the method of communication between authorities and those with information about the characteristics of the settlement remains open (see section 3.2.3). Regarding the Armed Forces, the plan assigns them primary and secondary evacuation tasks, in coordination with local authorities. The national emergency plan also includes collaboration with the Institutions Cáritas and the Portuguese Union of Misericórdias in evacuation efforts, search for missing persons, management of displaced persons’ camps, and with the Red Cross in evacuating the injured and transporting displaced and uninjured individuals.

As for the procedures, it is clear that the entity coordinating the evacuation of people will be the security forces (varying depending on the jurisdiction where the incident occurs). Depending on the situation, as provided in some plans, particularly district-level plans, there is a need for individual assessment to decide whether to evacuate or confine. The district plan for Coimbra, analyzed in this context, also mentions that «[...] the collective movement of the ZCI (Concentration and Irradiation Zones) will be guaranteed by transportation provided by Humanitarian Firefighter Associations, public or private transport companies, or other means provided by the logistics intervention area” (ANEPC, 2016). This definition shifts the responsibilities to the operatives at the site of the incident, who, based on the time and information they have, must ensure the provision of resources to support the evacuation of people.

3.2.2. Current forest management policies in Portugal

In June 2020, the Presidency of the Council of Ministers approved the National Plan for Integrated Rural Fire Management (PNGIFR - Plano Nacional de Gestão Integrada de Fogos Rurais), which establishes a coordinated risk governance strategy and fosters cooperation among the various involved authorities. The plan aims to protect against severe rural fires and, ultimately, to safeguard people and property from fire-related risks. This document outlines the national strategy for wildfire protection for the 2020–2030 period and underwent public consultation, engaging over 2,000 participants.

Decree-Law No. 82/2021, issued on October 13 and coming into force on January 1, 2021, introduced significant changes, presenting a thoroughly restructured approach compared to the previous National System for Forest Fire Protection, originally established by Decree-Law No. 124/2006, which had undergone multiple revisions.

This new legal framework clearly defines the responsibilities of each entity, mandating that municipalities maintain an inventory of shelter and refuge infrastructure, evacuation routes, logistical support bases, and other essential facilities. Figure 4 provides a summary of the key responsibilities assigned to municipalities in the protection of people and animals, in accordance with Decree-Law No. 82/2021.

Competences of local authorities in protection of people and property: DL 82/2021 in its current wording	
Inventory of:	• Shelter and refuge infrastructure network; • Evacuation routes; • Logistical support bases and other combat support infrastructure.
Emergency solutions planning:	• Provision of aid and assistance; • Evacuation; • Accommodation; • Supplying populations, including pets.
Promote awareness-raising actions on prevention and protection behaviors against forest fires;	
Implement, on a local scale, protection programs for population clusters to protect and prevent risky behavior, especially the “Safe Village, Safe People” and “Village Condominium” programs.	

Fig. 4 - Table Summarizing the Municipalities' Competencies under Decree-Law No. 82/2021.

The transfer of competencies to municipalities is clearly defined in the context of protecting populations from rural fires, assigning them the responsibility for evacuating residents. However, it remains unclear and unspecified who is responsible for evacuating individuals with mobility impairments or special needs and with what resources this should be accomplished.

Notably, this document introduces, for the first time in Portugal, the concept of animal evacuation. This concept applies to both companion animals and livestock, assigning the Directorate-General for Food and Veterinary Affairs (DGAV) the task of identifying, in priority prevention and rescue areas, animal population densities requiring additional protection. Furthermore, the DGAV is responsible for preparing evacuation strategies in coordination with other entities.

Municipalities now play a crucial role in protecting both people and animals in wild-fire situations. Their responsibilities begin with risk preparedness, including the implementation of the program “Aldeia Segura, Pessoas seguras”, public awareness initiatives, and the development of clear action plans for population evacuations when necessary.

A communication and warning strategy is also established to promote best practices and self-protection measures.

Although the system does not formally integrate parish councils, municipalities, through their executive bodies, may delegate or contract some of their assigned responsibilities to them. From a reflective perspective, parish councils represent the closest level of local government, possessing in-depth knowledge of the vulnerabilities of their populations and the most sensitive areas. As such, they should play an active role in civil protection and emergency response in Portugal.

3.2.3. Safe Village, Safe People program (Programa Aldeia Segura, Pessoas Seguras)

The Portuguese territory is characterized by a highly dispersed population across the entire country, creating a concerning wildland-urban interface issue throughout the mainland. In rural areas, this challenge is further exacerbated by the presence of small settlements and isolated houses, often embedded within forested areas with difficult access. This contributes to even small fires posing a significant risk to both human life and residential structures.

The Resolution of the Council of Ministers No. 157-A/2017, of October 27, seeks to engage local communities in their own safety by introducing measures to enhance population security through the establishment of two distinct programs: a) Safe People (Pessoas Seguras); b) Safe Village (Aldeia Segura).

Although these programs are frequently regarded as a single initiative, they operate under distinct premises.

The “Safe People” program focuses on individual awareness regarding risk behaviors and self-protection measures, culminating in evacuation drills organized by municipalities in cooperation with local representatives. Additionally, this resolution provides for the creation of an automatic warning system to alert populations on days of high fire risk, encouraging the adoption of preventive measures and safer behaviors.

On the other hand, the Safe Village program is a collective initiative aimed at protecting both rural settlements and forested areas. This program addresses the need for structural protection measures, not only for people but also for their assets, particularly buildings located within the wildland-urban interface. It establishes strategies for managing protective zones around settlements and critical infrastructure, identifying risk areas and designated refuge sites. Municipalities and parish councils are recognized as proactive entities responsible for mobilizing local populations and incorporating community-based knowledge into fire prevention efforts.

Given their complementary nature, many municipalities have opted to implement both programs simultaneously.

Although these initiatives are centrally managed by the national government, municipalities and parish councils—due to their proximity to local populations—are expected to play an active role in their practical implementation. The success of these programs relies on the direct involvement of local communities.

It is important to note that similar programs had already been developed and implemented before 2017. In fact, the name Safe Village was previously used in 2006–2007 as part of the National Awareness and Education Program for Forest Fire Defense, launched in 2006 under the Resolution of the Council of Ministers No. 65/2006, of May 26, and Decree-Law No. 124/2006, of June 28.

At that time, the program was developed by the former Directorate-General of Forest Resources (DGRF), now the Institute for Nature Conservation and Forests (ICNF), with a focus on creating defense systems for rural settlements that could be managed and implemented by local communities. The program, jointly executed by ANPC (now ANEPC) and by the DGRF (now ICNF), placed significant

emphasis on distributing self-defense kits that could be mounted onto open-bed vehicles. These vehicles were to be provided by the beneficiary entities, which were also responsible for logistics and maintenance. Parish councils and some producers' associations primarily assumed this role.

However, this approach raised several controversies, particularly concerning the lack of training for individuals operating the equipment and the increased risk for these volunteers, who were often recruited randomly and without clear selection criteria. Furthermore, the self-defense kits did not include personal protective equipment, further heightening the dangers faced by these individuals during fire situations.

Despite these challenges, the program's primary objective was to raise awareness among rural populations, emphasizing their responsibility for self-protection against wildfires. However, the program ultimately fell short of expectations. According to the Technical Study by the Independent Technical Observatory, the failure of the Safe Village initiative was largely attributed to the lack of funding mechanisms. The study further recommended that such programs should be implemented in collaboration with other active entities involved in wildfire prevention and response.

Additionally, the study highlighted an overlap with a separate government initiative that provided some parishes with self-defense equipment, leading to a lack of coordination between different measures. The observatory emphasized the importance of recognizing the existence of a similar program a decade earlier, suggesting that lessons from past experiences were not sufficiently considered to avoid repeating previous mistakes.

These programs are built upon five fundamental pillars, which are illustrated in Figure 5.

At all levels presented, municipalities and parishes must promote the mobilization of local communities to achieve greater citizen engagement, primarily through training and awareness initiatives. This approach aims to enhance confidence and understanding of the actions required should their settlement be at risk from a wildfire.

Currently, the implementation of the Safe Village and Safe People Programs results from a collaboration between three entities: the National Authority for



Fig. 5 - Fundamental Pillars of the Safe Village and Safe People Programs
(Rodrigues *et al.*, 2022)

Emergency and Civil Protection (ANEPC), the National Association of Portuguese Municipalities (ANMP), and the National Association of Parishes (ANAFRE). ANEPC develops the program's guidelines to ensure a uniform implementation across the territory, while municipalities and parishes assume more operational roles, such as executing concrete protection and awareness measures at the local level. They leverage their proximity to citizens and the capacity of local agents to mobilize their communities, strengthening trust and encouraging public participation (OTI, 2020).

To implement the program, it was necessary to create the role of the Safety Officer, an individual designated to act as a facilitator and coordinate the program's implementation within the community. This individual holds various responsibilities in both prevention and emergency situations. They are responsible for issuing alarms, directing evacuation and sheltering procedures, and maintaining direct contact with authorities and civil protection agents.

According to the implementation support guide, "*It is essential to ensure that this Officer is a key figure in the settlement, preferably a resident, who voluntarily acts as a facilitator between the Municipality/Parish and the wider community in implementing measures and disseminating information*" (ANEPC, 2018). There are reported cases where this role is assigned to the president of the parish council, and instances where a single Safety Officer is shared among multiple villages or localities.

As this is a community protection program, the creation of evacuation plans is also foreseen, defining and identifying shelter or refuge sites. Each village's plan designates a safe location where people can seek refuge in the event of a fire. It is expected that the plan will include a village map, supported by street signage, indicating the routes to follow so that residents and visitors can find the designated shelter site as outlined in alert and warning procedures. This document differentiates between shelter and refuge: a shelter is considered an enclosed space, whereas a refuge is an open area such as a football field or a public square.

The consolidation of this plan should be achieved through simulation exercises involving the population, where an alert is simulated to mobilize residents to gather at a pre-designated and signposted location—a shelter or refuge site. The OTI report, which analyzes the implementation of these programs, states that *“Unfortunately, the methodology employed in drills often insists on the complete evacuation of the settlement, sometimes after relocation and concentration at a designated village site, without considering that movement in the proximity of a wildfire may be riskier than remaining at home or at a neighbor’s house”* (OTI, 2020).

This analysis highlights a critical aspect that requires further discussion. The decision-making process regarding the safest actions for the population may involve evacuation, but also confinement. Evacuation may be partial or total, depending on necessity, with particular attention to priority groups. As stated in the implementation support manual: *“Children, the elderly, individuals with reduced mobility, and those who are physically debilitated or bedridden should be evacuated from the path of the fire as a priority and well in advance, necessitating prior identification of these vulnerable populations”* (OTI, 2020). It is important to note that the dynamics of wildfires do not always allow for timely and well-planned evacuations, a situation further aggravated by the lack of resources within the operational structure.

As of October 2021, the Safe People, Safe Village Program website recorded 2,064 participating settlements, 835 evacuation plans developed, and 289 simulation exercises conducted. The OTI presents some conclusions and recommendations, stating that *“The current designation of the programs as Safe Village Program and Safe People Program should be reconsidered, as it gives the impression of two separate programs, which is not the case in practice or public perception. Perhaps renaming it as*

Safe Village and Safe People Program would maintain the distinction between homes and people while emphasizing that protecting one implies protecting the other”.

This approach is highly relevant, as this is a program focused on protecting both individuals and their properties. It is essential that citizens clearly understand its objectives and perceive it as a unified project, recognizing that safeguarding their village is fundamental to their own safety.

Further analysis of the report’s conclusions reveals significant difficulties in implementing the program across the territory, with particular concern regarding the low incidence of execution in priority-classified villages. Additionally, in January 2020, the National Republican Guard launched a program with the common objective of safeguarding both individuals and emergency responders, called “Safe Forest 2020”. This initiative includes awareness campaigns for citizens and organizations, promoting behavioral change and the adoption of best practices (OTI, 2020).

3.3. Human Losses in Rural Fires

3.3.1. Data from Portugal

The loss of human lives as a result of wildfires will always be the most significant loss, regardless of the burned area of a single fire or the cumulative extent of wildfires in a given year.

The decline in forestry investment has contributed to the emergence of monocultural landscapes with a high fire load. *“When exposed to severe meteorological conditions, this scenario has resulted in large-scale wildfires, devastating vast forested and agricultural areas, infrastructure, and heritage sites, while endangering human lives. These events, in turn, fuel the vicious cycle of land abandonment, leading to ecosystem degradation and increased social and economic vulnerability in these territories”* (Portaria n. 301/2020, 2020).

It is important to note that the loss of human lives has been a recurrent issue over the years, with records dating back to 1966. Certain years stand out as particularly tragic milestones in wildfire history, notably 2003, when 21 people lost their lives,

and the catastrophic year of 2017, which saw a total of 112 fatalities—64 in June and 57 in October—according to reports from the Independent Technical Commission. TABLE I presents the historical record of wildfire-related fatalities over the years.

TABLE I - Historical record of rural wildfires with fatalities and injuries over the years in Portugal (Rodrigues *et al.*, 2021).

Year	Location	Total Deaths	Total Injured
1966	Sintra	25	
1985	Região de Lamego	14	N/C
1986	Região de Coimbra	15	50
2003	Vários - Todo o país	14	N/C
2004	Vários - Todo o país	2	N/C
2005	Região Porto, Castelo Branco	15	136
2013	Aveiro e Viseu (Caramulo)	9	N/C
2016	Madeira	4	200
2017	Pedrogão Grande (Leiria), Figueiró dos Vinhos, Nodeirinho, Castanheira de Pera; Coimbra (Gois, Pampilhosa da Serra, Arganil)	64	204
2017	Coimbra (Penacova, Oliveira do Hospital, Melo, Gouveia), Leiria (Pinhal de Leiria-Marinha Grande), Viseu (Netas, Tondela, Vouzela), Guarda, Castelo Branco	45	71
2018	Pena da Negra (Monchique, Silves e Portimão) Algarve	0	79

Data source: EN-DAT; www.emdat.be (search date: 10th of July 2021).

The year 2017 stands as a milestone in history due to the high number of fatalities recorded in two separate wildfire events occurring in the same year, spaced apart in time but geographically close. In the 2017 wildfires, 92% of the fatalities occurred in wildland-urban interface areas, highlighting the urgent need to develop models and protection mechanisms for populations residing in these environments.

The depopulation of rural areas and the continuous exodus of younger generations to large urban centers contribute to the abandonment of these regions, leaving elderly populations increasingly vulnerable to rural wildfires. A prevalent reality, particularly in Portugal's northern interior, is the existence of dispersed settlements, which often take the form of small, compact villages isolated within the landscape. Additionally, other settlement patterns are identified, among which the dispersed and scattered settlements are particularly relevant to this study. The scattered settlement type is characterized by a network of rural roads extending in multiple directions, with agricultural plots or gardens typically located behind the houses.

Conversely, dispersed settlements are decentralized, consisting of isolated buildings within a rural matrix. Agricultural plots are frequently repurposed for residential use, often as second homes that are not permanently occupied. This settlement type has been described as “[...] *the typology that best represents the illusory longing for a return to nature, and it is strongly associated with high-income groups, with most constructions being architect-designed*” (Carvalho, 2010). Portugal is notably characterized by highly dispersed urban clusters, particularly in its inland regions.

Retrospective studies on civilian fatalities resulting from wildfires worldwide are crucial for understanding the behaviors and circumstances that lead to loss of life. These studies often rely on forensic reports to determine the conditions surrounding each death. Globally, wildfires have consistently shown that late evacuation and a poor understanding of fire behavior are the primary factors leading to fatalities. Three main categories of victims have been identified:

- Victims who recognized the real threat to their safety with sufficient time to save their lives but chose an ineffective survival strategy;
- Victims who did not recognize the real threat to their safety in time to implement an effective survival strategy; and
- Victims who were physically incapable of implementing effective survival strategies (Handmer, 2005).

The victim profiles identified in global studies closely resemble the findings from the analysis of fatalities in the 2017 wildfires.

3.3.2. Analysis of fatalities in the 2017 wildfires in Portugal

The wildfire complex that began on June 17, 2017, will remain a significant event in Portugal’s wildfire history due to its devastating impact, causing 65 fatalities and over 200 injuries. This disaster stands as one of the most severe incidents in Portugal and among the worst in Europe. The complex consisted of multiple fire occurrences, with the most critical ones originating in Pedrógão Grande and Góis, later merging with three additional fires. Together, they consumed a total area of 45,328 hectares (Viegas *et al.*, 2017).

In response to these wildfires, the Portuguese Parliament established the Independent Technical Commission (CTI) through Law No. 49-A/2017, enacted on July 10. This commission was mandated to conduct an independent assessment of the events. Additionally, the Center for the Study of Forest Fires at the University of Coimbra, coordinated by Professor Domingos Xavier Viegas, was contacted by the government and tasked with conducting a study on the fire's conditions, ignition, and spread. The primary focus was to analyze its propagation and assess fatal incidents to support authorities in decision-making, drawing lessons to improve future wildfire management (Viegas *et al.*, 2017). These studies—conducted by the CTI and CEIF-ADAI—were complementary in nature.

Following the June wildfires, a second devastating wave of fires occurred in October 2017. In response, the Portuguese Parliament once again requested the establishment of the Independent Technical Commission and the production of a new analysis and report. This second investigation faced unique challenges, including concerns over redundancy with the June report, as the country was still reeling from the recent disaster. Similarly, as in June, the government also commissioned CEIF-ADAI to conduct a study on the most significant aspects of these fires, with a specific focus on analyzing personal accidents directly or indirectly related to the events.

Despite their aligned objectives, discrepancies emerged between the two reports regarding the total number of fatalities. The CEIF-ADAI report identified and analyzed 51 fatalities, whereas the CTI report recognized only 48. This difference primarily stemmed from the CTI's decision to account only for direct fire-related deaths investigated by the Judiciary Police, whereas CEIF-ADAI considered both direct and indirect fatalities, based on the analysis of 40 fatal incidents.

The Independent Technical Commission's report on the June 17–24 wildfires highlighted critical delays in evacuation efforts. Notably, no evacuation measures were recorded during the initial hours of the fires. The first preventive evacuations were documented only 20 hours after the outbreak—by which time 64 people had already perished.

Additionally, the delay in implementing the correct phases of the Operational Command System (SGO) was noted as a significant contributing factor. It was only

at 19:58 on June 17 that the official operations, planning, and logistics officers were formally established within the SGO, mandating the activation of planning and logistics cells. This delay likely impeded the timely planning of protective actions for the affected populations (CTI, 2017).

The report further emphasized two key measures that could have, and should have, been implemented:

- Timely evacuation of at-risk villages;
- Mandatory confinement of residents in their homes, based on findings that a large proportion of the victims perished on the roads while attempting to escape. Notably, homes of individuals who perished while evacuating remained undamaged by the fire (CTI, 2017).

The need for advanced methodologies to analyze and predict fire behavior was also underscored. Unlike other natural disasters, wildfires exhibit a degree of predictability both in their likelihood of occurrence and in their expected behavior, making proactive evacuation planning critical.

A key distinction between the June and October wildfires of 2017 was the distribution of fatalities. While the June fire victims perished within a concentrated time frame and location, the October fatalities were more dispersed, resulting from a complex of multiple fires. Regarding victim demographics, the CEIF-ADAI report highlighted crucial insights. In the June 2017 wildfire complex, half of the victims were local residents, while the other half was either regular or occasional visitors to the affected area, as illustrated in Figure 6a).

Being a region highly sought after by nature tourism enthusiasts for its river beaches and tranquility, half of the victims were individuals unfamiliar with the area and its wildfire risk dynamics. Analyzing the process that led to these fatalities, Figure 6b) shows that 47% of the victims died far from their homes—corresponding to those who were visitors to the region. However, the most striking conclusion from this data is that 43% of the victims perished between 100 meters and 5 kilometers from their residence.

The data clearly show that these victims, faced with the imminent wildfire, attempted to flee without official guidance or reliable information, turning their escape into a fatal decision (Figure 6c). Notably, none of the victims' homes were

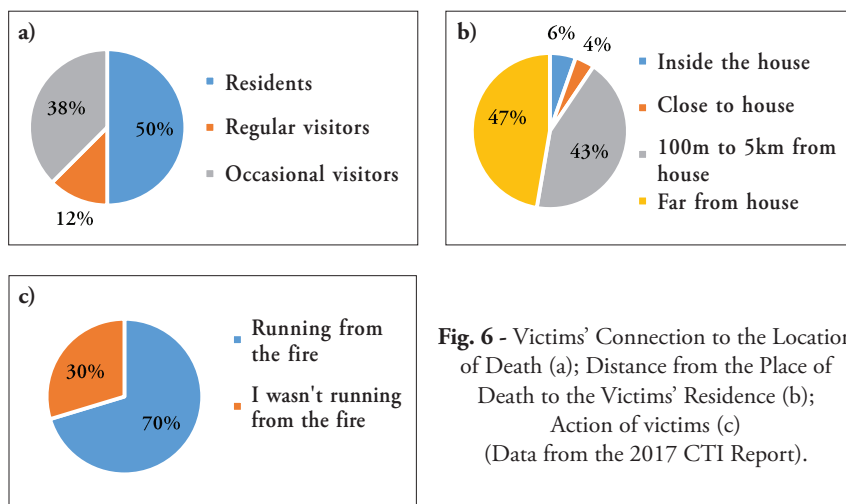


Fig. 6 - Victims' Connection to the Location of Death (a); Distance from the Place of Death to the Victims' Residence (b); Action of victims (c)
(Data from the 2017 CTI Report).

affected by the fire. Among those who were not fleeing, the report identified cases where victims were either caught inside their homes, returning from tourism activities, or driving to observe the fire. This behavior, deeply rooted in Portuguese culture, has been repeatedly flagged as problematic, contributing to road congestion and blocked emergency access. In this particular fire, curiosity tragically led to loss of life.

In October 2017, the situation differed slightly, with a significant decrease in victims attempting to flee. Additionally, the victims were generally older; more geographically dispersed, and mostly had a connection to the place where they perished (Rodrigues *et al.*, 2022).

3.4. Evacuation Actions – Historical Cases

3.4.1. Worldwide examples

In 2017, approximately 12,000 people were evacuated due to a wildfire in Bormes-les-Mimosas, southern France. Despite France's policy favoring sheltering over evacuation, around 10% of those evacuated were tourists (Ayuso, 2017). Official guidelines emphasize that "Votre habitation reste votre meilleure

protection” (“Your home remains your best protection”) (França, 2021). In 2018, wildfires in Mati, Greece, forced mass evacuations, yet the fire’s intensity resulted in many casualties. Some sought refuge in the sea, but overcrowded rescue boats led to further fatalities. In 2021, wildfires across the Mediterranean, particularly in Greece and Turkey, necessitated evacuations.

Similarly, in North America, California wildfires between 2017 and 2019 displaced over 10,000 people (Wong *et al.*, 2020). In 2021, a major fire in South Lake Tahoe prompted evacuation attempts for 22,000 residents. However, mass panic led to uncoordinated departures, causing severe traffic congestion (A. Lusa, 2021). In 2016, a wildfire near Haifa, Israel, led authorities to order the evacuation of 60,000 people (Marom and Toledo, 2021).

3.4.2 . Evacuation actions in Portugal

One of the major challenges in analyzing this issue in Portugal is the lack of historical data. The systematic recording of operational scenarios is a relatively recent development, and access to such information is generally limited. However, following the 2017 disasters, the subsequently established Independent Technical Observatory (OTI), under Law No. 56/2018 of August 20, began producing reports on major incidents in the country, improving the availability of data.

Prior to this, CEIF-ADAI had already conducted some studies analyzing past events. In 2012, a report commissioned by the Ministry of Internal Administration examined one of the largest wildfires recorded at the time. This fire occurred in an area characterized by a high number of dispersed settlements, most of which had small populations, predominantly elderly residents with limited mobility and resources to respond to the approaching threat (Viegas, 2012). Additionally, several isolated houses in the fire-affected area exacerbated the situation. Fortunately, there were no casualties. The report analyzed the event’s timeline and the corresponding emergency actions.

Contrary to common assumptions, this fire necessitated the evacuation of villages within the first 40 minutes. Fonte de Corcho, for example, was entirely evacuated with the assistance of two emergency vehicles from Vila Real de Santo

António and Faro. The dispersion of settlements and the imperative to protect the population meant that, during the initial attack phase, many available resources were allocated primarily to safeguarding individuals and their homes. From the early hours of the incident, the National Republican Guard (GNR) initiated the evacuation of individuals with mobility impairments and facilitated the relocation of all residents in at-risk areas to safer locations.

This case study highlights not only the challenges posed by the rapid and intense spread of the fire but also the pressing need to protect numerous houses and settlements in its path. The allocation of resources to these protective actions directly impacted firefighting efforts, as most evacuation operations were conducted using fire brigade resources. Reports from emergency responders in the field emphasized the fire's rapid progression and intensity.

Following the incident, the study's authors conducted meetings and surveys with affected residents to assess their perceptions of the situation. The majority of respondents believed that individuals should have the freedom to choose whether to evacuate or stay and defend their properties, with priority given to evacuating elderly individuals, those with illnesses, or those with mobility and resource limitations. However, it was also acknowledged that those who chose to remain should be better prepared and fully aware of the risks involved. The GNR's evacuation efforts were subject to significant criticism, as the report highlighted a general lack of public preparedness regarding evacuation procedures.

According to various media sources, the fire in Tavira resulted in the destruction of six permanent residences and 12 holiday homes, while in São Brás de Alportel, eight homes were completely lost and 14 were partially damaged by the fire.

Four years later, the tragic 2017 wildfires once again underscored the importance of analyzing fire incidents to improve preparedness and response strategies. Consequently, following these events and the establishment of the Independent Technical Observatory, major wildfires in Portugal have since been subject to systematic analysis and reporting. An examination of OTI reports on the 2018 Monchique and 2019 Vila de Rei wildfires revealed a growing concern among authorities for public safety, despite the often disorganized and improvised nature of evacuation procedures. In the Monchique fire of 2018, the report emphasized that "[...] *the safety of the population*

was a fundamental concern in this fire, as part of an effort to prevent a recurrence, albeit on a smaller scale, of the 2017 tragedies” (CTI, 2019). This report documented a large-scale evacuation of 608 individuals from 75 locations, as indicated in a GNR report, including the evacuation of a hotel in Caldas de Monchique. In the same report, the OTI recognized the need to reflect on local evacuation systems and procedures, noting that while this particular event resulted in no casualties, it should not deter further discussions on improving evacuation strategies.

In contrast, the 2019 Mação/Vila de Rei wildfire presented a different scenario. In Mação, wildfire prevention and mitigation were already ingrained within the community, largely due to the municipality’s history of fires (CTI, 2020). The local government had distributed approximately 80 first-response kits, and there was a strong collective effort to protect vulnerable individuals. A notable sociological phenomenon was observed: residents of villages not directly threatened by the fire mobilized to support and assist those in high-risk areas. This behavior was previously observed in 2017 and reoccurred in 2019. Such community-driven efforts may explain why residents in high-risk areas were reluctant to evacuate.

Meanwhile, in Vila de Rei, reports indicated that some villages had already implemented the Safe Village, Safe People program by the time of the fire. Residents were aware of designated shelter locations and followed the established protocols. For instance, in the village of Cabeça do Poço, five individuals sought refuge in a church as the fire approached. These findings highlight the evolving strategies in wildfire response and the increasing role of community resilience in mitigating the impact of such disasters in Portugal.

3.4.3. Previously adopted policies

When discussing public safety in the context of rural wildfires, different approaches are often detected depending on factors such as geographic location and culture. There is no one-size-fits-all evacuation model, and any plan should be based on the geographic reality (both physical and human) of the community, adaptable to the situation (ANEPC, 2018). A relevant example is Australia, which has long been

affected by such catastrophes. Over the years, Australia's wildfire protection policies have undergone continuous changes. Older studies, before 2009, emphasized that homes were the safest places to be, suggesting that people who stayed at home had a higher chance of survival, as noted by Webster in 1986 (Webster, 2000). However, recent fires have shown that many victims die in their homes, both from fire exposure and smoke inhalation, as seen in the 1997 Dandenong Ranges fire, where three people died while sheltering in their garage. In 2001, the Australian Fire Authorities Council (AFAC) advocated for encouraging fit individuals to stay in their homes if adequate fire protection measures were in place. Following the 2009 fires, Australian authorities revised their stance, advocating for early evacuation as the safest option. Despite various policies, few people had evacuation plans in place before the fires. Studies show that fatalities could have been lower if residents had evacuated earlier (McLennan *et al.*, 2012). In the United States, a 2011 study on wildfire behavior in three communities found that many residents waited before deciding to evacuate, with some later realizing they lacked the resources to escape safely, which in some cases proved fatal (Cohn *et al.*, 2006). International policies generally warn against last-minute evacuations, which are considered the most dangerous. Studies after the 2009 Victoria fires, which claimed 172 lives, highlight that sheltering should not replace early evacuation but may be necessary when evacuation is not possible (McLennan *et al.*, 2013).

The lack of safe and well-identified shelters in communities can increase insecurity and promote the autonomous evacuation of residents, a situation that, without the support of authorities, may lead them into risky situations. There is a danger that information about shelters can create a false sense of security, encouraging people to wait until the last moment before taking action. This may increase the risk of individuals being trapped in shelters with minimal or no preparation or undertaking late, dangerous evacuations (Blanchi, 2018). It is important to transfer knowledge gained from less positive experiences in other countries to the Portuguese context, which, despite cultural differences, may not be very different behaviorally, as evidenced by the loss of human lives in the June 2017 fires, where around 92% of the victims died while fleeing, either on foot or in their vehicles, without any support or communication from authorities. Recent wildfires in California and worldwide have exposed critical evacuation challenges. A study conducted by Wong *et al.* (2020)

analyzed 11 major wildfires involving complex evacuation actions between 2017 and 2019. Some common characteristics identified in these events include:

- Challenges in transmitting evacuation orders to residents;
- Significant evacuations via personal vehicles, leading to road congestion;
- Need for intervention by traffic authorities during evacuations;
- Blocked and inaccessible roads;
- Rapid filling of public shelters;
- Resources provided by various organizations, but a lack of formalized re-entry plans.

4.5. Concepts and Methodologies

One of the most effective means of reducing the danger to human lives is evacuation (Alexander, 2002). When people are required to leave the risk area, evacuations can be carried out using a variety of transport methods, including private vehicles, public transportation, walking, or being rescued by emergency response vehicles by land, air, or water (Rein *et al.*, 2017).

According to the Technical Regulation on Fire Safety in Buildings republished by Ordinance No. 135/2020, evacuation is defined as “[...] *the movement of occupants of a building to a safe zone in the event of a fire or other accidents, which must be disciplined, timely, and safe*” (Portaria n.º 135/2020, 2020). Often, this concept is mistakenly associated solely with the movement of people; however, various dictionaries define the term as the collective departure of people from a place or building.

Thus, within this context, evacuation refers to the departure of individuals from their homes and/or their residential cluster in the face of imminent danger, in this case, a fire. Within fire safety regulations for buildings, several related concepts emerge, requiring further analysis in this study. One example is the concept of an evacuation route or escape route, which is defined as “[...] *the path from any point, susceptible to occupation, within a facility or building to an external safety zone, generally comprising an initial route within the place of stay and another through evacuation pathways*”. Another key concept is evacuation distance, defined as “[...] *the length to be traveled along an evacuation route to reach a protected evacuation path, a safety zone, or a refuge zone*” (Portaria n.º 135/2020, 2020).

By analogy, and in the absence of clear concepts on this subject, it has been conventionally established that the best definition for rural fire situations is “[...] *the route between each dwelling within a cluster and its surrounding area to a designated safe zone, which may be a shelter or a refuge*”. Similarly, evacuation distance corresponds to the length of the evacuation route leading to a safe location. The concepts of evacuation distance and time are crucial tools for decision-makers, as they enable the assessment of the evacuation capacity of individuals or groups based on the route they must take to reach a safe place and the means available. This analysis can be fundamental in deciding whether to stay at home or evacuate.

In the literature, a clear distinction is made between different evacuation-related concepts, which are not commonly applied in Portugal. This differentiation is primarily based on temporal phases, as illustrated in Figure 7:

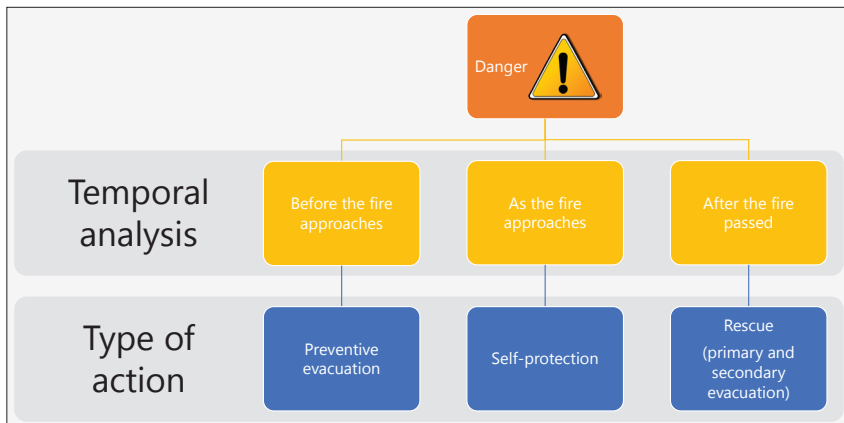


Fig. 7 - Temporal scheme of evacuation actions (adapted from Alexander, 2002).

To establish this clear distinction, the following conceptual framework was adopted:

- Self-evacuation or spontaneous evacuation – derived from the translation of “Self-Evacuation”. In both urban and rural fire scenarios in Portugal, evacuation is typically initiated in response to imminent danger. This term refers to situations where, upon perceiving the risk posed by an approaching fire, an

individual decides to leave for a safer location without official assistance. This decision may or may not be supported by an alarm or alert.

- *Assisted/supported evacuation* – refers to the departure of individuals from their homes and/or residential cluster who, due to physical or psychological conditions, require support for a safe evacuation in the face of an imminent fire.
- *Late evacuation or escape* – describes the evacuation of homes or clusters at risk due to the arrival of a fire front near residences.
- *Primary evacuation* – involves the transport of injured individuals to triage and pre-hospital care stations.
- *Secondary evacuation* – refers to the transport of injured individuals from the triage station to a hospital facility.

Clearly defining these concepts is highly useful for establishing effective procedures, creating clear distinctions between different types of actions. Preventive evacuation is particularly effective in situations where fire behavior can be predicted, allowing enough time to safely remove individuals.

In the case of wildfires, this type of emergency is highly predictable, enabling teams to strategically position resources in the field. Emergency planning, combined with the predictability of wildfires, allows for timely decision-making regarding population evacuations, selecting the appropriate means, equipment, and routes. If time is insufficient, confinement becomes the best option. In such cases, it is essential to identify and plan for buildings with better fire protection performance to ensure the safety of occupants.

Using hazard and risk maps, it is possible to determine which areas (residences, factories, etc.) may need evacuation under specific circumstances. Evacuation routes and centers should be designated in advance (Alexander, 2002). The creation of emergency plans and maps with graphical representations of optimal evacuation routes and meeting points is crucial for an effective evacuation process. As in buildings, it is essential that residents are familiar with these plans and aware of self-protection measures in the event of a wildfire. Evacuation routes and centers should be pre-designated and tested.

It is important to acknowledge that no evacuation plan will be fully implemented without adjustments and unforeseen interferences to which emergency managers

must respond and adapt. Even in repeated wildfires within the same geographic area, such as those in California, each event presents unique challenges, particularly regarding communication, transportation, and shelter response. These differences indicate the necessity of assembling a flexible and adaptable transportation strategy toolkit in real time. However, it is crucial to emphasize the need for a common foundational plan to support this strategy (Wong *et al.*, 2020).

Regarding evacuation planning, methodologies and proposals vary, but they all share the same fundamental principles: collaboration with the scientific community, anticipation, unified command, and continuous evaluation. Preventive evacuation methodologies are always based on progressive and evolutionary phases (Alexander, 2002).

When faced with imminent danger and the decision to evacuate a community, the evacuation process follows the phases outlined in Figure 8:

Such processes require adaptation to the reality of each country, passing through phases of public and authority approval, culminating in practical exercises to validate their applicability.

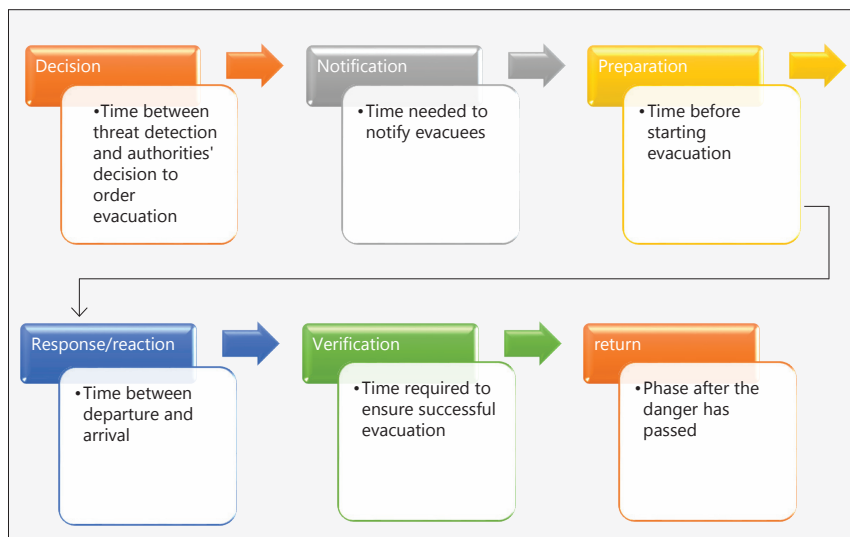


Fig. 8 - Proposed preventive evacuation model by Alexander (2002).

4.6. Regional Case Studies in the Evacuafloresta Project

Based on the preceding information in this chapter, specifically in Sections 3.3 and 3.4, municipalities of Lousã and Sertã (in central Portugal) were selected for the Evacuafloresta project. The municipalities of Lousã and Sertã have been frequently affected by wildfires, with major events occurring in 2003 and 2017.

Located in the central region of Portugal, the municipalities of Lousã and Sertã are characterised by being extremely suitable for forest growth, their hilly terrain, high ageing indices (around a third of the total population), strong population variation, high recurrence of forest fires, and past episodes where deaths, injuries, and evacuations were recorded. Sertã and Lousã have very different areas, 446.7 km² and 138.4 km², respectively, with the respective WUI boundaries being 942.64 km and 341.77 km (Figure 9). Around half of the municipality of Lousã has a slope of more than 20° and only 27% has a slope of less than 10°. In the case of Sertã, there is a very similar proportion between the classes (<5; 5–10; 10–15; 15–20; and >20°) of around 20% in each (Nunes *et al.*, 2024).

According to the 2021 census (INE, 2022), 17,006 and 14,769 people lived in the Lousã and Sertã municipalities, respectively, with a population density of 123 inhabitants/km² in Lousã and 33 inhabitants/km² in Sertã. Between 1950 and 2021, the two municipalities showed very different population variations; Lousã increased its population by 10% and Sertã showed a decrease of around 48%. In both municipalities, more than 70% of their territory is occupied by forests, with coniferous forests predominating, although eucalyptus and invasive species also feature significantly (TABLE II).

Both municipalities have a history of recurrent fires (Figure 10). Thus, between 1980 and 2020, Sertã recorded more than 100,000 hectares burnt and Lousã recorded 63,200 hectares burnt (Pinto, 2023). In Lousã, several areas have been ravaged by fire four or five times, while, in Sertã, around 44% of its territory has been ravaged by fire two or three times. In both cases, the worst affected areas are associated with higher altitudes, steeper slopes, and unbroken forest cover.

In view of the significant burnt area, all the parishes in the two municipalities under study were identified as priorities in accordance with Despacho [Order] 3780/2023 of 24 March, which identifies the priority parishes for the purposes of monitoring fuel management in 2023.

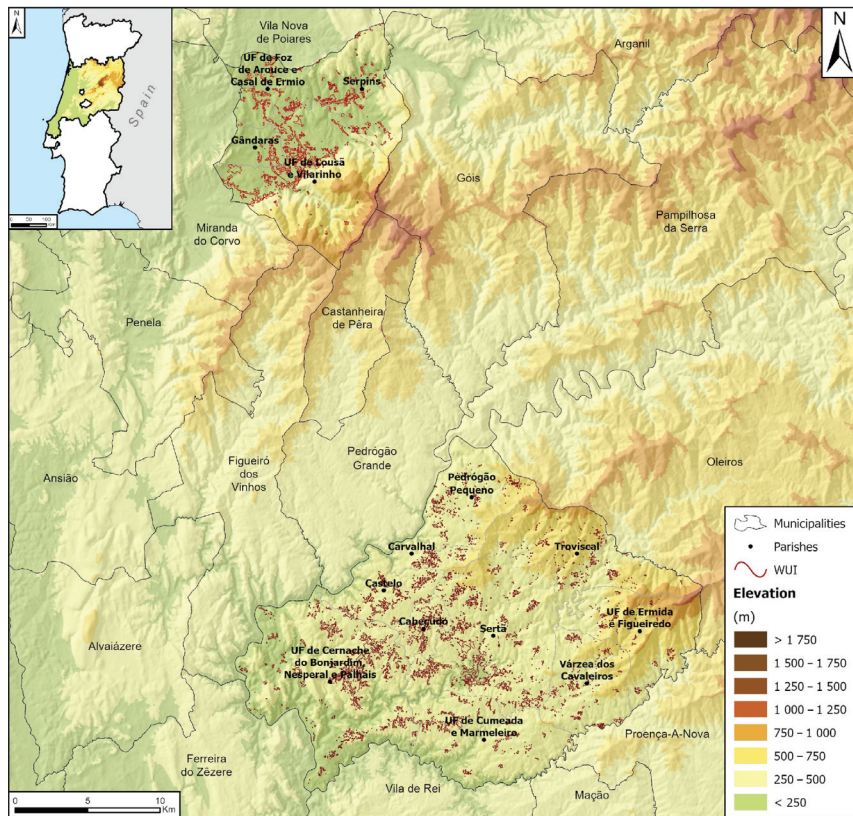


Fig. 9 - Location, elevation and wildland-urban interfaces of the municipalities of Lousã and Sertã (Nunes *et al.*, 2024).

TABLE II - Land use and occupation in the municipalities of Sertã and Lousã in 1995 and 2018 (Nunes *et al.*, 2024).

Land Use and Occupation Classes	Sertã				Lousã			
	1995		2018		1998		2015	
	km ²	%	km ²	%	km ²	%	km ²	%
Artificialized land	11.18	2.50	14.64	3.28	6.22	4.50	9.25	6.68
Agricultural areas	30.36	6.80	56.89	12.74	9.69	7.00	16.76	12.11
Pastures and agroforestry areas	33.09	7.41	1.60	0.36	9.74	7.04	0.35	0.25
Woodlands and open spaces	9.97	2.23	33.09	7.41	14.24	10.29	6.78	4.90
Oak, hardwood and chestnut forests	5.41	1.21	6.30	1.41	22.51	16.26	18.41	13.30
Eucalyptus forests and invasive species	55.60	12.45	111.30	24.91	22.22	16.05	31.37	22.67
Coniferous forests	291.29	65.21	214.63	48.05	53.38	38.57	54.79	39.59
Wetlands	9.82	2.20	8.27	1.85	0.40	0.29	0.68	0.49

Data source: Land Use and Occupation Maps for 1995 and 2018, Directorate-General for Territory.

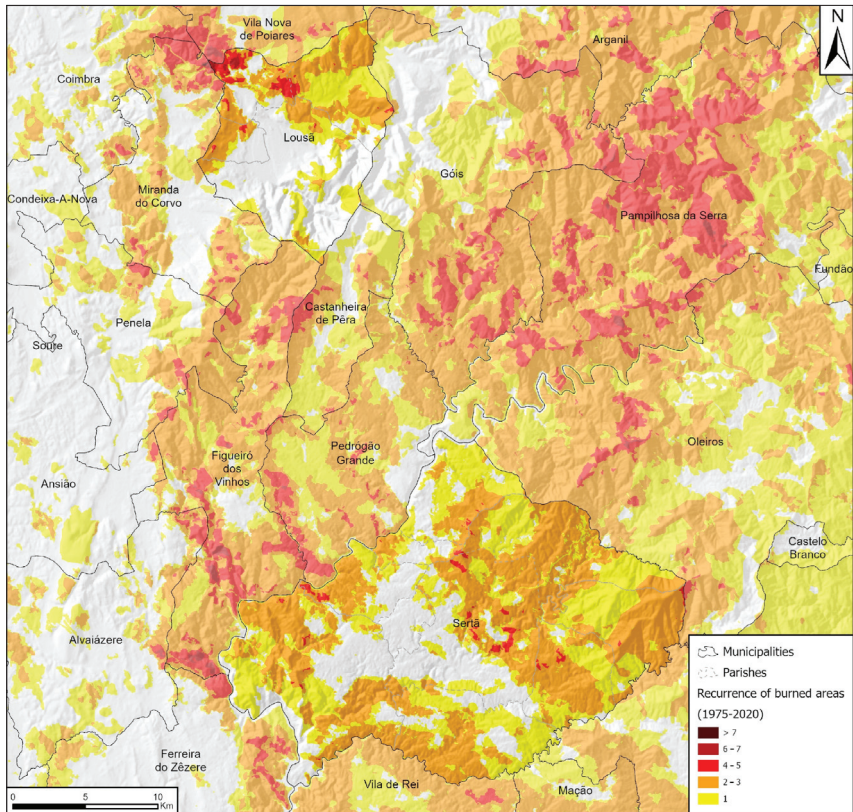


Fig. 10 - Recurrence of forest fires (1975 and 2020) (Data source: Portuguese National Authority for Nature Conservation, 2021) (Nunes *et al.*, 2024).

Chapter 4

HUMAN BEHAVIOUR UNDER THE THREAT OF WILDFIRE

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4.1. Introduction

Given the wide-ranging implications of wildfires, it is imperative to incorporate social dimensions into disaster response planning. Lessons learned from previous catastrophic events should inform policy recommendations aimed at fostering resilience and rebuilding community trust in governmental institutions. Integrated policies must establish effective preventive measures, operational protocols, detailed risk mapping, and regulations on urban and forest management.

Numerous international and national studies have highlighted the need to incorporate social factors into the analysis of risk management, both in general and specifically in relation to wildfire risk (Bright *et al.*, 2003; Ojerio *et al.*, 2010; Stein and Dueñas-Osorio, 2010; Mendes *et al.*, 2012; Tedim and Carvalho, 2013; Cañadas and Novais, 2014; Mourão and Martinho, 2014; Ageret *et al.*, 2015; Wigtil *et al.*, 2016; Tedim *et al.*, 2016). Most of these studies are grounded in the recognition that territories are shaped by distinctive

characteristics and that certain communities and individuals are more exposed to risk than others. The central concern underlying this body of work is that socioeconomic inequalities influence both the level of exposure to risk and the capacity of a given territory or community to cope with it—issues that are intrinsically linked to the concepts of vulnerability and social resilience (Mendes *et al.*, 2013).

Risk itself is, to a considerable extent, a social construct, and its perception varies across societies and individuals. The occurrence and extent of wildfires are not solely determined by biophysical conditions; rather, social systems interact with natural systems in a dynamic, reciprocal manner (Bright *et al.*, 2003). Risk perception is a multidimensional concept that differs from risk assessment and requires further exploration to better understand individual behaviour in the face of potential evacuation scenarios (Renn and Burns, 1992; Cohn *et al.*, 2008; Carochinho, 2011; Kinatader, 2015).

Perceived risk pertains to the perspectives of social actors and is primarily examined within the social sciences. It focuses on the consequences of hazardous events and is inherently multidimensional. In contrast, risk assessment is typically addressed by the natural sciences, concentrating on the characteristics and causes of such events and is generally unidimensional in nature (Cohn *et al.*, 2008).

Risk perception reflects the symbols, values, history, and ideology of a given society. What individuals perceive as threats to their well-being is shaped by their values, attitudes, social influences, and cultural identity (Slovic and Weber, 2002; Paek and Hove, 2017). This perception comprises two main dimensions: the cognitive and the emotional. The cognitive dimension pertains to the knowledge individuals hold about risks and how they understand and process this information. The emotional dimension, by contrast, relates to how individuals feel about the ongoing events (Moscovici, 2008).

Recognising that social perception is a subjective concept influenced by a multiplicity of factors, this study aims to analyse the representations and practices of social actors within the studied communities in relation to wildfires, to which they are frequently exposed. According to Serge Moscovici (2008), social representations allow individuals to make sense of the world around them. Denise

Jodelet (1997:36) defines social representations as “[...] *a form of knowledge, socially constructed and shared, with a practical purpose and contributing to the construction of a reality common to a social group*”. Although not scientific in nature, social representations play a vital role in social life by guiding and structuring social behaviour and communication.

With respect to risk, Kasperson *et al.* (2003) argue that the experience of risk is not limited to physical harm. Rather, it results from processes through which groups and individuals acquire or construct interpretations of risk that help them select, prioritise, and explain the signals they perceive in their environment. These signals are filtered through interpretative processes that may either amplify or attenuate the perceived risk.

For instance, Stasiewicz and Paveglio (2021) found that full-time residents and men were significantly more likely to plan to stay and defend their homes as a wildfire response, while women and part-time residents were more inclined to evacuate. Even within the same household or community, evacuation decisions may differ: at the family level, some members may choose to leave while others stay behind to protect the property. At the community level, families prioritising the protection of life may opt to evacuate, while others, focused on safeguarding property, may choose to shelter in place. An intriguing finding by Dash and Gladwin, cited by Sadri *et al.* (2021), revealed that some households that initially intended to evacuate ultimately did not do so, whereas others who had planned to remain ended up evacuating.

Qualitative methods—such as field notes and semi-structured interviews—are particularly suited to capturing subjective experiences across time and space (Bardin, 2006). These methods illuminate the underlying social processes that shape behaviour, offering essential insights for the design of inclusive and effective evacuation planning.

4.2. Fieldwork and Data Collection Activities

A range of research activities was conducted to support the study of human behaviour in the context of wildfires, with a focus on the municipalities of Lousã and Sertã. In 2021, statistical data were collected from secondary sources—including the National Statistics Institute, the Institute for Nature Conservation and Forests, and PORDATA—in order to characterize the socio-demographic and territorial profile of the selected municipalities. Concurrently, an extensive literature review was undertaken, focusing particularly on human behaviour during disasters, thereby providing a theoretical foundation for the empirical work. Within this phase, relevant institutions were identified and initial contacts established to support the fieldwork.

In the municipality of Lousã, the localities of Cabanões and Boque were selected for study, both of which were impacted by the 2017 wildfires. Additionally, the village of Cerdeira was included; unlike the former two, it has not experienced significant wildfires in recent years. Cerdeira is part of the “Aldeias do Xisto” network and hosts a fluctuating population composed of tourists and artists. In Cabanões, evacuation procedures had to be implemented during the 2017 fires.

In the municipality of Sertã, the localities of Vale do Laço, in the parish of Troviscal, and Trízio, located in the union of the parishes of Cernache do Bonjardim and Palhais, were chosen. Vale do Laço was severely affected by the 2003 and 2017 wildfires, with the 2017 event resulting in the deaths of two residents. In contrast, Trízio has not experienced major wildfires since the 1980s.

The selection of these localities considered not only their exposure to wildfire risk but also their social vulnerability, obstacles to evacuation, and, in the cases of Trízio and Cerdeira, their touristic appeal. Following a short description of the villages considered for case studies in the evacuation exercises will be presented.

4.2.1. Socio-territorial profile in Lousã

Lousã is a municipality located in the central region of Portugal, within the district of Coimbra. Since 2013, it has been part of the Intermunicipal Community of the Coimbra Region. Forests cover approximately 75% of its territory, with the parish of Lousã e Vilarinho accounting for the largest forested area—5,421.43 hectares—which represents 52.2% of the municipality's total forest area. This parish also contains the largest agricultural area in the municipality, with 1,399.33 hectares, corresponding to 46.5% of the total agricultural land in the municipality. The dominant tree species in the municipal forest area is maritime pine (*Pinus pinaster*), which occupies approximately 50% of the municipality's total area. Eucalyptus (*Eucalyptus* spp.), which has been expanding in recent years, now accounts for 25% of the forested area (Município da Lousã, 2020).

Lousã has a total area of 138 km², approximately one-third of which is occupied by the Serra da Lousã (Município da Lousã, 2020). The municipality comprises four parishes: Gândaras, Serpins, the Union of Parishes of Foz de Arouce and Casal de Ermio, and the Union of Parishes of Lousã and Vilarinho.

In 2021, the municipality had a population of 17,006 residents, representing a decrease of 598 individuals (3.4%) compared to 2011. However, between 2001 and 2011, the population increased by 1,851 individuals, thus countering the prevailing trend of depopulation in the surrounding region (Município da Lousã, 2020). According to data from the 2021 Census, the population density was 123.3 inhabitants per km².

In 2021, 13.1% of the population was aged between 0 and 14 years, 64.0% between 15 and 64 years, and 22.9% were aged 65 years or older. These figures indicate a trend of declining younger and working-age populations alongside an increase in the elderly population. Notably, the proportions of the population aged 0–14 and 15–64 in Lousã are slightly above the national averages (12.9% and 63.6%, respectively), whereas the proportion of residents aged 65 and older is slightly below the national average (23.5%).

The ageing index (number of residents aged 65 and over per 100 residents aged 0–14) in the municipality was 175 in 2021, up from 103 in 2011, and slightly

below the national average of 183. Nonetheless, the data reveal a clear upward trend in population ageing.

According to the provisional 2021 Census, the potential sustainability index stood at 2.8, indicating that for every person aged 65 or older, there were 2.8 individuals of working age (the national average is 2.7). The old-age dependency ratio in 2021 was 35.8, and the youth dependency ratio was 20.8, compared to the national averages of 36.8 and 20.2, respectively.

The illiteracy rate in 2021 was 2.3%, which is below the national average of 3.1%.

In 2021, of the total number of occupied buildings (10,454), 65% were used as permanent residences and 16% as seasonal dwellings. There were 2164 vacant housing units, of which 733 were listed for sale or rent. That same year, the building ageing index (ratio of buildings constructed before 1960 to those constructed after 2011) was 940.4—higher than the national average for the same period (746.6).

In terms of employment, the tertiary sector was the main employer in 2021 (71.1%), followed by the secondary sector (25.7%) and the primary sector (3.2%). A historical decline in primary sector employment is evident: in 1960, 46% of the population was employed in this sector. Between 1991 and 2021, the share of the primary sector decreased from 4.7% to 3.2%, while the tertiary sector increased from 47.7% to 71.1%. Notably, between 2011 and 2021, there was a slight increase in primary sector employment, rising from 2.8% to 3.2% (INE, 2021 and 2022).

The years 2005 and 2017 stand out for the extent of burnt area. According to the classification system defined by the ICNF—based on the number of fire occurrences and total burnt area—Lousã, like Sertã, is categorised as T2 (few occurrences, large burnt area) (Município da Lousã, 2020). Under Order No. 3369/2022, of 22 March, which identifies priority parishes for fuel management inspections in 2022, all parishes in the municipality of Lousã were designated as priority areas.

4.2.2. Socio-Territorial profile in Sertã

Sertã is a municipality located in the central region of Portugal, within the district of Castelo Branco. It forms part of the Pinhal Interior sub-region and is one of the municipalities most severely affected by wildfires, with major incidents recorded in 2003 and 2017. The past decade has been particularly devastating: between 2017 and 2020, over half of the territory of Pinhal Interior was affected by wildfires (Município Sertã, 2016). Forest land constitutes approximately 75% of the municipality's area. Within this forested zone, eucalyptus represented 62% and maritime pine (*Pinus pinaster*) accounted for 37.5% (GETIN-UA, 2016).

Sertã covers an area of 447 km² and is divided into ten civil parishes. As of 2021, the municipality had a population of 14,748, representing a decline of 1132 individuals since 2011—a 7.0% decrease. The population density is 33.1 inhabitants per km². Demographically, in 2021, 10.4% of the population was aged 0–14, 58.2% was between 15 and 64, and 31.4% was aged 65 or older. This demographic profile reflects an ageing population that has been steadily declining since 1960. The population variation rate between 1960 and 2021 was -47.3%.

The ageing index (the number of residents aged 65 and over per 100 residents under the age of 15) reached 290 in 2021, according to census data. In comparison, this index was 76.8 in the 1980s and is now substantially higher than the already elevated national average of 182.1. In 2021, there were 1.9 working-age individuals for every elderly person in Sertã (compared to a national average of 2.7). The old-age dependency ratio (elderly population relative to working-age population) stood at 53.5, and the youth dependency ratio (youth population relative to working-age population) was 18.4. National averages were 36.8 and 20.2, respectively.

While the illiteracy rate remains relatively high, it has shown a downward trend—falling from 10.2% in 2011 to 9.5% in 2021. This figure remains above the national average of 5.9%. Illiteracy is primarily a generational phenomenon; in 2011, 85.4% of the illiterate population aged 10 or older were 65 years of age or above.

In terms of housing, out of 10,702 occupied buildings in 2021, 59.1% were used as primary residences and 40.9% as seasonal homes. The building ageing index (the ratio between buildings constructed before 1960 and those built after 2011) was 1,053, significantly above the national average of 746.6.

In 2021, the tertiary sector employed the majority of the population (66.3%), followed by the secondary (27.4%) and primary sectors (6.3%) (INE, 2012, 2022).

Wildfires are a recurrent hazard in Sertã. The years 2005 and 2017 were particularly severe, with 38% of the municipality's territory burned in 2017 alone. According to ICNF's fire risk typology, Sertã falls under category T2, indicating few occurrences but a large area burned. The Ministerial Order No. 3369/2022, issued on March 22, identified nine parishes in Sertã as priority areas for fuel management inspections in 2022.

4.2.3. Socio-Territorial profile in Cabanões (Lousã)

Cabanões is located in the parish of Lousã and Vilarinho, created in 2013 (Law No. 75/2013 of December 12), about 9 km from the county seat (Figure 11). The parish has an area of 72.4 km² and a population density of 178 inhabitants per km². The parish lost 135 inhabitants between 2011 and 2021. The parish's ageing index in 2021 was 159.

Cabanões had 13 inhabitants, 7 males and 6 females. Between 2011 and 2021 it lost 3 inhabitants. Regarding the age structure of the population living in Cabanões in 2021, there was 1 inhabitant aged between 0 and 14; 3 were aged between 25

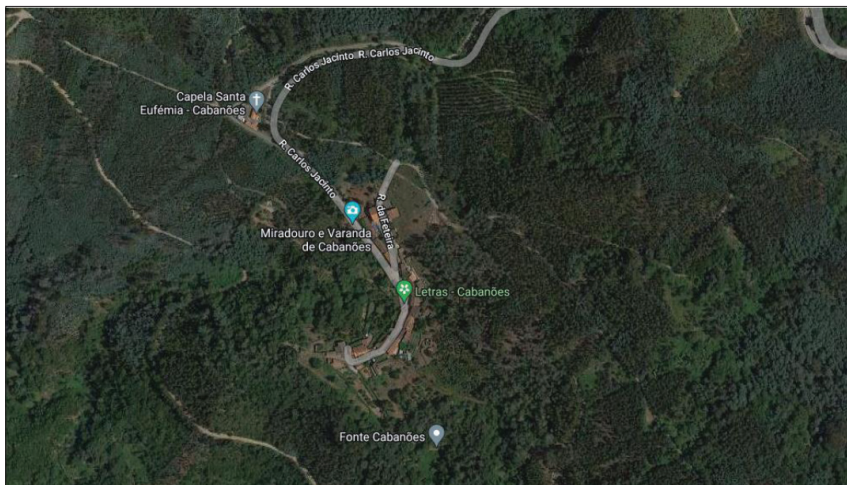


Fig. 11 - Cabanões (Data source: google maps).

and 64 and 9 were aged 65 or over. It had an elderly dependency ratio of x . The parish of Lousã e Vilarinho had a ratio of x .

The illiteracy rate in the parishes of Lousã and Vilarinho was 3.14 in 2011, lower than the national average (5.2). In 2021, the illiteracy rate in the parish was 2.2.

There were 20 classic buildings in Cabanões at 2021. The majority (18) were built before 2001, with an ageing index of 900.

In the parish of Lousã and Vilarinho, of the 7698 dwellings existing in 2021, 65.9% were used as primary habitual residences and 10.8% as secondary residences. The rest were vacant. At Cabanões 7 were used as primary habitual residences (35%), 12 as secondary residence (60%) and 1 (5%) is vacant (INE, 2012; 2022).

4.2.4. Socio-Territorial profile in Boque (Lousã)

Boque is located in the parish of Lousã e Vilarinho, created in 2013 (Law No. 75/2013 of December 12), about 6.8 km from the county seat and about 1.3 km from Serpins (Figure 12).

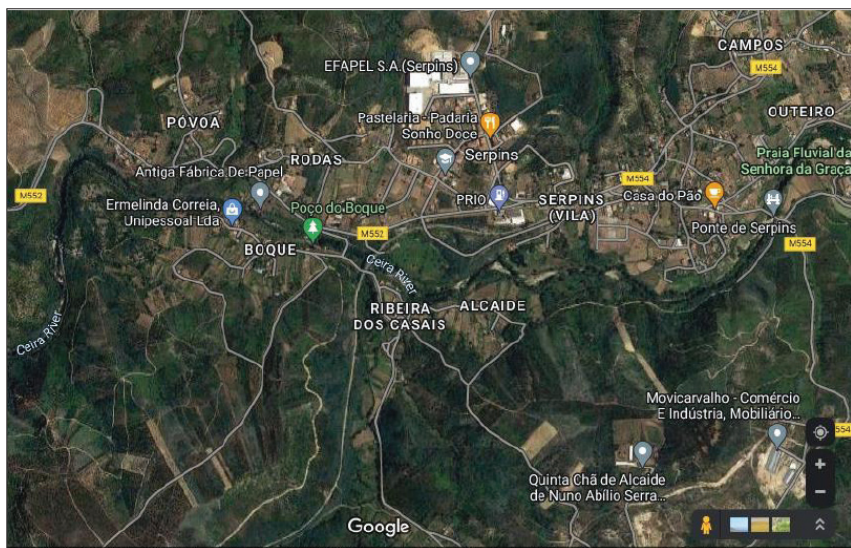


Fig. 12 - Boque (Data source: google maps).

Boque had 35 inhabitants in 2021 having lost 21 inhabitants between 2011 and 2021. Of these, 14; were aged between 15 and 64 and 21 were over 65.

There were 32 classic buildings in Boque, 21 were used as primary residences, 7 as secondary residence and 4 were vacant. The ageing index of the buildings was 1500 as 30 of the 32 were built before 2001 (INE, 2012; 2022).

4.2.5. Socio-Territorial profile in Cerdeira (Lousã)

Cerdeira is the smallest of the 27 villages that make up the network of Aldeias do Xisto. The village, which was abandoned until 2000, has been restored mainly for tourist purposes, with 10 accommodation spaces (Figure 13).

There is a wide range of activities, including international artistic residencies, workshops and the “Elementos à solta” festival, which takes place in July.

The village is still home to some permanent inhabitants, 5 (4 males and 1 female) at 2021. Of these, 1 is aged between 15 and 24, 3 between 15 and 64 and 1 is over 65.

In 2021, Cerdeira had 18 classic family dwellings, 4 (22,2%) were used as primary residence, 5 (27,7%) as secondary and 9 (50%) were vacant (INE, 2012; 2022).



Fig. 13 - Cerdeira (Data source: google maps).

4.2.6. Socio-Territorial profile in Vale do Laço (Sertã)

The locality of Vale do Laço is located in the parish of Troviscal, about 17 km from the county seat. The parish of Troviscal, in which it is included, lost 171 inhabitants between 2011 and 2021, falling from 864 inhabitants to 693. The parish's aging rate increased from 432.9 to 705 between 2011 and 2021 (Figure 14).

As expected, the place of Vale do Laço follows the same trend. In 2011 it had 42 inhabitants, 18 males and 24 females. In 2021 it had 26 inhabitants, 9 males and 17 females. With regard to the age structure of the resident population in Vale do Laço in 2021, 1 individual was aged 0-14; 9 were aged 15-64 and 16 were aged 65 or over.

In 2011, Vale do Laço had an ageing index of 950, which is quite high and higher than that recorded for the parish in 2011 (432.9). In 2021 had an ageing index of 1500.

In the parish of Troviscal, of the 677 occupied buildings, 48.3% had regular occupancy and 51.7% had seasonal occupancy in 2021. There were 44 vacant buildings.

In Vale do Laço, in 2011, of the 31 existing dwellings, 19 were used as the primary' habitual residence. In 2021 of the 33 existing dwellings, 11 were used as habitual residence, 17 as secondary residence and 5 are vacant. Of the 33 existing buildings, 25 date from before 2001, with an ageing index of 357 (INE, 2012; 2022).

The village has a social, recreational and cultural center based in the old elementary school.

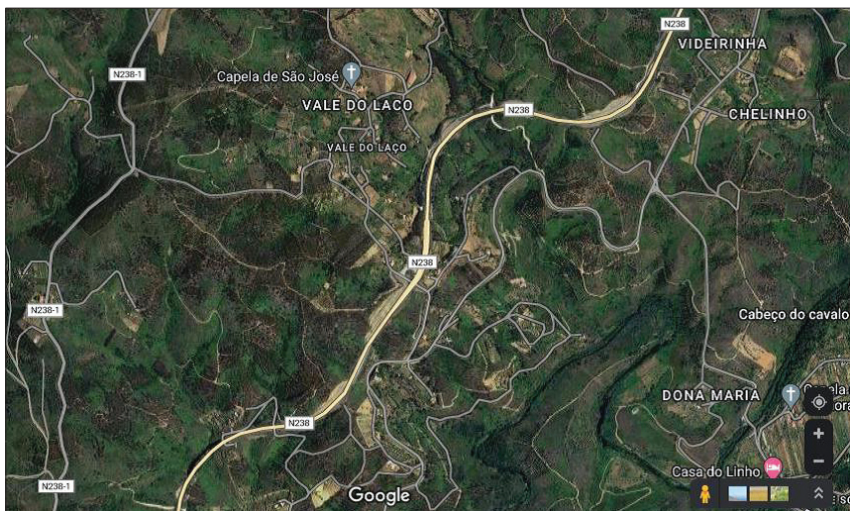


Fig. 14 - Vale do Laço (Data source: google maps).

4.2.7. Socio-Territorial profile in Trízio (Sertão)

The village of Trízio is located in the parish of União das Freguesias de Cernache de Bonjardim, Nespéral e Palhais, which is situated to the southwest of the municipality, about 19 km from the municipal seat. This parish was created in 2013 and brought together the parishes of Cernache do Bonjardim, Nespéral and Palhais. Until 2013, Trízio was part of the parish of Palhais (Figure 15).

In 2021, Trízio had 26 inhabitants (12 males and 13 females), having gained 2 inhabitants since 2011. The parish it is part of lost 340 inhabitants between 2011 and 2021, going from 3625 inhabitants to 3365. Palhais had 268 inhabitants in 2011.

Regarding the age structure of the population living in Trízio in 2011, 3 people were aged between 25 and 64 and 20 were aged 65 or over. In 2021, there are no inhabitants under 24, 3 were aged between 25 and 64 and 22 were aged 65 or over.

In Trízio, of the 55 classic buildings at 2011, 14 are the primary habitual residence. In 2021, Of the 53 classic buildings registered, 12 are the primary habitual residence, 38 are secondary residence and 3 are vacant. Of the 53 existing buildings, 43 date from before 2001, with an ageing index of 430 (INE, 2012; 2022).

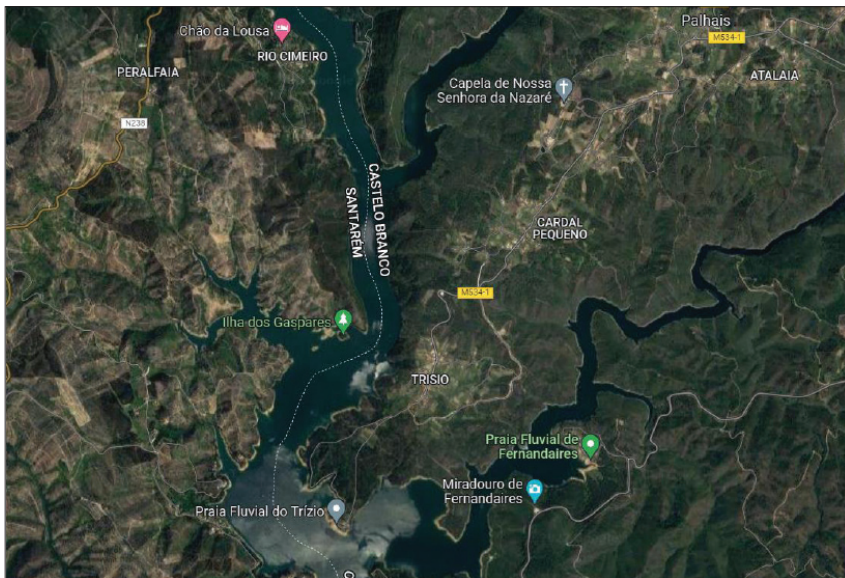


Fig. 15 - Trízio (Data source: google maps).

The town has a recreational, cultural and sports association. It has a nautical center where various water sports are practiced. Every year the center hosts the National Wakeboarding Championship, which is attended by athletes from all over the world. It also has a river beach which sees a large number of tourists in the summer.

4.3. Interviews and Surveys

4.3.1. Metodology

In alignment with the project's objectives, semi-structured interviews were conducted in 2022 with residents of the municipalities of Lousã and Sertã. This qualitative approach was employed to capture a wide range of personal experiences and perspectives related to wildfire risk, providing valuable insights across different locations and demographics. Following this, in 2023 and 2024, a nationwide online survey was developed and disseminated to further explore the public's views on the issue.

The interviews sought to gather a comprehensive understanding of local residents' awareness of wildfire hazards, perceived vulnerability, preparedness levels, challenges encountered, willingness to adopt preventive measures, and their interactions with local authorities, such as civil protection units, firefighters, and political leaders. The interviews were conducted across various locations in the municipality of Lousã, each with distinct demographic characteristics:

- **Cabanões:** Five interviews were conducted with eight participants, predominantly aged 70–85, with one younger interviewee (aged 30–40), living in the village with his family. Interviews lasted between 15 and 20 minutes;
- **Boque:** Four interviews were conducted (two male, two female), all with residents aged 70–85. These interviews lasted approximately 15 minutes;
- **Cerdeira:** Two interviews were carried out via Zoom with a seasonal resident and a tourism operator. These interviews were not recorded due to lack of consent;
- **Chã de Amiais:** One interview was conducted with a wildfire-affected resident, aged 30–40, living outside the immediate area.

Most of these interviews were recorded and transcribed (Figure 16); however, the Cerdeira interviews and group interviews were not fully transcribed due to recording or comprehension challenges. Content analysis was applied to categorize and synthesize the findings from these interviews.

In parallel, in the municipality of Sertã, contact was established with the presidents of the Parish Councils of Troviscal and Trízio, leading to group interviews in Vale do Laço and Trízio, each involving 20–25 participants. Further engagement included a meeting with the Councillor for Forests and an interview with the municipal psychologist, aimed at understanding the psychosocial challenges experienced during the 2017 wildfires. The interview data were subsequently analysed and synthesised, alongside a continuation of the literature review (TABLE III).



Fig. - 16 Interviews (Photograph of Câmara Municipal da Lousã, taken on 03/03/2022).

TABLE III - Number and time of the interviews.

Places	Date	N.º of Interviews
Cabanões	24-05-2025	8
Boque	24-05-2025	4
Cerdeira	July 2022	2
Chã dos Amiais	17-11-2022	1
Trízio	30-07-2022	20-25
Vale do Laço	30-07-2022	20-25

Additionally, the online survey aimed to provide a broader understanding of the general population's perceptions of wildfire risk and related behaviours. The survey was created using Google Forms and distributed from July 2023 to January 2024, with a total of 388 responses received from individuals aged 18 and above. Of these, 57 responses were excluded due to professional involvement in wildfire management (e.g., firefighters, civil protection officers, GNR military personnel). Military and public security police officers were not excluded. The final sample consisted of 331 valid responses, with a demographic breakdown of 54% female and 45% male. The majority of respondents were aged 45–54 and held a university degree. Notably, approximately 39% of participants lived in rural areas, a proportion similar to those from urban areas.

The survey was designed to assess participants' perceptions of wildfire risk, their preparedness behaviours, past experiences with wildfires (including evacuations), precautionary measures taken, the influence of wildfire risk on mobility and travel decisions, and the perceived quality of available information on the subject.

4.3.2. Results and discussion

Past Experiences

- The recurrence of wildfires has given residents some resilience to such events, although they acknowledged that the 2017 fire was of a different magnitude;
- Some men stayed behind to fight the fire – a common practice;
- Some individuals were away and could not return in time;
- Women and older residents left their villages;
- Some people were evacuated to safe locations;
- Others sought shelter in second homes or with relatives, particularly in the Lousã area;
- Firefighters warned residents to evacuate, but some refused to leave;
- Some individuals wanted to evacuate but were unable to do so because they were responsible for persons with reduced mobility who could not be evacuated;
- Family members (children, siblings, in-laws) came to help – some traveled from Lisbon;

- Some refused to leave while their children were assisting in firefighting efforts – they feared for their safety;
- People did not know where to flee, as they were unaware of the fire's location;
- Some felt that individuals must rely on themselves for protection;
- Others reported mutual aid among neighbors and family members;
- Fear and panic were common;
- There were shortages of water and electricity;
- Smoke filled the air;
- People found it difficult to stay indoors – they felt the need to see what was happening;
- Some returned home to care for their dog;
- There was intense heat and heavy smoke.

Difficulties

- Trivialisation of forest fires;
- Need for more general and specific information on what to do before and during fires – including prevention and response measures;
- Lack of or insufficient preparation;
- Lack of materials such as radios, hoses, and fire-fighting tools;
- Evacuation plans either vague or non-existent;
- Lack of consensus among residents regarding appropriate responses;
- Lack of knowledge about the location and use of fire hydrants;
- Difficulty in knowing how to evacuate bedridden individuals;
- The large number of tourists circulating in the mountains is perceived as a source of insecurity by some residents;
- Lack of or insufficient water supply to extinguish fires and protect dwellings;
- Difficulty in making decisions, such as what to take and what to leave behind;
- Difficult access routes that hinder movement during fire events;
- Inadequate maintenance and clearance of existing access routes;
- Poor condition or absence of alternative routes (e.g., forest roads);
- Need to raise awareness among tourists about appropriate behaviour during fires, particularly the importance of not blocking access routes;
- Insufficient knowledge of the number of foreign residents living in fire-prone areas;

- Poor coordination among institutions, particularly in relation to support mechanisms in evacuation scenarios.

Associations with other wildfires

- Fragmentation of land ownership;
- Abandonment of forest areas;
- Abandonment of residential properties;
- Lack of interest from those who no longer reside in the villages;
- The resident population is increasingly smaller and older, making forest investment more difficult;
- Fear of investing in forests and agricultural land;
- Widespread discouragement and disillusionment;
- Land abandonment by younger generations;
- Difficulties in maintaining land clearance;
- Firewood stored near houses;
- Lack of enforcement of land-clearing regulations;
- Tourists visiting the Lousã mountains often lack awareness of fire risks, leading to hazardous behaviours;
- A strong sense of neglect and abandonment;
- Arson.

Preparation for future wildfires

- In most cases, there was no specific prior preparation;
- The regular experience with wildfires before 2017 led to their normalization;
- After 2017, there was a widespread sense that any level of preparation would always be insufficient;
- Land clearing was practiced;
- Water storage was undertaken.

Sources of information before and during the wildfires

- Direct observation;
- Neighbours;

- Family members;
- Mass media;
- Firefighters;
- Internet.

List of identified priorities

- Increased supervision of land and forest clearance;
- Support for the population, especially the elderly with low incomes, in clearing land;
- Maintenance of roads and paths;
- Awareness-raising among absentee landlords to keep their properties and homes clean;
- Articulation between entities in fire prevention and evacuation;
- Development of appropriate training for different types of actors with responsibility for evacuations, namely mayors, social workers, psychologists, etc.;
- Development of evacuation plans suited to the needs of the population and their characteristics;
- Involving the population, especially those most affected by fires, in making evacuation plans appropriate to their reality;
- Specific information actions for fire-prone populations on what to do before, during and after fires;
- Provision of clear and easily understandable information for everyone;
- Investing in visual rather than written information;
- Supporting parish councils in disseminating information on rural fires;
- Advance planning on what to do to support people with reduced mobility and their families;
- Development of frequent fire drills;
- Specific information for tourists on precautions to take and what to do in the event of a fire, namely through panels and leaflets.

4.3.3. Conclusions

The villages of Trízio (Sertã) and Cerdeira (Lousã) have not suffered significant damage from wildfires in recent years. The last major fire in Trízio occurred in the 1980s, while tourists remain a constant presence, especially in Cerdeira, where permanent residents are scarce. In contrast, Cabanões, Boque, and Vale do Laço were affected by fires in 2003 and 2017, with the latter resulting in two fatalities.

Interviewees expressed concerns about the lack of forest clearing, particularly near homes. They emphasized the need for better enforcement of regulations, as many landowners neglect their properties and store flammable materials close to homes. However, land clearing is costly, and aging residents struggle to manage their properties, often hiring help at a high cost. Road maintenance is another issue, with forest tracks often damaged by loggers, which can hinder evacuation efforts.

Water scarcity is also a significant concern, with some residents storing water in barrels or tanks. The maintenance of hoses is another issue that interviewees pointed out. In Trízio, the only safe village in the municipality, interviewees expressed the need for clearer guidance on how to respond to a wildfire, mentioning the lack of radios, megaphones, and hoses.

While many residents do not take specific precautions beyond land clearing, they have become accustomed to wildfires. After the 2017 fires, some felt there was little they could do. This normalization of wildfires may hinder their ability to effectively evacuate in the future. Moreover, the aging population and mobility issues complicate the evacuation process, especially for bedridden individuals, as seen in the 2017 fire when an interviewee could not evacuate her bedridden husband due to road blockages.

The presence of tourists in these areas is another challenge, as many are unfamiliar with the terrain and may hinder evacuation efforts. Tourists, unaware of the risks, often engage in dangerous behaviors, further complicating the situation.

Mutual aid within the community plays a crucial role before, during, and after wildfires. While some interviewees mentioned that people tend to fend for themselves, many reported instances of neighbors and family members helping each other during emergencies. However, this can also complicate evacuation, as

additional people may remain in the village. Some interviewees mentioned that women left the village while men stayed to control the fire.

Communication during fires relies heavily on family and neighbors, alongside mass media. Regarding firefighters and security forces, interviewees expressed mixed feelings, balancing trust with criticism.

Chapter 5

EVACUATION RISK ASSESSMENT

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5.1. Introduction

In recent decades, a growing body of research has highlighted the increasing destructiveness of wildfires globally (Moritz *et al.*, 2014; Bowman *et al.*, 2017; Tedim *et al.*, 2020). When wildfires reach wildland–urban interface (WUI) zones—areas where human development meets or intermingles with fire-prone vegetation (FEMA, 2024)—the consequences for communities can be catastrophic, with severe environmental and socio-economic impacts. Major wildfire events in recent years have resulted in significant loss of life and mass evacuations. Examples include

the 2009 Australian fires (173 deaths), the 2014 Vastmanland fire in Sweden (1 fatality, 1000 evacuations), and multiple incidents in Portugal (21, 16, and 116 fatalities in 2003, 2005, and 2017, respectively). In California (2017–2018), wildfires caused 44 deaths, while in the 2018 Mati fire in Greece, nearly 100 people perished and 187 were injured (Mitsopoulos *et al.*, 2012; Guerreiro *et al.*, 2018, 2022; Palaiologou *et al.*, 2019).

Investigations consistently show that over two-thirds of injuries and more than half of fatalities could potentially have been avoided through timely evacuation (Hall, 2004; Kuligowski, 2008). Despite the challenges posed by fire—such as smoke, heat, and reduced visibility—many experts advocate evacuation as the safest option for residents under threat (McCaffrey, 2015; Stasiewicz & Paveglio, 2016; Edgeley & Paveglio, 2019). Accordingly, evacuation is mandatory in countries such as the USA and Canada (McLennan *et al.*, 2019), and Greece has adopted similar protocols following the 2018 Mati tragedy (Zikeloglou *et al.*, 2023).

Nonetheless, evacuation is not always appropriate, especially in areas with limited access or under extreme fire behaviour (Neto *et al.*, 2023). Complications include late warnings, evacuation delays, pets, and individuals unwilling or unable to leave. Furthermore, evacuation carries inherent risks: Haynes *et al.* (2010) found that 32% of fatalities in Australian fires (1900–2008) occurred during late evacuations, while only 8% occurred among individuals who sheltered in defensible homes. Post-fire assessments also reveal that many homes are destroyed by embers before or after the fire front passes, destruction that could be mitigated by residents defending the property in place (Quarles *et al.*, 2010).

Alternative strategies, such as “stay and defend” or shelter-in-place models, have been implemented in North America and Australia (Walpole *et al.*, 2020; Stasiewicz & Paveglio, 2021). These approaches highlight the complexity of evacuation planning (Cameron *et al.*, 2009), which has prompted research involving evacuation simulations (Intini *et al.*, 2019), coupled fire-evacuation modelling (Wahlqvist *et al.*, 2021), and threshold-based evacuation triggers (Li *et al.*, 2018). Various tools have been developed to support evacuation planning across different scales (Beyki *et al.*, 2023), but many still lack detailed integration of wildfire dynamics with human decision-making processes. Key individual factors—age, gender, cultural

background, disability, visitor status, income—along with hazard proximity, significantly affect evacuation behaviour (Beyki *et al.*, 2023).

In Portugal, evacuation planning remains at an early stage. Rodrigues *et al.* (2022), analysing the 2017 Pedrógão fire (66 fatalities), found that 65% of deaths occurred during unauthorised or uncoordinated evacuations. The study highlights the need for informed evacuation strategies and proper emergency management in WUI contexts. This aligns with Thompson *et al.* (2016) and North *et al.* (2015), who stress that effective response to wildfire relies on comprehensive pre-incident planning. Research by Oliveira *et al.* (2020) in a Portuguese mountain parish—characterised by high fire recurrence and an elderly population—emphasises the value of assessing risk levels, travel times to safety, and route availability in determining emergency response priorities. Such data are essential to design tailored evacuation and shelter protocols for each locality.

Thus, identifying the areas with the most vulnerable inhabitants, especially from the point of view of evacuation, and cross-referencing them with the territory's biophysical favourability to the progression of fires, seems to be a necessary exercise that can produce effective results in terms of risk assessment and evacuation planning. Taking the above perspectives into consideration, the main objective of this study was to identify priority WUIs in terms of evacuation in two municipalities in Portugal (Lousã and Sertã), located in the central mountain range, notable for repeated forest fires. To achieve this objective, the following steps were undertaken:

- The hazard level of and social vulnerability to forest fires, by combining biophysical and sociodemographic variables to support the evacuation decision, were assessed;
- Evacuation times in two scenarios, namely walking to nearby shelters/refuges and driving to large shelters, were modelled; and
- High and very high fire risk classes at WUI scale and highest evacuation times were correlated.

The final goal was to produce maps that identify the WUIs with high and very high wildfire vulnerability, i.e., where communities and assets are more liable to damage in a wildfire scenario. This information can both influence the decision to evacuate or not by the organisations responsible for managing the national

emergency system, and also result in a safer and well-timed community response. Moreover, it allows fire risk mitigation measures to be designed that can reduce the danger to people and their exposure to the need to evacuate in the context of a forest fire.

5.2. Study Area

Located in the central region of Portugal, the municipalities of Lousã and Sertã are characterised by being extremely suitable for forest growth, their hilly terrain, high ageing indices (around a third of the total population), strong population variation, high recurrence of forest fires, and past episodes where deaths, injuries, and evacuations were recorded. Sertã and Lousã have very different areas, 446.7 km² and 138.4 km², respectively, with the respective WUI boundaries being 942.64 km and 341.77 km (see Figure 9). Around half of the municipality of Lousã has a slope of more than 20° and only 27% has a slope of less than 10°. In the case of Sertã, there is a very similar proportion between the classes (<5; 5–10; 10–15; 15–20; and >20°) of around 20% in each.

According to the 2021 census (INE, 2021), 17,006 and 14,769 people lived in the Lousã and Sertã municipalities, respectively, with a population density of 123 inhabitants/km² in Lousã and 33 inhabitants/km² in Sertã. Between 1950 and 2021, the two municipalities showed very different population variations; Lousã increased its population by 10% and Sertã showed a decrease of around 48%. In both municipalities, more than 70% of their territory is occupied by forests, with coniferous forests predominating, although eucalyptus and invasive species also feature significantly (see TABLE II).

Both municipalities have a history of recurrent fires (Figure 10). Thus, between 1980 and 2020, Sertã recorded more than 100,000 hectares burnt and Lousã recorded 63,200 hectares burnt (Pinto, 2022). In Lousã, several areas have been ravaged by fire four or five times, while, in Sertã, around 44% of its territory has been ravaged by fire two or three times. In both cases, the worst affected areas are associated with higher altitudes, steeper slopes, and unbroken forest cover.

In view of the significant burnt area, all the parishes in the two municipalities under study were identified as priorities in accordance with Despacho [Order] 3780/2023 of 24 March, which identifies the priority parishes for the purposes of monitoring fuel management in 2023.

Also, after the disastrous year of 2017, in terms of forest fires, the Portuguese government prioritised boosting the safety of the residents, creating the Safe Village and Safe People programs. The first program aims to establish ‘structural measures to protect people, property, and buildings at the urban–forest interface, whilst the second aims to promote ‘awareness-raising actions for the prevention of risky behaviour, self-protection measures and evacuation plan drills, in conjunction with local authorities’ (Council of Ministers Resolution 157-A/2017).

The program’s online site (<https://aldeiasseguras.pt/>, accessed on 10 May 22) shows that there are 17 Safe Village in the two municipalities as a whole. Sixteen are in the municipality of Lousã and just one is in the municipality of Sertã (Figure 17). Even though the 16 villages in the municipality of Lousã have signed up to the program, none of them has an evacuation plan, no drills have been carried out, and no places of shelter or refuge have been identified. There is only a reference to the existence of a Local Safety Officer. In the case of the municipality of Sertã, specifically the village of Trízio, the following actions are stipulated: collective shelter, collective refuge, safety officer, and evacuation plan.

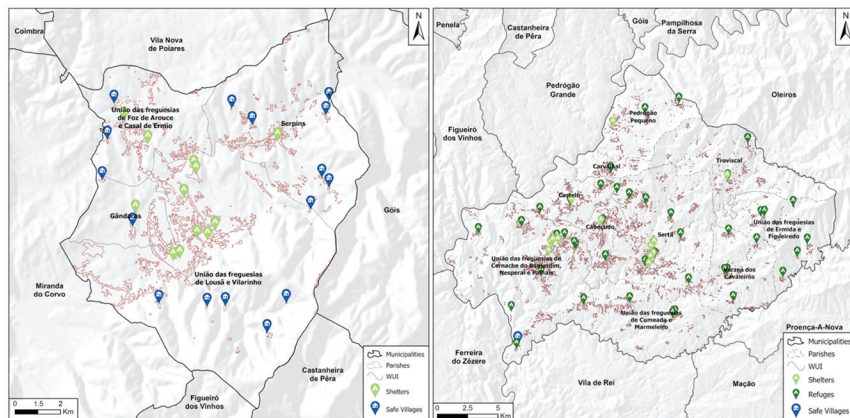


Fig. 17 - Location of safe villages, refuges, and shelters (Nunes *et al.*, 2024).

However, both municipalities have identified in their respective Municipal Civil Protection Emergency Plans (PMEPC) places that can accommodate people in the event of an evacuation. In the case of Sertã, the document dates from 2012 and identifies 66 sites, classified into two types: temporary shelters and local concentration zones. Temporary shelters are only referenced for primary evacuations, i.e., the removal of the inhabitants from risk areas to a place of safety, followed by the second phase of evacuation, i.e., travelling to shelter facilities, where all basic needs can be met. In the case of Lousã, the PMEPC identifies 12 sites. Although no typology is specified, all the sites are large and capable of sheltering a significant number of people. The final selection of these sites basically involves schools, day centres, parish councils, pavilions, and sports centres, i.e., fixed structures that are well known to the population.

5.3. Methodology

With the aim of mapping priority WUIs to be evacuated in a wildfire scenario, an integrated framework was applied based on the following components: wildfire hazard, social vulnerability, and wildfire risk assessment, in support of evacuation and modelling the travel time—either on foot or by car—to the nearest refuge or shelter. Figure 18 shows the integration of these components.

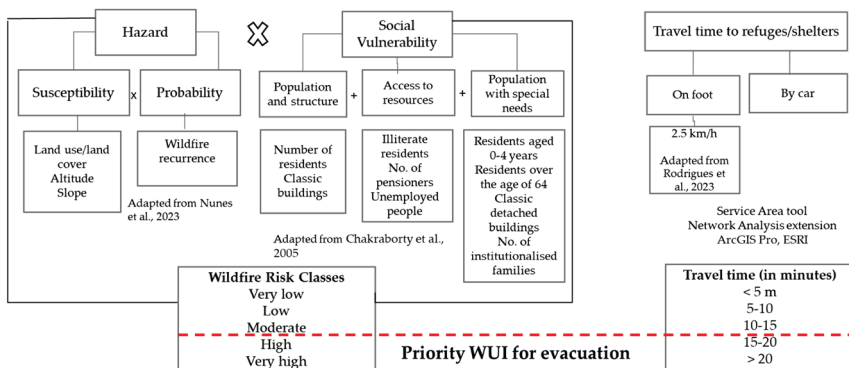


Fig. 18 - Implementation flow chart components to map priority WUIs for evacuation (Nunes *et al.*, 2024).

5.3.1 Wildfire risk assessment in support of evacuation

The methodological proposal was adapted from the work of Chakraborty *et al.* (2005) applied to evacuation in the context of hurricanes in the Florida region. This methodology is applied to the risk of forest fire in support of evacuation because these two risks have some similarities, identified by Folk *et al.* (2019) and Intini *et al.* (2019), including, (i) the problem of predicting the direction of travel, (ii) the ability to displace a large number of people, and (iii) a change in direction without warning. In addition to these issues, in an evacuation situation for either of these risks, an early warning allows people to leave by driving vehicles. The original methodology of the work by Chakraborty *et al.* (2005) is based on the following steps: (i) assessing the hazard, (ii) assessing the social vulnerability for evacuation support (SVES), and (iii) assessing the degree of support needed for evacuation resulting from the hazard x social vulnerability for evacuation support.

Wildfire Hazard - The hazard assessment was based on the methodology used in the work by Nunes *et al.* (2023) and involved the following steps: (i) assessing susceptibility, using the slope, altitude, and land use and occupation variables, (ii) calculating probability based on the areas burnt between 1975 and 2020, and (iii) calculating hazard by multiplying susceptibility by probability. The validation process was supported by the ArcSDM toolbox, ArcGIS 10, which helped calculate the AUC (area under the curve). This assessment summarises the ROC (receiver operating characteristics) curve into a value that basically measures the quality of the model's forecasts, i.e., if the model's forecasts were 100% correct, the AUC value would be 1. The results indicate that the model performed well, with an AUC of over 0.80.

Social Vulnerability for Evacuation Support (SVES) - The data used in the SVES assessment were taken from the Geographic Base for Referencing Information (BGRI), relating to the year 2011. The limited list of data for the year 2021 meant that more recent census information could not be used. A total of nine variables were selected. They are subdivided into three important characteristics of the

population from an evacuation standpoint, identified in the work by Chakraborty *et al.* (2005) as the following: (i) population and structure, (ii) differential access to resources, and (iii) population with special needs for evacuation (TABLE IV).

TABLE IV - Variables included in the calculation of social vulnerability for evacuation support.

Approaches (APP)	Statistical Subsection (BGRI2011)
(1) Population and structure	Total number of residents
	Classic buildings
(2) Differentiated access to resources	Residents who can neither read nor write
	Residents who are pensioners
	Residents with no economic activity
(3) People with special needs for evacuation	Residents between 0 and 4 years old
	Residents over the age of 64
	Classic detached buildings
	Total number of institutionalised families

The procedure used by Chakraborty *et al.* (2005) to calculate SVES consisted of adapting the procedure used by Cutter *et al.* (2003). In the present study, the Chakraborty *et al.* (2005) approach was retained, and the assessment consists of the following three stages:

- Step 1: Calculate . For each variable i determine the ratio of variable i to the total number registered in the municipality;
- Step 2: Standardisation for each variable, as follows:

$$\frac{R_i}{R_{max}}$$

where R_{max} = maximum value of the ratio calculated previously.

- Step 3: Combining the multiple variables by calculating the arithmetic mean.

The author presents the final SVES as the result of combining the three above-mentioned approaches (population and structure, differentiated access to resources, and population with special needs for evacuation).

The Natural Breaks (Jenks) classifying method was used to prioritise wildfire risk (Hazard $\times$ SVES) into five categories, since the variance within each class is minimised while the variance between classes is maximised (Wang *et al.*, 2015).

5.3.2. Modelling travel time to refuges and shelters

Two exercises were carried out for both municipalities under study, namely determining the time it takes to walk to identified shelters and refuges, and determining the time it takes to drive to larger shelters. As both municipalities have high rates of an ageing population (22.9% in Lousã and 31.1% in Sertão), we adopted the figures obtained by Rodrigues *et al.* (2023) in real evacuation tests on foot in Cabanões, a village in the municipality of Lousã. Rodrigues *et al.* (2023) identified the following average speeds: for individuals over 65 without mobility difficulties, 3.13 km/h uphill and 3.65 km/h downhill; for individuals over 65 with mobility difficulties, 2.24 km/h uphill and 2.47 km/h downhill; and for group evacuation, 2.5 km/h. The average speed in a group falls thanks to the support and mutual help given to people with difficulties. We therefore opted for the group average speed, i.e., 2.5 km/h. The travelling time was assessed using the Network Analysis extension, with the Service Area tool in the ArcGis Pro 3.0 software.

The exercise of travelling by car has a dynamic speed depending on the speed limits of the localities. The service area shows the road networks that can be reached within different times, in minutes from the assembly points, and have been applied in evacuation route planning in disaster-susceptible areas (disasters such as floods and tsunamis) (Ashar *et al.*, 2018; Parajuli *et al.*, 2023). These outputs were then cross-referenced with the urban–forest interfaces of the two municipalities to find the travel times between these contact areas and the refuges and shelters.

Finally, the travel times of the different WUIs were then cross-referenced with the fire risk maps to highlight the WUIs with a high or very high fire risk and travel times of more than 15 min.

5.4. Results

5.4.1. Spatial variability in wildfire hazards

The results show the significant expression of the highest hazard classes in the municipalities under study. Sertã has almost 80% of its territory in the highest hazard classes (40.7% very high and 38.2% high), while, in Lousã, this figure is around 70%. In both municipalities, the lowest hazard classes coincide with the central area, where the larger settlements and lower slopes are located (Figure 19).

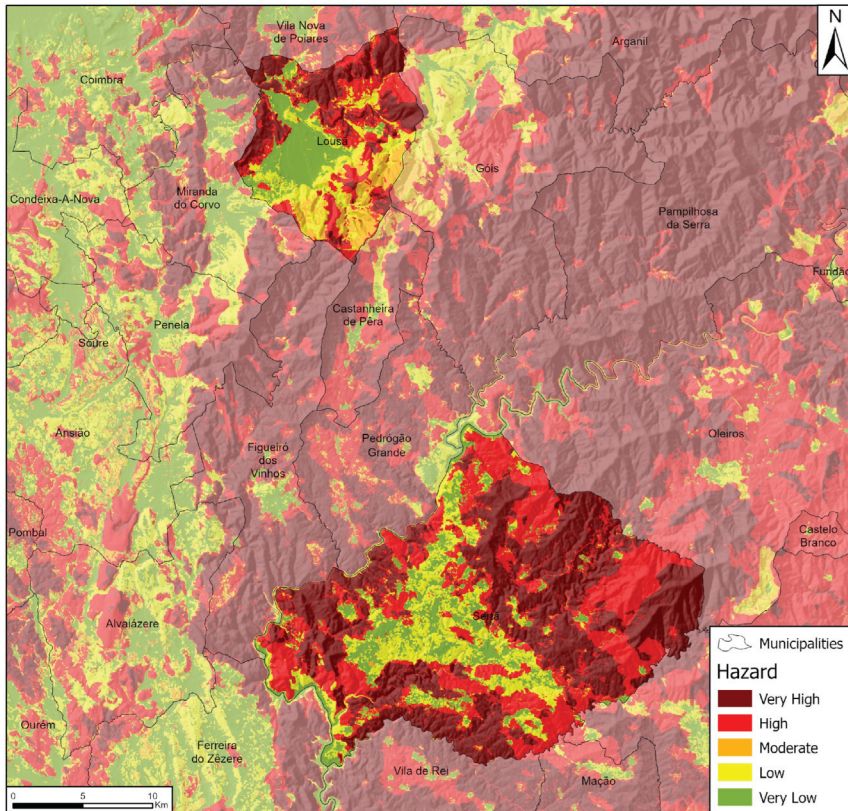


Fig. 19 - Hazard results for forest fires in *the municipalities of Lousã and Sertã* (Nunes et al., 2024).

5.4.2. Spatial distribution of social vulnerability

The results of assessing the social vulnerability components are shown in Figure 20. In the case of Lousã, the results obtained through the APP1, APP2, and APP3 approaches show a concentration of the most vulnerable areas in the main population centre and settlements located in the north-east and north-west of the municipality. These coincide, respectively with the Union of Parishes (UF - União de Freguesias) Lousã and Vilarinho, and the parish of Gândaras.

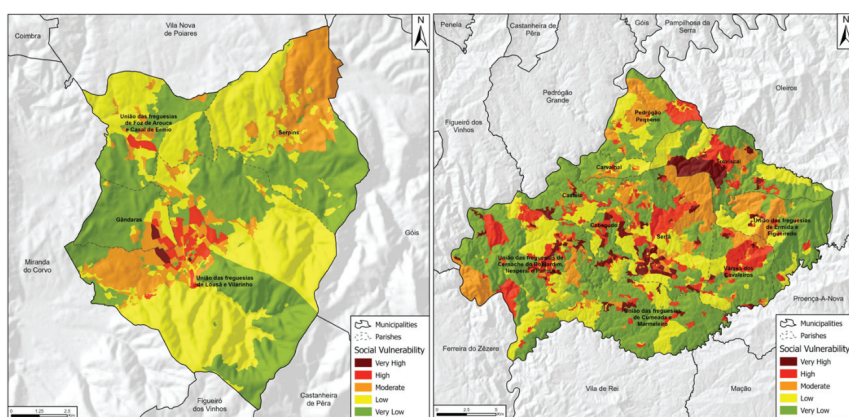


Fig. 20 - Social vulnerability to evacuation support (SVES) in the in the municipalities of Lousã and Sertã (Nunes *et al.*, 2024).

In the case of Sertã, considering the three approaches, the highly vulnerable settlements are scattered throughout the territory. Consequently, the municipality of Sertã has a greater number of areas with high and very high vulnerability than the municipality of Lousã.

5.4.3. Wildfire risk in support of evacuation

The fire risk maps show quite different results from the previous ones. In the case of the municipality of Lousã, its population centre, previously classified as very vulnerable, is now classified as “Very Low”, “Low”, and “Moderate” in terms of fire risk for evacuation support (Figure 21).

In the case of the municipality of Sertã, the localities in the eastern strip are very problematic, especially when all the approaches are combined (Figure 21). Compared to Lousã, the municipality of Sertã has a predominance of small settlements that are spread throughout the municipality, with a very high risk of fire.

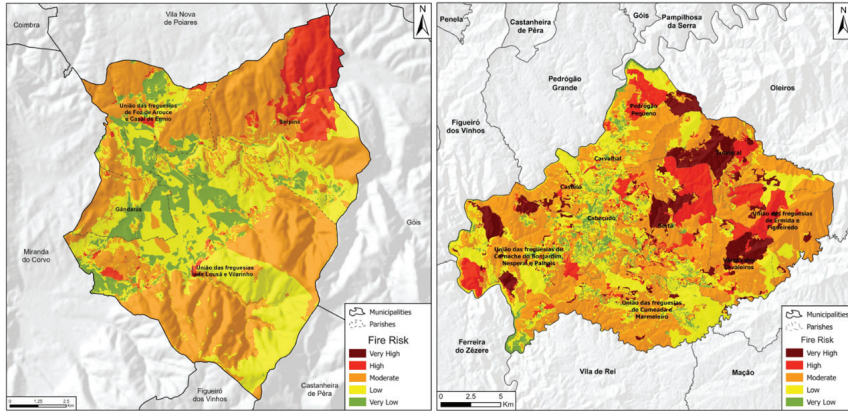


Fig. 21 - Fire risk in support of evacuation in the municipalities of Lousã and Sertã (Nunes *et al.*, 2024).

5.4.4. Travelling time to the nearest refuge/shelter

In the municipality of Lousã, around 70% of the WUIs are more than 20 minutes' walk from the nearest refuge or shelter, while, in Sertã, the figure is slightly lower, at around 66.6% (Figure 22). If we analyse the results at a parish level, the situation is quite critical in all the parishes in the municipality of Lousã, because between 66 and 72% of their WUIs are more than 20 min away on foot. In the case of Sertã, the most problematic parishes are Pedrogão Pequeno, Cabeçudo, Troviscal, and the UF of Cumeada and Marmeleiro, with figures of over 70%.

When it comes to travel time by car (Figure 23), the municipality of Lousã is generally more straightforward when it comes to travelling to shelters and refuges than Sertã. Almost 80% of Lousã's WUIs are within a five-minute drive of a shelter. In Sertã, only 42% of the WUIs are in similar conditions, i.e., five minutes or less away from a shelter. Additionally, in Sertã, 36% of the WUIs are between 5 and 10 min from a shelter, 16% are between 10 and 15 min away, and 7% are more than

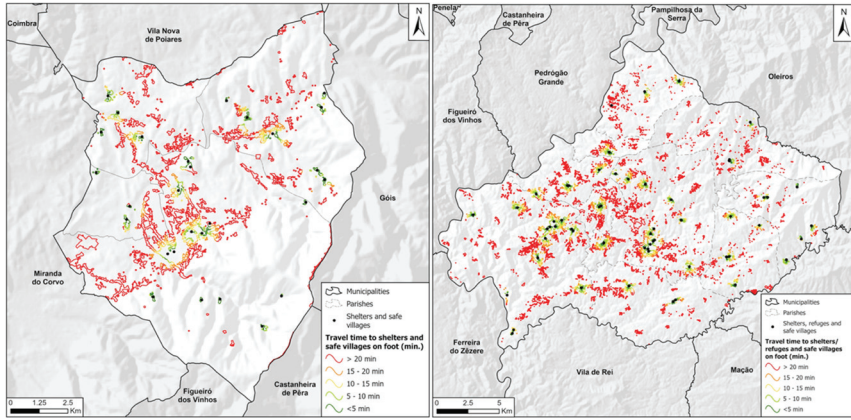


Fig. 22 - Travel time on foot to the nearest refuge or shelter (Nunes *et al.*, 2024).

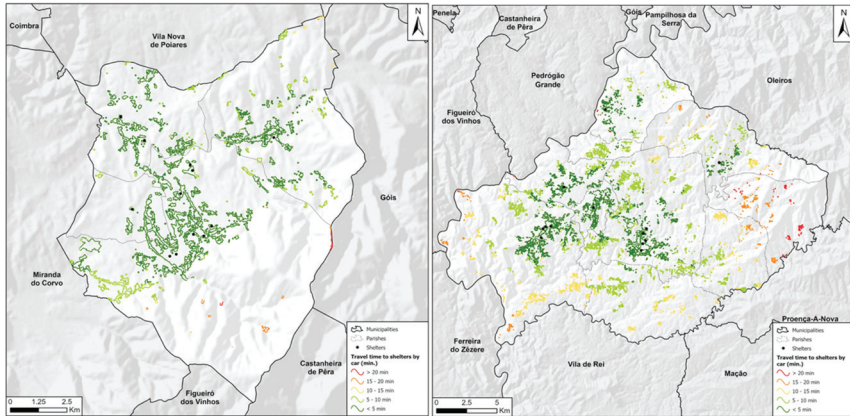


Fig. 23 - Travel time by the nearest refuge or shelter (Nunes *et al.*, 2024).

15 min away. In Lousã, 16% of the WUIs are between 5 and 10 min from a shelter and 3% of them are more than 25 min by car from a shelter.

In the UF of Ermida and Figueiredo, in the municipality of Sertã, around 60% of its WUIs require travelling for between 15 and 20 min by car to reach a shelter and 32% spend between 20 and 25 min on the journey (TABLE III). This is not the case in the municipality of Lousã, as all the parishes there assure residents that around 91% of WUIs are no more than 10 min travel by car from a shelter. The most worrying situation in the municipality of Lousã concerns the 5.1% of WUIs in the Lousã and Vilarinho parish union where it takes residents more than 25 min to reach the nearest shelter.

5.4.5. Correlating the wildfire risk with evacuation time

The correlation between forest fire risk classes and evacuation times, especially the highest fire risk classes with the highest evacuation times on foot or by car (Figures 24 and 25), makes it possible to identify the priority interfaces in terms of evacuation. The results for the two municipalities are quite different, since, in the case of Lousã, there are practically no WUIs more than 15 minutes' walk from the shelter points (refuge or shelter) with a high or very high fire risk. In the case of

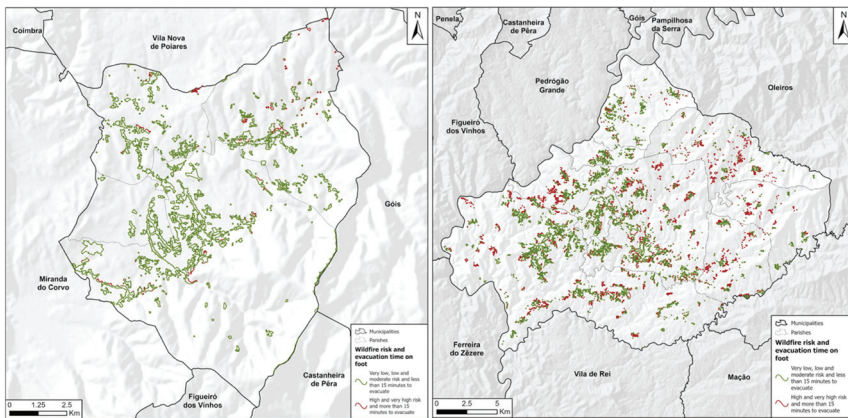


Fig. 24 - Correlation between the highest forest fire risk classes and evacuation times on foot longer than 15 min. (Nunes *et al.*, 2024).

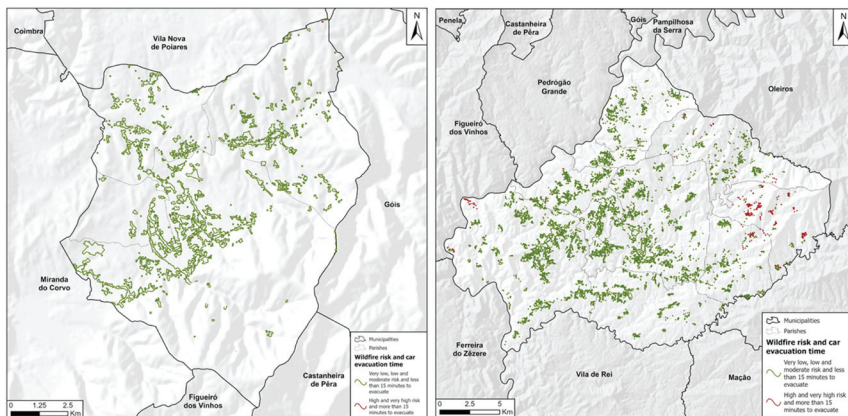


Fig. 25 - Correlation between the highest forest fire risk classes and evacuation times by car longer than 15 min. (Nunes *et al.*, 2024).

Sertã, the situation is particularly critical in more than 20% of the municipality's WUIs, which are characterised by a high or very high risk of fire and are located more than 15 min from the shelter points. These WUIs are predominantly located in the outlying areas of the municipality (Figure 24). When using a car to travel to the nearest shelter points, in the case of Lousã, all the WUIs with a high or very high risk are less than 15 min away, while in Sertã this figure is 3.4% (Figure 25).

5.5. Discussion

Over the past few decades, wildfires have impacted extensive regions of Portugal, frequently damaging and threatening urban areas ranging from small rural villages to the outskirts of large towns and cities in central Portugal (Lourenço, 2021). The most catastrophic, measured by the number of victims and material damage caused, occurred in 2017 (June and October). After these events, early evacuations began to take place more often in Portugal to prevent human casualties. The two municipalities studied are in the extensive territory that Lourenço *et al.* (2020) define as favourable to the cyclical progression of large forest fires, thanks to natural features such as orography and vegetation cover, but also due to human influence. In the central region, these areas include the more mountainous and inland areas (Nunes *et al.*, 2023). Because of the topographical conditions, the type of occupation, which is predominantly forest/woodland, and sociodemographic characteristics, the cases studied belong to the group of municipalities with the highest hazard as well as vulnerability to wildfires.

When the preponderance of coniferous and eucalyptus forests with high combustibility and flammability (Xanthopoulos *et al.*, 2012) is combined with steep slopes, the rapid progression of flames is assured. Several authors confirm that areas occupied by coniferous forests and scrubland are the most prone to fire (Rego, 2014; Nunes *et al.*, 2016; Nunes *et al.*, 2023) compared to other uses of the land, notably agricultural. In fact, the very low and low wildfire hazard classes are dominant where agriculture is the most widespread land use. The less fire-proneness of agricultural areas has been recognised in several works in different geographical

areas (Oliveira and Zêzere, 2020; Sil *et al.*, 2019) where farmland around isolated houses and villages can act as a buffer zone against wildfires. This only fails in the case of extreme wildfire events when fire selectivity in specific land cover types is drastically reduced (Oliveira *et al.*, 2020). Various studies have shown that wildfire hazard can be changed by interventions based on fuel management at the landscape scale to reduce the probability that a wildfire would reach a given settlement (Gibbons *et al.*, 2019; Syphard *et al.*, 2021).

Analysing this variable in isolation in the context of evacuation planning makes it possible to prioritise intervention areas with specific biophysical conditions, although the population to be evacuated is a determining component to be considered in conjunction with hazard (Chakraborty *et al.*, 2005). Thus, when the hazard is cross-referenced with the SVES, resulting in the forest fire risk, it is possible to identify the most critical zones in terms of evacuation. The combination of high hazard classes and high social vulnerability, plus the greater dispersion of population centres in its territory, means that Sertã has a greater preponderance of high and very high fire risk classes than Lousã. In the case of Lousã, the combination of these two single dimensions has tended to attenuate the level of risk, with one component counterbalancing the other. The results are in line with those reported in Oliveira *et al.* (2020b). These state that settlements with more exposure to hazard do not necessarily have the highest social vulnerability, in a parish located near the Lousã municipality. For most villages, they found that the aggregation of these two components tend to decrease the level of fire risk.

On the other hand, when we look at the time it takes to walk to the nearest shelters, we see that the situation is almost the same for the two municipalities, with around 70% of the WUIs more than 20 min from the shelter. When travelling by car, Lousã has better results than Sertã. However, when travel times are correlated with the degree of fire risk, Sertã shows very significant weaknesses, as more than 20% of its WUIs are characterised by a high fire risk and are more than 15 min from the shelter/refuge sites. The combination of high fire hazard classification and a very elderly population (higher than 30%), together with the greater dispersion of the population, explain the high number of WUIs in critical situations in terms of evacuation.

Many studies have shown that older people are particularly vulnerable during the evacuation process, noting the importance of considering the elderly when planning for evacuation (Pekovic *et al.*, 2007; Jia *et al.*, 2020) the physical difficulties that they may have with evacuation, especially without social support (Asfaw *et al.*, 2019; Asfaw *et al.*, 2020) and the community-level support. Also, several studies indicate that significant numbers of people delay evacuation during a wildfire event, which often increases evacuation danger (McCaffrey *et al.*, 2015). Tedim (2018) also points out that people often resist or choose to stay in their homes to defend their property. This behaviour is associated with low levels of preparedness both for defending the home and for evacuation, which can heighten the risk to life and loss of property (McNeill *et al.*, 2015). Many individuals will prefer to wait and assess the development of the fire while carrying out measures to protect their homes and property rather than evacuating immediately (Strahan & Gilbert, 2021). In this context, Melton *et al.* (2023) note that the ways people in general and the more elderly in particular respond to or are impacted by wildfires are still relatively new and need further development and exploration to better learn from and support this population in the face of worsening wildfire disasters.

Portugal does not have a compulsory evacuation system and so the efficiency of this strategy depends on the willingness of the residents and the capacity of the authorities. Furthermore, in the municipality of Sertá only one “Aldeia Segura” was identified and in the “Aldeia Segura” of Lousã there were no evacuation plans. In addition, there is no explicit reference to places of shelter or refuge, even though they are identified in the PMEPCs. These findings are in line with the results obtained by Vaqueiro (2022), who stated that of the total of 2057 settlements that had signed up to the Safe Village program at the time, only 172 had a set of planned actions, stating that only these could be considered as safe village. The results of Tedim *et al.* (2022) further reinforce these difficulties; in a questionnaire applied to 139 municipalities that had joined the program, 91% reported constraints in its implementation.

In this context, considering the level of risk of each WUI, it is urgent to set priorities for emergency intervention, as well as to establish safety and evacuation protocols suited to each village. Moreover, considering that more and more

catastrophic wildfires will occur with climate change, institutional and suppression capacities will probably be overridden (Podur and Wottonm, 2010; Moreira *et al.*, 2020). For these reasons, fire management approaches must include strategies to mitigate the wildfire hazard and improve community preparedness and people's coping capacity, tailored to their needs and abilities, and so enable a suitable adaptation to fire-prone environments.

5.6. Conclusions

The focus of the study presented in this chapter was to map the urban–forest interfaces that are exposed to the worst wildfire risk, while at the same time identifying the population centres with the greatest constraints on the evacuation process. These could be due to the nature of the population exposed and the time it takes to reach the nearest shelter/refuge. The lack of integration of biophysical hazards, social factors in community vulnerability, and the evacuation time analysis proved to be a gap in the evacuation process planning in Portugal.

The key research findings are based on two case studies. They have shown that risk levels depend on different combinations of hazard and vulnerability. The intersection of the fire risk as time taken to travel to the nearest refuge made it possible to identify the WUIs that need to be prioritised with respect to protection and emergency actions on a local scale. The maps obtained at WUI scale, which is an innovative approach in wildfire risk management in Portugal, might be a useful tool since they can assist in designing suitable prevention measures and improving the effectiveness of fire prevention. This approach can also provide support for environmental and civil protection policies, such as the allocation of firefighting resources, and enhance the development of evacuation and safety strategies suited to each local context. This methodological approach also can be applied successfully to map priority WUIs in terms of evacuation in different Portuguese settings, particularly in rural areas in the mountainous and inland areas of Portugal, which are dominated by small, scattered villages with ageing populations.

However, future research must aim at a better understanding of the integration of strategies focused on community preparedness and people's coping capacity, according to their needs and abilities, in the identified fire-prone environments. Understanding residents' intended evacuation behaviours must also be an increasingly important component in the complex fire management approaches, to ensure the safety of both firefighters and residents during fire events, which continue to grow in size and severity.

Chapter 6

WILDFIRE EVACUATION MODELLING AND SIMULATION

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6.1. Simulation Techniques and Management Tools for Wildfire Simulation

6.1.1. Historical context and challenges

Wildfire simulation and modeling are essential for fire management, as they mitigate risks through fire rise exposure assessment and assist in evacuation planning and management (Beyki *et al.*, 2023). The ability to forecast wildfire behavior accurately will ensure the safety and effectiveness of wildfire control and fire management (Countryman, 1972). The behavior of wildfires is a complex phenomenon influenced by numerous interrelated factors. This inherent complexity presents challenges when attempting to model and accurately predict wildfire behavior. Factors such as weather conditions, topography, vegetation

types, fuel moisture, and human activities all contribute to the dynamic nature of wildfires. The intricate interactions between these variables make it difficult to develop models that capture the full spectrum of wildfire behavior (Cruz *et al.* 2018), (Mell *et al.*, 2007). The current wildfire behavior models are limited in their ability to account for all the factors involved. While significant advancements have been made in wildfire modeling, there is still room for improvement to enhance the accuracy and reliability of these models. The challenge lies in accurately representing the complex interactions and feedback loops between various factors. Additionally, the availability and quality of input data also play a crucial role in determining the accuracy of the models. Insufficient or unreliable data can further limit the accuracy and reliability of the predictions (Cruz *et al.* 2018), (Mell *et al.*, 2007). Show (Show, 1919) conducted the first known field research on fire's rate of spread in the wildlands by documenting the growth of experimental point source fires in northern California from 1915 to 1917. In addition, the first wildfire case study was published by Gisborne (1927). Eventually, more in-depth studies, including field tests, started in Canada and the United States in the 1930s (Bickford and Bruce, 1939; Paul, 1969). The research in this field gained momentum, and the size of experiments gradually expanded to larger scales by the 1960s (Countryman and Schroeder, 1960; Van Wagner, 1968). Moreover, laboratory experiments with different types of equipment (e.g., wind tunnels) were carried out to better understand the behavior of fire spread in forests (Curry and Fons, 1938; Fons, 1940). The first guide to predicting wildfire behavior was produced by Barrows (1951), which was based on analyzing the fire report data as a source of information to estimate the rate of spread. The next step of research in wildfires was developing numerical solutions and simulations. Wildfire simulation models are distinguished into two basic categories regarding their fundamental approach: physical models and empirical or semi-empirical models. The behavior of fire is defined by both chemistry and physics. The physical model aims to integrate these phenomena into a simulation, enhancing our understanding of the processes that govern fire propagation and behavior (Alexander and Cruz, 2013). On the other hand, an empirical model incorporates no physics or chemistry, and the modeling structure is based on statistical data.

In addition, some semi-empirical models exist with some form of the physical framework (Alexander and Cruz, 2013). The actual development of the combustion process is not the aim of empirical or semi-empirical simulations but rather to be used in the management and decision-making process (Papadopoulos and Pavlidou, 2011). Many identified a coupling of both approaches as the best solution to simulate better the characteristics of wildfire and fire behavior (Cruz and Gould, 2009).

Richard Rothermel (1972) published a detailed mathematical model of wildfire to predict the fire's rate of spread in wildland fuels, which is the basis of many software. It is one of the most widely used models for predicting fire behavior and serves as the foundation for many modern fire simulation systems. The model is semiempirical, derived from physical principles, and complemented by extensive experimental data collected from various types of wildland fuel, such as grass, brush, and timber. The model's primary output is the rate of spread of a fire front. Still, it also provides insights into other critical fire behavior parameters such as flame length and fire line intensity. It simplifies the complex dynamics of fire spread by focusing on the energy balance between the heat required to ignite the fuel and the heat generated by the fire. This model could not be used to incorporate the crown fires, while it could only predict the fire's intensity and spread rate in a continuous fuel bed on the ground. Additionally, this model was applicable to bushfires or grasslands since they are considered close to the ground with fuel continuity. As this model does not consider the firebrands as an essential factor in advancing the fire, the effect of firebrands was not considered.

Richard Rothermel model's outputs were mainly a mean value for the rate of spread and fire intensity, which were obtained following the fuel characteristics and topography of the land as inputs. Nevertheless, the complexity of such models was cast away by the use of visualization and slide-rule devices (Cheney and Sullivan, 2008), graphical computation in the form of nomography (Albini, 1976a), and the development of computer programs, e.g., Albini, which was one of the most successful (Albini, 1976b). Finally, with the development of such models and programs, computer calculations started their use for operational and research purposes in the field of wildfires in the 1970s (Burgan, 1979; Frandsen, 1973).

The cellular automata (CA) model was another innovative approach that was used by Karafyllidis and Thanailakis (1997) for the very first time to predict the fire spread in homogenous and heterogeneous forests (also referred to as the KT model). The advantage of this model was the ability to incorporate weather conditions and land topography. An algorithm was developed based on this model to determine the fire front in some hypothetical forests and showed good agreement with the fire spread in real wildfires. Later on, in an attempt to create software to simulate small-scale fires in the Mediterranean regions, with the scope of fire management and firefighter deployment, Guarsio and Baracani (2002) combined the mathematical model introduced by Rothermel for the simulation of fire spread with the CA theory. The cellular automata included two layers: the upper represented the tree crown, and the lower represented the coverage on the surface.

Additionally, other affecting factors, such as air temperature, fuel moisture, and terrain slope, were included in the model as coefficients. The effect of wind on the fire shape was considered utilizing Alexander's ellipse theory (Alexander, 1985).

Regardless of the model used, three principal factors are pointed out by Albini (1976a) as the sources of error or disagreement between the acquired results from models and real-life fire behavior data:

1. The model may not be applicable to the situation.
2. The model's inherent accuracy may be at fault.
3. The data used in the model may be inaccurate.

Therefore, applying a model to a situation where it was not intended to be operated could result in significant prediction errors (Kessell & Potter, 1980). Through simplification of the relationships, minor factors are neglected, and the model would be based on idealized conditions, which leads to discrepancies between results and the actual fire behavior (Brown & Davis, 1973). Approximations for distinct purposes can be made by observing the fire-modeling laws to increase the data accuracy. Still, it is easily forgotten that they are only approximations, which leads to the tendency to apply models beyond their effective area. For instance, eighteen assumptions are made in Rothermel's crown fire models (R. C. Rothermel, 1991a) in the U.S. Northern Rocky Mountains that should be considered and followed through when using the model. Frequent re-examination

and redefinition of assumptions on which the models are based, and the range of conditions under which the models are applicable are crucial to avoid these types of errors (Brown & Davis, 1973). Most models that intend to predict the wildfire rate of spread have limiting assumptions and must not be used to simulate what they do not represent (Albini, 1976a).

Numerous wildfire spread models assume the fuel complex to be homogenous, continuous, and uniform, which results in variation between predictions and the observed fire behavior. Further research and innovative approaches were used to overcome this issue. Frandsen and Andrews (1979) modeled a nonuniform fuel bed forest fire spread, Fujioka (1985) applied the non-uniformity to the spatial aspect, and Finney *et al.* (1998) developed a model to calculate the wildfire rate of spread across random landscapes, which eventually led to the development of FARSITE (Finney, 1998). Additionally, other innovations emerged to address this issue, including Rothermel's two-fuel model concept (R. Rothermel, 1983), which was later developed by Martin (1988). Geographic information system (GIS) fire growth models adopted by Beck (2000) and Tymstra *et al.* (2010), also aimed to mitigate this problem. Assuming that the fuel bed has only one layer and is adjacent to the ground, neglecting the fire spread by spotting (flying embers), and neglecting the fire spread under the effect of fire whirlwinds are the main assumptions that were the source of variation in results up to that date (Albini, 1976b).

Another challenge in modeling wildfires is the accuracy of input data. As mentioned, the behavior of wildfires is affected by parameters such as wind speed and direction, topography, and fuel moisture. Consequently, the predictive simulation models are sensitive to these parameters as inputs. Thus, if input data is not accurate enough or the simulation operator fails to grasp the variation of these parameters over spatial and temporal dimensions, the model results can be biased (Albini, 1976a). The nonlinear nature of wildfire behavior complicates the relation between input and output data accuracy. As a result, the model must establish its input data tolerance over the range of variable values used as input. Therefore, the accurate selection of data inputs remains a challenge for a fire simulation operator, since neither the wind speed nor direction remains constant, nor the topography of the area or even the fuel complex (Albini, 1976b).

6.1.2. Advanced computational tools

As previously discussed, fire models are classified into three broad types: empirical, semi-empirical, and physical (Pastor *et al.*, 2003). Empirical models are solely based on statistical correlations derived from experimental data and do not include the physical phenomena of the fire. Semi-empirical models include the energy conservation equation but do not differentiate between heat transfer modes, i.e., radiation, convection, and conduction. Theoretical methods or physics-based models attempt to solve all the governing equations (fluid dynamics, heat transfer, and combustion) with reasonable assumptions and approximations (Mell *et al.*, 2007). TABLE V presents the most widely used wildfire simulation software.

Since other works comparing and analyzing the previously mentioned software already exist, for example, the works of Bova (2016), Mell *et al.* (2007), Sullivan (2009), Morvan (2011), Papadopoulos and Fotini-Niovi (2011), and Cruz *et al.* (2018), Fox-Hughes *et al.* (2024), FireStation (FS), Fire Dynamic Simulator (FDS), and Wildfire Analyst (WFA) are chosen for this study. Even though there are published papers and manuals for the software, each software's model, their inputs, the input/output formats, and their different features will be explained briefly in the following chapter according to their published works, so that the reader can have an understanding of each software.

6.2. Comparison of Three Simulation Software Tools

6.2.1. Software descriptions

FireStation (Version 1.0.16) - FireStation is a software designed to simulate the fire spread over complex topography. The modeling of the wind field over the terrain employs two separate models. Both models base their wind predictions on local observations made at meteorological stations, including wind speed and direction. The coupling effect of the wind field with the fire can be simulated using one of the wind prediction models (Lopes *et al.*, 2002).

TABLE V - Summary of software platforms (Beyki *et al.*, 2025b)

Software	Model Type	Key Features	Limitations	Availability	Computation Intensity
BEHAVE	Semi-empirical	- One of the first computational formulations of the Rothiermel model and would result in fire spread values - Simple energy balance model; - Later coupled with GIS for landscape-scale simulations	- Lacks complex terrain and wind modeling; - Difficulties in defining appropriate fuel models - Does not account for crown fires, spotting, or fire-atmosphere interactions	- Free, publicly available	- Low; -suitable for desktop use.
FARSITE	Semi-empirical	- Uses Huygens' principle for fire front expansion; - Includes surface fire spread, crown fire transition, and spotting distances	- Weather forecast difficulties; - Absence of 3D wind flow	- Free, publicly available	- Moderate; - Desktop use with GIS integration
FlamMap	Semi-empirical	- Non-temporal fire spread simulation - Primarily used for risk assessment of the fire conditions of an area under specific conditions	- Absence of 3D wind flow - Lack of fire-atmosphere interactions - Weather does not vary with time	- Free, publicly available	- Moderate; - Desktop use with GIS integration
SPARK	Semi-empirical	- Uses level set method; - Integrates various fuels using gridded inputs - High flexibility for defining fire spread models	- Lack of predefined models - Advanced Knowledge requirement for setup and simulation	- License required; - Free to use for research purposes	- Moderate
FIRESTAR	Physics-based (2D-implicit)	- Includes multiphase combustion model; - Accounts for both radiation and convection; - Suitable for small-scale simulations	- Limited by 2D assumptions; - Less suitable for large-scale simulations	- Research use; typically, not available to the public	- High
FIRETEC	Physics-based (3D-explicit)	- Suitable for large-scale simulations; - Includes 3D numerical solution; - Various fuel types included	- Limited combustion model (no transport phase)	- Research use; typically, not available to the public	- Very High
FIRELES	Physics-based (3D-explicit)	- Suitable for small-scale simulations; - Includes explicit 3D numerical solution; - Simulates multiphase combustion	- Limited to small scales; - Does not support multi-fuel modeling - No turbulence radiation interaction model	- Research use; typically, not available to the public	- Very High

In the year that FireStation was released, it was claimed that no previous wildfire simulation software (to the developers' knowledge) incorporated any type of model for wind field calculation other than FireStation. Another claimed feature of this package was the software's user-friendliness, not only towards the input parameters but also regarding the results and output comprehensiveness. FireStation contains an interface based on the Windows command system, on top of the mathematical models for fire and wind simulation. This enables the user to grasp a simple understanding of the required inputs and resulting outputs (Lopes *et al.*, 2002).

FireStation uses Rothermel's surface fire spread model (R. C. Rothermel, 1972) for the fire behavior and rate of spread. The Rothermel model is compatible with different fuel models, which makes it a suitable choice for many wildfire simulation software. Nevertheless, the Rothermel model only provides the rate of spread toward the maximum spread direction, and it is not enough to simulate the fire propagation and burning area. Another model to anticipate the fire shape is also required, for which the FireStation uses the Anderson model (M. E. Anderson, 1983) and the Alexander model (Alexander, 1985). The input for the fire shape model is the wind speed at mid-flame height.

For the wind field simulation, a significant feature of this software, FireStation implements two models: NUATMOS and CANYON. NUATMOS is a linear model, developed by Ross *et al.* (1988), which solves the continuity equation in a three-dimensional grid. This model takes the wind speed and direction as its input, and as the first step inserts interpolation/extrapolation estimate values of the wind field into all grid points, which later are adjusted using a variational analysis method until it reaches a divergence-free flow field to satisfy the continuity equation. The result's accuracy could be increased by increasing the number of wind observation points in the study area. Despite the limitations of this model, posed by the fact that it cannot simulate the buoyancy and separation phenomena, the solutions provided are quite realistic in most cases, and the simplicity of the code and short computation times, make this model quite favorable.

The second model available in FireStation for wind field simulation is CANYON, a model developed by Lopes *et al.* (1995) that solves the three-dimensional Navier-Stokes equation in addition to the continuity equation. The effects of turbulence on the flow

field are incorporated with the K-E model, and the effects of terrain or vegetation roughness and thermal effects of fire on the flow field are also accounted for.

Wildfire Analyst (Version 2.9) - Wildfire Analyst is developed by Technosylva, with the primary objective of using it in real-time or on-field operations. This software is designed to have flexibility toward predefined scenarios, which include fuel maps, vegetation, and weather. This feature eliminates the need to integrate data every time the software is being used, which can save time. Wildfire Analyst enables the user to access GIS data directly from the platform since it is based on ArcGIS™ (Ramirez *et al.*, 2011).

This software uses the model developed by Rothermel (1972) with the modifications proposed by Albini (1976b). In addition to the Rothermel and Albini fuel models, the Scott and Burgan (2005) fuel model is used, with the ability to incorporate other custom fuel models. The fire evolution is a single ellipse, using the Anderson (1983) model with the approach presented by Finney (2006) in Farsite. Crown fires can also be simulated based on the models developed by Rothermel (1991b) and Wagner (1977). Moreover, the Kitral model (Julio *et al.*, 1998), an empirical fire propagator model developed by the University of Chile and INTECCHILE, is also available in Wildfire Analyst.

The simulation is capable of integrating various semi-empirical models thanks to a robust set of equations that describe fire characteristics influenced by multiple factors, including weather, topography, fuel type, fuel moisture, and the presence of firebreaks. Furthermore, it offers several modes for fire management that authorities can employ, such as probabilistic mode, reverse time simulation, and evacuation timing (Ramirez *et al.*, 2011).

For the simulation of the wind field, WFA uses WindNinja, which is an independent software. WindNinja uses the model developed by Forthofer (Forthofer, 2007; Forthofer *et al.*, 2014) which is a 2D High-resolution wind system. The temperature of the surface is integrated into the calculations through the coupling of the energy equation.

Wildfire Analyst offers a range of innovative tools that can enhance fire management and planning. The Exposure Analysis tool is based on the minimum

travel time concept proposed by Finney (2002). This tool calculates the time fire needs to reach a certain point of interest under a specific situation (fuel, topography, and wind). This mode can be instrumental in creating defensive measures for communities against wildfires.

Fire Dynamic Simulator (Version 6.8.0-1246) - Fire Dynamic Simulator is a CFD model for fire-driven flows, developed by the National Institute of Standards and Technology of the United States. The Navier-Stokes and chemical reaction equations are solved numerically for flow fields with a Mach number below 0.3. FDS is based on FORTRAN and does not have an interface. Input data must be provided through a text document that defines the domain and the required outputs specified by the user. FDS reads the input from this document, numerically solves the governing equations, and presents the user-defined outputs in various files. It also has a companion software called Smokeview, which features a graphical interface that generates results in the form of animations (McGrattan & Forney, 2004); (Parsa *et al*, 20025)

Three different methods can be used to simulate a wildland fire using FD:

- Modeling the vegetation or fuel using a set of particles that can be heated through convection or radiation;
- Modeling the vegetation or fuel as a porous solid with a thickness equal to vegetation height;
- Modeling the fire propagation using empirical methods and level set model.

The first two methods use physical models to simulate the fire. They require a very fine mesh grid and require high computation resources. Only the third method will be explained, as the first two are not relevant to this work.

Level set models are suitable for scenarios on a large scale, in which the study area cannot be gridded finely enough to use a physical model. The fire front propagation model is based on the model used in FARSITE by Finney (1998), which are models of Rothermel (1972) and Albini (1976b, 1976a) and the fire shape of a single ellipse modeled by Richards (1990). The fuel family model used in FDS is the 13-fuel family presented by Rothermel (1972) and Albini (1976a, 1976b) with the ability to introduce custom fuels if necessary.

Four level set modes (Bova *et al.*, 2016) with different features are available that should be selected according to the requirements from the simulation. The first mode only simulates the surface propagation model without simulating the actual fire, and the wind is applied globally to the domain without being affected by the terrain. The second mode develops the wind field over the terrain before the ignition time and remains the same (frozen) when the propagation starts. The third mode develops the wind field over the terrain dynamically throughout the whole simulation time, but there is still no actual fire. In the level set mode number 4, the wind field is affected both by the terrain and the fire, by calculating the heat release rate per unit area and coupling the energy equation with the Navier-Stokes solver (McGrattan & Forney, 2004).

Several third-party software is available to help the users create the text document input file for FDS. For wildfire simulation on a large scale, the qgis2fds plug-in from QGIS Desktop (v. 3.30.3) which is a GIS software will be used.

6.2.2. Test case scenarios

The test case scenarios for this study, as presented in TABLE VI, were methodically designed to follow a systematic progression, beginning with the simplest possible scenario and gradually adding more complications. The starting scenario has flat terrain, a single fuel type, and no wind. Subsequent versions gradually introduce one more component at a time, allowing for examination of the software's responses to increasing complexities. In addition, the Rothermel (1972) rate of spread and Anderson (1983) double ellipse fire shape equations were solved manually as direct analytical solutions. The outcomes from the software platforms are compared to the analytical

TABLE VI - List of test case scenarios (Beyki *et al.*, 2025b).

Scenario	Wind (m/s)	Terrain Slope (degree)	Fuel Model
1	0	0	1
2	0	5, 10, 15	1
3	1, 2	0	1
4	1, 2	5, 10, 15	1

results of the equations. This structured methodology allows for a comprehensive investigation of how each program responds to incremental changes in environmental parameters, revealing information on the software's sensitivity and dependability in capturing the dynamics of wildfire behavior under different situations.

The decision to use only one type of fuel in this study is based on the need for a controlled and systematic evaluation of wildfire simulation software. By maintaining the same fuel type in all situations, we can better isolate the effects of other factors such as wind and geography on fire behavior. This deliberate simplicity allows for a more focused assessment of how each program responds to varying environmental conditions while keeping the fuel type constant. Introducing multiple fuel types could add unnecessary complexity, making it challenging to determine whether differences in results are due to variations in the fuel model or other factors. However, exploring the effects of different fuel types could be a valuable topic for future research.

All simulations across different scenarios were consistently conducted over a 10-hour burning period with a mesh size of 25 meters. The choice of a 10-hour burning period is in line with wildfire incident norms, as it captures the average duration of fire incidents. Additionally, a mesh size of 25 meters was selected to reflect the typical grid size used for input data, which includes fuel maps and terrain elevation. This grid size ensures that the simulations are based on realistic and relevant spatial information, thereby enhancing the accuracy and applicability of the results to real-world situations for practitioners.

In this study, simulation results are compared based on four key metrics: the maximum spread length from the ignition point, the head-to-back length of the burnt area, the total burnt area, and the burnt area perimeter, chosen for their significance in capturing various elements of wildfire behavior. The maximum spread length indicates the rate and extent of fire propagation, while the head-to-back length reveals the overall shape and geometry of the burnt area. Additionally, the total burnt area encompasses both intensity and geographic coverage, while the burnt area's perimeter refines our understanding by considering boundary features. Moreover, from a practical and managerial perspective, these parameters are vital for evaluating fire intensity and spatial extent, aiding strategic decision-making in fire

management and mitigation. By comparing these aspects, the study aims to provide insights into how simulation results from different tools influence operational and management choices, improving decision support systems for more informed and adaptive wildfire response and mitigation measures. In addition to the metrics illustrating wildfire behavior, the required run-time for each simulation is a vital component of the results presentation. Recognizing the practical implications for operational and management applications, the time efficiency of the simulation process is crucial. The integration of run-time data is critical for stakeholders and decision-makers who value both the accuracy of simulation and the speed with which these results may be received for timely and adequate decision-making. The variation of runtimes of the software platforms was compared to FireStation's runtime as this platform took less time among all three.

6.2.3. Results – example of scenario 1

Scenario 1 represents the baseline simulation with no wind, flat terrain, and a single fuel type (TABLE VII).

TABLE VII - Scenario 1 simulation results for a 10-hour burning period
 (Beyki *et al.*, 2025b).

Software	Max Spread (m)	Head to Back (m)	Burnt Perimeter (m)	Burnt Area (ha)	Runtime (s)
Analytical	1,080	2,160	6786	366.4	-
FireStation	1,080	2,125	8,073	349.8	1
WFA	1,075	2,122	8,210	332.2	38
FDS	1,059	2,107	6,843	346.1	1090

The results for Scenario 1, which represents the most basic modeling scenario, are almost equal across FS, WFA, and FDS. In theory, under such simplified conditions, the simulation results should be identical. However, small discrepancies in reported metrics can be due to intrinsic measurement errors or computational subtleties within each software. Despite these minor variances, the overall results show a high level of consistency among the three tools in capturing key fire behaviors. Taking

the results from the direct analytical solution as a point of reference, the variation of results is presented in TABLE VIII and Figure 26.

TABLE VIII - Variation % Results of Scenario 1 (Beyki *et al.*, 2025b).

Software	Variation (%) Max Spread	Variation (%) Head to Back	Variation (%) Burnt Perimeter	Variation (%) Burnt Area	Variation (100%) Runtime
FireStation	0.04	-1.6	19	-4.5	-
WFA	-0.4	-1.7	21	-9.3	37
FDS	-1.9	-2.5	0.8	-5.5	1089

Detailed simulation results for the other scenarios is presented and described in the paper (Beyki *et al.*, 2025b).

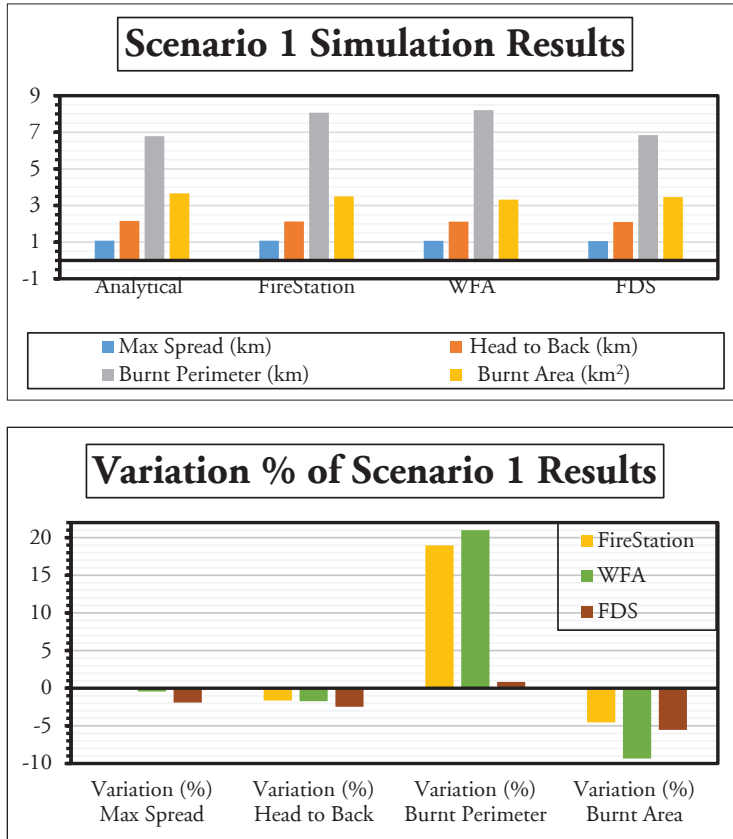


Fig. 26 - Results and their variation of scenario 1 simulations (Beyki *et al.*, 2025b).

6.2.4. Discussion of Results

In the first scenario, simulation results showed that all software tools produced similar results in the simplest case. This validates the foundation models used, emphasizing their ability to deliver consistent findings when simulation complexity is reduced. However, when scenarios expanded to include more elements like slope and wind, the differences in results grew more obvious. Despite close maximum spread values, variances in fire form, as determined by the software's fire shape sub-models, resulted in considerable discrepancies in the final burned area. This underscores the need to consider other indicators in addition to maximum spread when conducting a comprehensive evaluation.

The final scenario, which combined wind and slope parameters, revealed significant variances in results. Although the scenario was relatively basic compared to real-world scenarios, the combination of wind and slope highlighted the complexity and sensitivity of fire behavior models, revealing the software tools' different responses to these interacting aspects. It is worth noting that the findings from scenario 4, done by FDS on level-set 3, were removed owing to unrealistic wind behavior in lateral directions, resulting in turbulence and lateral fire propagation. This demonstrates the limitations of particular setups and the importance of careful analysis when combining specific factors. Additionally, the time required for simulations emerged as a crucial practical consideration. FDS, being significantly time-consuming (hours or days compared to minutes for FireStation and Wildfire Analyst), is more suited for investigative purposes rather than operational decision-making, underscoring the trade-off between accuracy and computational efficiency. Even though all software platforms use the Rothermel surface spread model, significant variations were observed among their results. These differences arise due to several key factors, one of which is the simulation technique employed by each platform.

The first factor to consider is the underlying simulation approach. Wildfire Analyst and FireStation rely on cellular automation (Lopes *et al.*, 2002; Ramirez *et al.*, 2011), a method that divides the landscape into a grid where fire spread is calculated in discrete time steps based on localized conditions. In cellular

automation, the landscape is divided into a grid of individual cells. The fire spreads from one cell to its neighboring cells in discrete steps, with the spread rate determined by local conditions such as wind speed, fuel type, and slope. Since the fire moves in grid-like patterns, the shape of the fire front tends to follow the grid's structure. This is why WFA and FS tend to produce fire fronts that appear more rectangular or blocky, as the spread is constrained by the underlying cell structure. In contrast, platforms like FDS (and FARSITE or BEHAVE) use an elliptical wave propagation method (McGrattan & Forney, 2004). This method models fire spread as an elliptical front, where the rate of spread is calculated continuously in all directions, producing smoother and potentially more accurate simulations of fire behavior over complex terrains. In this method, the fire spreads outwards from a point in all directions, but at different rates depending on the influencing factors like wind and slope. This results in smoother, more natural curves in the fire front. The differing approaches between cellular automation and elliptical wave propagation contribute significantly to the variations in fire behavior predictions across these platforms, despite their shared reliance on the Rothermel model.

The second factor that needs to be considered is the fire shape model used by the different software. WFA and FS both rely on the Anderson (Alexander, 1985; Anderson, 1983) model, whereas FDS uses the Richards (1990) model. These two models differ in how they conceptualize and simulate the shape and spread of fire, which contributes to variations in the results. Anderson's model is based on empirical data, where the dimensions of the fire ellipse are defined as proportions of the maximum fire spread relative to the wind speed at mid-flame height. This provides a simplified but effective way to estimate fire growth in typical conditions. On the other hand, Richards' model uses the concept of wave propagation to create the fire shape. It treats each point along the fire front as a new ignition point for further propagation, allowing for a more sophisticated and dynamic fire behavior simulation. This approach accounts for continuous changes in environmental factors, making it more adaptable to complex fire scenarios.

To delve deeper into the differences in the implementation of the Anderson fire shape model, it's important to note that FS and WFA have taken distinct approaches. In FS, the fire shape is approximated using a 16-point method. Specifically, it

selects 8 points at the head of the fire and 8 points at the back to approximate an elliptical shape (Lopes *et al.*, 2002). This relatively straightforward method gives FS a consistent fire spread shape but can result in fire fronts that appear more angular or pointy, particularly at the head of the fire.

WFA enhances this approach by integrating both 8-direction and 16-direction models, while also introducing a novel 12-direction implementation. In this model, WFA selects 8 points at the head of the fire and 4 points at the back, where 4 of the head points are automatically chosen from the third ring of cells based on the wind direction, which drives the fire's greatest advance (Ramirez *et al.*, 2011). This gives WFA a more refined ability to model fire spread, particularly at the head, where the fire shape more closely follows the natural wind-driven propagation but also makes the backing fire size smaller compared to other methods. As a result, the fire shapes in FS tend to be more pointed, while WFA produces a less pointy head and a shorter backing fire. These differences in fire shape models and the ellipse simplification methods are the reason that the fire shapes attained from software platforms differ as demonstrated, which correlates to the fire shapes produced by FS being the most pointy and rectangular, WFA rectangular but less pointy, and FDS with smooth curves. This can also explain the underestimation of the fire area from FS and WFA compared to the analytical solution and bigger areas from FDS, as the ellipse approximation leaves out some part of the ellipse area created from Anderson's model. In scenario 2 for instance, the burnt area obtained on 5° slope from WFA is the smallest (-11.6%), followed by FS (-7.6%) and then FDS (64.6%), in which negative variation meaning the simulated areas are smaller than the analytical solution. In the following cases of 10° and 15° slopes, the burnt area obtained from WFA continues to be the smallest with the highest negative variation values (-31.71% on 10° and -44.64% on 15° slope), due to the smaller backing fire size, followed by FS with smaller negative values due to ellipse approximation (-7.09% on 10° and -15.20% on 15° slope), and FDS with positive values which shows bigger burned areas (42.31% on 10° and 25.64% on 15° slope).

The FDS simulations seem to exhibit a more circular fire spread pattern compared to the analytical solution, suggesting that its fire shape model has a lower length-to-breadth ratio than the analytical solution. This implies that while

the head-to-back distance in FDS may be like or even shorter than the analytical prediction, the lateral spread is greater. As a result, FDS often overestimates the total burned area, as the fire spreads more uniformly in all directions rather than forming the elongated elliptical shape typically anticipated in wildfire propagation models. This explains the significantly larger simulated fire area from FDS in contrast to the analytical solutions.

The third factor contributing to the variation in results among the three software platforms is the application of wind models. WFA employs the simplest approach, which interprets the provided wind characteristics—whether sourced from a forecasting organization or manually input—as representing wind speed at open ground, typically measured 20 feet (6.1 m) above the surface. WFA then applies the correction factor proposed by the Rothermel (1972) model (0.4) to adjust this open-ground wind speed to the mid-flame height wind speed, which is used for solving surface fire spread.

FireStation, on the other hand, takes a more sophisticated approach. It reads wind inputs as points within the grid, typically simulating weather station readings that include wind speed, direction, and the height at which the reading was taken. It then offers two methods for solving the wind field across the grid: NUATMOS and CANYON. After calculating the wind field, each point on the grid receives a unique wind vector, meaning that wind speed and direction vary across the landscape, accounting for local influences like terrain and topography.

FDS offers four different methods for applying wind, though only level sets 1 and 3 were used in this study. In level set 1, FDS creates a uniform wind field across the grid, similar to WFA, where the wind is applied uniformly without accounting for terrain effects on the wind field. In contrast, model 3 solves the Navier-Stokes equations over the grid, allowing it to incorporate the effects of terrain on wind behavior, resulting in varying wind vectors across the grid, similar to FS's method.

Thus, two main methods of wind application emerge among the software: a constant wind applied uniformly across the grid, used by WFA and FDS level set 1, and a more complex wind field calculation where unique wind vectors are applied to each grid point, used by FS and FDS level set 3. These differences in the wind models make direct comparisons of the results challenging. As shown in Scenario

3, FDS Level Set 3 produced the closest results for maximum fire spread, with a variation of 0.39% for a 1 m/s wind and -11.20% for a 2 m/s wind, followed by FDS Level Set 1, which showed a variation of -5.15% for 1 m/s and -12.62% for 2 m/s. WFA came in third, with a difference of -7.86% for 1 m/s and -14.57% for 2 m/s, while FireStation (FS) had the largest variation at -9.62% for 1 m/s and -17.50% for 2 m/s wind. However, when comparing the burnt area based on the final fire shapes simulated by each platform, the trend follows that of scenario 2. WFA resulted in the smallest area variation from the analytical solution, with -20.07% for 1 m/s and -42.33% for 2 m/s wind. FS followed closely, showing a variation of -20.47% for 1 m/s and -33.05% for 2 m/s. FDS Level Set 1, in contrast, produced much larger area variations, with 33.56% for 1 m/s and 3.34% for 2 m/s wind. Finally, FDS Level Set 3 had the largest area variation, with 45.73% for 1 m/s and 6.28% for 2 m/s wind. These discrepancies highlight how differences in wind modeling among the software significantly impact both the fire spread and burnt area predictions.

When the results for Scenario 4 from FDS using Level Set 3 were obtained, significant differences in the simulation of the fire front and fire shape were observed. Due to the drastic deviations from expected behavior, these results were removed from the study to maintain the integrity of the comparison. Upon investigating the cause of the issue, it was found that the wind field developed unusual behavior over the terrain in the lateral direction, leading to inaccuracies in fire spread modeling.

FDS employs rectangular mesh grids, representing geometry with structured Cartesian grids. This method approximates the terrain using stacked horizontal layers, where each elevation change is limited by the set grid resolution. The text command for the simulation was prepared using the “qgis2fds” add-in from the QGIS software, which converts terrain into discrete elevation blocks. The size of these steps depends on the cell size of the input data, which in this study was set to 25 meters—consistent with the available data for fuel maps and elevation models. For consistency, the mesh size across all platforms was also set to 25 meters. However, when FDS simulates Scenario 4 using Level Set 3, which incorporates the interaction between the wind field and the terrain, these

simplified steps on the sloped ground introduced problems. Specifically, the stepped representation of the terrain created circulations that moved laterally to the wind direction, causing wind vectors to increase in the lateral direction rather than flowing predominantly upslope. As a result, the fire spread more laterally than upslope, shifting the head of the fire to the direction perpendicular to the slope. This abnormal fire behavior significantly altered the fire shape and front, leading to unreliable results.

This outcome from the FDS simulation could be a subject for further investigation. The interaction between wind and terrain, particularly when terrain is simplified into steps that are the same size as the simulation mesh, raises important questions. The “step effect”, where simplified terrain creates wind circulations, may influence fire behavior in ways that require deeper exploration, especially when the grid resolution is coarse enough to rough out the terrain details.

The effects of each sub-model or method used in different software platforms can significantly influence the outcomes of specific simulations, and this is an essential consideration for any practitioner working with such tools. First and foremost, practitioners should be thoroughly familiar with the specific tool they are using, including its sub-models and methods. A solid understanding of these components can help reduce errors or biases that may impact real-life operations.

Second, it is crucial for users to understand the range of effects these sub-models can have on the results. This knowledge allows for better judgment and more effective decision-making in wildfire management or simulation tasks. This study demonstrated the impact of different sub-models and methods incorporated in three software platforms, all of which use the same surface propagation model. A user not fully aware of these subtle differences might assume that the tools will produce the same results with identical inputs, but this study showed that this is not the case.

However, this research has its limitations due to insufficient resources and time constraints, and there remain many topics within this scope that could be explored in future studies. The effects of adjacent fuels, different wind directions relative to slope, variations in fuel moisture content, and the sensitivity of each factor on the final result could all be interesting subjects for further investigation in this field.

6.3. Wildfire Simulation Using Satellite Data and Rate of Spread Adjustment

6.3.1. Introduction

Wildfire simulators are fire behavior prediction tools that can be used to manage and fight fires. However, many factors affect the accuracy of these simulations and the results are prone to uncertainties. Satellite active fire data presents the spread of fire near real-time and is a cost-effective way to assess and analyze the accuracy of simulations. In this chapter is discussed the use of Visible Infrared Imager Radiometer Suite (VIIRS) active fire data to adjust the simulated fire rate of spread using the Wildfire Analyst (WFA) through the simulation reinitialization method in real time. This method proposes to simulate the fire for 12-hour intervals aligned with the VIIRS data production and adjust the rate of spread based on the provided satellite data. To reduce the arrival time discrepancy between the simulated fire and a series of satellite active fire data control points where the arrival time of the detected fire is known, the software automatically calculates the fire rate of spread adjustment factors for each fuel model based on the satellite control points. Five case studies in Portugal show promising results in reducing error and matching the simulated fire rate of spread to the actual fire spread. This led to more accurate fire spread simulations during subsequent burning periods, despite some limitations related to satellite active fire data for fire detection and monitoring. The discrepancies between adjusted and unadjusted simulated rates of spread and satellite data hotspots' rate of spread are analyzed. Results show significant decreases in adjusted simulation errors as well as an increase in the accuracy of the following simulations based on previous interval adjustments. The parallel utilization of reinitialization and rate of spread adjustment shows great potential in optimizing simulations. It can be used as a cost-effective approach in real-life incidents for battling and managing fires to increase the accuracy of operation, resource allocation, and decision-making in real-time.

6.3.2. Methods

Methodology Overview - The methodology employed in this study integrates satellite active fire data into wildfire simulation models to enhance their accuracy and reliability. A baseline simulation is initially conducted using a standard wildfire spread model (Rothermel), which estimates fire ROS. To improve the accuracy of these simulations, a reinitialization approach is applied at fixed 12-hour intervals, aligning the modeled fire perimeter with the observed fire spread from satellite data.

In wildfire simulations, the accumulation of errors refers to the compounding of small inaccuracies in fire spread predictions over time, which can lead to significant deviations from actual fire behavior in longer simulations. These errors often stem from uncertainties in input data (e.g., wind, fuel conditions), simplifications in the model, and unpredictable changes in fire dynamics. As the simulation progresses, these small discrepancies accumulate, reducing the reliability of the forecast. To mitigate this issue, the method used in this study reinitializes the simulation every 12 hours using updated VIIRS active fire detections. By restarting the model at regular intervals with fresh satellite data, the simulation is corrected and realigned with the observed fire front, preventing the propagation of earlier errors. This interval-based reinitialization approach enhances the temporal accuracy of predictions and maintains consistency with the evolving fire conditions.

In addition to periodic reinitialization, the methodology incorporates a dynamic ROS adjustment mechanism. The ROS from the baseline simulation is compared against the actual fire spread recorded in the satellite data, and a correction factor is derived for each 12-hour interval. This correction factor is then applied to the subsequent simulation step to minimize discrepancies between the modeled and observed fire behavior. Figure 27 shows the flow chart illustrating how the work is conducted. By iteratively refining the fire spread predictions, this approach allows for continuous simulation calibration, ensuring greater accuracy in wildfire modeling.

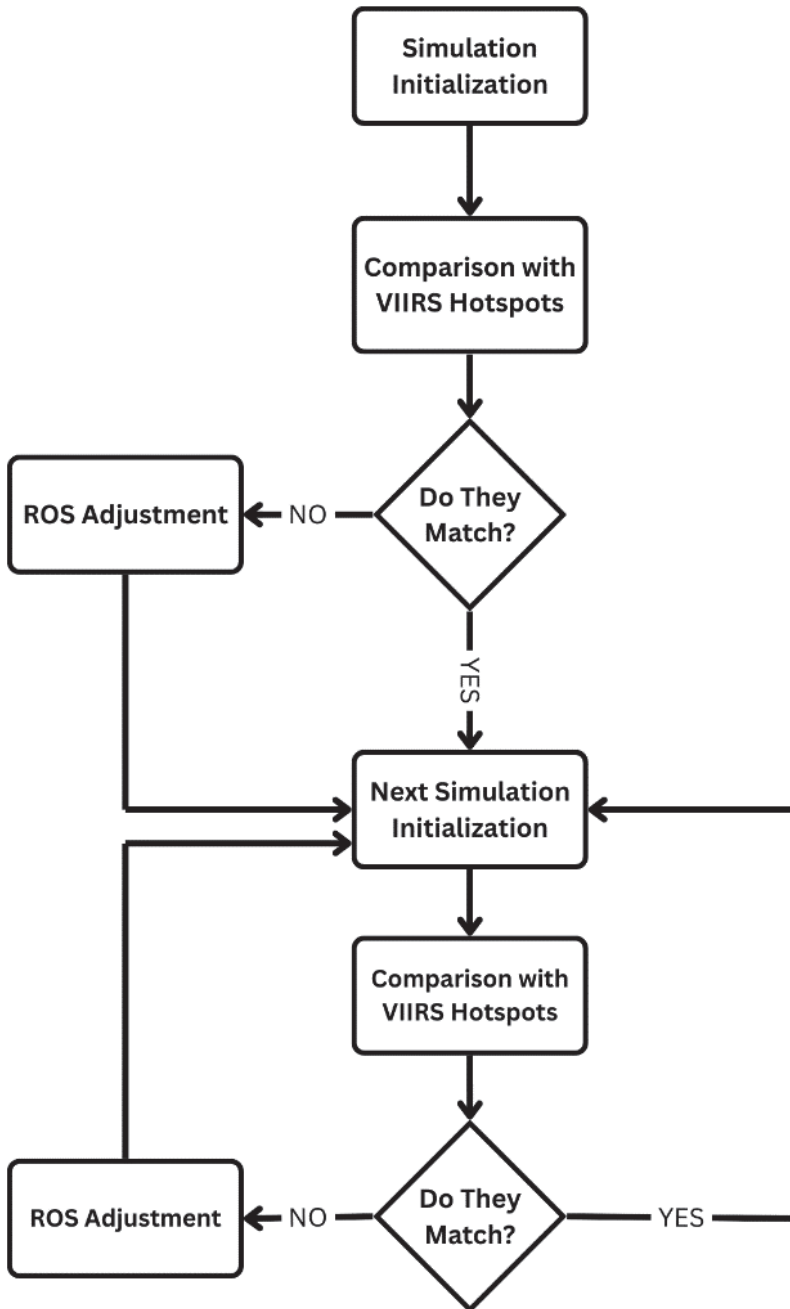


Fig. 27 - Methodology Overview, representing study workflow diagram (Beyki *et al.*, 2025a).

Rate of Spread Adjustment - Various sources of uncertainty, such as spotting, active crown fire runs, inaccurate input data, model restrictions and assumptions, or a lack of local-scale fire model calibration, might cause variations between the simulated and real fire behavior (Albini, 1976; and Cruz, 2013). As previously outlined, the ROS adjustment was proposed (Finney, 1998; Rothermel and Rinehart, 1983) to improve the accuracy of forecasts. However, they are time-consuming, manually calculated algorithms that are prone to error and challenging to utilize in cases of emergency. WFA can adjust simulated fire growth automatically to match actual fire progression. It uses a data assimilation method that quickly matches observed fire behavior with results from the simulation models (Cardil, *et al.*, 2019). To do that, WFA requires control points or lines where the actual fire's arrival time is known as adjustment input data (these control points will be sourced from EO in this study). Then, using a least squares technique, the method determines the ideal ROS adjustment factors. The adjustment factor will be multiplied by the original ROS of each fuel model to reduce the difference between the simulated and real fire arrival time (Cardil, *et al.*, 2019; Rothermel & Rinehart, 1983). The adjustment factor is unique to each fuel model, meaning a factor is calculated for each fuel model and is specific only to that model. The calculated adjustment factors will also be applied to fuel models for the next simulations.

Mathematically, the method finds the best adjustment factor for the fuel j () by minimizing the following function:

$$\|t_i - T_{ij}\alpha_j\|^2 + \lambda^{-1}\|1 - \alpha_j\|^2$$

Where $\|-\|$ is the Euclidean length, T_{ij} is the residence time of the fire on fuel type j on the i^{th} control path (the linking curve between ignition source to the control points and perpendicular to the fire propagation isochrones), $\alpha_j = 1/Adj_j$ and T_j is the actual arrival time on the i^{th} control point. $0 < \lambda < 1$ is manual strength modification and can be selected by the operator, where lower values (closer to 1) decrease the algorithm strength and the arrival time differences are higher but more realistic (Cardil *et al.*, 2019).

With its non-recursive nature and near-immediate solution, this approach provides fire managers with an easy-to-understand means of interpreting operational

alterations with few input requirements (Cardil *et al.*, 2019). This allows WFA to provide more accurate and reliable results for future simulations utilizing ROS adjustment factors.

Using Satellite Hotspot Data for Simulation Reinitialization and ROS Adjustment Control Points

- As mentioned above, the control points where the actual location and arrival time of fire are known are required as input for the ROS adjustment algorithm. Nevertheless, these control points were mostly obtained through ground or aerial operation, and getting reliable data, especially in inaccessible regions, was challenging. Satellite data is beneficial in assessing wildfires in remote locations or in situations where fire monitoring is inconsistent or scarce (Benali *et al.*, 2016). So, this EO product will be used to provide control points for ROS adjustments. In addition, the accumulation of errors is minimized by separating the duration of the simulation into segments and reinitializing them with each data production after the satellite overpass. The temporal and spatial evolution monitoring and assessment of wildfires for this study were obtained from VIIRS 375 m active fire data, which has proven effective in detecting wildfires across various geographic regions (Schroeder *et al.*, 2014). The detection algorithm of VIIRS is based on the MODIS Fire and Thermal Anomalies product, which can identify both day and nighttime fires and other thermal anomalies (Schroeder *et al.*, 2014). The 375 m spatial and 12-hour temporal resolution of VIIRS fire data offers enhanced capabilities for detecting smaller fires and shorter in duration, accurately capturing fire front evolution, and reducing time requirements compared to the 24-hour temporal resolution of MODIS data (Anderson *et al.*, 2009).

Simulation Software and Configurations - The fire spread simulations were conducted using WFA (version 2.9) (Ramirez *et al.*, 2011) software. WFA, developed by Technosylva, prioritizes real-time or field operation simulation. It offers maximum flexibility for predefined scenarios, integrating fuel maps, vegetation, and weather data directly from the platform which is based on ArcGIS™ (Ramirez *et al.*, 2011). The software utilizes Rothermel's model (Rothermel, 1972) with Albini's modifications (Albini, 1976) and includes fuel models such as Scott and Burgan

(Scott and Burgan, 2005), with options for custom models. The adjustment tool was used to adjust the ROS based on the satellite data observations to better match the simulation ROS with the actual fire. For wind field simulation, WFA integrates WindNinja, utilizing Forthofer's 2D high-resolution wind model (Forthofer, 2007; Forthofer *et al.*, 2014) coupled with surface temperature.

The software configurations for the simulations are as follows: The Rothermel (Rothermel, 1972) model was used for fire spread, dead fuel moisture was estimated using Nelson's equation (Nelson Jr, 2000), and the wind field was calculated using the WindNinja feature. The Rothermel and Albini 10-fuel family model (Albini, 1976; Rothermel, 1972) was used. The weather data was incorporated through the weather reconstruction feature, inputting wind speed and direction, temperature, and relative humidity every 1 hour. The satellite hotspot data were imported into the software through its ArcGISTM platform as shapefiles for each 12-hour interval. After the simulation of the first interval, the control points (hotspots) were introduced to the adjustment algorithm by selecting the hotspot points on the map and specifying the fire's arrival time. The manual strength modification (tuning strength, λ) is at the default value of 0.2. The calculated adjustment factor was applied to the fuel models for the next interval simulations.

To use the proposed methods for this study, the simulations are conducted in the following steps: 1) The total fire duration is segmented into 12-hour intervals aligned with satellite data. 2) The simulation is initialized for 12 hours. 3) The simulation ROS is adjusted based on satellite data. 4) The adjustment factors are applied to the fuel models. 5) The simulation is reinitialized for another 12 hours. 6) The simulation would be adjusted if required. 7) Conduct steps 2 through 6 until the end of the burning period.

Input Data - The fuel map was provided by the Registo Nacional de Dados Geográficos do Sistema Nacional de Informação Geográfica (National Geographic Information System) (Instituto Da Conservação Da Natureza e Das Florestas. (n.d.). Geoportal: Catalog of the ICNF. <https://Geocatalogo.Icnf.Pt/Catalogo.Html>, n.d.) as a single shapefile, that was incorporated into WFA through its ArcMap (version 10.8.1) platform. This land cover map consists of 10 fuel-family with a resolution of

25 meters. The digital elevation model was provided by Copernicus (“Copernicus DEM,” 2022) with a resolution of 30 meters as a single raster file that was also set through ArcGIS into WFA. The weather data was provided by Instituto Português do Mar e da Atmosfera (Portuguese Institute for Sea and Atmosphere). The hotspots data was obtained from NASA’s FIRM website by downloading VIIRS S-NPP 375m satellite active fire data archive, for the country of Portugal and the dates of fires (NASA MODIS Fire Information for Resource Management System. (n.d.). FIRMS: Fire Information for Resource Management (<https://Firms.Modaps.Eosdis.Nasa.Gov/Download/>, n.d.). The hotspots were downloaded using the provided link in the archive download. The hotspots are provided in shapefile format. Each data point has an attribute table including information related to that spot, including reading time, fire radiative power (FRP), latitude, and longitude. The hotspots were filtered and categorized using ArcGIS Pro (version 3.2.1) according to their detection time, allowing for the distinction of each 12-hour interval, as well as their Fire Radiative Power (FRP) and geographical location to align with the case studies. Hotspots with an FRP lower than 1 megawatt were excluded as they are likely to be false readings or indicate very low-intensity fires that are unlikely to contribute to fire progression. The criterion for the hotspot locations was based on the area of the burned scar plus a 5 km buffer. The ignition time and point are set to the first hotspot readings.

Case Study - Five wildland fires in Portugal were chosen as case studies to analyze the “Reinitialization with the ROS Adjustment” approach. These fires have different sizes, duration, and associated fuel types. The summer of 2022 was a critical period with many wildfire incidents in Portugal. Five of these incidents were chosen for the purpose of this study. The location, shape, and size of each fire are illustrated in Figure 28. The image illustrates the geographical locations of the five case studies across Portugal and displays the corresponding satellite active fire data for each site. The central map marks the positions of Samarda, Vila Real, Linhares, Loivos, and Landal on the Portuguese map. Surrounding the central map are detailed insets for each location, showing the burnt areas and active fire hotspots detected by the satellite. Each inset includes a color-coded legend representing the interval of hotspots detected at different times, providing a visual representation of

the fire's progression. This layout effectively integrates spatial and temporal data, highlighting the extent of the fires and their specific locations within the country.

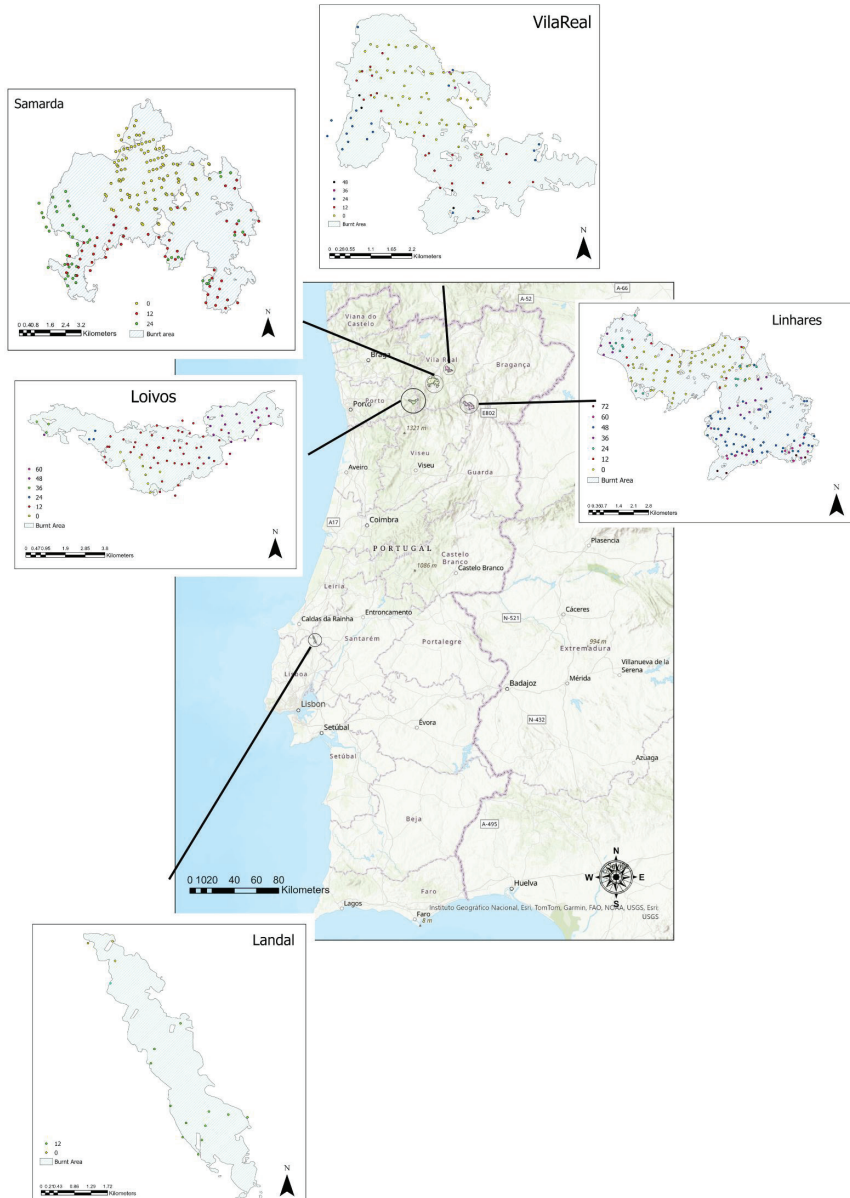


Fig. 28 - Location of case studies and the satellite active fire data related to them (Beyki *et al.*, 2025a).

The characteristics of each fire, such as burnt area, duration, and associated weather station are presented in TABLE IX. Note that the fire duration refers to periods that significant and observable fire spread was detectable by satellite data, and the actual fire duration from the ignition to complete extinction could be longer.

TABLE IX - Description of fire case studies (Beyki *et al.*, 2025a).

Name of the Fire	Burnt area (ha)	Duration (hours)	Satellite Overpasses	Associated Weather Station
Landal	614	12	2	Rio Maior
Samarda	5668	24	3	Aldeia do Souto / Quinta Lageosa
Vila Real	1638	48	5	Vila Real
Loivos	1692	60	6	Carrazeda de Ansiães
Linhares	3330	72	7	Mirandela

Obtaining Results, Error Metrics, and Statistical Analysis - The impact of fire suppression, which typically focuses on the flanks where fire intensity is lower and containment is more achievable, has a direct effect on the final burnt area and perimeter. However, the effects of suppression are neglected in simulations, and the simulated burnt areas are larger than reality. Consequently, the final burnt area of fires is not an appropriate basis to assess the efficacy of the method. To eliminate this bias and ensure a fair evaluation, we compared the ROS at the head of the fire (i.e., Max ROS). The fire intensity is highest at the head, and its spread is unaffected by suppression activity. Therefore, the Max ROS from satellite data, which represents the real fire behavior, is compared to the unadjusted and adjusted simulation Max ROS.

A range of analytical metrics was employed to assess the outcomes of the simulations. These statistical measures are used to assess the accuracy of a predictive model in similar works (Cardil *et al.*, 2023; Cruz *et al.*, 2018). Mean absolute error (MAE), mean bias error (MBE), MAPE, and MBPE which is the ratio between the MBE and MAE are used to analyze the results. MAE, MBE, MAPE, and MBPE were chosen as evaluation metrics for their ability to assess the accuracy and reliability of ROS adjustments in our wildfire simulations. MAE measures the average magnitude of errors, addressing both overestimations and underestimations. MBE reveals the model's directional bias, indicating whether it overpredicts or

underpredicts fire spread. MAPE and MBPE normalize errors relative to actual fire spread, allowing for percentage-based comparisons across case studies with varying fire sizes and conditions.

Although MAPE can be sensitive to small denominator values, this was not an issue in our dataset, as all case studies involved significant fire spread. Thus, the denominator remained within a reasonable range. To ensure a complete evaluation, we combined MAPE with MAE, MBE, and MBPE, which provide robust assessments without the influence of small-ROS issues. This approach strengthens the reliability of our findings and accurately reflects the improvements from the ROS adjustment method.

Statistical analyses were conducted to evaluate the reliability and impact of the proposed method. Significance (p-value) was used to determine whether the differences between unadjusted and adjusted simulations were statistically meaningful, with a threshold of $p < 0.05$ indicating that improvements were unlikely due to chance. Effect size (Cohen's d) measured the magnitude of these differences, ensuring that any observed improvements were not only statistically significant but also practically relevant. Finally, confidence intervals (CI) provided a range within which the true effect likely falls, offering insight into the precision and reliability of the results

6.3.3 Results and discussion

Case Study Results - This section outlines the preliminary results of the case study. The satellite rate of spread ROS is derived using the ArcGIS measurement tool. By measuring the maximum distance from the ignition point to the head of the fire and dividing this distance by the burning duration—which corresponds to the satellite overpass interval of 12 hours—we can calculate the actual ROS. The simulated ROS from the WFA is compared against these values. Additionally, both the adjusted and unadjusted simulations' ROS are measured from the ignition point to the head of the fire using the ArcGIS measurement tool. TABLE X presents the preliminary results derived from satellite active fire data and simulations.

TABLE X - ROS derived from satellite Active Fire Data vs. Unadjusted and Adjusted Simulation ROS (Beyki *et al.*, 2025a).

Fire Location	Satellite ROS (m/min)	Unadjusted Simulation ROS (m/min)	Adjusted Simulation ROS (m/min)
Landal	8.87	7.43	8.33
Samarda	7.91	13.19	7.78
Linhares	2.47	3.07	2.85
Vila Real	3.74	7	3.9
Loivos	3.6	5.46	3.78

The results will be analyzed in the next sections using error measures and statistical analysis to provide insights into the improvements and significance of the proposed method.

Interval Simulation Reinitialization Results - TABLE XI presents the error statistics of the simulation using only the interval reinitialization. Results show MAE ranging from 1.44 to 5.28 (m/min). The smallest absolute magnitude of the ROS error is 1.44 m/min for the fire of Landal, which is the shortest in duration and smallest in size. But as the fire duration gets longer, the magnitude of error becomes larger. This is due to the accumulation of errors, which refers to the progressive build-up of small inaccuracies in predicted fire spread over time. In wildfire simulations, even slight deviations in predicted rate of spread, wind direction, or fuel behavior can compound with each simulation step, leading to increasingly inaccurate predictions the longer the simulation runs without correction. For the fire of Samarda, which has the biggest burnt area in a relatively short period (fast-moving fire), the error magnitude is the highest among case studies with 5.28 (m/min), highlighting how both fire duration and rapid spread contribute to greater accumulated errors when left uncorrected.

TABLE XI - Error statistics derived from unadjusted reinitialized simulations (Beyki *et al.*, 2025a).

Fire Location	MAE (m/min)	MBE (m/min)	MAPE (%)	MBPE (%)
Samarda	5.28	5.28	64.4	64.4
Linhares	2.267	0.607	108.01	52.275
Vila Real	3.25	3.25	96.35	96.35
Loivos	2.07	1.85	72.2	66.35
Landal	1.44	-1.44	16.23	-16.23

On the other hand, MBE shows better values in some cases. The closer the MAE or MBE is to zero, the better the concordance with satellite data. This indicates that the overestimation in some intervals is canceled out by underestimation in other intervals and vice versa. So that the overall result of a simulation is closer to that of reality. For instance, the case of Linhares has MAPE of 108% whereas the MBPE is almost half of that at 52.27%. Also, the positive MBEs show more overestimation of simulations rather than underestimation.

Simulation Interval Reinitialization with ROS Adjustment Results - The error statistics from adjusted reinitialized simulations show great improvement, which shows the effectiveness of this approach. TABLE XII presents the error statistics derived from adjusted reinitialized simulations.

TABLE XII - Error statistics derived from adjusted reinitialized simulations.

Fire Location	MAE (m/min)	MBE (m/min)	MAPE (%)	MBPE (%)
Samarda	1.415	-0.125	18.2	2
Linhares	0.566	0.386	27.17	18.87
Vila Real	0.44	0.205	13.67	5.125
Loivos	0.175	0.175	4.85	4.85
Landal	0.54	-0.54	6.08	-6.08

For instance, the MAE for Samarda decreased significantly from 5.28 (m/min) in the unadjusted simulations to 1.415 (m/min) in the adjusted ones. Similarly, the MBE dropped from 5.28 (m/min) to -0.125 (m/min), indicating a substantial reduction in the bias of the simulation results. The MAPE for Samarda improved from 64.4% to 18.2%, and the MBPE decreased from 64.4% down to 2%, showcasing a more accurate representation of the fire's progression. In the case of other locations, the adjusted simulations also show enhancements. For Linhares, the MAE reduced from 2.267 (m/min) to 0.566 (m/min), and the MAPE dropped from 108.01% to 27.17%. The reduction in error metrics across all locations indicates that the reinitialization method, combined with the ROS adjustments based on satellite data, enhances the reliability and accuracy of wildfire simulations. These improvements highlight the method's capability to provide more accurate

and actionable data for wildfire management, making it a valuable tool for fire analysts and decision-makers.

Comparison of Results - Even though the reinitialization method has shown to be effective in avoiding accumulated errors by segmenting the whole fire duration into 12-hour intervals and restarting the simulation (Cardil, *et al.*, 2019), discrepancies persist between the simulated ROS and the actual ROS obtained from satellite data. However, the parallel utilization of reinitialization and ROS adjustment substantially improves the overall accuracy of simulations. Figure 2 shows the fire propagation simulation of the Vila Real fire only as an example to visually compare the results from the unadjusted and adjusted ROS simulations. The focus of this work is not on the burnt area or perimeter, but rather on the head fire rate of spread, as previously outlined.

Each color gradient represents the burnt area obtained from a simulation reinitialization interval equal to 12 hours. The total burning duration (48 hours for this case) was segmented into 4 intervals, and after simulation initialization, each interval was adjusted using satellite data and then reinitialized for another 12 hours. This was done in a loop until the end of the burning period. The fire propagation patterns from the unadjusted simulations (left) show overestimation in all simulation intervals. Even though the results after the adjustment still show overestimation, the utilization of the proposed approach shows a meaningful reduction in the simulation error, as can be seen in the fire propagation patterns (right) with adjusted ROS in Figure 29. In this figure, the black outer line represents the actual fire-burnt perimeter.

The ROS discrepancies between the simulation and satellite data decrease significantly at each interval after adjusting the ROS. The graphs in Figure 30 provide a comparative analysis of the ROS for the Vila Real case study over simulation intervals. The left graph illustrates the ROS obtained from satellite data alongside the unadjusted and adjusted simulation ROS for each interval. Initially, the unadjusted simulation significantly overestimates the ROS compared to the satellite data, showing a notable decline after the first interval. Conversely, the adjusted simulation closely aligns with the satellite ROS, reflecting the effectiveness of the

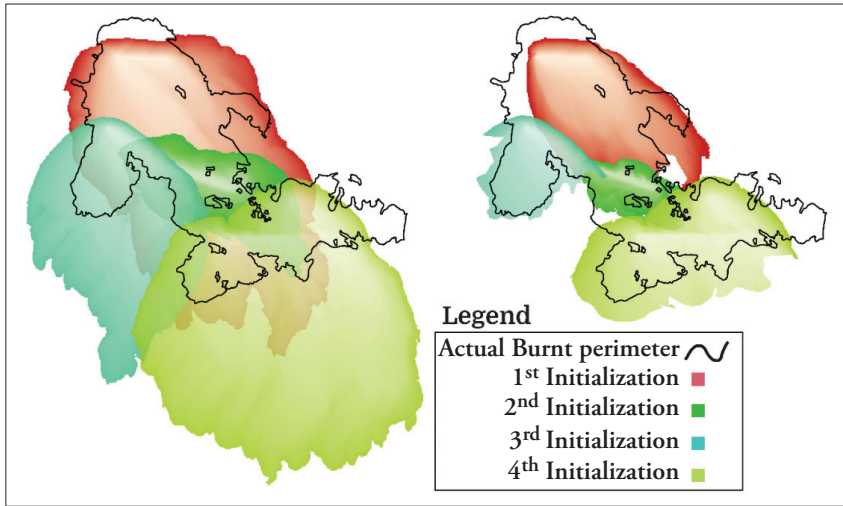


Fig. 29 - Fire Propagation Simulation of Vila Real Case Study; (left) simulation using only reinitialization without ROS adjustment, (right) simulation with reinitialization and ROS adjustment. The total burnt period (48 hours for this case) was segmented into 12-hour intervals, aligned with satellite data production. The fire was simulated for 1 interval, adjusted based on satellite data, and then reinitialized for another 12 hours. Each color gradient represents a simulation interval as specified in the legend and the black outer line is the actual burnt area (Beyki *et al.*, 2025a).

proposed adjustment method. The right graph depicts the ROS error percentage for both unadjusted and adjusted simulations relative to the satellite data for each reinitialization interval. The unadjusted simulation shows a substantial error of around 50% on average, with the highest discrepancy in the third interval, which is significantly reduced in the adjusted simulation down to below 10%.

TABLE XIII compares the performance of unadjusted and adjusted fire spread simulations based on four key metrics for five fire cases. Across all cases, the adjusted simulations demonstrate a significant improvement in accuracy over the unadjusted simulations. In the Samarda fire, the MAE decreased from 5.28 m/min (unadjusted) to 1.415 m/min (adjusted), while the MAPE dropped dramatically from 64.4% to 18.2%. Similar trends are observed for the Linhares fire, where the MAE reduced from 2.267 m/min to 0.566 m/min, and the MAPE decreased from 108.01% to 27.17%. In the Vila Real case, the adjusted simulation substantially reduced MAE (from 3.25 m/min to 0.44 m/min) and MAPE (from 96.35% to

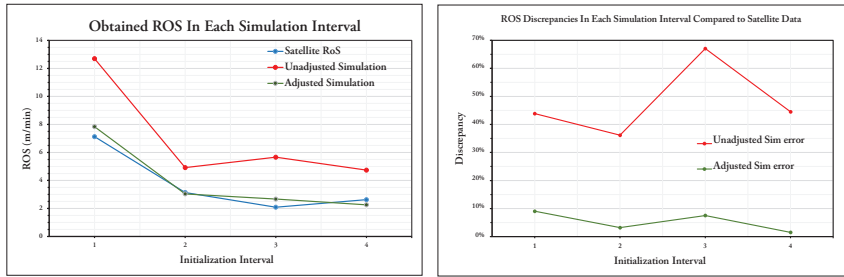


Fig. 30 - ROS obtained from satellite data, unadjusted simulation, and adjusted simulation of each interval for the fire of Vila Real (left); ROS error of unadjusted and adjusted simulation compared to satellite data for each interval (right).

The horizontal axis represents the number of initialization intervals, each equal to 12 hours (Beyki *et al.*, 2025a)

13.67%). Likewise, Loivos saw the MAE fall from 2.07 m/min to 0.175 m/min, and the MAPE dropped from 72.2% to 4.85%. Lastly, for the Landal fire, while the MAE increased slightly (from 1.44 m/min to 0.54 m/min), the MAPE decreased from 16.23% to 6.08%.

TABLE XIII - Statistical metrics for Interval Initialization simulation of wildfire case study with and without ROS adjustment (Beyki *et al.*, 2025a).

Fire	Method	MAE (m/min)	MBE (m/min)	MAPE (%)	MBPE (%)
Samarda	Unadjusted	5.28	5.28	64.4	64.4
	Adjusted	1.415	-0.125	18.2	2
Linhares	Unadjusted	2.267	0.607	108.01	52.275
	Adjusted	0.566	0.386	27.17	18.87
Vila Real	Unadjusted	3.25	3.25	96.35	96.35
	Adjusted	0.44	0.205	13.67	5.125
Loivos	Unadjusted	2.07	1.85	72.2	66.35
	Adjusted	0.175	0.175	4.85	4.85
Landal	Unadjusted	1.44	-1.44	16.23	-16.23
	Adjusted	0.54	-0.54	6.08	-6.08

Figure 31 presents the error statistics charts, clearly comparing the effects of reinitialization and the ROS adjustment approach on wildfire simulation accuracy. The results demonstrate improvement in accuracy across all metrics in the case study after employing this method.

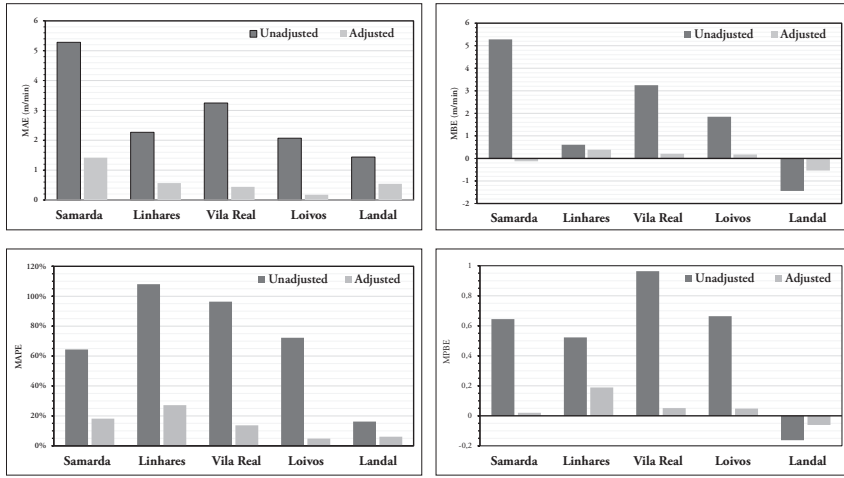


Fig. 31 - Error statistics of wildfire simulations utilizing reinitialization approach with unadjusted and adjusted ROS for 5 case studies (Beyki *et al.*, 2025a).

The MAPE values for the unadjusted simulations in this study range from 16.23% to 108.01%, with higher errors observed in cases such as Linhares (108.01%) and Vila Real (96.35%). After applying the adjustment method, MAPE values significantly decreased, ranging from 2% to 13.67%, demonstrating a notable improvement in the accuracy of ROS predictions.

Compared to previous studies, Cruz *et al.* (2018) reported MAPE values between 42% and 124% for the original models and 40% to 120% for improved versions of those models, indicating that even their improved models still exhibited relatively high errors. Furthermore, the MAPE reported for the Rothermel model in their study ranged from 49% to 76%, which is substantially higher than the adjusted MAPE values obtained in this study.

Similarly, Cardil *et al.* (2023) reported MAPE values between 26% and 67% for operational fire spread models in California. While some of the unadjusted MAPE values in this study (e.g., Linhares at 108.01%) exceed this range, all adjusted values (2% to 13.67%) are considerably lower, highlighting the effectiveness of the adjustment approach used here. Overall, the adjusted simulations in this study demonstrate improved accuracy in predicting ROS compared to the works of both

Cruz *et al.* (2018) and Cardil *et al.* (2023). The significant reduction in MAPE after adjustment suggests that the applied correction method enhances fire spread predictions beyond the performance of previously studied models.

Statistical Analysis - A statistical analysis was performed to assess the accuracy of wildfire simulations across different case studies. TABLE XIV presents results on statistical assumptions, p-values, confidence intervals, and effect sizes to determine the significance of the proposed method. Normality and homogeneity of variance tests showed that most error distributions deviated from normality (Shapiro-Wilk p-values < 0.05), and variances were unequal (Levene’s test), supporting the use of non-parametric methods. The Wilcoxon signed-rank test revealed statistically significant differences (p-values < 0.05) between unadjusted and adjusted simulations, confirming that the ROS adjustment improved model accuracy. Confidence intervals further validated these improvements by demonstrating reliable reductions in prediction error.

TABLE XIV - Statistical Analysis of the results (Beyki *et al.*, 2025a).

Case Study	Adjustment Impact	Significance (p-value)	Effect Size (d)	Confidence Interval
Landal	Not enough data	N/A	N/A	N/A
Samarda	No significant difference	0.5 (Wilcoxon)	N/A	N/A
Linhares	Significant improvement	0.0018 (t-test)	Large (2.63)	(0.27, 0.51)
Vila Real	Significant improvement	0.0059 (t-test)	Large (4.36)	(0.23, 0.62)
Loivos	Significant improvement	0.0669 (t-test)	Large (1.94)	(-0.04, 0.67)

Effect sizes, calculated using Cohen’s d, indicated moderate to large effects in most cases, reinforcing the meaningful impact of the proposed method on simulation accuracy. These results highlight the importance of refining fire spread modeling techniques to improve predictive reliability.

Practical Implications - To effectively manage wildfires—whether it be suppressing the fire, deciding whether to evacuate an area or allocating resources to various fire flanks—fire analysts must continuously assess and monitor wildfire

behavior and spread through simulations. Given that decision-makers often base their actions on the outcomes of these simulations, it is crucial to reduce the discrepancies between predicted and actual fire behavior. Time is of the essence in these situations, as fire management tactics and strategies typically hinge on the results of wildfire simulations. Quick and accurate assessments are essential to ensure effective and timely responses to rapidly changing wildfire conditions.

Satellite active fire data has proven to be an excellent resource for monitoring and analyzing the temporal and spatial evolution of wildfires (Cardil *et al.*, 2019; Oliva and Schroeder, 2015). Additionally, ROS adjustment can optimize simulations by aligning the simulated ROS with field observations, thereby enhancing the accuracy of subsequent simulations. Historically, this task posed a significant challenge for fire analysts during fire incidents due to the time-consuming and error-prone calculations and challenges in obtaining control points.

The proposed approach of wildfire simulation reinitialization utilizing satellite active fire data and ROS adjustment demonstrates significant potential as a cost-effective and time-efficient framework, by using the EO as control points (removing the need for costly aerial or ground operations to obtain data point) and quickly calculating the ROS adjustment factors using WFA, for real-world wildfire scenarios management. The practical implications of the results are valuable. For example, the predicted location of fire using the unadjusted simulation for 12 hours in the case of Samarda would be 3.8 km further away from the actual location of the fire. This would mean that this overestimation results in ineffective resource deployment, potentially leading to wasted resources in areas where fire is not spreading. Conversely, underestimating fire spread (for instance, the case of Landal) could lead to delayed evacuations and insufficient suppression measures.

This method also proved that it is useful for both long-lasting where the effects of accumulated errors in fire simulations become more evident and fast-moving fires, where sources of error are more prominent. For instance, the fire in Samarda, which consumed a very large area (5568 ha) in a relatively short period of 12 hours (i.e. a case of fast-moving fire), showed very high discrepancies in MAE and MBE before the ROS adjustment (5.28 m/min). After reinitializing the simulation with adjusted ROS based on satellite active fire data, the absolute error

was substantially reduced (1.415 m/min). However, when considering the biased error, the discrepancy becomes negligible (-0.125 m/min). On the other hand, the fire in Linhares, which had the longest duration of 72 hours (i.e. a case of long-lasting fire) among the cases studied, exhibited a very high absolute error without adjustment (108%). After applying the proposed approach, the error decreased significantly (27%).

The manual strength modification parameter, λ , in the WFA adjustment algorithm is crucial for balancing accuracy and realism in simulations. Increasing this parameter, called the tuning parameter in WFA, results in a significant reduction in the final error of fire arrival times, aligning the simulated fire more closely with the hotspot control points. However, this considerable decrease in error comes with the trade-off of applying greater adjustment factors to the fuel ROS. If λ is set excessively high, the ROS values may become unreasonably large or small, undermining the accuracy of subsequent burn periods and diminishing the overall reliability of the simulation. To achieve an optimal balance between enhanced accuracy and realistic fire behavior, a moderate value of 0.2 was chosen for all simulations in this study. Since WFA can run on standard laptops, it provides a practical solution for supporting decision-making directly in the field. Fire analysts can access real-time simulations and adjust operational strategies with minimal infrastructure, needing only an internet connection to obtain hotspot data. The training required to effectively use this approach is relatively minimal, with fire analysts familiar with fire simulations requiring about six hours of training to operate the system efficiently. The main expense associated with implementing this method is the purchase of a WFA license, which makes it a feasible and cost-effective tool for improving wildfire management operations.

Limitations - Even though the proposed approach shows great potential, some limitations and challenges must be considered when using this method. While VIIRS products offer a resolution of 375 meters, they can still introduce errors. This means that the fire could be anywhere in a 375 m square, and since the exact location of the fire is required to make a more accurate ROS adjustment, this causes errors in adjustment factor calculations. 375 meters of error in the

fire's location translates to 0.52 (m/min) in ROS of the fire, and the fire analysts must be mindful of this uncertainty. The 12-hour interval between each satellite overpass of VIIRS is an improvement over the 24-hour interval of MODIS, but it still poses limitations in the assessment and monitoring of fire evolution. For fires lasting less than 12 hours, the satellite may miss the entire event, resulting in no data being reported, or if the fire starts after a couple of hours of satellite overpass from that location, the first 10 hours or so of fire would not be recorded. Additionally, since the adjustment of ROS is dependent on satellite active fire data, this long interval between overpasses limits the efficacy of the adjustment and reinitialization process. Shorter periods of reinitialization mean less accumulated error and adjustment in the earlier stages of the fire. Moreover, Active fire data products are typically available 1 to 3 hours after the actual satellite overpass. This latency can impact the real-time monitoring and assessment of fire evolution and limits the practical implications of this method. In real-life emergencies, 1 to 3 hours can make a difference, and this latency decreases the efficacy of timely simulation and, consequently, latency in protective and operational measures. Lastly, the accuracy of satellite hotspots can be affected by issues with capturing thermal data, such as errors from cloud cover that can mask a hotspot or high-temperature smoke plumes that can mimic a hotspot that does not exist. Cautious and experience of the operator in filtering the satellite data determines the accuracy of simulations. The task of hotspot data filtering can be subjective and may introduce bias into the analysis.

The ROS adjustment algorithm has associated limitations as well. ROS adjustments are made only for fuels that were burned during the interval. If there are other types of fuels ahead of the fire, they remain unadjusted, necessitating further readjustments in subsequent intervals. Fire analysts should be mindful of this limitation, and closely examine the associated fuel model in each simulation interval. In addition, the accuracy of the results depends on the number of control points introduced into the adjustment process. The more control points available, the more reliable the ROS adjustment results. Moreover, environmental factors, such as the presence of local winds or wind gusts, can affect ROS adjustments differently compared to their absence,

potentially leading to inaccuracies. Wind gusts can temporarily increase the ROS, leading to rapid fire expansion over short periods. In contrast, steady wind conditions result in a more consistent ROS. When the algorithm adjusts the ROS based on observed fire behavior, it may interpret these short-lived gust-driven increases as part of the overall trend. As a result, the algorithm could overcompensate by decreasing the ROS of fuels in subsequent burn periods. This adjustment can introduce inaccuracies, potentially underestimating fire spread and affecting the reliability of future simulations. Finally, Fuels that comprise a smaller proportion of the fire area should be left unadjusted, as they have minimal effect on the ROS. Operators should be mindful of fuel models with small relevance when using this method.

Fire suppression activities play a crucial role in influencing fire behavior, but they are primarily conducted along the fire flanks, where intensity is lower and suppression efforts are more feasible. Given this, the present study focuses on measuring the ROS at the fire head (max ROS), as detailed in Section 2.5, to minimize the impact of suppression-related variability. However, the authors acknowledge that suppression efforts, even if concentrated on the flanks, can still introduce uncertainties and influence the accuracy of the final results. These potential discrepancies highlight the inherent challenges in fire behavior modeling and the need for careful interpretation of simulation adjustments in the presence of active suppression operations.

Addressing these limitations and challenges is crucial to enhancing the reliability and accuracy of wildfire simulations using the proposed approach. Also, addressing these challenges can be the aim of further research. Future research could explore the effects of varying tuning strengths to better optimize the trade-off between error reduction and long-term simulation fidelity. Although this method can potentially be applied to other countries or regions, this study focused on just five case studies in Portugal. Additional research is needed to verify its reliability and applicability to different geographic areas and fire regimes. In addition, further research can be done on creating a dataset of adjustment factors for each fuel family in different regions or countries, by methodically simulating past fires and adjusting them by historic satellite active fire data.

6.3.4. Conclusion

The proposed method for wildfire simulation, which utilizes satellite active fire data reinitialization and adjustments to the ROS, presents a promising and cost-effective solution. It can serve as a decision-support tool by enhancing simulation accuracy, ensuring that managers make informed decisions about resource allocation, evacuation planning, and suppression efforts. By eliminating the need for ground or aerial operations to collect fire arrival control points, it significantly lowers operational costs. Furthermore, improving the accuracy of the simulation it helps prevent errors in resource allocation and minimizes costs associated with fire damage. This approach is also time-efficient, dramatically reducing the manual calculation time of the adjustment algorithm from hours to mere minutes, thereby offering considerable advantages for real-world wildfire management. By leveraging VIIRS wildfire hotspots, this method enables fire analysts to monitor fire evolution, assess discrepancies between simulated and actual fire spread, and adjust simulations in near real-time. The results from five case studies in Portugal highlight the effectiveness of this approach in reducing discrepancies and enhancing simulation accuracy, as evidenced by substantial improvements in various error statistics. The results show that MAPE decreased from 71.43% on average for 5 case studies to 13.99%, and the MBPE decreased from an average of 59.12% down to 7.38%.

From a practical standpoint, the improved accuracy in fire spread prediction has direct implications for resource allocation, evacuation planning, and suppression efforts. The significant reduction in prediction errors ensures that firefighting resources are deployed more efficiently, minimizing unnecessary efforts in areas where fire is unlikely to spread and focusing on regions at greater risk. More accurate fire front predictions also enhance public safety by improving early warning systems and evacuation protocols, reducing the likelihood of underestimating fire threats. While the proposed method shows great promise, addressing its current limitations, such as uncertainties in satellite data, the impact of fire suppression, and the need for further research to assess generalizability, will be crucial for maximizing its utility in operational wildfire management. Future work should focus on improving data resolution, reducing latency, and enhancing the robustness of ROS adjustments to environmental factors. By doing so, this approach could significantly contribute to more accurate wildfire simulations, better-informed decision-making, and more effective wildfire management strategies.

6.4. Evacuation Simulation Research Overview

6.4.1. Introduction

Various simulation models have been developed for evacuation planning, including models solely produced for evacuations, e. g. TransCAD, TRANSIMS (Hardy and Wunderlich, 2007), a model that tries to simulate the wildfire and evacuation simultaneously, e. g. WUI-NITY (Wahlqvist *et al.*, 2021), simplified simulations and models to define the evacuation trigger by setting up a parameter that would activate once crossed by fire (Countryman 1972, Li *et al.* 2019), e. g. MedSpread (Duane *et al.*, 2016), HURREVAC (Cova, 2005), WUIVAC (Larsen *et al.*, 2011).

The mentioned models and simulations have different approaches regarding microscale or macroscale points of view. A microscale approach simulates the evacuation scenarios and manages them in small urban areas, like small villages or communities. This microscale approach analyses the behavior of each individual in terms of decision-making and evacuation means of transport and handles them on a small scale. On the other hand, a macroscale approach must be considered for larger communities to plan and manage an effective evacuation. Due to herding and the mass movement of the population, these types of evacuation must be handled macroscopically to avoid traffic jams or lack of equipment in different community sectors (Hardy and Wunderlich, 2007, Mithilesh *et al.*, 2004).

6.4.2. Warning systems and region division

Effective wildfire evacuation strategies are crucial as these disasters become more frequent. Clear and persuasive communication of evacuation orders is essential, given the initial skepticism often encountered (Darbek, 1999; Perry *et al.*, 2001). The urgency, departure points, and destinations of evacuees are influenced by message content, source, and distribution channel (Lindell and Perry, 2012). Vocabulary inconsistencies across regions and the use of acronyms on social media may hinder clarity (Wolshon, 2009). Studies show variability in terminology

used by officials, with “Mandatory” and “Voluntary” being the most common. However, the legal enforcement of “mandatory” evacuation remains ambiguous (Baker, 1991). Geographic zoning can help clarify who must evacuate, with zone definitions varying by disaster type (Arlikatti *et al.*, 2006). Proper zoning is also crucial for macro/meso-scale evacuation modeling (Wilmot and Meduri, 2005).

6.4.3. Evacuation model design

Evacuation models require data on individual decisions and behaviors, such as vehicle usage, route selection, and safe point destinations (Alsnih and Stopher, 2004). However, wildfire evacuation data is scarce, limiting model accuracy (Koligowski, 2021). Existing models often assume ideal behavior (Leon and March, 2017) or focus on a single mode of movement (Veeraswamy *et al.*, 2018; Shahparvari *et al.*, 2019). Due to this lack of data, models rely on user judgment, often unrelated to wildfires (Carole and Gaudo, 2017; Cova and Johnson, 2002).

Traditional evacuation simulations tend to be overly optimistic about clearance times (Murray-Tuite and Mahmassani, 2003). Realistic simulations considering delayed evacuations and familiar route preferences show reduced effectiveness (Bulumulla *et al.*, 2017; Chiu and Mirchandani, 2008). Incorrect behavioral assumptions can compromise community safety by underestimating evacuation time and delaying alerts.

Household evacuation involves multiple time phases, from preparation to arrival at a safe point (Ronchi *et al.*, 2019). Effective models must incorporate decision-making factors, transportation modes, and road network usage (Koligowski, 2021). Different modeling approaches—macroscale, microscale, and mesoscale—simulate evacuation at varying levels of detail (Murray-Tuite and Wolsohn, 2013). Each requires data on behavioral patterns, vehicle choices, and road network distribution to enhance accuracy.

Recent research has advanced wildfire evacuation modeling. Agent-based models simulate evacuee behavior in fast-moving fires (Grajdura *et al.*, 2022). Studies highlight how demographics, smartphones, and community evacuation

plans influence awareness and response time (Grajdura *et al.*, 2021). Ronchi *et al.* (2019) proposed an integrated framework combining fire, pedestrian, and traffic simulations for realistic evacuation modeling.

Fire spread models and GIS-based methods have been used to establish evacuation trigger points (Cova *et al.*, 2005). Wahlqvist *et al.* (2021) developed WUI-NITY, a platform that integrates fire and evacuation modeling. Mitchell *et al.* (2023) linked wildfire and evacuation models to create improved trigger perimeters. Data-driven simulations, considering car ownership and occupancy rates, have further refined evacuation time predictions (Li, 2022). Benchmarking studies using evacuation drills provide critical validation for modeling assumptions (Gwyne *et al.*, 2023).

To develop a comprehensive evacuation model, four key sub-models must be created: pedestrian evacuation (trip generation), sheltering (destination selection), transportation mode choice, and traffic modeling (route selection). The following sections will explore existing research in these areas.

Pedestrian evacuation modeling (Trip Generation) - Trip generation modeling predicts the number of evacuees and their departure times (Murray-Tuite and Wolsohn, 2013; Pel *et al.*, 2012). Studies by Folk *et al.* (2019) and McLennan *et al.* (2019) analyzed factors influencing evacuation decisions during WUI fires, including sociodemographics, environmental cues, experience, responsibilities, and perceived risk. Self-efficacy has also been identified as a key factor (McCaffrey *et al.*, 2018; Strahan *et al.*, 2019).

Evacuation policies significantly impact decision-making. Before Australia's 2009 wildfire disaster, many residents opted to stay and defend their properties. Afterward, authorities shifted towards recommending evacuation while acknowledging that sheltering may sometimes be necessary (McCaffrey *et al.*, 2018). In the U.S. and Canada, evacuation is generally mandated based on wildfire severity, though some areas, such as indigenous territories, cannot enforce evacuation orders (Cova, 2005).

Decision-making data is crucial for modeling household evacuation probabilities. Discrete choice models estimate evacuation participation at macro and micro levels (Lindell *et al.*, 2018). Hurricane studies have provided participation rate data,

though independent of incident type, helping to develop models based on storm characteristics and demographics (Pel *et al.*, 2012).

Data on wildfire evacuation timing is scarce. Typically, departure time is linked to official evacuation alerts. While no explicit wildfire studies exist, no-notice disaster research (Golshani *et al.*, 2019) provides insights, showing over 50% of participants evacuated within 30 minutes and nearly all within three hours. Factors delaying evacuation included disabilities, larger families, and lower risk perception, while awareness of alerts and trip preparation accelerated departure.

Researchers have used binary choice models to estimate evacuation timing in wildfires and hurricanes (Alsnih *et al.*, 2005; Fu and Wilmot, 2004). These models treat evacuation as sequential decisions influenced by environmental and social factors (Lovreglio *et al.*, 2019). Exogenous response curves predict departures based on risk-prioritized zones, with various statistical distributions applied (Pel *et al.*, 2012). However, differences in hurricane and wildfire timeframes require adjustments for wildfire-specific evacuation modeling (Murray-Tuite and Wolsohn, 2013).

Pedestrian sheltering (Destination) - Research on the 2007 San Diego wildfire (Sorensen *et al.*, 2009) found that evacuees preferred staying with relatives or friends, followed by hotels, holiday houses, and public shelters. In contrast, Golshani *et al.* (2019) observed that in no-notice evacuations, public shelters were the primary choice. Their study also identified factors influencing destination preferences, including returning home post-incident, previously unconsidered in wildfire evacuations. Similar trends were found in hurricane evacuations, where evacuees favored private accommodations over public shelters (Mesa-Arango *et al.*, 2013). Discrete choice modeling has been used to predict evacuation destination preferences based on societal and environmental cues.

Evacuation transportation (Mode Choice) - The evacuation timetable is influenced by vehicle type, quantity, and capacity, which impact road network congestion. Toledo *et al.* (2018) studied vehicle usage during the Haifa wildfire evacuation, finding that 92% used private cars, with an average of three people per vehicle and 0.89 vehicles per family. Compared to the U.S., fewer personal vehicles were used, likely due to lower car ownership in Israel. U.S. hurricane studies also

showed a preference for private cars, with socio-demographic factors influencing public transport use (Sadri *et al.*, 2014). Additionally, American evacuations involved larger vehicles, such as trailers and boats, increasing traffic congestion (Murray-Tuite and Wolsohn, 2013).

Studies on unplanned evacuations (Auld *et al.*, 2012) and wildfire evacuations (Toledo *et al.*, 2018) revealed that many evacuees make short trips before leaving, mainly to pick up household members. In Israel's wildfire, evacuees averaged 1.1 intermediate trips (Toledo *et al.*, 2018). These side trips add to evacuation time (Murray-Tuite and Wolsohn, 2013). Even non-evacuating family members may contribute to road congestion as "background traffic".

Traffic modeling (evacuation routes selection) - This stage of evacuation modeling predicts the routes individuals take to reach safety. Evacuees may use highways, rural roads, or a combination of both, though WUI fires are primarily evacuated by car. Data for WUI-specific models remain limited, as most studies focus on flood or hurricane evacuations. Research indicates that individuals prefer familiar routes over the fastest or shortest ones (Murray-Tuite *et al.*, 2012), with factors like media, emergency protocols, and maps playing a smaller role (Wu *et al.*, 2012). Additionally, route type, availability, length, and amenities such as gas stations and rest areas influence decisions (Dow and Cutter, 2002).

Driving behavior is affected by route familiarity, with speed increasing as drivers use a road more frequently (Colonna *et al.*, 2016). Dixit and Wolsohn (2014) analyzed hurricane evacuation traffic, distinguishing between "maximum evacuation flow rates" and "maximum sustainable evacuation flow rates". However, data on individual vehicle behaviors, such as following distances and lane changes, remain scarce. Pel *et al.* (2012) emphasized that non-emergency driving data cannot be directly applied to evacuation modeling.

Niu *et al.* (2022) examined road network connectivity and wildfire fatalities, finding that well-connected networks reduce fatalities by providing alternative evacuation routes. However, their model was less effective in densely populated areas, where fatalities are higher. Small sample sizes and inconsistencies in evacuation policies further limit its applicability.

6.4.4. Computational tools for evacuation modeling

As mentioned in previous sections, there are three main approaches in the simulation of an evacuation. Each approach has its specific use and applies to certain situations. This section introduces software used for certain case studies and research, categorized by their approach. Nevertheless, other software is available, but government organizations use them, and there is not much data available.

Macroscale - Macro models are primarily used for evacuation planning, particularly for large-scale events like hurricanes or floods. Metropolitan planning organizations employ these models to simulate evacuation processes. However, they are not suitable for implementing real-time traffic strategies or analyzing congestion causes.

These models also include real-time decision-support tools to assist authorities during evacuations. EMME 4.6 is a city transportation planning system offering a comprehensive set of traffic and transportation modeling tools. It allows planners to evaluate multiple scenarios, from basic four-step evacuation plans to more advanced simulations. This software enables users to modify road networks, transportation systems, or socioeconomic factors to analyze different evacuation outcomes (Rontiris and Crous, 2000).

The Evacuation Traffic Information System (ETIS) is an internet-based platform for southeastern U.S. state authorities to share real-time evacuation and traffic data. Developed by the Federal Highway Administration, the U.S. Army Corps of Engineers, and FEMA, ETIS assists in selecting evacuation styles (voluntary, mandatory, or staged) and implementing contraflow or lane reversals. Designed to predict large-scale traffic flows, ETIS allows emergency personnel to input location-specific data and forecast evacuation bottlenecks (Moriarty *et al.*, 2007).

The Oak Ridge National Laboratory (ORNL) developed the Oak Ridge Evacuation Modeling System (OREMS) to estimate evacuation timelines and optimize strategies under varying conditions, such as different times of day or weather scenarios. OREMS evaluates alternative routes, evacuation destinations, evacuee response rates, and traffic management strategies. It calculates evacuation duration and predicts traffic factors

like average speeds and bottlenecks. ORNL researchers highlight its role in assessing risk areas, proposing alternative strategies, and optimizing traffic operations through measures like contraflow and shoulder lane use (Bhaduri *et al.*, 2006).

TransCAD is an operational package that integrates GIS with macro-level simulations. It includes an Evacuation Analysis Procedure for modeling network evacuations. This tool tracks traffic flow changes over time and space, providing clearance time estimates and identifying bottlenecks. By analyzing dynamic vehicle flow data, operators can refine evacuation plans and assess traffic strategies, including route-specific signaling, contraflow implementation, and high-capacity vehicle deployment (Sun *et al.*, 2015).

Mesoscale - Mesoscale traffic simulation models emerged to balance the detailed representation of microscale models with the analytical scope of macroscale models. These models simulate vehicle flow over network links rather than individual lanes, making them useful for evacuation planning. They provide a more accurate depiction of congestion and time-based traffic patterns than macroscale models while covering larger areas than microscale simulations. By reproducing congestion and dissipation loops from previous evacuations, mesoscale models help refine future evacuation strategies.

DYNASMART is a mesoscale traffic modeling software designed to simulate dynamic traffic flow across road networks. It enables operators to forecast vehicle locations within the network at specific times rather than reacting solely to real-time conditions. DYNASMART has two versions: DYNASMART-P, a standalone simulation tool, and DYNASMART-X, a real-time simulation system with hardware-in-the-loop capabilities. It integrates traffic simulation models for operational studies and road network models for long-term traffic demand forecasting. Compared to macro- and microscale models, DYNASMART offers enhanced analytical power by explicitly modeling traffic processes over time and providing a comprehensive representation of road networks (Chiu, 2007; Kwon and Pitt, 2005). Additionally, it allows for more detailed simulations of evacuee decision-making behavior (Mahmassani, 1992; Mahmassani and Abdelghany, 2002).

Cube Avenue employs mesoscopic methods to analyze time-dependent traffic flow. It models input data in specific time intervals (hours and minutes) while

incorporating vehicle, time, and road network characteristics. Using this data, it calculates the most cost-effective route for each vehicle based on departure time while also simulating vehicle interactions within the network. The software determines vehicle speed by considering road occupancy at any given moment. Cube Avenue can simulate time-sensitive traffic rules, such as variable toll pricing or lane closures. It was used in the Houston-Galveston region to aid emergency evacuation planning. Following Hurricane Rita, which required the evacuation of 2.4 million people in 24 hours, authorities used Cube Avenue to reconstruct the evacuation, identifying system inefficiencies and improving future response strategies. The software also allows the creation of scenario libraries, enabling authorities to prepare for various emergency conditions (Sin and Joo, 2013, 2017).

The Transportation Analysis and Simulation System (TRANSIMS) models traffic as a collection of individual agents and is primarily used for transportation planning and emissions analysis. It integrates simulations, models, and databases, providing a regional transportation study platform that applies advanced computational and analytical techniques. TRANSIMS' ability to simulate and track individual travel patterns allows for detailed impact assessments across different regions and travel markets. It can analyze highly congested scenarios and evaluate operational adjustments to road and public transit networks. TRANSIMS differs from traditional travel demand forecasting models by incorporating continuous time representation, detailed population and household modeling, time-dependent routing, and a person-based microsimulation framework (Lee *et al.*, 2014; Nagel *et al.*, 1999; Smith *et al.*, 1995).

Microscale - Microscale simulation models are designed to predict the detailed traffic behavior of individual vehicles and pedestrians in road networks. These models simulate vehicle movement based on distinct characteristics, allowing interactions within the system. However, a key limitation is their high computational demand and the need for extensive data on roadway design and traffic regulations. Many traffic management organizations integrate both micro- and macro-level models to assess the impact of changes on transportation capacity and service efficiency. Microscale simulations are commonly used to evaluate emergency evacuation strategies, such

as contraflow, as well as to analyze congestion points and the influence of vehicle movement on overall traffic patterns. Quadstone Paramics (Hidas, 2005) is a suite of microscale simulation modules designed to address various transportation challenges, applicable at scales ranging from individual intersections to entire urban networks. The Mission Canyon Neighborhood was modeled using the Paramics system to study wildfire evacuation dynamics, referencing the 1991 Oakland Hills fire in which 25 people lost their lives (Church and Sexton, 2002). This software was also employed to test micro-level traffic simulations for evacuation planning in wildland fire scenarios (Cova *et al.*, 2002). EXODUS (Veeraswamy *et al.*, 2018), developed by the University of Greenwich, is an agent-based evacuation model designed to simulate large-scale evacuations, incorporating human-to-human, human-to-fire, and human-to-structure interactions. To enhance its capacity for large urban environments, an additional interface called Urban EXODUS was created (Neis *et al.*, 2011). This system is capable of modeling evacuations involving thousands of individuals across extensive geographic areas (Chooramun *et al.*, 2012). These simulation tools are valuable for assessing wildfire evacuation strategies and improving emergency response planning across different contexts.

6.4.5. Gaps and future directions

Wildfire evacuation modeling presents significant challenges, particularly in decision-making representation and evacuee behavior analysis. Existing models often employ binary choice methods—evacuate or stay—overlooking critical factors such as prior experience, situational awareness, and individual risk perception. More research is needed to integrate these variables for a realistic depiction of evacuation decisions. Additionally, the scarcity of standardized evacuation behavior data complicates model accuracy. Data on destination choices, transport modes, and route selection during wildfires remain limited, often relying on surveys rather than real evacuation events. This gap hinders a comprehensive understanding of evacuees' responses, particularly in wildland-urban interface (WUI) areas. Critical questions remain: how does background traffic impact evacuations? Which communities

depend on public transport? How do fire-related environmental changes—smoke, firebrands, and rescue team locations—affect evacuee behavior? Addressing these uncertainties through extensive and standardized data collection is essential for refining evacuation models and enhancing emergency response strategies.

A major limitation in existing evacuation models is their insufficient consideration of the interrelated effects of wildfire behavior on the evacuation process. Many models primarily focus on human movement while overlooking the evolving nature of wildfire, which significantly influences evacuee decisions. Wildfires are dynamic phenomena, with their intensity, direction, and spread affected by weather, fuel availability, and topography. These variations impact evacuation timelines, route availability, and decision-making. To enhance model accuracy, it is crucial to integrate wildfire behavior dynamics, including fire spread, smoke production, and fireline intensity, into evacuation simulations. Coupling wildfire and evacuation models can provide a holistic representation of evacuation processes, capturing critical feedback loops. Furthermore, understanding evacuees' responses to uncertainty, risk perception, and real-time information updates is essential for refining decision-support tools and communication strategies. Another challenge is the reliance on unrealistic assumptions due to limited behavioral data, which may compromise model reliability. Bridging this gap requires improved data collection, refined model parameters, and methodologies that align evacuation models more closely with real-world behaviors.

6.5. Evacuation Simulation under Wildfire Threats Using AnyLogic

6.5.1. Introduction

The growing severity and frequency of wildfires, fueled by climate change and urban encroachment into forested areas, has led to the urgent need for comprehensive evacuation planning. Wildfires present unique challenges for emergency responders due to their unpredictable spread, high-intensity behavior, and capacity to overwhelm communities, especially those in the wildland-urban interface quickly. As a result, researchers and emergency planners are increasingly turning to simulation modeling as a critical tool for testing and optimizing evacuation protocols. Among the various tools available, AnyLogic stands out for its flexibility and its unique ability to integrate multiple modeling paradigms, namely agent-based, discrete-event, and system dynamics modeling (Beyli *et al.*, 2023).

Agent-based modeling (ABM) represents each individual—such as a resident, firefighter, or vehicle—as an autonomous agent with defined behaviors and decision-making rules. In the context of wildfire evacuation, ABM is particularly effective in capturing how different individuals respond to emergency alerts, choose evacuation routes, or decide to shelter in place. Factors like social interactions, past experiences, health conditions, or risk perception may influence each agent's decisions (Borshchev, 2013).

Discrete-event modeling (DEM), on the other hand, is well suited for representing systems where changes occur at specific points in time. This is especially relevant for logistical operations during evacuation, such as the arrival and departure of buses, the opening or closure of evacuation centers, and the scheduling of rescue operations. Events like traffic signal changes, roadblocks, or the loading and unloading of evacuees can be modeled discretely to simulate their impact on evacuation timelines (Borshchev, 2013).

System dynamics modeling focuses on capturing feedback loops and accumulations over time. In wildfire scenarios, this could include the spread of the fire itself, the depletion of emergency resources, or the rate at which public compliance to evacuation orders increases or decreases. It is valuable for analyzing broader patterns and long-

term strategic planning, such as how information dissemination affects community behavior or how delayed evacuations amplify systemic stress (Borshchev, 2013).

By combining these paradigms, AnyLogic allows modelers to simulate both individual behaviors and system-level operations simultaneously. This chapter explores the application of such multimethod modeling in simulating evacuation processes during wildfire emergencies, providing a comprehensive framework for understanding fire behavior, human decision-making, and logistical challenges in small urban areas.

6.5.2. Wildfire behaviour modeling

Accurate simulation of wildfire spread is a prerequisite for effective evacuation planning. Wildfires are influenced by a combination of fuel characteristics, topography, and meteorological conditions. These include vegetation type and density, terrain slope and elevation, and environmental factors such as wind speed, temperature, and humidity. To capture these dynamics, simulation frameworks often integrate specialized wildfire modeling tools such as FireStation, which uses empirical and semi-empirical models to forecast fire front propagation. The output of wildfire modeling is not only a spatial projection of fire spread, but also a temporal forecast of when and where the fire will reach critical zones (Lopes *et al.*, 2002).

This information plays a pivotal role in the evacuation modeling process. Firstly, it enables emergency planners to identify which areas are most threatened and in need of priority evacuation. Secondly, it allows for the calculation of safe windows of time for evacuation before roads become inaccessible or visibility is too poor due to smoke. Thirdly, it supports the dynamic adjustment of evacuation routes and strategies in real time, as the simulation can account for roads that are predicted to be overtaken by fire or become hazardous due to smoke density.

Moreover, integrating wildfire modeling into evacuation simulations allows for a more realistic representation of how the physical hazard evolves and interacts with human mobility. For instance, fire behavior data can influence the movement logic of agents within the simulation by limiting route options or increasing perceived risk, thus affecting evacuation decisions. In addition, the timing and location of

emergency vehicle deployment can be better optimized by forecasting when specific areas will become unreachable.

Ultimately, the coupling of wildfire and evacuation models ensures that evacuation strategies are not based on static assumptions, but are dynamically informed by the projected evolution of the hazard itself. This integrated approach significantly enhances the accuracy and utility of simulation outputs for real-world planning and decision-making.

In the context of this study, FireStation is employed to simulate the temporal and spatial evolution of the wildfire. The simulation outputs critical information such as the predicted path of the fire, its intensity, and the timeline of fire arrival in different zones. This data is crucial for planning evacuation routes and determining which areas are most at risk. Furthermore, smoke dispersion is modeled using Lagrangian particle-based dispersion models, such as the Fire Dynamics Simulator (FDS), which allows for the evaluation of visibility and air quality in real-time. These environmental outputs are then integrated directly into the evacuation modeling phase within AnyLogic (McGrattan *et al.*, 2008).

The integration is achieved by importing spatial and temporal data from the wildfire simulation into the evacuation model, which in turn adjusts agent behavior and route selection based on current and forecasted conditions. For example, if a specific road is predicted to be engulfed by fire within a certain time frame, the evacuation model can dynamically reassign routes to avoid that area. Similarly, areas with high smoke density may be assigned increased travel times or marked as impassable due to health risks or limited visibility. This linkage ensures that the evolving nature of the fire and smoke hazards is continuously reflected in the evacuation simulation, enabling realistic and adaptive decision-making by both residents and emergency vehicles.

By using wildfire modeling data in this manner, the evacuation model gains a high degree of responsiveness and situational awareness, which is essential for testing contingency plans and identifying vulnerabilities. The dynamic nature of the coupling allows emergency planners to assess not just what evacuation plans work under normal conditions, but which strategies remain viable under extreme or rapidly changing fire scenarios.

6.5.3. Agent-based evacuation modeling in AnyLogic

AnyLogic enables the construction of detailed agent-based models (ABM) where each resident in a community is represented as an autonomous agent with unique behavioral attributes and decision-making rules. This approach allows for a high degree of realism, as it captures the diversity of human responses in emergencies. In wildfire scenarios, residents must decide whether to evacuate, delay their departure, or stay behind to defend their property. These decisions are influenced by proximity to the fire, risk perception, official alerts, social cues, physical condition, and availability of transportation (Borshchev, 2013).

Each agent's decision-making process is typically modeled using decision trees or finite state machines. These trees define a set of states an agent can be in—such as unaware, alerted, preparing, evacuating, or sheltering—and the transitions between them, which are triggered by specific conditions or thresholds. For example, an agent might move from the "alerted" state to the "preparing" state once the perceived fire risk surpasses a certain threshold, and then to "evacuating" after a delay that simulates real-world preparation time (Borshchev, 2013).

Attributes such as age, mobility, risk aversion, and access to transportation are defined at the agent level and are used to inform these transitions. Risk perception might be modeled as a dynamic variable influenced by proximity to the fire front, visibility conditions due to smoke, and the behavior of neighboring agents. Physical conditions determine movement speed and whether an agent requires assistance to evacuate. The flexibility of AnyLogic allows for these attributes to be assigned probabilistically based on population demographics or tailored to specific case studies using real data. By incorporating such detail, the simulation provides a nuanced view of community behavior under stress and allows for more precise evaluation of evacuation strategies (Borshchev, 2013).

The evacuation simulation begins with the triggering of alerts, which may originate from government notifications, community warnings, or personal observations. Agents then assess their situation and make decisions based on internal parameters such as perceived urgency, past experience with wildfires, and social influences. Some agents may decide to evacuate immediately, while others may

take time to prepare by gathering belongings or contacting family members. The model includes variability in these preparation times to reflect real-world behavior. Once agents decide to evacuate, they proceed toward predefined evacuation points, taking into account the shortest or safest routes available.

Movement dynamics within the model consider walking speeds, road conditions, physical limitations of agents, and interactions with other evacuees. Congestion is dynamically simulated, leading to potential delays and bottlenecks, especially in densely populated areas. Emergency vehicles, also modeled as agents, are deployed from base stations and navigate through the simulation space to collect evacuees. These vehicles are governed by capacity constraints and route optimization algorithms that account for fire progression, traffic congestion, and road closures. The model includes stochastic elements to simulate uncertainties in fire behavior, agent decisions, and environmental changes (Borshchev, 2013).

6.5.4. Behavioral factors in evacuation decisions

Human behavior under emergency conditions is complex and often deviates from idealized rational models. Research has shown that individual decisions to evacuate are rarely based solely on official instructions. Instead, they are shaped by personal beliefs, risk perception, community dynamics, and past experiences. In the context of wildfire evacuation, social influence plays a significant role; for example, people are more likely to evacuate if they observe neighbors doing so.

To simulate these nuances, the AnyLogic model incorporates psychological models such as the Belief-Desire-Intention (BDI) framework, where agents evaluate information and form intentions based on their beliefs and goals. The BDI model is a cognitive architecture that mimics human decision-making processes by structuring agent behavior around three components: beliefs, which represent the agent's perception of the environment; desires, which indicate goals or preferred outcomes; and intentions, which are the specific actions or plans the agent commits to in pursuit of those goals. For example, an agent may believe a nearby road is blocked by fire, desire to reach a safe zone, and intend to reroute through a less direct but safer path (Siam *et al.*, 2022).

Implementing BDI in AnyLogic can be achieved through the use of statecharts and decision logic. Beliefs can be represented as dynamic variables, such as distance to fire or congestion on roads, which are updated in real time as the environment changes. Desires are reflected in agent priorities or objective functions—like minimizing evacuation time or avoiding high-risk areas. Intentions are then executed as transitions between states in a statechart, such as moving from ‘deciding’ to ‘preparing to evacuate’ or from ‘preparing’ to ‘evacuating’. These transitions are governed by logical rules that combine an agent’s beliefs and desires to determine appropriate behavior (Siam *et al.*, 2022).

This layered decision-making framework improves the quality of simulation by providing agents with the ability to adapt their behavior dynamically in response to evolving wildfire conditions. Unlike simple rule-based models, BDI allows for more realistic and context-sensitive responses, such as delaying evacuation to wait for a family member or altering routes in response to emerging threats. Additionally, behavioral diversity is introduced by assigning demographic attributes to agents, such as age, mobility, health status, and access to private vehicles. Elderly or disabled agents may require assistance or more time to evacuate, while others may refuse to leave due to attachment to property or pets. Integrating BDI within the simulation enables richer behavioral scenarios and enhances the fidelity of emergency response planning (Borshchev, 2013; Siam *et al.*, 2022).

The model also considers the impact of conflicting information and misinformation. During wildfires, residents may receive contradictory messages from social media, news outlets, or informal sources, which can delay decision-making or lead to poor evacuation choices. These aspects are captured through probabilistic behavior rules and communication networks embedded in the simulation.

To implement this within the simulation, each agent can be connected to a communication network modeled using AnyLogic’s built-in link agents or environment-level broadcasts. These networks allow agents to receive information from various sources, which are assigned varying levels of reliability. For example, official alerts might update an agent’s belief state with high confidence, while messages from peers or social media may be given lower confidence weights.

Within a BDI (Belief-Desire-Intention) framework, these inputs influence the belief component and subsequently affect the agent's decisions. If beliefs are shaped by conflicting sources—such as a government alert advising evacuation and a neighbor suggesting it's safe to stay—the model uses probabilistic thresholds or fuzzy logic to determine which belief prevails. These conflicts might delay transitions in the agent's statechart or prompt reevaluation of intentions.

By modeling information flow and reliability, the simulation captures how communication breakdowns or misinformation propagate and affect collective behavior. This approach not only enriches the behavioral realism of the simulation but also allows for testing communication strategies, message clarity, and the effectiveness of various alert systems under different conditions.

6.5.5 Evacuation logistics and route planning

Logistical planning is a critical component of evacuation simulation. In many rural and semi-urban areas, the road network is limited, and bottlenecks can form quickly as residents converge on major routes. The AnyLogic model incorporates a detailed GIS-based road network, which includes road capacities, directionality, and real-time updates based on fire spread. The model dynamically adjusts route availability as certain roads become impassable due to fire proximity or smoke density.

Evacuation vehicles, such as buses and emergency services vans, are scheduled to make multiple trips between evacuation points and designated safe zones. Their deployment is optimized using heuristic algorithms that aim to maximize the number of evacuees transported per trip while minimizing total evacuation time. Loading and unloading times are modeled explicitly, reflecting the delays encountered in real scenarios (Borshchev, 2013).

In scenarios where evacuation is not feasible for all residents, the model evaluates the effectiveness of sheltering-in-place strategies. Safe zones within the village, such as community centers with fire-resistant infrastructure, are identified and used as fallback options. These zones are represented within the simulation as spatial areas

with high safety ratings, and agents are programmed to recognize them as viable destinations when evacuation is no longer possible or is assessed as too risky based on real-time fire and smoke data. The model accounts for agent decision-making that considers proximity to these zones, perceived safety, and time required to reach them.

To implement this within the simulation, a conditional logic structure is created where agents assess the feasibility of reaching a distant safe zone outside the village versus a closer internal shelter. When agents detect that all viable routes are blocked by fire or congestion, or when time constraints indicate they will not reach the evacuation zone before fire arrival, they are redirected to the nearest shelter-in-place location. This is achieved through a combination of proximity analysis, time-to-impact estimations, and state transitions in the agent's decision tree or BDI logic.

The simulation then evaluates the outcome by comparing agent survival rates, time spent exposed to hazardous conditions, and overall system efficiency under different scenarios. These scenarios include full evacuation, exclusive sheltering, and hybrid approaches. The ability to switch dynamically between these strategies within the model adds robustness to the planning process, allowing emergency managers to prepare flexible protocols that adapt to the evolving nature of wildfire threats.

6.5.6. Proposed application and expected results

We propose to apply the developed simulation framework to a case study in central Portugal, focusing on a small village with approximately 30 residents. GIS data will be used to construct the spatial layout of the community, including residential buildings, road networks, and surrounding vegetation. The FireStation software will be utilized to simulate wildfire propagation and smoke dispersion, and this data will be integrated with an agent-based evacuation model built in AnyLogic.

The simulation is expected to produce a variety of outputs, such as projected evacuation timelines, congestion analysis on key routes, and resource utilization metrics for evacuation vehicles. By adjusting key parameters such as fire spread rate, resident response times, and communication effectiveness, we aim to evaluate the sensitivity of the evacuation process to different conditions.

Our hypothesis is that early evacuation triggers, coupled with efficient vehicle deployment and clear public communication, will significantly improve evacuation efficiency and reduce potential casualties. We also anticipate that the inclusion of shelter-in-place options for immobile or delayed evacuees will enhance the overall resilience of the evacuation strategy. The simulation will help identify potential bottlenecks, assess the feasibility of mixed evacuation approaches, and offer insights into the optimal allocation of resources under various wildfire scenarios.

6.5.7. Conclusion

Agent-based evacuation modeling using AnyLogic provides a powerful platform for analyzing the complex interplay between wildfire behavior, human decision-making, and logistical constraints. By incorporating realistic fire spread data, behavioral diversity, and dynamic route planning, the simulation framework offers valuable insights for emergency planners. The case study in Portugal highlights the applicability of this approach to small urban areas and underscores the importance of early intervention, flexible evacuation strategies, and comprehensive community engagement. Future developments may include real-time data integration, mobile decision support tools, and expanded demographic modeling to further enhance the realism and utility of wildfire evacuation simulations.

Chapter 7

UTILITY OF SHELTERS IN WILDFIRE EVACUATIONS AND DECISION OF THEIR LOCATION IN ARTICULATION WITH THE TERRITORIAL PLANS

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7.1. Introduction

Several studies analysing evacuation drills indicate that the primary factor affecting evacuation time is the population's response—specifically, the delay

between warning reception, decision-making, and actual departure (Gwynne *et al.*, 2023). Nonetheless, literature consistently shows that last-minute evacuations are associated with higher fatality rates. For instance, around 11% of wildfire-related deaths in Australia (1900–2008) were attributed to absent or delayed evacuation warnings (Haynes *et al.*, 2010).

Self-evacuation in wildfire scenarios exposes individuals to severe hazards, increasing the likelihood of injury or fatality. Evacuation alerts aim to guide populations toward designated assembly areas considered safer and more accessible (Shahparvari *et al.*, 2019). However, late arrivals may face delays due to limited vehicle capacity, prolonging their exposure to danger. Wildfire evacuations are further complicated by time constraints, possible disruption to logistics or infrastructure, and unpredictable fire behaviour (Shahparvari *et al.*, 2019).

In Portugal, the ageing population poses an additional challenge. While interior regions still show the highest ageing rates, this demographic shift now extends to urban areas (Moreira and Pinheira, 2023). Individuals over 55 tend to evacuate more slowly (Toledo *et al.*, 2018), a trend observed by Portuguese emergency responders. In predominantly elderly communities, warnings may require customised approaches—such as door-to-door communication—aligned with local cultural contexts (Grajadura *et al.*, 2022). Sparse rural settlement patterns in inland Portugal necessitate context-specific evacuation strategies.

The procedures carried out and presented in this chapter are intended to test the best and safest procedures to carry out in the event of an approaching forest fire, reporting on all the steps taken. The procedures tested, in the form of a simulation exercise, were based on involving the population and collecting testimonies from past situations, so that the procedures tested were as close to reality as possible. In the end, it was possible to collect a range of data, including warning times and methods, evacuation times and evacuation constraints.

7.2. Case studies

This case study presents an analysis of four villages in central Portugal (in the municipalities of Lousã, Sertã and Coimbra), selected for their comparable physical qualities but differing demographic characteristics, focusing on their vulnerability to forest fires and evacuation processes. Here's a brief description of the tested villages is presented:

Cabanões is located in the Lousã and Vilarinho parish, surrounded by scrubland, pine trees, and eucalyptus. Its orography and location make it particularly vulnerable to forest fires. Cabanões has one narrow paved access, making it difficult for emergency vehicles to reach. Over time, the population has declined, with only 26 inhabitants, 9 of whom are permanent residents. The remaining residents are retirees who return for a significant portion of the year. Approximately 62% of the population is over 65 years old, and only one child, aged 6, resides in the village. This demographic and the village's vulnerability to fire risk make it a key subject of investigation.

Cerdeira, also situated in the Serra da Lousã, shares similar physical characteristics but has a distinct demographic profile. Originally a schist settlement, Cerdeira was abandoned by 1980 due to harsh living conditions and poor access. However, a rejuvenation project led by a young sculptor in the 1980s and a rural tourism center established in 2012 revitalized the village. Today, the village is a tourist destination, with just one permanent resident, though its infrastructure accommodates up to 50 visitors. The contrast in Cerdeira's demographic and functional use—primarily tourism-focused—makes it an interesting case for the study.

Trizio located in the Union of Parishes of Cernache do Bonjardim, Nespéral, and Palhais in Sertã, combines residential and tourist features. It has approximately 40 occupied structures, with a population of 55, of which 40 are permanent residents, predominantly over 65 years old. The village's location next to the River Zezere and its steep slopes contribute to the high risk of forest fires. The main access road is narrow and steep, with limited evacuation routes. Trizio's popular River Beach attracts many tourists during the summer, further increasing the village's vulnerability to fires, as evacuation from the beach would require passage through the town.

Additionally, near the end of the project, and in collaboration with the municipality of Coimbra, Ribeira da Misarela was also considered in the evacuation exercises. **Ribeira da Misarela**, located in the parish of Torres do Mondego, Coimbra, is another remote village with limited access. Situated on the right bank of the Mondego River, it has 16 permanent residents, with an average age of 55. The village's steep terrain, dense forest environment, and narrow access roads further compound the fire risk. Two houses in the village are particularly vulnerable, as they are inaccessible by vehicle, requiring residents with mobility difficulties to navigate stairs and narrow paths. The absence of a suitable shelter within the village means that evacuation outside the housing complex is the safest option.

7.2.1. Methodology and data collection

The study involved conducting evacuation exercises with local authorities' support. Key steps included:

Demographic Survey and Georeferencing: Identification of residents' locations and specific needs for evacuation (see Chapter 3).

Community and Civil Protection Meetings: Discussions on past fire experiences, population concerns, and current vulnerabilities.

Evacuation Scenario Development: A hypothetical fire scenario was created to test the villages' response. Sheltering was considered within the villages where possible, but in Cerdeira and Ribeira da Misarela, no safe sheltering infrastructure was available.

Evacuation Exercises: Simulated evacuation scenarios were carried out, with observers placed throughout the villages to assess various aspects of the community's response, including pre-evacuation times, route use, and evacuation times. This data collection, following methods similar to those used by Gwynne *et al.* (2023), aimed to provide insights into the dynamics of community evacuations and generate data that could be used for evacuation modeling. The objective was to quantify evacuation performance and improve future evacuation planning and response strategies.

7.2.2. Results and discussion

The combined challenges of high fire risk and poor vehicular access in mountainous regions have led disaster management authorities to explore non-traditional evacuation strategies. One such alternative is the use of community fire shelters, although their practicality is still debated. A key concern is that poorly chosen shelter locations can increase the risk of injury (Steer *et al.*, 2017). The analysis of each evacuation exercise focused on identifying evacuation times and constraints specific to each village (TABLE XV).

TABLE XV - General Information About the Exercises.

Village	Date	Number of inhabitants involved	Total duration of the evacuation exercise	Evacuation time to the refuge or meeting point to go away
Cabanões	14/10/2022	15+1*	58 minutes	15 minutes
Cerdeira	15/03/2023	25	95 minutes	22 minutes
Trizio	13/05/2023	32	70 minutes	24 minutes
Ribeira da Mizarela	25/01/2025	9+1*	91 minutes	33 minutes

*- bedridden resident in need of evacuation by ambulance

A- Cabanões, two locations were considered: a central meeting point and a shelter at the village chapel. In the scenario, fire surrounded the village, making evacuation impossible via the main access. Authorities informed the village security officer, who was tasked with notifying residents of the need to take refuge (Figure 32). Observers were positioned to record evacuation times and behaviors, with the results summarized in TABLE XVI.



Fig. 32 - Development of the exercise in Cabanões (Photographs of a) Gonçalo Martins (CM da Lousã) taken on 19/10/2022 and b) Luís Laím (ISISE) taken on 19/10/2022).

TABLE XVI - Cabanões Exercise Timeline.

Total duration of the evacuation exercise	58 minutes
Alert time for the population	approximately 5 minutes
Evacuation time to the refuge (from alert to arrival in the village centre)	15 minutes
Evacuation time from the start of the evacuation to arrival at the shelter (chapel)	38 minutes

Weaknesses identified included:

- The village chapel, 250 meters from the center, was designated as a shelter. Traditional bell ringing was not viable, so evacuation alerts were given door-to-door;
- Not all residents participated in the survey, and some would prefer to stay to protect property, particularly given the high proportion of elderly residents;
- The bedridden resident's evacuation caused a delay in the general population's evacuation. Security forces should have directed the residents to shelter without waiting for this evacuation;
- The route to the shelter, lined with forest fuel, posed a significant risk. If public transport is unavailable, walking is the only option, thus requiring an early evacuation procedure.

Observers' perspectives were synthesized to provide a comprehensive analysis, leading to recommendations for improving future evacuation exercises.

B - Cerdeira is a tourist village with only one permanent resident, and the accommodation can host up to 50 people. Tourists typically arrive in private vehicles, which are a key factor in evacuation planning. Interviews with local tourism agencies revealed that tourists tend to evacuate at the first sign of a fire, even if distant. To simulate maximum occupancy, extras were placed throughout the village, as shown in Figure 33.

Observers were positioned in key locations, and upon reaching the refuge (in the car park), extras and observers would proceed by vehicle to a Concentration and Support Zone for the Population (ZCAP) in Lousá. The evacuation timeline is shown in TABLE XVII.

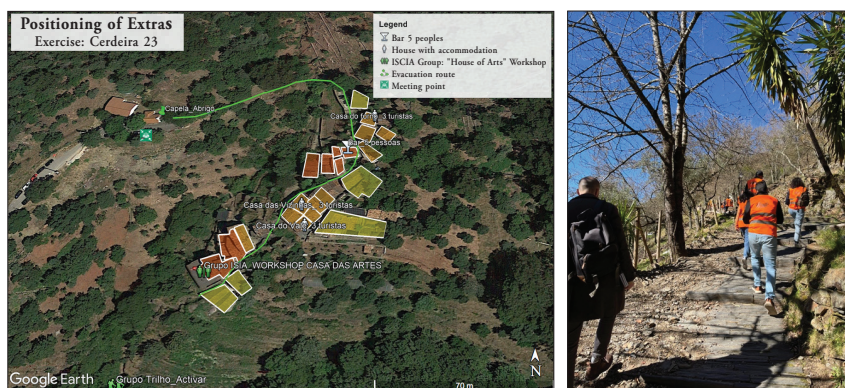


Fig. 33 - Position of observers and victims (Prepared by Andreia Rodrigues, ISISE).

TABLE XVII - Cerdeira Exercise Timeline.

Total duration of the evacuation exercise	95 minutes
Alert time for the population	≈ 15 minutes
Evacuation time to refuge (from alert to arrival in the village centre)	22 minutes
Travel time from the village to the ZCAP	40 minutes
Evacuation time from the start of the evacuation to the ZCAP (BML)	38 minutes

Several weaknesses were identified in the exercise:

- The village square is 225 meters from the outermost point, making the use of the bell impractical;
- The security officer used door-to-door notifications, which was stressful due to steep terrain. It would be more efficient to use alternative methods, given that the officer is aware of guests at the hotel;
- Tourists delayed departure for about 10 minutes waiting for a driver who had been left behind;
- Some tourists may try to leave independently, risking accidents. It is recommended that authorities manage the evacuation to avoid this;
- Resistance during real evacuations could cause delays, especially as tourists may need time to pack belongings.

The village's infrastructure does not meet the safety standards for sheltering. Timely evacuation guided by authorities is the safest option.

C - Trizio village exercise aimed to evaluate the integration of previously tested scenarios, focusing on the differing behaviors of residents and non-residents. The goal was to assess the operational effectiveness of a scenario encompassing both groups. A simulated scenario required both the village and the tourist area to seek refuge. The locals would shelter in the village recreation center, while tourists would gather at the river beach (Figure 34).

Upon receiving the alert, the local security officer rang the bell and conducted a door-to-door survey to inform residents. Authorities were also notified about the need for a specialized vehicle to evacuate a resident with specific needs. In the river area, limited tourist presence prevented meaningful conclusions, but procedures, such as directing tourists to shelter, were followed. The evacuation timeline is shown in TABLE XVIII.

TABLE XVIII - Trizio Exercise Timeline.

Total duration of the evacuation exercise	70 minutes
Alert time for the population (calculated estimate)	2.10 km / 5*km/hour = 0.42 hours Approximately 25 minutes Time distributed between two security officers = average of 12.5 minutes each, to cover their part of the village
Evacuation time to the refuge (from alert to arrival in shelter)	24 minutes

Key constraints identified include the size of the village, where the chapel bell's sound does not reach all areas. Reduced mobility residents were evacuated promptly, with those unable to reach safety remaining at home with family members.

Despite some areas requiring improvement, significant insights were gained:

- The village security officers and forces ensured that all houses were checked;
- A pre-existing map, combined with a digital version, enabled effective coordination with authorities;
- The use of two security officers reduced the survey time significantly;
- Inhabitants did not resist during the exercise, but real-life resistance could delay evacuations.

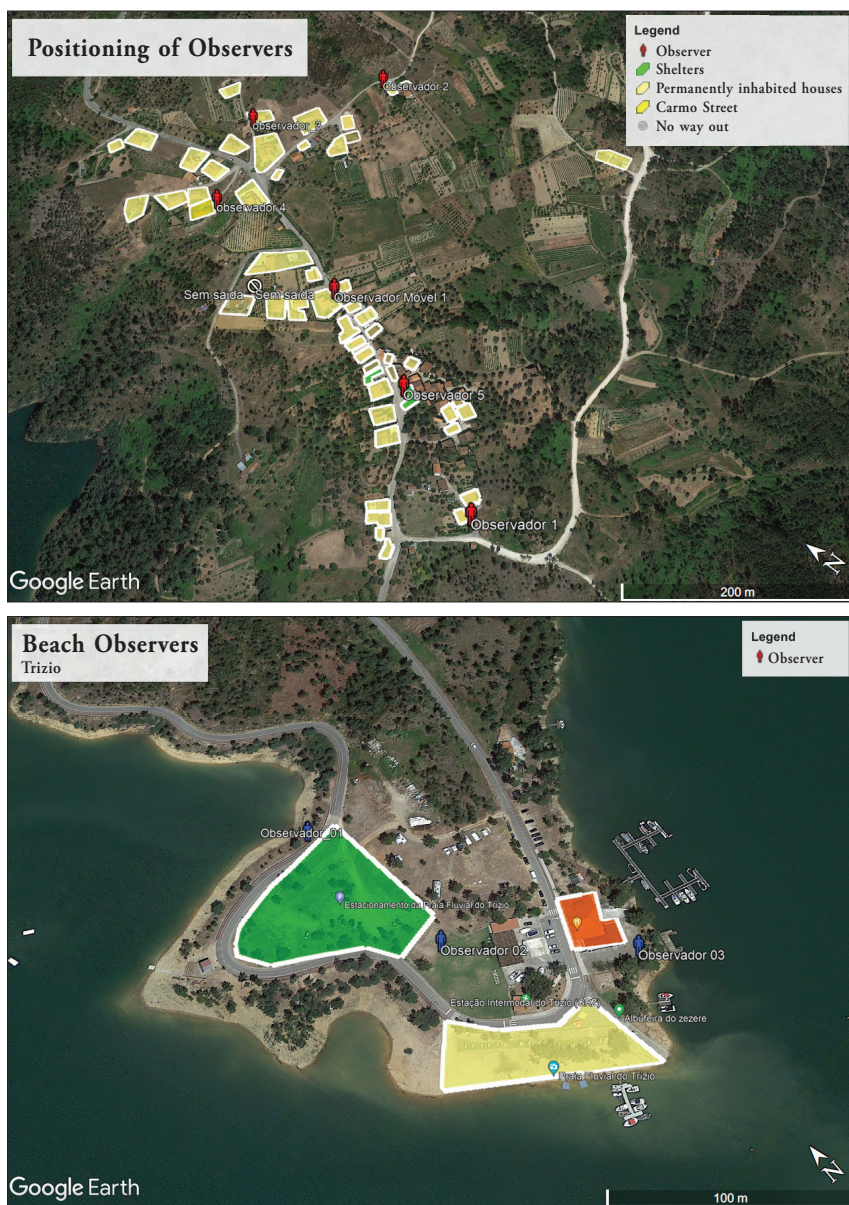


Fig. 34 - Position of observers and victims (Prepared by Andreia Rodrigues, ISISE).

The evacuation time was efficient, but issues with parking near shelters and the use of personal vehicles could complicate real-world evacuations.

D - Ribeira da Misarela exercise aimed to simulate a rural fire scenario affecting the entire right bank of the Mondego River, with widespread evacuation needs (Figure 35). The scenario tested the ability of the inhabitants and parish council to work autonomously during the initial moments, before the arrival of rescue entities, with coordination and communication managed by the command post.

Upon receiving notification from the command post about the approaching fire, the local security officer, the parish council president, and police began informing residents door-to-door using a megaphone, a process necessitated by the village's terrain.



Fig. 35 - Surroundings of Ribeira da Misarela (Data source: google maps).

During this process, authorities identified a resident in a difficult-to-access area with mobility challenges, requiring specialized evacuation support (Figure 36). Once gathered in the town square, residents were registered and transported to a shelter. The recorded information was then organized and presented in the TABLE XIX.



Fig. 36 - Evacuation support at Ribeira da Misarela
(Photograph of Andreia Rodrigues (ISISE) taken on tirada a 25/01/2025).

TABLE XIX - Ribeira da Misarela Exercise Timeline.

Total duration of the evacuation exercise		91 minutes	
Evacuation time to the shelter, after notification by the authorities		33 minutes	
Calculated time to warn the population, without counting downtime.		1.13 km / 5**km/h = 0.226 hours Approximately 14 minutes	
Inhabited Houses with participants	9	Average time spent in each house: 2 minutes	Total time in each house (ring doorbell, describe what is happening and ask to leave) 2 minutes *9 houses ≈ 18 min.
Removal time for bedridden elderly woman		30 min from ambulance activation to leaving the village	
Number of inhabitants with resistance to leaving		2	
Number of animals evacuated		2 dogs	

Key constraints identified:

- The lack of a safe shelter within the village necessitates evacuation;
- There is no automatic alert system, such as a bell or siren, making door-to-door notification time-consuming,
- Narrow roads create challenges for simultaneous vehicle passage, particularly emergency vehicles;
- Limited telecommunication and radio network coverage hinders communication.

Positive aspects:

- The pre-existing mapping and identification of vulnerable individuals facilitated communication with authorities;
- Two residents, who initially resisted evacuation, eventually complied, highlighting the need to reinforce evacuation urgency, especially for those wanting to stay to protect property;
- The evacuation process was orderly, with residents bringing pets in response to the evacuation order.

7.3. Conclusions from Evacuation Exercises

In all villages, a hypothetical scenario involving the approach of a high-intensity rural fire was simulated, requiring a decision from the Operational Command Post regarding the protection of the inhabitants. In Cabanões, a residential village with a high percentage of elderly and mobility-impaired residents, the evacuation to a local chapel, 250 meters from the village center, was tested. This evacuation was deemed effective when undertaken with anticipation, but it would have been challenging if the fire were imminent. The chapel is considered the safest refuge in the village, providing an accessible option in an emergency.

In Ribeira da Misarela, no suitable shelter exists, and evacuation outside the settlement is necessary. Due to the steep terrain and the risk of rapid fire behavior, the buildings in the village are insufficiently fire-resistant to offer protection. Therefore, evacuation is the only safe option, requiring early preparation and training.

In Cerdeira, a tourism-only village, evacuation is a priority for tourists, who, unfamiliar with fire risks, may attempt to self-evacuate, which can lead to greater exposure to danger. This finding highlights the need for enhanced communication and training for tourist accommodations to ensure guests are informed about safety options and that local authorities are involved in evacuations.

Trízio, with both residential and tourist elements, showed that a secure shelter exists within the village, but communication with beachgoers is vital to prevent self-evacuation, which could obstruct the evacuation of residents and visitors. The safest

option is to direct beach users to the shelter while maintaining clear communication and coordination with authorities.

It was observed that no village had a reliable general alert system, and in all cases, local security officers had to personally alert residents and guide them to safety. The evacuation time is closely related to the walking distance to the shelter and the terrain's slope, which significantly delays the process. The time to react to the alert was generally around 3 minutes, with residents collecting essentials and securing their homes. Training and awareness were found to reduce evacuation times, but individuals without prior training took longer to decide on actions.

The evacuation of people with special needs, such as bedridden individuals or those with mobility impairments, significantly delays the process. It is recommended that such individuals be pre-identified to ensure quicker activation of specialized resources, allowing the evacuation of other residents without delay.

Chapter 8

EVACUATIONS PLANS AND RECOMMENDATIONS

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8.1. Emergency Management at the Parish Level

8.1.1. Introduction

In Portugal, many isolated settlements are difficult to access and are predominantly inhabited by elderly people or individuals with disabilities. These areas are often located in regions with a high risk of wildfires. Rural abandonment, particularly in the northern and central regions, has intensified this issue: villages are becoming increasingly isolated, populations are aging, and forest areas are encroaching on inhabited zones due to residents' reduced capacity to engage in agriculture or clear surrounding vegetation. These dynamics, together with broader sociodemographic changes, have increased the number of vulnerable people exposed to wildfire hazards (Manzello *et al.*, 2018).

The aforementioned factors, combined with the sociodemographic changes experienced in Portugal, result in an increasing number of inhabitants being exposed to the danger of rural fires (Molina-Terrén *et al.*, 2019). An analysis of the victims of wildfires in Portugal in 2017, focusing on their behavior when the fires approached, revealed that 25% of the victims died inside their homes, having been caught by the fires, without receiving an alert or evacuation order (Rodrigues *et al.*, 2022). This highlights the urgent need to identify in advance the locations and individuals with limited perception or mobility, so that authorities can evacuate them from danger zones proactively.

Emergency management refers to the period between the onset of a crisis and the arrival of organized assistance, aiming to protect people and property while reducing adverse impacts (Alexander, 2002). In Portugal, parishes are the lowest level of local government, operating within municipalities to serve local populations (Freitas do Amaral, 1987). There are currently 3,091 parishes: 2,882 in mainland Portugal, 155 in the Azores, and 54 in Madeira. Parish councils play a vital role in governance due to their proximity to communities, allowing them to identify local vulnerabilities more effectively. They are particularly well positioned to support the most at-risk groups and to assist in emergency preparedness. By maintaining updated local databases, parish councils contribute to timely and informed decision-making during emergencies.

8.1.2. Proposed approach

Considering the awareness raised above, a methodology was developed involving parish councils, where individuals working within this structure could actively contribute to maintaining an updated database of the most vulnerable people and those with special needs who require special attention during natural disasters.

Steps

The identification and analysis of population vulnerabilities are fundamental in the current scenario of climate change, both for preventing and preparing for

disasters and for facilitating relief during emergencies. To facilitate the inventory process of the most vulnerable population and those with special needs, three essential steps were established:

- Identification of clusters at risk: In this step, local authorities identify the highest priority villages to focus on, based on the type of population, the village's surroundings, and its accessibility.

- Survey of the vulnerable population: Visits are carried out to the villages, with purposes such as monitoring the local inhabitants, finding where the inhabited houses are and surveying to identify the type of inhabitants and recording of any special need that must be taken into account in case of an emergency.

- Processing and making data available: All collected information is entered into Google's My Maps, with only data relevant to emergency planning being recorded.

The simple step-by-step application scheme allows us to identify some implementation advantages that allow for greater acceptance by those involved (Figure 37).

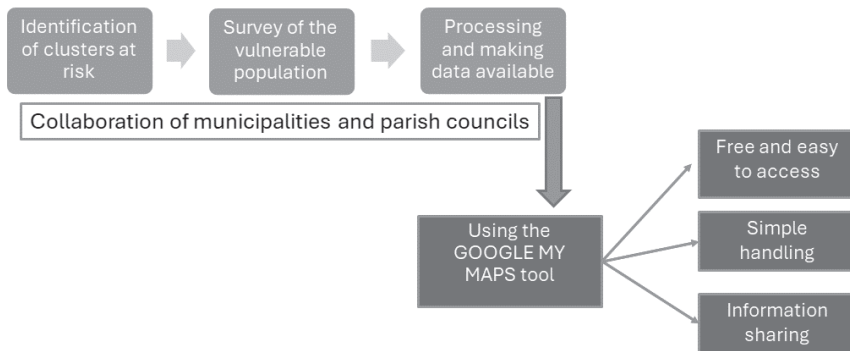


Fig. 37 - Inventory procedure (Rodrigues *et al.*, 2025).

After identifying the villages at greatest risk, an on-the-ground survey of people with physical and mental limitations is carried out, and these are recorded on a grid but also marked in the Google My Maps tool. This tool provides easy and free access, requiring only internet access and a smartphone for the operator. The application only records the location of the person with limitations, their housing conditions,

and any special needs, without adding any personal information or sensitive data. Once the database is established, authorized users can add or update information at any time. All this information can be printed off or consulted offline on a mobile phone without the need to install any software or use complex GIS tools.

Validation - After organizing the steps, this procedure was tested in four parishes in the center of Portugal, in the municipalities of Lousá, Miranda do Corvo and Anadia. Meetings were held with parish council representatives to discuss the added value and challenges of the procedure. The aim is to use this system for a year to evaluate its advantages.

Following the surveys, in which the local population was involved, council staff updated the database whenever there were changes in occupation, e.g., death of a resident or new inhabitants. As the population felt involved and was satisfied with these procedures, the village inhabitants themselves began alerting the council to changes in occupation, becoming important players in the entire process. The information remains constantly updated in platform (Figure 38), and in two cases, it has been tested through a simulation exercise.

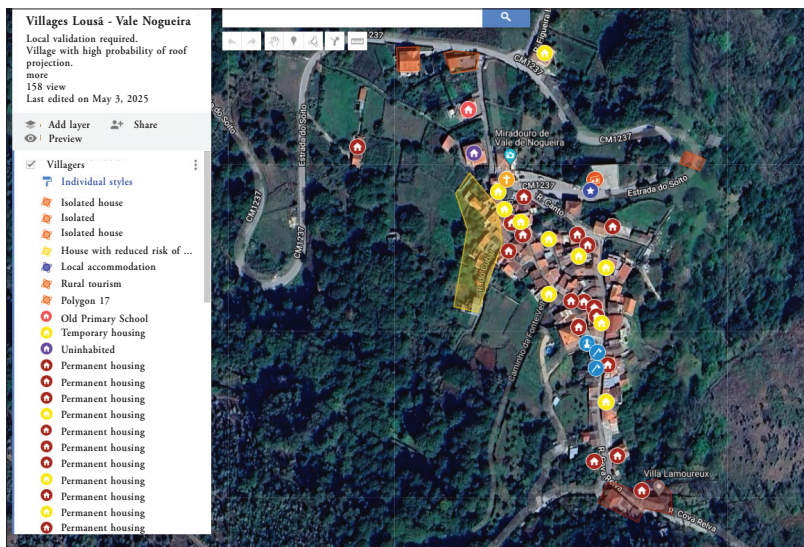


Fig. 38 - Graphic representation in MyMaps by Google of the village of Vale Nogueira, with all georeferenced inhabitants (Adapted from Rodrigues *et al.*, 2025).

In this exercise, it was observed that information was easily shared with operational decision-makers, facilitating decision-making and resource planning. When a large fire approaches, the command post provides real-time information, which can be integrated into decision support systems, thus being used in decisions such as the need to evacuate a village.

After a year of use, those responsible for the parish councils were interviewed and were invited to present the advantages and limitations of the procedure. The parish councils identified the following advantages:

- The ease of use of the application motivated them to use it in other villages;
- Georeferencing the most vulnerable people and those with special needs become important, not only for forest fire situations but also for other relief needs;
- The ease of sharing this information allowed, for example, the improvement of patrolling actions by security forces.

The main constraints were identified:

- There are mobile network difficulties in some areas of the interior of Portugal—in some situations, data insertion and updating could not be carried out in the village itself. This same difficulty could compromise the sending of information to the command post in a real fire situation;
- In larger parishes, to keep the database up to date, it was suggested that each village have a liaison officer.

8.2. Relevant National Legislation and Framework for Actions on Emergency Evacuations

It is highlighted regulatory provisions related to fire safety—both in terms of buildings themselves and their location in areas considered particularly hazardous—with emphasis on Decree-Law No. 82/2021 of October 13, which approved the so-called Integrated Rural Fire Management System. This system contains provisions related to both fuel management and building restrictions. Regarding fire safety in buildings, it was found that Decree-Law No. 220/2008 of November 12 establishes the Legal Framework for Fire Safety in Buildings, regulating minimum standards

for construction materials and equipment, and identifying locations and risk categories. However, these regulations are mostly restricted to protection against fires originating within the building itself and do not consider the risks of rural fires. It is Order No. 8591/2022 of July 13, in turn, that addresses rural fire safety in buildings. Additionally, since they are related to the adaptation of behaviors to best practices for minimizing the risk of rural fires, the relevant regulations concerning insurance, tax matters, and criminal matters were also presented.

Regarding the legal framework for evacuation actions, territorial planning instruments and civil protection legislation were of particular relevance. The former, due to their purpose of minimizing fire risk and establishing rules that allow for proper land use planning, including in relation to forest occupation. As instruments for anticipating future actions, these regulations not only enable the consideration of building locations in fire-hazard areas but also allow for the anticipation and planning of evacuation routes, emergency exits, and shelter locations when such buildings are erected in these areas. Civil protection, in addition to being integrated into territorial planning instruments, provides the basis for evacuation procedures in emergency situations. In this regard, the following relevant legal instruments were identified: the Civil Protection Framework Law (Law No. 27/2006); the National Operational Directive for the Special Device for Combating Rural Fires (DECIR); and the Municipal Forest Fire Defense Plans. The key entities involved in evacuation processes include the National Emergency and Civil Protection Authority (ANEPC), the Institute for Nature Conservation and Forests, and the National Command for Relief Operations.

Finally, the most common phases of the systematic evacuation processes of areas affected by forest fires to safe shelters were identified, notably:

- Education and public awareness, aiming to inform the population about emergency risks and prepare them to act when necessary;
- Pre-planning/emergency planning, including the identification of vulnerable areas, mapping of evacuation routes, provisioning of shelters, and communicating evacuation needs to the population;
- Alert and notification, aiming to inform residents about the imminent threat of a fire;

- Inter-institutional coordination, involving civil protection authorities in defining an incident management team and coordinating efforts to ensure a safe and efficient evacuation;
- Evacuation orders, which must be clear and specific;
- Assistance to evacuees, including the provision of transportation for individuals who cannot evacuate on their own;
- Continuous communication with evacuees;
- Monitoring and evaluation, particularly regarding the fire situation, the condition of evacuation routes, and the capacity of shelters;
- Regular training and drills involving both the community and personnel responsible for evacuation procedures;
- Registration of evacuee data, including contact information, special needs, and current location; and
- Post-fire recovery, aimed at facilitating the safe return of evacuees to their homes and providing psychosocial and psychological support, along with resources for recovery.

8.3. Legal Aspects of Evacuation Planning in Wildfire Scenarios

This section aimed to present guidelines—drawing from national, international, and comparative law—that can support the development of evacuation plans for populations in forest fire situations in Portugal. The objective was to complete Task 6 by defining the procedures that should guide a systematic evacuation of disaster-affected areas to safe shelters, including recommendations on their preparation.

Specifically, this study analyzed: (i) the legal framework governing evacuation plans in Portugal, covering relevant civil protection legislation and the national guidelines of the Safe Village, Safe People (Aldeia Segura, Pessoas Seguras) Program; (ii) the enforceability of evacuation orders and plans for individuals; (iii) foreign regulatory strategies that guide systematic evacuations during forest fires; and (iv) international perspectives on natural disaster management relevant to evacuation planning in forest fire contexts.

8.3.1. Legal framework for evacuation planning in wildfire scenarios in Portugal

Evacuation planning is essential to ensure that all people at risk are evacuated safely and in a timely manner, to address the population's needs for shelter and assistance, and to enable the proper mobilization and management of personnel, resources, and capacities. Disaster risk prevention, planning, and reduction are fundamental responsibilities of states, as outlined in the Sendai Framework for Disaster Risk Reduction 2015-2030, which establishes targets, priorities, and principles adopted by UN Member States to enhance global disaster resilience for both present and future generations. Under these guidelines, governments are responsible for strengthening the capacity of local authorities to evacuate people living in disaster-prone areas.

In Portugal, as previously noted in the legal study, risk management—from prevention and preparedness to response and relief—falls under the scope of Civil Protection. Emergency planning, which includes evacuations in cases of risk manifestation (Amaro, 2023), is a key aspect of preparedness activities. In this regard, Article 50 of the Civil Protection Framework Law establishes civil protection emergency plans as formal documents that outline the operational guidelines for civil protection authorities, bodies, and services at different levels. These plans are automatically activated in cases of a contingency declaration or a calamity declaration (Articles 17 and 21) and may also be triggered in alert situations, subject to assessment by the territorially competent political coordination structures (Article 14).

Furthermore, Article 8 of Resolution No. 30/2015 of the National Civil Protection Commission states that these plans not only serve as frameworks for the organization of operational command posts, civil protection agents, and support entities but also provide a reference for drafting other directives, operational plans, or prior intervention plans that put the strategic guidelines into action. Within this framework, evacuation plans for forest fire scenarios are classified as operational plans and must align with and adhere to the guidelines set out in general or special civil protection emergency plans, depending on the circumstances.

Following the devastating forest fires in June and October 2017, Council of Ministers Resolution No. 157-A/2017 introduced structural changes to wildfire

prevention and response strategies. Among these measures, two key programs were established to enhance public safety:

- Safe People Program – Focused on raising awareness about risk prevention, self-protection measures, and conducting evacuation drills in coordination with local authorities;
- Safe Village Program – Designed to implement structural measures for protecting people, property, and buildings located in the urban-forest interface.

Within the scope of these programs, evacuation plans have been developed specifically for rural fire-prone areas with heightened risk levels.

The study also examined the Safe Village, Safe People program: Implementation Support Guide, published by the National Civil Protection Authority. This document provides guidance for implementing activities that ensure the protection and security of people and property in rural fire scenarios. It covers five key areas: *“I. The protection of built-up areas through the management of buffer zones and the creation of self-protection mechanisms; II. Prevention of risky behavior that could lead to fires starting; III. Raising the population’s awareness and notifications; IV. Evacuation of built-up areas; V. Preparation of shelters and places of refuge”*.

Regarding evacuations, the document outlines essential planning considerations: preliminary study of the community; awareness, preparation, and training of the population; consideration of spontaneous evacuations (without a formal plan); consideration of mandatory evacuations (ordered by civil protection services and/or agents); and assessment of situations where remaining in place may be preferable to evacuation.

The guide also highlights key variables to be considered when designing an evacuation plan:

- Identification and profiling of potential evacuees, with special attention to vulnerable groups (children, the elderly, people with reduced mobility, individuals with disabilities, and residents who can assist in operations);
- Presence of tourist areas or locations with foreign nationals (requiring multilingual information) and areas with restricted access;
- Available transport capacity (both private and collective), taking into account the number of people to be evacuated and evacuation routes;

- Time available for evacuation, factoring in the time needed to issue warnings, ensure acceptance, mobilize resources, select routes, and move the population;
- Identification and selection of key stakeholders, such as civil protection agents, volunteers, local security officers, and influential community members;
- Identification of evacuation routes and designated shelter or refuge areas;
- Identification of vegetation-free zones suitable for relocating livestock.

The guide emphasizes the importance of public participation in evacuation plan development and highlights the need for training and exercises to test the effectiveness of warning mechanisms, evacuation times, road suitability, and priority evacuation procedures. It also presents a model evacuation plan, which should include:

- Situation – A summary of the fire risk, affected population, and supporting maps.
- Entities involved – A list of individuals and organizations participating in the evacuation plan, as outlined in the Municipal Emergency and Civil Protection Plan.
- Warning procedures – Steps for notifying relevant entities about a rural fire requiring evacuation, including communication mechanisms.
- Notification procedures – Methods for informing the population, including phone contacts and alerts issued by the Municipal Civil Protection Service, Parish Council, National Republican Guard (GNR), Fire Department, or volunteer associations.
- Evacuation procedures – Steps for safely relocating residents, prioritizing vulnerable individuals, marking evacuation routes, and ensuring security forces enforce evacuation orders.
- Shelter/refuge procedures – Locations for in-place sheltering if evacuation is not feasible.
- Temporary accommodation procedures – Identification of temporary housing locations and the provision of essential services such as food, clothing, and medical care, along with the responsible entities.

Regarding the enforceability of evacuation orders, international legal guidelines—such as those established by the UN Inter-Agency Standing Committee

and the UN Guiding Principles on Internal Displacement—stipulate that forced evacuation is only not considered arbitrary if:

- (1) It is provided for by the law.
- (2) It is absolutely necessary to address an immediate and serious threat to life and health, and no less intrusive measures would suffice.
- (3) To the extent possible, affected individuals have been informed and consulted before the evacuation.

If these conditions are not met, individuals who refuse to leave cannot be forcibly evacuated. Additionally, even when all legal requirements are satisfied, some legal scholars argue that the state cannot impose coercive measures to remove individuals from at-risk areas, given the fundamental rights of self-determination and autonomy (Bruce, 2018).

8.3.2. International regulatory strategies

After analyzing Portuguese legislation to understand the framework of evacuation plans, the guidelines for their preparation and reflecting on whether or not they bind individuals, an analysis on guidelines for evacuation planning from other countries prone to forest fires – Australia, the United States of America, Spain and Greece – and international human rights law was carried out, which can contribute to improving evacuation planning in Portugal, respecting the differences between legal systems.

With regard to Australia, the analysis was based on the recommendations contained in the Evacuation Planning handbook (2023), prepared by the Australian Institute for Disaster Resilience in conjunction with the Australian Government National Emergency Management Agency. Although the manual in question does not deal exclusively with forest fires, applying to a variety of natural disasters, it incorporates and reflects recommendations and lessons learned from the fires that occurred between 2019-2020; and serves as a reference for the preparation of emergency plans in the context of forest fires in Australia. Hence the importance of analyzing its insights, which may contribute to the planning of evacuations in forest

fires in Portugal. Going into the manual's guidelines, it follows that evacuation planning needs to consider and have five phases:

- Decision to evacuate: With regard to this phase, the evacuation plan needs to: 1) identify which organization or person has the authority to decide to evacuate; 2) identify the relevant stakeholders involved and impacted by the decision to evacuate; 3) indicate how stakeholders and the affected community will be informed about the evacuation decision; 4) identify the resources needed for subsequent phases, where they will be acquired from and how they will be activated; 5) present a template to facilitate the risk analysis that will assist in making the decision to evacuate;
- Warning: In relation to this phase, the evacuation plan needs to: 1) identify the person or entity with the authority to activate the evacuation alarms/warnings; 2) identify the triggers for warnings; 3) present templates with the content of the warning messages (with specific actions that people should take, location of meeting points, evacuation routes); 4) identify the community groups, businesses and organizations to whom the warnings should reach, including considerations about specific needs that need to be taken into account when sending such warnings; 5) identify a series of methods for making the warnings that can be used to ensure reach to the affected community, such as websites, social networks, mobile applications, telephone, in person, sirens, radios, etc.;
- Withdrawal: Specifically regarding the evacuation phase itself, it is important that the evacuation plan: 1) identifies the person or entity with the authority to manage the evacuation of people and other actors involved in the evacuation; 2) details specific plans for risk groups, including the location of shelters and contacts; 3) locates exit routes, including alternatives; 4) locates vehicle control points and transit areas; 5) presents transportation possibilities with contact information; 6) contains provisions for managing community safety (police patrols, for example); 7) presents a communication sub-plan, in order to identify how information about the evacuation will be communicated to those managing the evacuation and also to the evacuees;

- Shelter: With respect to shelters, the evacuation plan should: 1) identify the organization with authority and competence to manage the shelter phase; 2) identify the different shelter options, their different purposes and characteristics, and how they can be used; 3) consider how the needs of specific groups will be met in the shelters; 4) identify measures to ensure the health and safety of shelter staff and evacuees; 5) identify sources for services and supplies needed in evacuation centers, such as food, water, hygiene products, bedding, animal feed, etc.; 6) consider places to shelter animals and also evacuees who are assisted by animals; 7) present the necessary procedures for the use of a registration system during the shelter phase; 8) include a communication sub-plan that identifies how evacuees will be kept informed about issues affecting shelter and recovery; 9) Identify alternatives in case shelter capacity is exceeded or compromised; 10) Present exit strategies;
- Return: Finally, with regard to the return phase, the evacuation plan must: 1) identify the entity or person with authority and competence to manage the return of evacuees; 2) identify the actors involved in the return phase; 3) present guidelines for a risk analysis related to the return phase; 4) identify restricted areas; 5) identify return options; 6) present a communication sub-plan concerning the return phase.

In relation to the United States of America, the study analyzed the guide prepared by the US Department of Homeland Security, entitled Planning Considerations: Evacuation and Shelter-In-Place – Guidance for State, Local, Tribal and Territorial Partners (2019), a document that aims to support state, local, community and territorial actors in planning evacuations or shelter-in-place, summarizing characteristics that jurisdictions must consider in this process. It should be noted that, as in the case of Australia, the guide is not exclusively intended for planning evacuations in the context of wildfires, but also for other natural disasters. However, the background that led to its preparation involves, among other disasters, the wildfires that occurred in California in 2017, which forced the evacuation of more than 100,000 people.

The document highlights the roles and responsibilities of individuals and families, who must develop their own plans to be prepared to take protective measures in the event of a disaster; private sector entities, which must also prepare,

plan, coordinate, and execute evacuation and shelter-in-place processes in the event of disasters impacting workplaces; and state, local, tribal, and territorial governments, which have the primary authority and responsibility for evacuation and shelter-in-place planning.

In the context of evacuations, it is up to governments to:

- 1) Establish clear expectations of community partners (i.e., what the community is expected to do in the event of a disaster) through informational, educational and training sessions;
- 2) Establish and clearly communicate evacuation routes and zones to the community, as well as alternative routes in case of changes in evacuation dynamics;
- 3) Identify community evacuation centers and shelters to which evacuees can go to other communities if needed, working cooperatively with these neighboring communities to establish notification and operation procedures;
- 4) Develop accessible, pre-approved messages for rapid dissemination of incidents and instructions concerning shelter and evacuation;
- 5) Have an ongoing plan to maintain operational responses if they are interrupted;
- 6) Provide real-time mapping and navigation route systems through the Geographic Information System and private sector tools.

The document also points out that evacuation and shelter planning should consider that the evacuation process itself has five phases: mobilization; evacuation and shelter-in-place; impact; displacement/mass care; and re-entry. The existence of these phases contributes to the construction of plans, organization and coordination of response strategies, communication, tasks and decision-making. It is also worth highlighting the reference to the complex issues that must be considered by planners and civil protection during the preparation of the plan, its simulations or execution, such as: accessibility, children and unaccompanied minors, domestic and sexual violence in shelters, evacuation time, fuel supply, homeless people, animals, legal requirements and authorities, mass care and shelter services, population assessment, terminology used in communication, and tourists.

As for Spain, it was found that the country has a civil protection system aimed at providing effective and coordinated responses to emergencies arising from the risks of forest fires, floods, other diverse meteorological phenomena, seismic,

volcanic and technological risks; this system organizes the actions inherent to the emergency cycle, covering anticipation, prevention, planning, immediate response and recovery. The Civil Protection Code (Updated edition of July 10, 2024) in the country systematizes the basic regulations concerning civil protection, the regulations applicable to each specific risk, and the civil protection laws of the autonomous communities. Special attention was given to the study of evacuation planning by Royal Decree 893/2013, of November 15, which established the “Basic guideline for planning civil protection for emergencies due to forest fires”. The aforementioned directive was repealed by Royal Decree 524/2023, however it will continue to be applied in Spain until the approval of a new planning instrument to replace it.

The aforementioned directive establishes the minimum requirements to be met in forest fire emergency plans, in terms of foundations, structure, organization, operational and response criteria; both for the state plan and for the plans of the autonomous communities, for local action plans and for the so-called self-protection plans. The aforementioned plans concern civil protection measures that allow the risk of catastrophic situations to be reduced for people, property and the environment. It can therefore be concluded that in Spain, evacuation planning in the context of forest fires is inherent to the emergency planning itself, and there is no mandatory separate evacuation plan.

The regulation establishes the following basic elements for emergency civil protection planning arising from forest fires: (1) risk analysis (danger, vulnerability, territory zoning and danger periods); (2) potential severity index of a forest fire; (3) operational situations contemplated in the plans, including emergency situations that seriously affect the population and non-forest assets, requiring the immediate adoption of measures aimed at protecting and assisting the population; and (4) basic actions to be considered in the plans.

It is in the element relating to basic actions that the need for evacuation planning to be included in civil protection plans is expressly foreseen. In fact, the basic actions to be considered in the plans are: detection, extinction and warning; public safety; health support; information to the population; confinement, evacuation and accommodation; and logistical support.

Civil protection emergency plans, according to the regulations, must provide for the network for detecting and warning of forest fires; foresee actions necessary for controlling access and traffic, as well as for the custody of goods and maintaining public order; establish a medical device necessary for assisting the injured and how coordination is structured for eventual transfer to other health centers; determine the appropriate mechanisms for warning the population, in order to alert them about the fire and the most appropriate measures to be adopted in the event; foresee evacuation routes, evacuation points, actions aimed at transferring the population that is in the risk zone, and adequate accommodation in safe areas; and stipulate how the supply of equipment and supplies necessary for carrying out all the previous actions will occur.

The guideline also highlights the importance of considering appropriate assistance for people with disabilities or in other vulnerable situations in planning. Civil protection emergency plans must, at this point, present specific action protocols in the different phases of the emergency that guarantee effective assistance, with procedures for mobilizing and implementing the resources necessary to meet the needs of people with disabilities. Furthermore, the plans must contain preventive information and alert programs, enabling citizens to adopt timely measures; these programs must have appropriate formats and mechanisms necessary to be accessible and understandable to people with disabilities or in other vulnerable situations. Finally, the guideline provides that the different services that intervene during forest fires must receive specific training to serve this population.

Following these basic elements inherent to all plans, the guideline goes on to address the different levels of plan (state, autonomous communities, local and self-protection). In what concerns the report, the local action plans stand out, as they are the ones that most directly address the procedure for evacuating the population affected by fires to a safe area. These plans can be municipal or local entities, and their objectives are: a) to provide for the organization and procedures for intervention in forest fire emergencies within the territory of the municipality or local entity to which it corresponds; b) to establish systems of coordination with organizations of other local administrations; c) to zone the territory according to the risk and possible consequences of forest fires; d) to provide for the organization

of local groups for prevention and first intervention against forest fires and to encourage self-protection; e) to establish information and training measures for the population; f) to catalogue means and resources to implement the planned activities; g) to implement self-protection measures for urban centers and buildings.

In order to achieve these objectives, local plans must comply with the minimum content set out in the guideline, which covers fundamental aspects not only for preventing and fighting fires, but also for evacuating the affected population and their respective accommodation, as per the following list: purpose and territorial scope of the plan; territorial description; cataloguing of situations in the urban-forest interface and their associated risk; description and location of support infrastructures for fire-extinguishing work; local organization for fighting fires and dealing with emergency situations in their different phases – fire detection and notification, actions during the fire and at the end of it; operational organizational procedures, including with regard to forest fire alarm/warning; specification of basic actions and procedures for informing the population for their self-protection, evacuation and accommodation; specific procedure for management and actions for evacuating the population during forest fires; specification of basic logistical support actions; catalogue of the resources available to implement the planned activities; promotion of actions to promote, disseminate and control corporate and citizen self-protection; and annexes of self-protection plans drawn up within its territorial scope.

Finally, in relation to Greece, it was found that following the fires that occurred in 2018, the country sought to improve its disaster management system, enacting Law No. 4,662/2020, which strengthened the country's civil protection regulations. When commenting on the explanatory memorandum of the aforementioned law, Zacheilas and Papadakis (2020) emphasize that the continuous increase in the intensity and extent of natural and technological risks in Greece in recent years has made it urgent to adopt a more modern, effective and flexible mechanism in terms of risk and crisis management, prioritizing the guarantee of life, safety, health, property and cultural heritage. Under the aforementioned law, the responsibility for developing plans to mitigate the effects of natural disasters (including forest fires), including with regard to the implementation of early evacuations, lies with

municipalities and regions. On 18 April 2023, the Secretary General for Civil Protection issued specific guidelines to the responsible authorities on the creation of special plans for early evacuation in forest fire scenarios, which are developed in collaboration with a number of entities, such as the fire department, the police, health services, etc.

The guidelines provide that early evacuation is a measure to be adopted to protect life and health in situations where the risks of remaining at home in the face of the threat posed by fires are greater than the risks of moving to a safe place. Evacuation may be total or partial and the decision regarding this is made by mayors in the case of a disaster occurring at a local level; by the regional governor in the event that the disaster affects more than one municipality; or by the general secretary of civil protection in the event that the disaster affects more than one region. According to the regulations, evacuation decisions are not mandatory, that is, they are not binding on citizens; however, citizens must be informed in advance about the risks and possible consequences if they choose to remain in their homes.

Evacuation plans, in turn, must include: (i) procedures to be adopted for decision-making about evacuation; (ii) alternative routes for the removal of citizens and measures to ensure them; (iii) means and possibilities for transporting citizens, including public transport; (iv) procedures for providing information to the population before and during the evacuation, including people with mobility difficulties or other special needs; (v) actions to be taken to provide temporary shelters/refuges for evacuees and the necessary care.

Specifically with regard to the places where evacuees will be sheltered and which must be included in the evacuation plans, the guidelines highlight the fundamental importance of these shelters protecting the population from hot gases, smoke and other combustion products released and dispersed into the atmosphere as a result of the fire.

After the local authorities have made the decision to evacuate, the regulations emphasize that in addition to the affected population and those to be evacuated being notified by means of mass emergency messages, the municipality must also inform citizens door-to-door at every opportunity through official vehicles, social networks, among other mechanisms. The communications must ensure that people

are informed about the limits of the area from which and to which citizens will be evacuated; whether all people in the affected area will be evacuated or only specific groups identified by priority (people with respiratory problems, children, the elderly, etc.); what the safe routes are if the population is to evacuate on their own/by their own means of transport; what temporary shelter locations there are; what measures citizens must adopt to ensure the protection of their property (such as closing doors, windows, etc.); how pets will be evacuated; etc.

Other points to be considered when planning evacuations include estimating the number of people to be evacuated, determining meeting points and how people will gather at the meeting point, the time needed to notify citizens, traffic control and management, communication between the different agencies involved in the evacuation, reception and registration of citizens who are being evacuated, the time needed to evacuate people from the affected area, how evacuated citizens will return to the area where they lived, and official telephone contacts so that the population can request information.

The guidelines also highlight the care that must be taken with communication between people belonging to vulnerable groups and their respective caregivers. To this end, when planning evacuations, it is possible to consider the option of organizing a register (which will be an annex to the evacuation plan), provided that consent is given, of the people who are part of these groups – with contact details, addresses, type of disability, contacts of any caregivers or relatives, and means of transport necessary for their travel. This register will facilitate communication in the event of a fire and when it is necessary to implement the evacuation. It is also necessary to adequately plan the transport of these groups and also how support (such as care) will be provided in the accommodation/shelters.

8.3.3. International perspectives on evacuation planning

Having understood the main recommendations for planning evacuations in forest fire scenarios in these countries, we proceed to analyze international human rights standards that must be observed both in the planning and execution of evacuations.

At an operational level, a human rights framework allows for a better understanding of the needs and interests of the affected population, the identification of rights and duties holders, the recognition of limitations on what can be asked of individuals, and the assurance that humanitarian actions align with human rights standards. This framework underpins the requirements for forced evacuations and relocations; it also justifies the necessity for health services, food, and shelter to be accessible to people with special needs, requiring actions to guarantee this, among other considerations.

In this regard, several international legal documents, particularly soft law instruments, provide important guidelines for planning and implementing evacuations resulting from natural disasters such as forest fires. In addition to the Sendai Framework for Disaster Risk Reduction 2015-2030 and the UN Guiding Principles on Internal Displacement, which have already been discussed, two key references stand out: the IASC Operational Guidelines on the Protection of Persons in Situations of Natural Disasters and The Mend Guide – Comprehensive Guide for Planning Mass Evacuations in Natural Disasters.

The IASC Operational Guidelines on the Protection of Persons in Situations of Natural Disasters categorize the principles and measures to be adopted by States in natural disaster contexts into four main groups:

- Group A: Focuses on protecting life, safety, physical integrity, and family ties;
- Group B: Relates to protecting rights to food, health, housing, and education;
- Group C: Concerns the right to housing and property, employment, and access to secondary and higher education;
- Group D: Covers rights related to documentation, freedom of movement, re-establishment of family ties, freedom of expression and opinion, and electoral participation.

Within Group A, eight key principles must be observed during evacuations, which must also be considered when developing evacuation plans:

- The life, physical integrity, and health of people exposed to risks from natural disasters, including those with specific needs, must be protected to the maximum extent possible, regardless of their location;
- If the above measures are insufficient to protect lives, efforts must be made to facilitate the safe exit of those at risk from the danger zone;

- If individuals cannot leave the danger zone on their own, their evacuation must be ensured;
- No person should be forcibly evacuated unless: the evacuation is provided for by law, is absolutely necessary to address a serious and imminent threat to life and health, less intrusive measures have proven inadequate, and—where possible—people have been properly informed and consulted;
- Regardless of whether the evacuation is forced or voluntary, it must fully respect the life, dignity, freedom, and security of those affected, without discrimination. To the extent possible, communication should be accessible and provided in a language understood by the affected population, explaining the evacuation process, duration, and reasons;
- Support must be provided to enable evacuees to remain as close as possible to their usual residences, provided that these locations are safe;
- Evacuation centers or temporary shelters must be safe, protect evacuees from additional risks, and provide adequate and dignified living conditions;
- International and non-governmental organizations involved in humanitarian aid should not organize or participate in forced evacuations, except when an imminent and serious threat to life, physical integrity, and health cannot be mitigated without their intervention.

The Mend Guide: Comprehensive Guide for Planning Mass Evacuations in Natural Disasters (2014) serves as a reference for local, municipal, regional, and national bodies to develop or improve evacuation plans based on best practices in emergency management. According to the guide, evacuation is a process that begins with preparing for a potential evacuation in high-risk disaster situations and only concludes when evacuees are safely and voluntarily reintegrated into their original homes or alternative locations. Some issues are relevant to all phases and must be considered in both the planning and execution of evacuation plans. These include:

- The legal basis for evacuations and the protection of evacuees (covering both national and international legislation);
- The distinctions between voluntary and forced evacuations, as well as the specific requirements for the latter;

- Other legal aspects, such as prior agreements with potential evacuation centers, custody arrangements for unaccompanied minors, allocation of resources, agreements between municipalities or countries depending on the disaster's scale, regulations on evacuees' data protection, and evacuees' rights under the applicable legal framework.

Understanding the roles and responsibilities of different actors in evacuations is crucial. Thus, when developing an evacuation plan, all stakeholders and decision-makers involved must be identified, along with their respective responsibilities and the decision-making process. Furthermore, during a disaster, there must be emergency response entities operating 24/7.

Among the various actors involved, governments bear the primary responsibility for protecting at-risk populations. However, the role of civil society organizations at local and national levels must not be overlooked, as they support evacuations and provide shelters for evacuees. The media also plays a fundamental role in disseminating crucial information regarding the disaster and evacuation procedures.

The guide also emphasizes the synergy between different levels of planning—community, local, regional, national, and, when applicable, global. Each level's plan should align within the legal and operational framework of the others. This ensures that additional resources can be identified and that response capabilities from other levels can be activated if necessary. Moreover, specific institutional evacuation plans (e.g., for hospitals, schools, and prisons) must be integrated into the general evacuation framework of the respective community or municipality to ensure efficiency and effectiveness.

Before an evacuation plan is even developed, governments must establish Early Warning Systems, which should include risk awareness and assessment; monitoring, analysis, and forecasting of potential disasters; communication and dissemination of alerts and warnings; and local response capacity. These warning systems are crucial, as they ensure that scientific data is translated into practical information for the population.

Evacuation planning must take into account the specific needs of vulnerable groups, including:

- Women, particularly regarding reproductive health, primary care responsibilities, and protection from violence, abuse, and exploitation, especially in mass evacuations and collective shelters where privacy and dignity may be at risk;
- Unaccompanied children, who must be protected from risks such as human trafficking, exploitation, and abuse;
- People with disabilities and the elderly, who may require assistance with mobility and access to essential services;
- Prisoners, isolated communities, school groups, tourists, and third-country nationals, who may need specialized support, including translation services and documentation assistance.

To protect evacuees, shelters must guarantee basic needs, including sanitation, water, food, electricity, telecommunications, first aid, and security. Additionally, services should be planned to support evacuees' recovery and reintegration, such as financial assistance, employment and livelihood counseling, interpretation and legal services, family tracing assistance.

Planning these services requires an assessment of: the expected duration of the evacuation/displacement, the immediate, medium-term, and long-term service needs, the service providers involved, and the storage and distribution of essential goods.

8.4. Summary of Key Evacuation Procedures

The legal study conducted over the past two years has highlighted essential aspects of evacuation planning. Whether established as a standalone operational plan or integrated into broader civil protection emergency plans, evacuation planning must encompass several critical phases: the decision to evacuate, notifying relevant authorities, alerting the population, executing the evacuation process by moving people to shelters or safe locations, providing temporary accommodation and necessary care, and finally, facilitating the return process.

Evacuation plans must be developed with community participation, regularly tested through training and simulations, and continuously reviewed, discussed, and

disseminated. These plans must align with Portuguese legal requirements (particularly civil protection laws) and adhere to international standards for disaster response.

A crucial element of evacuation planning is distinguishing between voluntary and compulsory evacuations, as well as the option for individuals to remain in shelters within their community. Compulsory evacuations should only be implemented if explicitly authorized by law, deemed absolutely necessary to protect lives and public health, and if less restrictive measures are insufficient. Additionally, affected populations should be informed and consulted whenever possible. Failure to meet these conditions renders compulsory evacuations arbitrary under international human rights law.

Another key factor in effective evacuation planning is communication at every stage of the process. This includes coordination between responding agencies and clear, accessible messaging for the affected population. Plans should define communication channels (ranging from social media to door-to-door notifications), use clear and understandable terminology, provide official contact numbers, and include standardized message templates. Inadequate communication, especially if it fails to account for the specific needs of different population groups, can hinder the evacuation process and increase risks to public health, safety, and lives.

Evacuation plans should also outline designated evacuation routes, meeting points, transportation options (including public transport), and shelter locations. Considerations such as evacuation timing, population size, traffic management, and resource allocation must be carefully addressed to ensure a well-coordinated process.

Furthermore, the needs of vulnerable groups—including children, women, the elderly, migrants, refugees, homeless individuals, and people with disabilities or chronic illnesses—must be prioritized throughout the evacuation process, from initial notification to transportation and shelter arrangements. Special provisions should also be made for the evacuation of animals and individuals who require assistance animals, as this involves additional logistical considerations such as tracking, feeding, and veterinary care.

Additionally, ensuring the safety of evacuees within shelters is critical, particularly in preventing risks such as domestic violence. It is also important to emphasize that evacuation planning extends beyond simply relocating individuals

from high-risk areas. Authorities must also plan for ongoing support during the displacement period and ensure a structured and safe return process—whether to their original homes or to alternative housing.

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Wildfires are increasingly recognized as one of the most complex and intensifying natural hazards, exacerbated by the impacts of climate change. Their frequency and severity have escalated notably in Mediterranean and temperate regions, posing significant threats to human lives, infrastructure, and ecosystems. In Portugal, the devastating wildfires of 2017 exposed critical vulnerabilities in emergency response systems and highlighted the pressing need for a more integrated approach to wildfire risk assessment, evacuation planning, and community resilience.

Against this backdrop, effective evacuation planning, coordinated territorial management, and informed community engagement have become essential elements of wildfire risk mitigation. This book provides a comprehensive approach to these issues, drawing on the EvacuarFloresta research project (2021–2025). By combining field research, spatial modeling, and behavioral studies, the book bridges the gap between academic knowledge and practical applications, focusing on effective evacuation planning, coordinated territorial management, and informed community behavior.

This book is aimed at researchers, emergency planners, and students in fields such as geography, civil protection, and urban planning. It serves as both a scientific resource and a practical guide for improving wildfire risk management, contributing to safer, more resilient communities.

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