MIGUEL ALMEIDA
COORD.

SCIENTIFIC PERSPECTIVES ON WILDFIRE RISK MANAGEMENT AT THE WUI PROPERTY SCALE

The dramatic impacts of wildfires worldwide, particularly when they reach Wildland-Urban Interface (WUI) areas, are the primary motivation for this book, which focuses on fire risk management in the defensible space around buildings. It offers different perspectives on WUI characterization, vulnerability, ignition mechanisms, fuels management, self-protection systems, fire behavior modeling, and regulations. With contributions from experts worldwide, the book provides an integrated view of key aspects and developments in WUI fire risk management.

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Technical abstract

The increasing prevalence of fires in the Wildland-Urban Interface (WUI) poses significant threats to both built heritage and human life safety. Understanding the complexities of fire behaviour in WUI areas is crucial, prompting the need for widespread knowledge dissemination. Lamsaf *et al.* (2024)[1] conducted a comprehensive analysis of scientific publications related to WUI, revealing a substantial growth in research since 2000, when publications on this topic were minimal. This underscores the importance of compiling and organizing existing knowledge addressing various aspects of fire risk management in the WUI.

Understanding the diversity of the WUI scope, this book primarily focuses on fire risk management at the defensible space, encompassing one or more isolated buildings and their surroundings within a range of some tens of meters. While not the main focus of the book, much of its content can be extended to community-level fire management or to fire risk management at the wildland-industry interface areas.

Authored by contributors from various fields of knowledge and different countries, this book comprises nine chapters.

[1] Lamsaf, H.; Lamsaf, A.; Kerroum, M.A.; Almeida, M. ”Assessing trends in wildland-urban interface fire research through text mining: a comprehensive analysis of published literature”. Journal of Forestry Research (2024): https://doi.org/10.1007/s11676-024-01722-w

These chapters begin with an introductory overview (Chapter 1) and a characterization (Chapter 2) of WUI; Chapter 3 addresses the classification of vulnerability, also providing basic definitions on WUI fire risk; in Chapter 4 the main mechanisms of ignition affecting infrastructure are described; Chapter 5 is dedicated to the fuel management practices in the building surroundings, while Chapter 6 focuses on self-protection systems; WUI fire behaviour modelling is developed in Chapter 7; finally, Chapter 8 outlines an international perspective on the main regulatory aspects in the field. The book closes with the conclusions chapter.

Each chapter has a dedicated coordinator who, due to his/her internationally recognized scientific contributions in the field, was invited to perform this role. In turn, each chapter coordinator invited a group of coauthors with work experience related to the chapter's subject matter to contribute texts, in a sequence that provided coherence and allows readers to gain an integrated view of the scientific knowledge in that area. Thus, although the book has overall coherence and an integrated structure, the chapters present some independence from each other.

With no intention to cover all topics or include every scientific development in WUI fire risk, the book aims to provide a comprehensive overview of fire risk management in the defensible space, facilitating an understanding of key aspects and current developments in the field.

This book was produced within the scope of the project "House Refuge - Development of Best Practices and Standards for Buildings and their Surroundings in Wildfire Risk Areas" (https://houserefuge.adai.pt), which was funded by the Foundation for Science and Technology (https://www.fct.pt), with reference PCIF/AGT/0109/2018. However, as previously mentioned, this book was written by various authors with different affiliations, not all of whom being part of the House Refuge Project Consortium.

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Scientific perspectives on wildfire risk management at the property scale of WUI

Preface

Jack Cohen
Ph.D., US Forest Service Research Scientist, retired; WUI fire expert

A trend of increasing community destruction during wildfires is apparent. The United States (US) provides a prime example. In 1985, 1400 homes and structures burned during wildfires. This motivated the establishment of the US national “Wildland-Urban Interface (WUI) Initiative”, a collaboration of Federal and state agencies directed by the National Fire Protection Association, a US private organization (Laughlin and Page 1987). Approximately 9000 homes burned during US wildfires from 1985 to 1994, the first decade of the WUI Initiative. The recent decade from 2012 to 2021 had over 45,000 US homes burn during wildfires. The US policy and funding response has predominantly focused on increasing firefighting capacity and fuel treatment to increase wildfire suppression effectiveness. However, community fire destruction will continue as long as reactive wildfire suppression is the primary approach.

Disastrous community destruction (100 homes and greater) has only occurred during extreme wildfire conditions when initial attack fails, and control is not possible (Cohen 2010; Calkin *et al.* 2014). The inevitability of extreme wildfires, exacerbated by increasingly frequent, persistent hot-dry weather due to climate change, suggests inevitable disastrous home destruction. However, readily observable patterns of unconsumed tree canopies and other vegetation surrounding totally destroyed homes indicate high intensity wildfires did not spread through communities. Research results indicate practical opportunities for effectively creating ignition resistant homes and thereby preventing community fire disasters without necessarily controlling wildfires (Cohen 2000a; Cohen 2001; Cohen 2004; Cohen and Stratton 2008; Cohen 2010; Calkin *et al.* 2014; Cohen 2017; Cohen and Westhaver 2022).

Patterns of Home Destruction during Extreme Wildfires

Wildland-urban fire disaster examinations reveal the typical post-fire pattern is unconsumed vegetation, often remaining green, adjacent to and surrounding total home destruction during extreme wildfires (Cohen 2000b; Cohen and Stratton 2003a; Cohen 2003b; Cohen and Stratton 2008; Graham *et al.* 2012; Cohen 2017; Cohen and Westhaver 2022). The typical WU fire pattern, exemplified in Figure 1, indicate the following:

- High intensity wildfires typically do not continuously spread through residential areas as a wave or flood of flame (Figure 1a).
- Unconsumed shrub and tree canopies adjacent to homes do not produce high intensity flames that ignite homes (Figure 1a,b).
- Homes typically ignite from lofted burning embers on the home, low intensity surface fire spreading to contact the home, or in high density development, structure-to-structure fire spread (Figure 1a,b,c).
- The “big flames” of high intensity wildfires are typically not the cause of total home destruction (Figure 1a,b,c).

(a) *(b)* *(c)*

Figure 1. Patterns of destruction

Disaster examinations have determined that intense wildfire flame fronts do not continuously spread within communities having moderate to high structure density (for example, Figure 1a; density greater than 3 homes per hectare). A community's streets, utility corridors, driveways, parking areas, building sites, etc. create gaps in the continuous tree and shrub canopies that cease high intensity wildfire spread (Cohen 2010). Extreme wildfire conditions initiate ignitions within residential areas but burning structures and vegetation continue fire spread within the community. Burning structures become the principal source of burning embers and flames continuing community fire spread hours after significant wildfire activity ceases adjacent to the community (Cohen and Stratton 2008; Cohen 2010; Cohen and Westhaver 2022).

Local Conditions Determine Ignitions

The converging agreement of WU fire research from disaster examinations, modelling and laboratory and field experiments has found that local conditions principally determine structure ignitions during extreme wildfires. Research (Cohen 2000; Cohen 2004) has quantified local ignition conditions to include a home and its immediate surroundings within 30 meters. Within that area, ignition potential depends on the degree of structure ignition vulnerability related to its burning ember and flame exposure. This area has been called the home ignition zone — HIZ (Cohen 2001; Cohen 2010; Cohen and Westhaver 2022).

The typical WU fire patterns indicate a structure's local conditions principally determine its ignition. The unburned area surrounding the destroyed home in Figure 2a indicates lofted burning embers as the principal source of ignition directly on the home or from ignited materials immediately adjacent to the home, or both. Regardless of the lofted distance, burning ember ignitions depend on a structure's materials and design that make it vulnerable to ignition. This home's ignition vulnerability determined the high HIZ ignition potential.

Equally, local ignition conditions determine low ignition potential. The home in Figure 2b survived without controlling the extreme wildfire (Graham *et al.* 2012). The relatively small surrounding area that did not burn with high intensity wildfire did not produce sufficient radiant heating or flame contact to ignite the house, and the house was sufficiently resistant to sustained burning ember ignitions — an ignition resistant HIZ.

(a) *(b)*

Figure 2. Local ignition conditions

Effective Reduction of Community Wildfire Risk

Community wildfire risk analysis indicates structure ignition resistance, and collectively the community, as the most effective approach for preventing WU fire disasters (Finney and Cohen 2003; Calkin *et al.* 2014). Community ignitions leading to WU fire disasters have only occurred when wildfire control fails during extreme wildfire conditions in all fuel types: grass, shrubs and forests (Cohen 2010). These wildfires typically burn during high wind speeds and low relative humidity producing high spread rates and intensities that overwhelm control. These are the “target conditions” of community wildfire risk (Calkin *et al.* 2014). Given significant potential for an extreme wildfire exposure, community fire risk factors are wildfire control, home and structure ignition potential, and structure protection effectiveness. Reducing community wildfire risk depends on the degree (probability) of controlling wildfire to critically limit community ignition exposure, reducing structure ignition potential, and increasing community fire protection to prevent and extinguish sustained structure ignitions. Given the inevitability of extreme wildfires, a reactionary wildfire suppression and control approach fails and cannot reliably reduce community wildfire risk. During extreme wildfire conditions, an ignition vulnerable community can simultaneously ignite multiple structures thereby overwhelming community structure protection. Thus, structure fire protection cannot reduce community wildfire risk without sufficient structure ignition resistance. Reducing structure ignition potential remains the principal factor for reducing community wildfire risk; thus, WU fire disasters must be defined and approached as a home-structure ignition problem, not as a problem of wildfire control.

We can effectively and practically reduce community wildfire risk and prevent WU fire disasters by creating ignition resistant homes-structures and collectively, the community. In high density community development, increasing structure-to-structure fire spread resistance is additionally essential. Without necessarily controlling extreme wildfires, ignition and structure fire-spread resistant communities can increase community fire protection effectiveness, provide options for increasing resident and firefighter life-safety, and increase options for more effective management of inevitable wildfires.

Jack Cohen

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1.

Introduction to wildland-urban interface fires — relevance of the problem

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1.1. Emergence of the problem of the WUI

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In the late eighties of past century in wildfire science and practice the term Wildland-Urban Interface was introduced, referring to the places where potentially flammable vegetation and houses meet (Blue-Ribbon Panel, 2007) highlighting the importance of a problem that already existed, but which was becoming of increasing importance in the whole issue of wildfire risk management. Possibly it is not "the problem", but it is certainly one of the major problems that fire managers must deal with and one that adds even greater complexity to all aspects of fire management.

The main reason for this is because at the WUI it is not just forests, houses and fires that meet, but as rightly recalled by Ribeiro in (Ribeiro, 2016) it is also the place where persons are and can be affected by spreading fires. The protection of people and their assets brings new dimensions to the already multidimensional problem of fire management in the context of the WUI, that of structure and civil protection. The term Wildland-Human Interface (WHI) was even proposed to highlight this complexity (Robinne *et al.*, 2016).

In the context of the WUI when we mention the threat posed by a wildfire, we must consider both the heat released and the smoke produced by the combustion process.

The problem of WUI is increasing throughout the World, mainly because settlements in cities or in rural areas are growing, moving into areas covered by vegetation. However, in other cases, the abandonment of cultivated areas around villages gave place to forested plots or shrublands. Many new houses are built as a second residence to be used in vacations, but as in many countries these coincide with the summer season when the fires are more frequent, the problem is compounded by the fact that sometimes they are occupied by tourists that are not used to the presence of fire and require more guidance and help. In a research note J. Cohen (2008) rightly indicates that the wildland-interface fire problem is a consequence of the fire exclusion paradigm, although this is not the only cause, it is certainly a very important factor.

Unfortunately, the problem of the WUI acquired great visibility due to an important number of accidents in various countries in which fires threatened populations living in the WUI, causing many deaths and an incommensurable loss of property. Examples of these are Peloponnesus in 2007 (Koutsias *et al.*, 2012), Victoria in 2009 (VBRC, 2009), Pedrógão Grande (Viegas *et al.*, 2017) in 2017, Matti in 2018 (Lekkas *et al.*, 2018), Maui in 2023 (HSDH, 2023), and Viña del Mar, Chile in González, M. E., Syphard, A. D., Fischer, A. P., Muñoz, A. A., Miranda, A., “Chile’s Valparaíso hills on fire”, Science, 383(6690), 1424-1424 (2024).

Associated to the problem of WUI there is the emergence of another problem related to the impact of wildland fire on industrial settlements and also on infrastructures of common interest. This problem is designated generically as the Wildland Industrial Interface (WII) (Planas *et al.*, 2023) and encompasses not only industrial and commercial areas, that are very often implanted near forested areas and therefore subject to fire hazards, but also other structures that support the life of the communities. As they are usually of relevant economic value and a source of employment, their loss can have a great socio-economic impact. The same can be said about some critical infrastructures, like roads, electrical, gas and telecommunication networks, which loss can affect the safety of the population and the capacity to protect them (Johnston and Flannigan, 2018). Although this problem cannot be dissociated to that of the WUI, given the scope of the House Refuge Project and its focus on the community protection scale the problem of the WII will be only briefly mentioned in this Book.

1.2. Diversity of situations

Wildfires depend on the following factors: (i) fuels, (ii) topography, (iii) meteorology and, as they are intrinsically of dynamic nature, (iv) chronological time (Viegas, 2004), which can vary from one place to another and at a given place can change in the course of time. The WUI adds many other factors to the control parameters, like for example, the layout of the houses and structures, the type of constructions, the number, age and occupation of the residents or visitors, their economic level, the layout of gardens or other spaces surrounding the houses, fuel accumulation (both natural and non-natural), the existence of fire protection systems, or other equipment that can increase the risk, like gas containers. All these factors bring a large diversity of situations and specific problems in different settlements, making it necessary to approach the problem of the WUI in the various countries and regions in a piecemeal fashion, to cope with the specificities of each case. Even so, it is possible to address some common and general aspects of the WUI problem, as we try to do in this Book, although it covers mainly the situations in Southern Europe and specially in Portugal.

One of the main differences between the situation of the WUI among the various countries is the type of housing and their construction materials. In some countries, like the USA, Canada and Australia, the house structure and panelling, mainly near forested areas, is made of wood and other flammable materials, making these constructions very vulnerable to fire. In some regions of Southern Europe houses in the rural areas are mostly built with bricks and stones, with ceramic tiled roofs that make these houses in principle more resistant to fire. In other regions of the world, informal settlements do not have any kind of planned or imposed resistance to wildfires. In both cases — of wooden or brick houses, — usually the impact of fire is not caused directly by the approach of the flaming fire front, but rather by embers projected by the main fire at a short to medium distance. These embers may reach flammable materials in the outside of the houses or fall inside openings and other weak points of their structure — like the roofs or ventilation openings - and ignite them, sometimes even several hours after the passage of the main fire. This may happen in both cases of wooden or brick houses and cause their destruction, especially if there are no firefighting forces or other people to protect the house after the passage of the main fire.

Besides the so called conventional or usual areas of WUI we may have also some unusual or unconventional areas such as camping sites, musical, sport, religious or political festivals or get-together events, which may promote the movement and sojourn of a large number of persons — often unfamiliar with the area — into places that can be potentially affected by fires. This type of events creates particular problems to fire managers because usually there are no structures to facilitate the ingress or egress of persons and fire protection resources, or spaces to separate the vegetation from the people and their accommodation. In camping areas, besides the vehicles, the caravan and tents, there may be gas containers, that compound the risk to the people and to firefighters.

We cannot forget that in some cities, especially in developing countries, there can exist urbanizations consisting of poorly built houses, located close to each other. Even if there is no vegetation inside these neighbourhoods, a fire that reaches them or that starts inside them, can have devastating effects, as fire can spread easily from house to house, as it is observed in some WUI fires.

The presence of domestic animals at the WUI creates and additional and sometimes very difficult problem to citizens and managers. The life of animals, although not so important as that of persons, must be preserved and suffering or death of animals should be avoided as far as possible. Pets and other domestic animals mean a lot to their owners, and it is important to plan ways to evacuate them in good conditions or to keep them safe during a fire. There are many cases in which people risk their lives and sometimes even perish, trying to save their animals. A particular case is a site where large numbers of pets or other animals are kept, like stables, veterinary hospitals, pet hotels and others. They should be a concern to city planners and to civil protection authorities. The transfer or the protection of these animals may create particular problems that require planning and preparation as they may require specialized personnel and equipment to perform it and these will certainly be difficult to get at short notice during a fire.

As was mentioned above, a case of particular relevance is the presence of commercial or industrial areas in the outskirts of towns and villages, in the vicinity of forested areas. These are usually large areas with relatively large buildings with relevant occupation of people or materials that are flammable, both inside and outside the buildings. Given the social and economic importance of these areas for the local communities, the protection of these areas deserves a special attention.

In fire prone regions the authorities may identify areas that are particularly risky, due to their orography and past fire history. In some countries restrictions can be imposed, regarding limitations or even abolishment of new constructions or the need to review the protection of existing houses or the need to install protective systems, like water sprinklers to complement obligatory fuel reduction measures.

1.3. Challenges of the WUI

Due to their implicit complexity the problem of the WUI poses challenges to a large group of stakeholders, namely to scientists, engineers, policy makers, fire managers, fire fighters, citizens. An interesting approach to the risk management at the WUI is proposed in Calkin *et al.* (2014). It is out of the scope of this book to address all these challenges, but to illustrate their connections and the need to have an integrated approach to its management with a dialogue and collaboration of the various stakeholders, we shall briefly describe some of them. A good review of the current research approaches and needs can be found in Mell *et al.* (2010).

The very definition of the problem of the WUI, its description and the characterization of the parameters required to describe and analyse it, are challenges that scientists from various areas must address, to create a set of concepts and a specific terminology to facilitate the dialogue among the various stakeholders that are involved in the management of the problem. This is very important as sometimes there are ambiguities, poorly defined concepts, and lack of consensus that make the problem of the WUI an attractive topic for many scientific disciplines.

The description of the WUI environment in its various scales, goes beyond the usual fuel mapping and characterization, as other types of natural and non-natural fuels are present, requiring more detailed analysis and the use of concepts that are more familiar to combustion and chemistry. From the scientific and engineering standpoint, the WUI requires the merging of wildfire and structural fire sciences. At the WUI the process of fire spread in the vegetation is compounded by the presence of structures and materials that ignite and burn in different ways. Therefore, the problem of predicting the spread of a fire in an area of WUI is even more complex, as we may have vegetation burning and spreading the fire to other vegetation or to houses. We may have houses burning independently or spreading fire to each other or to more vegetation, and so on. A good review of the pathways to build fire spread in the WUI can be found in Caton *et al.* (2017) or Hakes *et al.* (2017) in which emphasis is put on the role of spot fires. We may also have fire suppression activities which may reduce the problem, or, on the contrary, cascading effects, like explosions and other complex processes, like for example the burning of industrial facilities or gas stations.

The problem of the WUI affects a wide set of stakeholders, besides those involved in common wildfires. We consider the city planners, as the design of the cities and their neighbourhoods near forested areas require special attention to increase the resilience of the communities. This is important not only to newly planned communities but also to existing communities. For example, ingress and egress roads for both residents and rescuers must be designed to minimize congestion problems and the width of the streets and roads must be adequate to reduce the house-to-house ignition probability.

As was explained the layout of the urban areas can influence the probability of a house, a group of houses or even a whole village not being affected by an approaching fire. Although there are many uncertainties in this process, due to the random behaviour of spot fires, there are nevertheless guidelines that city planners should follow to improve the resilience of a settlement and to reduce the probability of it having great damages. The structure ignition assessment model proposed by Cohen (1995) established the path to assess the potential risk for structures which has been improved by later work including more extensive experimental work and numerical modelling (Caton *et al.*, 2017); Hakes *et al.*, 2017; Cohen, 2000). For already existing villages, especially in the case of old or historical places, there is less freedom to intervene, as it may not be possible to change existing narrow and winding streets that limit the access to fire trucks for example. In these cases, in some countries the interesting experience of building ring roads around the villages was performed. This facilitates the egress of the residents to any required direction and also the access of fire suppression forces to any sector of the village and their capacity to give a peripheric protection to the settlement.

In the case of new constructions, the layout of the streets, trying to keep them sufficiently wide, with good signals and with frequent roundabouts or turning points is recommended. Houses should be built at sufficiently large distances to minimize house to house fire spread and the existence of inclined terrain should be dealt with particular care.

It is important to find in each settlement or village one or more location where the citizens can shelter or take refuge in case of a fire. These facilities should be prepared not only for the usual residents but also for visitors and for rescuers as well. We consider a refuge a place that can even be open, like a plaza, a sport field or similar, where people can stay and be protected from direct impact of flames and embers, and possibly from smoke, at least for the duration of the major fire passage. We consider a shelter an enclosed space where people can remain for longer time without being affected by the heat and smoke of the fire. In some cases, the own homes or annexes are a good shelter, but this may not be the case, as in the fire of Lousã in October of 2017, where two brothers died while seeking refuge inside a warehouse that was not prepared to resist the intensity of the approaching fire (Viegas *et al.*, 2019). In these situations, places like churches, schools, social clubs must be designated and referenced in the plans as possible shelters. Some communities purposely built shelters that were planned to fulfil this role (Caballero *et al.*, 2021).

Cars and other vehicles are an important asset for many persons, due to their commercial and practical value. Therefore, many persons put a great put a great effort in sheltering their vehicle to avoid its loss, sometimes losing their lives in this process. Provisions and plans to avoid these actions in the last minute should be taken to reduce the number of fatalities.

For fire fighters the WUI creates additional challenges and uncertainties as in the WUI there are many more factors affecting and modifying fire behaviour. At the same time a set of houses and buildings can provide a shelter or safety area for firefighters in the case of a threatening wildfire, at least temporarily.

The suppression of fire in the houses may require specialized equipment, like urban-firefighting vehicles and heavier protective equipment for the fire fighters, as very high thermal loads can be created in some of these fires, not to mention the case of commercial or industrial facilities that was already mentioned.

Policy makers must produce adequate regulations and laws for the layout and construction of the houses and of their surroundings, namely on the use of construction materials or solutions that are recommended or should be avoided in WUI high risk areas.

According to our experience in Portugal, stone and brick houses are not usually destroyed by direct flame impact during the passage of the fire. Very often they are affected by spot fires that land on some weak point — a roof, an open window, a heap of litter or wooden material near the house — and remain burning for some time and then inflaming and spreading the fire to the house. This process can take several hours and according to the experience that we have collected, if there are persons, either fire fighters of residents, near the house, if they manage to detect and reach these hot spots, there is a large probability of extinguishing these initiating fires and saving the house. For this reason, many citizens chose to remain at their homes when a fire is approaching. If they have mental and physical capacity to face the situation and if the house provides them sufficient protection during the fire impact, this decision can contribute to reduce the amount of damage to the built environment. Given the risk that it implies it must be considered carefully by both the citizens and the authorities, as it is well illustrated in the paper by Haynes *et. al.* (2010). It should be the object of previous planning but subject to a change of decision in a case-by-case basis.

The medical services also must be prepared for the case of a catastrophic event, with multiple injuries or even fatalities. The existence of personnel, specialized medical products and facilities should be planned as these accidents may occur in remote areas with limited access.

1.4. An Engineering approach to the WUI

As stated above, wildfires spread through a series of complex mechanisms involving the transport of heat and mass from the flame front, which in WUI areas can damage and ignite assets and structures. It is the ignition of several assets in quick succession which typically leads to catastrophic events at the WUI, particularly when the response capabilities of fire brigades are overwhelmed (Karels, 2022). With the current trends of increasing populations living in WUI and more generally wildfire-prone areas, coupled to land-use changes and the effects of climate change already being perceived in several parts of the world, it is becoming apparent that several societies are experiencing a shift towards greater wildfire risks (Planas *et al.*, 2023; Pandey *et al.*, 2023).

The magnitude of the problem outweighs the available resources and human capacity to control the most severe incidents, posing a problem for fire safety engineers and decision makers striving to protect their communities. Since all risks and hazards are spatially distributed, it is advisable to allocate time and resources in a systematic manner which focuses on those areas subjected to higher risks. Other disciplines which also face high consequence loss scenarios, like the chemical process safety, atomic energy, and aerospace industries (CCPS, 2000) have a long tradition in quantifying and managing risks, particularly using probabilistic (or quantitative) risk analyses. These structured methods have been highly successful, becoming a model of how approaches based on first principles and sound engineering judgement can deliver solutions that meet all the required safety goals.

This brief account will use risk-based process safety (CCPS, 2007) as a blueprint for structuring the problem of risk management from a fire safety engineering perspective. Together with the following chapters of this Book, it is expected that this section will help the reader grasp a broad perspective of the problem at hand and understand how all the elements in the coming chapters fit into place. Additionally, we have attempted to generally show research needs associated with every component of WUI risk management from an engineering perspective. Part of the information presented herein is based on the work carried out as part of the Society of Fire Protection Engineers (SFPE) Foundation's WUI Working Group Initiative (SFPE, 2023), a collaborative effort to identify gaps and critical needs in several engineering aspects related to WUI fires, in which the three authors participated.

1.5. Fire risk management at the WUI

In terms of fire phenomena, risk can broadly be defined as the probability of suffering physical damage due to the release of energy contained in a fire hazard. Depending on the nature of the analysis, fire risk can relate to injuries or deaths in the case of risk to individuals and communities, or to property losses if the engineer is dealing with industrial or urban sites. In this sense, fire risk is a function of an ensemble of energy release scenarios for a particular site associated to the different hazards identified, their frequency (or likelihood) and their consequences (a combination of the magnitude of the physical insults on a target and its response) on individual assets (Kaplan, 1997). Additionally, risk is related to the safeguards, a combination of passive, active, and procedural layers of protection implemented and eventually inherently safer designs, which act to reduce the likelihood and consequence of particular scenarios (Severino, 2022; Moore, 2013). However, regardless of all the efforts in implementing safeguards and reducing hazards, it must be recognized that risk can never be zero.

Risk should also be regarded as a relative, rather than an absolute, metric. Considering the nature of risk, it gives a measure of the likelihood of future events and their consequences, and therefore is expressed in the probability domain (Kaplan and Garrick, 1981; Johansen, 2010). Consequently, it can be argued that risk cannot be measured (CCPS, 2000), rendering impossible all attempts to validate risk estimates or probability statements in general (Lind, 1996; Goerlandt *et al.*, 2017). Therefore, risk analysis is most useful when used as a systematic way to compare and rank the risk to assets, locations or communities, and guide decisions regarding the implementation of different safeguards, and in general the management of those risks.

There are many challenges associated with carrying out a risk analysis in WUI areas. They include the potentially large geographic extent of the study area, the nature of the hazards or fuels (e.g. wildland/structural fuels, vegetation species, morphology, moisture content, age, stress state) and their spatial and temporal variations, uncertainty on ignition frequencies, particularly when the anthropogenic component must be considered, uncertainty in wildfire behaviour modelling, lack of understanding of firebrand generation, transport and spotting ignition, the large variability in fire loss scenarios in urban/industrial locations due to the wide spectrum of assets and their state, and large uncertainties in human behaviour and evacuation procedures at the community scale (Planas *et al.*, 2023; Severino *et al.*, 2022). This highlights the need to improve the fundamental knowledge in several aspects of wildfire behaviour, but also a need for reliable data (Manzello *et al.*, 2018).

Fire risk estimation is only one component of a comprehensive risk management system (Planas *et al.*, 2023; CCPS, 2007). With knowledge of the risks in the study area, the decision maker should act to mitigate the risks (this is typically known as risk assessment). These decisions could be guided by provisions defined in building codes or by local authorities. These provisions should include some form of risk tolerability criteria, which correspond to goals for the maximum value of risk at particular locations. However, this poses the problem of using risk in an absolute sense, but if these documents also include guidance on the risk analysis methodologies, the equivalence between different analyses will be assured. Risk mitigation actions can include a reduction of the fire hazards in the wildland area and actions to reduce the vulnerability of assets on the urban side.

Additionally, the implementation of these actions requires the commitment of the local community to mitigating risks and maintaining these conditions in time. Efforts are thus needed to create awareness of the problem; programs like Firewise in the USA and FireSmart in Canada are good examples of this while also contributing to community preparedness and structure resilience. Finally, the risk management system should be able to learn from experience, both locally and from other WUI fire incidents. This includes the application of best practices, keeping metrics on system performance, a review and correction of system failures or shortcomings revealed by near misses and incidents, and monitoring the evolution of the wildfire hazards and risks, particularly under a climate change scenario. It is through the combination of these elements that the risk management system will produce consistent results in a sustainable manner during the entire life cycle of the area being protected.

1.6. Risk estimation

The use of quantitative risk analysis (QRA) to estimate risks is a well-established practice, e.g. in the chemical process industry or in the atomic energy industry. In fire safety engineering, the use of these tools is also an accepted practice (Ramachandran and Charters, 2011), but there have been few attempts to adapt it to WUI - and WII - related settings (Planas *et al.*, 2023; Severino, 2022; Khakzad *et al.*, 2018; Vacca, 2023). This can be mainly attributed to the challenges presented previously, but also to a lack of progress of fire safety engineering techniques for WUI fires. Additionally, there have been attempts to implement risk analysis frameworks which are mostly applicable to the landscape or regional scales rather than the property scale and have mostly focused on wildfire risk and land management rather than fire risk at the WUI (Calkin *et al.*, 2011; Johnston *et al.*, 2020; Oom *et al.*, 2022; Chuvieco *et al.*, 2023). Moreover, these frameworks do not incorporate all the components of a QRA for them to be considered entirely quantitative.

A QRA firstly requires a definition of the fire scenarios at the WUI or WII. Unlike QRAs applied to industrial sites, no standards are available that guide scenario definition in WUI fire risk (CCPS, 2007). Scenario definition should be carried out on the urban/industrial part of the interface, considering the ignition and exposure from fuels located within the parcel under analysis. However, it should be noted that there is still a need to quantify exposure to make sure that these efforts support efficient fire mitigation (Maranghides and Mell, 2013). Scenarios must include weather conditions, information about fuels and fire propagation mechanisms, and should be a combination of catastrophic and less severe incidents, depending on the scope of the study (CCPS, 2000).

The next step involves quantifying the frequency (incidents/year) of the energy release scenarios, which effectively correspond to fire ignitions. In the WUI, it is reasonable to consider that these occur mainly due to human action, and if it is assumed that past behaviours are likely to be repeated in the future, frequency values can be obtained from statistical records. However, each scenario (with the different degrees of incident severity) should have an associated frequency, which implies that knowledge about the development of the fire is required. This can be accomplished with logical structures (e.g. event trees or fault trees) that consider the different successive events which lead a wildfire in its early stages after ignition to propagate to the WUI and cause catastrophic or localized consequences. Assigning a probability to each successive event distributes the initial ignition frequency among the different scenarios previously defined. Knowledge of these probabilities is therefore important, for which more research and data analysis is required.

In parallel, the consequences associated with each of the previously defined scenarios should be quantified. This corresponds firstly to a quantification of the physical magnitudes of the wildfire, including radiant heat fluxes and firebrand exposure. The most popular tools currently are semi-empirical models, which do not yield all the required level of detail at the parcel level, while more detailed, deterministic models based on Computational Fluid Dynamics (CFD) models are under development and an active area of research. The deterministic nature of CFD fire codes also highlights the need of research to convert these results into the probability space. In the case of firebrand exposure, the available tools are far from delivering predictive capabilities. Additionally, the analysis should consider the exposure from other fuels located within the parcel, which can damage the asset being analysed. There have been several pioneering attempts to quantify heat fluxes to a structure using different types of tools (SFPE, 2023), but much more progress is required before the development of a systematic methodology is accomplished. Secondly, the response of the asset must be evaluated. This is typically expressed as a probability of failure or damage (depending on the type of the analysis) as a function of the physical magnitude being imposed on the asset. This converts the consequences to the probability domain, and therefore allows their multiplication with the scenario frequencies mentioned previously, thus calculating risk, which is expressed as a damage or loss frequency. In a WUI fire context, information that allows obtaining probability failures for different building and wildland materials subjected to radiant heat fluxes or firebrand exposure is virtually non-existent, highlighting a significant research need (Severino *et al.*, 2022).

Perhaps the greatest difficulty when performing a QRA is its need of considerable resources, including data, modelling tools, and time. The costs and resources are particularly important when the analysis covers large areas, as in the case of the wildland-urban interface. There are other techniques that allow to cover large areas more quickly, but at the expense of comprehensiveness in the analysis. These are mainly qualitative techniques, and include hazard identification methodologies, scenario and non-scenario-based procedures (CCPS, 2008). Several methodologies used in wildfires fall in this category, including fire weather and fire danger indices, checklists and vulnerability assessment tools, and models based on historical events used by insurance companies. It must be noted, however, that these techniques are valid, but it could be argued that they do not provide a sufficient level of detail at the parcel scale. Moreover, the expected scientific progress in our understanding of wildfire dynamics would render them redundant at this scale.

1.7. Risk mitigation strategies

Knowledge of the risk components, frequency, and consequences, allows outlining a risk mitigation strategy that acts on both elements. Risk mitigation actions can be taken on both the wildland and urban systems, however engineering solutions are more likely to be implemented on the urban or industrial settings, so more focus will be put in that element of the problem in this section. As previously mentioned, the engineer can make a choice between different layers of protection, which have different natures. Experience has shown that there is a hierarchy in the effectiveness of these layers of protection to mitigate fire risks during the entire life cycle of the asset being protected, with passive protection being generally more reliable than active fire protection, which requires the system to detect hazardous conditions and subsequently respond. Finally, procedural protection is considered the least reliable of all since it is subject to human errors. Note that for all these layers of protection to operate effectively, they must work independently from each other and be adequately designed, implemented and maintained (Hendershot, 2006).

Considering WUI settings, the proper design of passive and active layers of protection requires further research, as well as the development of test and design standards, which in turn should be incorporated into the applicable building codes and regulations (SFPE, 2023). Current engineering tools focus on passive building fire protection from wildfires, revealing a lack of mature technologies for exterior active fire protection. There is also a lack of quantitative engineering tools for calculating structure-to-structure propagation. More fundamentally, the design of these layers of protection requires an accurate knowledge of the thermal exposure to the wildfire, which ties in with the definition of fire scenarios and to the required accuracy of wildfire models. Considering the nature of the WUI fire problem, the thermal exposure should consider both an incident radiant heat flux from flames and incident heat and mass fluxes provided by firebrands. The latter represents a significant challenge in terms of fundamental and applied research. Finally, and deriving from the characterization of the thermal exposure, fire tests representative of real conditions during different fire scenarios should be developed and adopted, to test building materials and systems to be used in the WUI/WII.

A major weakness of protection layers is that they do not act upon the fire hazards and the engineering designs which are at the source of the fire risk at the WUI (Hendershot, 2006; Kletz and Amyotte, 2010). Inherently safer designs essentially deliver systems which fail in a safer manner. This is achieved by eliminating and reducing the fire hazards both within the wildland and urban systems, thus reducing the potential severity of the fire incidents. Inherently safer designs are also fulfilled by designing systems which limit the effects or consequences of fire incidents. This is accomplished through hardened structures and property layouts, which minimize ignition and fire spread. At larger scales, inherently safer communities should have designs which minimize fire propagation between properties, have fire resistant landscapes, and facilitate community evacuation without hindering the access to fire brigades. The engineer should therefore continuously strive to produce better, safer designs against WUI fires. However, it must always be remembered that inherently safer designs will never eliminate risk completely and are also liable to fail.

Further research to characterize the thermal exposure of structures due to flames and firebrands is required to perform fire safe designs and layouts of properties and structures. For example, there are discrepancies in the depths of the buffer or structure ignition zones in the regulations of different countries, pointing to uncertainties in thermal exposure, particularly due to firebrand transport. This again brings forth the fact that this requires further developments on wildfire dynamics in order to attain quantitative predictive capabilities which allow anticipating wildfire behaviour near the site under analysis. These models are crucial to define the extent of the required wildland vegetation control to minimize the likelihood of experiencing severe fire conditions in the WUI. Finally, similar efforts should be carried out to model the fire behaviour of ornamental vegetation and the exposure from structures fully involved in flames.

In terms of structure hardening, perhaps the greatest deficit lies in the ability to predict the behaviour of structural fuels due to firebrand action. Experimental and theoretical developments to describe and predict the ignition of solid and porous materials by firebrands are required to adequately design structures which have less propensity to being damaged from wildfire attacks. These results should then be extrapolated to understand the firebrand behaviour of building systems, including ignition and flame propagation. In summary, there are several engineering tools available nowadays, many coming from structural and industrial fire analyses, that can be adapted to effectively mitigate fire risks in WUI settings. Nevertheless, some specific features of the problem imply that the fire engineering community still cannot provide designs with the level of safety expected by the population and authorities, requiring further fundamental and applied work.

1.8. Concluding remarks

An overview of the emergence and relevance of the problem of the WUI in the context of the wildfire risk management problem by using engineering tools and approaches was presented. It was shown that although the problem existed much earlier it achieved greater importance during the past decades due to the increase of frequency and intensity of very large fires, the growth of the rural areas in fire risk regions occupied by houses. Unfortunately, the importance of the problem was highlighted by a series of accidents in which great loss of lives and properties were registered.

The problem of the WUI has a large diversity of situations, as it depends on many factors, making it difficult to typify the conditions and make a systematic approach. Even in the same country the topography, the vegetation cover, the road network, the type of construction, the layout of the houses and the composition and preparation of the population can change from one region to another, creating a complex kaleidoscope of cases that must be addressed.

The presence of people that can be endangered by the smoke and fire is the single factor that makes the problem of the WUI so important and demanding of attention from the fire risk management system, involving a large number of stakeholders. Even the treatment of the local scale problem, which is the object of the House Refuge project remains a great challenge to the fire suppression agencies and to the scientific community.

An engineering approach to providing fire safety in WUI or WII settings should be based on an appropriate estimation of the fire risks involved. However, the current state of knowledge has several gaps which prevent the practicing engineer from carrying out accurate and comprehensive analyses, leaving several aspects to personal judgement and consequently to designs with excessive safety factors. This section has presented an outline of a quantitative risk-based methodology deriving from established approaches used in hazardous industries. Using sophisticated tools such as these requires a level of maturity which is far from being attained in the case of WUI fire safety. We have attempted to highlight research and informational needs corresponding to every stage of this methodology. Considering the pressing nature of the problem and the increase in wildfire risks all over the world due to climate change, the research challenges will require a collective effort by the global fire safety engineering community to provide the adequate level of protection required by all our societies.

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2.
Wildland-urban interface characterization

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2.1. General WUI characterization

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This chapter presents the definition of Wildland-Urban Interface (WUI) and some state-of-the-art methods to identify and characterize it, from the meso to the microscale. Some concepts are common between the different topics related to WUI, so they may be repeated, not only in this Chapter, but throughout this book. We believe this is necessary to ease the reading and understanding of the topics but also to give some independence to the different chapters and sections.

With more or less variations, it is commonly accepted that the WUI is the space where vegetation, structures, and (usually) people, merge together in a fire prone environment (e.g. Stewart *et al.*, 2007; Ribeiro *et al.*, 2020; Maranghides *et al.*, 2022). The way these components meet in space may vary and different terminologies may be adopted. Usually, WUI is divided into three categories (e.g. Federal Register, 2001; Stewart *et al.*, 2003; Haight *et al.*, 2004; Mell *et al.*, 2010; Ribeiro *et al.*, 2020a). When considering its simplest form, vegetation and structures have a distinct border between them, hence the name "interface". This usually happens when the urban area is somehow dense (Johnston *et al.*, 2019). When this border is diffuse and the structures are scattered inside a wildland area, the WUI is considered to be “intermix”. The third type of WUI occurs when a wildland area is enclosed inside a urban area, and it is called “occluded” interface. The criteria to identify these types is not unanimous, and different thresholds can be found as shown by Stewart *et al.* (2009), Mell *et al.* (2010), Bar-Massada *et al.* (2013) or Maranghides *et al.* (2022).

Some authors further subdivide these categories according to the main land use and its relationship with the house clustering. For instance, Long-Fournel *et al.* (2013) account for the density of the residential structures and the horizontal structure of the vegetation, and Ribeiro (2016) identifies isolated houses, groups of houses (different sizes) and industrial areas classifying WUI according to the main wildland occupation in which they are inserted: forest, shrubland or agroforestry mosaics.

One important issue, when addressing WUI, is to recognize that it is not necessary for the flames from the wildland fire to physically contact with a structure in order for it to ignite (Ribeiro *et al.*, 2020a). Since the first known definition of WUI (or one of the first) that it is acknowledged that for this to happen, “wildland fire must be close enough for its flying brands or flames to contact the flammable parts of the structure” (Butler, 1974). Although structures can ignite due to any one of the three heat transfer mechanisms — conduction (Restuccia, 2019), radiation (Hu & Delichatsios, 2019) and convection (McAllister *et al.*, 2018) — the fact is that it is commonly observed that house ignition is usually caused by the deposition of burning embers (or firebrands) that are transported by air flows from the fire front, that can be hundreds of meters or even a few kilometres away (Manzello *et al.*, 2007; Cohen *et al.*, 2008; Maranghides & Mell, 2011; Manzello & Foote, 2014; Caton *et al.*, 2017; Babrauskas, 2018). This fact is highly important in some methodologies for WUI mapping, as not only the direct interface needs to be considered but also the multiple cases when there are gaps with different sizes between structures and wildland areas (e.g. Radeloff *et al.*, 2005; Pereira *et al.*, 2014 or Bar-Massada *et al.*, 2013).

It is unquestionable that the importance of the WUI topic, namely its wildfire related risk, has been increasing all over the world. One of the reasons is the fact that WUI itself has been expanding over the years (Radeloff *et al.*, 2018), as the urban settlements are growing and entering wildland areas, increasingly exposing people to danger. There are numerous infamous events that demonstrate this, some of them very recent. For instance, the 2017 Portugal wildfires (Ribeiro *et al.*, 2020b), either in Pedrógão Grande, in June (Viegas *et al.*, 2017) or in Central Portugal, in October (Viegas *et al.*, 2019), the events in Mati, Greece (Efthimiou *et al.*, 2020) and more recently the disaster of Maui, Hawaii (Marris, 2023), among others. Consequently, at least in the last two decades, the scientific community has been increasing efforts to help cope with the consequences arising from these events (Mell *et al.*, 2010). Some of the major concerns that have been addressed are related to the need to increase the resistance of the communities (e.g. Gill & Stephens, 2009; Syphard *et al.*, 2013; Smith *et al.*, 2016; Caton *et al.*, 2017; Evers *et al.*, 2019; Gollner, 2020; Intini *et al.*, 2020) and the structures (e.g. Cohen, 1995 & 2000; Penman *et al.*, 2015; Hakes *et al.*, 2017; Manzello *et al.*, 2017; Syphard *et al.*, 2017; Syphard & Keeley, 2019; Ribeiro *et al.*, 2020a; Lopes *et al.*, 2023), the identification of WUI areas (e.g. Stewart *et al.*, 2003; Platt, 2010; Calkin *et al.*, 2011; Herrero-Corral *et al.*, 2012; Pereira *et al.*, 2014; Bar-Massada *et al.*, 2013; Caggiano *et al.*, 2016; Johnston & Flannigan, 2018; Bar-Massada *et al.*, 2023) and its characterization, namely in terms of wildfire risk (e.g. Bar Massada *et al.*, 2009; Calkin *et al.*, 2014; Mitsopoulos *et al.*, 2015; Westhaver, 2015; Calviño-cancela *et al.*, 2016; Radeloff *et al.*, 2018; Vacca *et al.*, 2020).

Despite all the work that has been done throughout recent years, there are still some gaps to be filled (Mell *et al.*, 2010; Pellegrino *et al.*, 2013) and, especially, new technologies to be explored. In this sense, this chapter is intended to present some of the recent methodologies that have arisen in this field. The next sections will address three specific subjects:

i. The identification of WUI areas at the mesoscale level, which discusses the conceptual approach for mapping the WUI at mesoscales and provides examples of different methods and implementations worldwide.
ii. The characterization of WUI at the microscale level, describing concepts and exploring virtual reality techniques to allow deeper immersion into the parcel microscale.
iii. Remote sensing applications to WUI fuel management assessment, exploring the use of Sentinel-2 remote sensing data to monitor interventions on WUI fuel breaks of different types in order to reduce the necessary time and resources to scout them. The approach is promising, scalable, and first results support the proposed approach, namely, to train machine learning classifiers to identify the intervened fuel breaks as well as time range when the operations were performed.

2.2. The identification of WUI areas at the mesoscale

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Globally, the overwhelming majority of WUI mapping approaches have been developed and applied at the mesoscale, i.e., at national (Radeloff *et al.*, 2018), regional (Bar-Massada *et al.*, 2023), or even global geographic extents (Schug *et al.*, 2023). Pioneering works on the subject began in the early 2000's, with the development of two WUI mapping approaches to quantify WUI patterns in the US (Radeloff *et al.*, 2005; Theobald & Romme, 2007). These methodological developments spawned a large and diverse set of WUI studies which varied in location, scale, and approach (see below). Our goal in this section is to build on those studies to synthesize the concept of WUI mapping at the mesoscale.

In principal, any WUI mapping approach is based on the spatial juxtaposition of two data sources: the location and characteristics of human settlements, and the spatial distribution of flammable vegetation (Bento-Gonçalves & Vieira, 2020). Because WUIs are defined as those areas where these two types of landcover overlap or are adjacent, WUI mapping approaches mostly differ in the ways they define the following components of the WUI definition: [1] the spatial relationship between settlements and vegetation; [2] the definition of settlements; and [3] the definition of flammable vegetation. Additional methodological considerations are [4] the thematic resolution of the WUI map and [5] the geometry of the WUI representation in it. These five components are discussed in detail in the following paragraphs and are exemplified in Figure 3.

As the principal motivation to mapping the WUI is to provide a simplistic estimate of wildfire exposure to settlements, defining

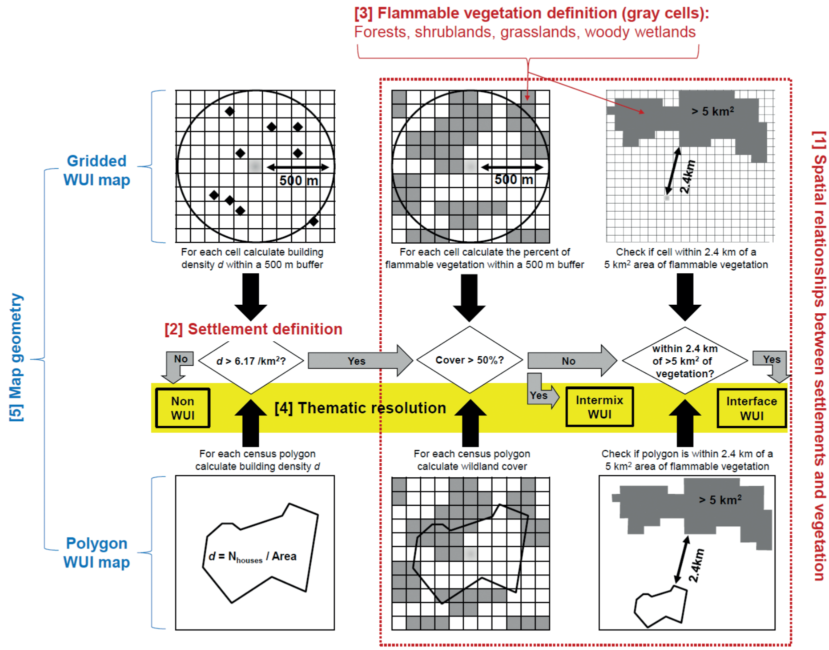

Figure 3. A schematic representation of various WUI mapping components. Numbers in brackets correspond with those appearing in the text. The top row is based on Bar-Massada et al. *(2013) and the bottom row is based on Radeloff et al. (2005).*

the spatial relationship between settlements and vegetation has to account for the two mechanisms that drive wildfire exposure in built-up areas in the first place (Beverly *et al.*, 2010). These two mechanisms are direct exposure to the fire front, which may cause structure ignition either directly or by convective hear transfer (Cohen, 2000); and indirect exposure by the arrival of flaming embers (i.e., spotting) which travel ahead of the fire front. Consequently, WUI mapping approaches typically use two distance parameters to assess these two potential types of exposure: a short-range parameter to identify direct exposure (typically between <100 m and <500 m), and a long-range parameter (anywhere from 400 to 2400 m) to reflect the potential of long-distance exposure to flaming embers. The application of these distance parameters is typically combined with an estimate of the amount of flammable vegetation within them to decide whether a minimal mapping unit is or is not a WUI. For example, a study in Canada (Beverly *et al.*, 2010) defined the WUI in 5-by-5 m map cells according to three distance thresholds: direct exposure to radiant heat as occurring within 30 m, short-range spotting at a distance up to 100 m, and long-range spotting at distances from 100 to 500 m. In all cases, the magnitude of exposure was defined as the proportion of fuels within each buffer distance. In another example, a building-centric approach which was used to map the WUI across the entire US (Carlson *et al.*, 2022) used a 500 m buffer distance to quantify direct exposure, and 2400 m to account for spotting potential. Mapping the European WUI, Bar-Massada *et al.* (2023) reduced the 2400 m distance to 600 m to account for the known travel distribution of embers based on empirical data, while retaining the 500 m distance to quantify direct exposure. Both these studies (and many others) utilized a threshold approach to identify WUI areas subjected to direct exposure (termed 'intermix WUI', see below), which they defined as more than 50% flammable vegetation cover within that 500 m buffer around each built-up area. A different approach altogether was taken when creating the first European WUI map (Modugno *et al.*, 2016). That approach did not account for long-range exposure and defined the WUI as any location within 200 m of artificial areas which is also within 400 m of vegetative fuels. Finally, the first WUI map in France (Lampin-Maillet *et al.*, 2010) accounted only for direct exposure, and as such utilized a 100 m buffer distance around buildings, overlapping it with vegetation maps using a 200 m buffer, to identify potential WUI areas. These studies are just a few examples of the multiple approaches for assessing the spatial relationship between settled areas and vegetation, which forms the first component of any WUI mapping method.

The second component of WUI mapping is the definition of settlements or built-up areas. While most WUI maps focus on homes or dwellings (Radeloff *et al.*, 2005; Lampin-Maillet *et al.*, 2010), some are less restrictive and allow for all building types to form a WUI, regardless of their purpose (Bar-Massada, 2021; Bar-Massada *et al.*, 2023). Another parameter that is commonly used is the criterion of housing density, which in many cases has to be above a threshold of 6.17 per square km to form a WUI (Haight *et al.*, 2004; Radeloff *et al.*, 2005). This definition was set by the US Federal government (USDA and USDI, 2001), which dictated that only settlements can form WUIs, whereas isolated houses cannot be deemed settlements, and hence should not be considered as potential WUI. This restriction considerably reduces the amount of WUI in regions with highly scattered development patterns, and as such can result in an under-estimate of wildfire exposure. To counter that, Bar-Massada *et al.* (2023) omitted this threshold altogether, thereby allowing even isolated buildings to be part of the WUI. Ultimately, though, these parameterizations are subjective by definition and there is no one 'correct' set of parameters for WUI mapping (Stewart *et al.*, 2009).

The third component of WUI mapping methods is the characterization of flammable vegetation. In theory, any vegetation type can support wildfire spread given suitable meteorological conditions, hence a simplistic WUI map can account for any vegetated area (regardless of species or cover) to identify settlements that are exposed to potential wildfire spread. Such a binary approach ("flammable" vs. "non-flammable", excluding agricultural areas) was taken, for example, in the US maps of Radeloff *et al.* (2005, 2018), and the European maps of Modugno *et al.* (2016) and Bar-Massada *et al.* (2023). Yet in practice, vegetation types differ profoundly in flammability (according to fuel type and conditions) and propagation potential (as a function of moisture content and continuity), hence WUI mapping approaches can take this variation into account and some indeed do. One study (Caballero & Beltrán, 2003) classified different types of WUIs in Spain according to multiple combinations of fuel types (dense forest, shrublands, agroforest mosaics) and settlement patterns; while Lampin-Maillet *et al.* (2010) used a binary fuel type classification, but accounted for fuel continuity in their WUI typology to refine their estimates of exposure. Schug *et al.* (2023) differentiated between forest-dominated WUI and grassland WUI in their global-scale analysis of WUI distribution. Ultimately, the choice of fuel categorization in WUI mapping methods depends on data availability (i.e., how detailed is the available data on fuels), and the mapper's choice of thematic resolution (see below). The consequence of these choices is the capability of the resulting WUI map to produce relevant estimates of wildfire exposure across locations with varying fuel compositions and configurations.

As alluded above, WUI maps can differ considerably in their thematic resolution, that is, the number of categories according to which they represent different WUI types. In the simplest, binary case, the map portrays WUI vs. Non-WUI areas and all WUI areas are considered as the same thematic entity (Modugno *et al.* 2016). A more commonly-used classification differentiates between intermix WUI, where built-up areas (or buildings) are interspersed within flammable vegetation so that wildfire spread occurs mostly through vegetated fuels; and interface WUI, where settlements are clearly separated from surrounding fuels and fire propagation occurs mostly through house-to-house ignition or through urban fuel types (Haight *et al.*, 2004). The intermix vs. interface distinction is still the most common among contemporary WUI mapping approaches (Carlson *et al.*, 2022; Bar-Massada *et al.*, 2023; Schug *et al.*, 2023). Yet the are several WUI typologies that extend the WUI classification into multiple combinations of settlement and vegetation configurations. Lampin-Maillet *et al.* (2010) defined a 12-class WUI typology, based on four types of settlement patterns and three types of fuel configurations. Categories range from "isolated housing and no vegetation in contact" up to "very dense clustered housing and continuous vegetation". Similarly, Caballero & Beltrán, (2003) defined a 17-class WUI typology based on combinations of multiple settlement types and three vegetation types. Ultimately, the thematic resolution of the WUI map determines its potential to reflect actual wildfire exposure, and to a greater extent, fire risk in general.

The last methodological aspect of WUI maps is their mapping geometry. Generally, WUI maps may have three different geometries: gridded (i.e., the map comprises cells of equal area, with each cell belonging to a specific WUI category or non-WUI) (Bar-Massada *et al.*, 2023), line-based (the WUI is represented as the boundary line between built-up areas and flammable vegetation)(Pereira *et al.*, 2014); and polygon-based (the landscape is represented by a set of polygons that can have any shape or size, with each defined as a given WUI class or as non-WUI) (Radeloff *et al.*, 2005). Each one of these geometries implies a different meaning to the summary statistics of the WUI in a given area (e.g., the line based WUI represents WUI amounts in units of length, while the other two represent it in areal units) and requires different GIS algorithms to compute. Often, the choice of geometry stems from the availability of building and vegetation data. For example, the US-based mapping approach of Radeloff *et al.* (2005, 2018) relies on census data for estimates of housing density, and these data are collected in polygons (census blocks). Similarly, the EU-based approach of Modugno *et al.* (2016) utilizes Corine landcover data as its main input source, and these data are also represented by polygons. In contrast, the point-based WUI mapping approach (Bar-Massada *et al.*, 2013) utilizes the availability of exact building locations, which are subsequently converted to grids of housing density to yield a high-resolution gridded WUI map.

To summarize, the considerable variation and complexity of the many existing WUI mapping approaches described above highlight that WUI mapping is an increasingly subjective endeavour. This is not to say that any specific WUI map is inaccurate or wrong, but rather, it stresses that the interpretation of WUI maps requires advanced knowledge on the choices made in their creation, and the corresponding assumptions made about wildfire spread and different types of settlement exposure to wildfires (Stewart *et al.*, 2009). When comparing WUI maps to actual fire histories, discrepancies might emerge as a result of choices made during map creation. For example, an empirical analysis of the US census-based (Radeloff *et al.*, 2018) and building-based (Carlson *et al.*, 2022) WUI mapping approaches based on empirical data on settlements affected by wildfires revealed that the distance threshold of 2400 m used to assess building exposure to spotting is probably too large, but at the same time the vast majority of building losses to wildfires occurred in areas identified as WUI (Caggiano *et al.*, 2020). This is encouraging, as it implies that even when using rather coarse rules-of-thumb to identify WUI areas (as is done in nearly all meso-scale WUI mapping approaches), the resulting maps can provide a reasonable estimate of exposure. At the same time, the over-estimation of exposure in many areas resulting from the usage of permissive parameters (such as the inclusion of low-flammability fuels and exceedingly long spotting distance parameters) can and should be solved by developing more precise evaluations of building exposure inside settlements (Vacca *et al.*, 2023).

2.3. Characterization of the WUI at the microscale

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The WUI micro-scale represents the realm of immediacy and ownership, encompassing the few meters surrounding a structure. Experience has shown that this zone holds paramount significance in safeguarding properties, surpassing even the effectiveness of perimeter firebreaks. Indeed, the combustion of objects, materials, and vegetation in close proximity or in contact with facades, roofs, or glazed surfaces is a significant contributor to the impacts and destruction of buildings during urban-forest interface fires. Traditionally, the Defensible Space has been defined as an area around the dwelling devoid of combustible materials, preventing the progression of secondary ignition sources and eliminating objects prone to combustion.

Moreover, the defensible space not only ensures accessibility but also provides room and, ideally, a water supply for executing manoeuvres and defensive operations for the protection of buildings.

Figure 4. The defensible area of a home not only encompasses the property plot but also extends to neighboring plots. In this illustration, on the left, an unmanaged plot with abundant vegetation (grasses, shrubs) is evident, alongside a forested plot with a dense understory. In the background, another plot features a residence with its surroundings cleared of vegetation. On the right, the depiction illustrates the potential scenario in the event of a forest fire, emphasizing that the threat could originate from neighboring plots.

2.3.1. Gardens

Typically, homes are nestled within a landscaped plot. The vegetative elements arranged therein influence the behaviour of fire around the house, while also potentially serving as conduits for the spread of the inferno to neighbouring plots. Experience has revealed that certain garden species are more prone to ignition than others, meaning they readily and swiftly combust when exposed to embers or the advancing flame front. Particularly perilous are cypress and other conifers that store resins and other volatile elements. Moreover, they tend to leave residues on the ground, atop the house, over objects, on the roof, or among other garden plant components. Understanding the flammability of garden flora is crucial, as it directly impacts the vulnerability of homes to the peril of fire. Identifying and managing these combustible elements within the garden landscape becomes paramount in fortifying against the potential devastation brought about by wildfires.

Figure 5. An example illustrating the flammability and combustibility of Cupressaceae green hedges, which propagate flames throughout the entire plot and ignite other elements or the structure itself.

The accumulated dry needles of pine and other conifers may not carry a high fire load, but they excel in efficiently igniting and spreading flames within a plot towards more energetic combustibles. The arrangement of plants in the garden significantly influences the initiation and propagation of combustion on the premises. A commonly applied guideline is maintaining a distance of 2.5 times the height of trees and other ornamental elements to mitigate the spread of flames from one plant to another. Green hedges are a prevalent feature in landscaped plots, chosen for their ease of maintenance, minimal water requirements, and resistance to pruning. Numerous species serve as popular hedge choices, offering a combination of practicality and aesthetic appeal. Strategic planning of plant placement and adherence to guidelines not only enhance the visual allure of the garden but also play a crucial role in minimizing the

Figure 6. In this instance, a wildfire, sweeping across herbaceous vegetation, flanked the urbanization, igniting a highly flammable Arizona Cypress hedge (Cupressus arizonica). This set off a chain reaction, spreading flames around the plot and also impacting neighbouring plots and houses.

risk of fire propagation within the landscape. As we delve into garden design, understanding the impact of plant disposition on fire initiation and spread becomes instrumental in creating both a beautiful and fire-resilient outdoor space.

Among these, species of Cupressaceae are widely utilized, with the Arizona Cypress (*Cupressus arizonica*) standing out, particularly gaining popularity in the 1970s in the developments along the Mediterranean.

Arizonica hedges tolerate continuous pruning exceptionally well, creating a dense structure that blocks out light and accumulates a substantial load of fine, dead plant material. In the event of a fire, this can result in a pronounced curve of heat emission — short and intense — leading to challenging-to-extinguish combustions.

The irrigation patterns in gardens wield a double-edged sword: neglecting them or introducing ornamental elements with a high

Figure 7. In this case, it can be observed how an unmanaged Arizona cypress hedge has led to the uncontrolled growth of inflammable vegetation around the homes, one of which is constructed with wood. In these situations, it is crucial for both property owners to collaborate on prevention efforts in a coordinated manner.

load of dry fine fuel turns gardens into highly vulnerable areas during ember showers, fostering highly energetic combustions. Conversely, consistent irrigation and the selection of plant species that retain moisture significantly reduce the likelihood of ignition and combustion development.

Understanding the interplay between plant choices, pruning practices, and irrigation strategies is pivotal in crafting resilient landscapes that not only contribute to aesthetic appeal but also act as a formidable defence against the potential ravages of fire. As we delve into the complexities of garden management, balancing the allure of greenery with fire-wise practices becomes paramount for creating outdoor spaces that are both beautiful and safe. Additionally, there are solutions centred around water cannons, known as rain-guns, which project a flow in the form of small droplets, simulating rain. These devices are employed as wildfire defence mechanisms. The presence of flammable and lightweight materials, highly prone to initiating and sustaining combustion—such as plastics, fabrics, paints, woods, garden furniture, cushions, and mattresses—can compromise a structure, especially if situated close to or against the facade, or beneath porches and terraces, impacting nearby glazing (windows, etc.). These lightweight residential fuels (LRF) can also contribute to the spread of fires within the urban environment and generate columns of toxic smoke.

Liquefied Petroleum Gas (LPG) tanks may be exposed to radiation and flame contact, resulting in overpressure due to the forced evaporation of the liquid phase of the stored gas. This can lead to the opening of the safety valve and the potential activation of a fire dart (jet fire). These fire darts can ignite other objects and materials or affect the dwelling if in close proximity. Understanding and mitigating the risks associated with these elements become crucial components of a comprehensive strategy for safeguarding against the multifaceted threats posed by fires in residential areas.

Figure 8. In this photo, the impact of radiation from the combustion of surrounding hedges on a liquefied petroleum gas tank is evident, leading to forced evaporation, an overpressure inside, and the opening of the safety valve. The circular burned zone observed on the tank is a result of the radiation from the jet fire itself.

2.3.2. Houses

Homes must be prepared for the passage of fire, the shower of embers, and other interconnected risk phenomena, akin to a domino effect.

Various types of buildings exist, but for the classification of vulnerability, it is pertinent to consider whether it is a rural structure or one in an urban fabric or housing development. Equally crucial is the consideration of age (year of construction) and the overall maintenance condition.

In Europe, a diverse range of buildings populates the wildland-urban interface. This spectrum spans from the typical rural houses in the Mediterranean, constructed with brick or stone and featuring wooden roof structures, to the wooden houses prevalent in the central and northern regions of Europe. Recognizing this diversity and understanding the specific vulnerabilities associated with different building types is integral to developing effective strategies for mitigating the impact of wildfires across varied landscapes and architectural styles.

As rural areas experience a decline in activity, numerous structures in towns and villages either stand abandoned or receive minimal maintenance. Experience teaches us that these houses, more often than not, are particularly susceptible to the ravages of wildfires.

When assessing a home's vulnerability, our focus centres primarily on three components: the roof, the glazing, and the openings. The most delicate and vulnerable part of a building's envelope is the glazing, especially when subjected to the direct contact of flames from nearby combustion or radiant heat.

Figure 9. An example of an abandoned house in a rural setting, bearing the consequences of a forest fire's passage. The presence of objects and materials around the building, the absence or breakage of windows, and the lack of roof maintenance are factors that contribute to the increased vulnerability of these homes.

Glazing is exposed to radiation or flame contact, and if this exposure is differential (meaning significantly higher heating in one area of the glass compared to others), it can induce mechanical stresses, breakage, and potential collapse.

Double pane glazing, and tempered glass exhibit greater resistance to mechanical stresses. In the event of fracturing, they are less prone to collapse, making them more suitable for areas with a heightened risk of wildfires.

Blinds provide an additional layer of protection for windows. When lowered, blinds act as a barrier against radiation and potential flame contact. Blinds made of PVC, however, can heat up and soften, losing their mechanical strength and potentially falling if exposed to intense and sustained heat. This leaves the glass pane exposed to the elements.

Figure 10. In this case, a building with single-pane glazing is exposed to the combustion of a nearby tree, leading to the breaking and collapse of the glass and allowing the entry of fire and embers. The entire structure was subsequently affected by the combustion of objects and materials inside.

Figure 11. PVC blinds have succumbed to the radiation from the nearby flame front, resulting in a loss of mechanical strength and partially exposing the glazing.

On the other hand, aluminium blinds prove more robust in the face of radiation and flame contact, reflecting a portion of the radiation and offering an added layer of protection. Incorporating double pane glazing with tempered glass and durable aluminium blinds not only enhances a building's resistance to mechanical stresses but also provides a comprehensive defence against the complex challenges posed by wildfires in forested areas.

Contrastingly, wooden blinds, while rare, provide a level of protection due to their tendency to char without readily igniting. Recognizing the vulnerabilities of structures, especially during short exposures to fire, underscores the importance of utilizing resilient materials and maintaining a closed building envelope.

Experience further demonstrates that an open window during a forest fire allows embers, smoke, and flames to infiltrate, rendering virtually any building vulnerable. It is crucial to emphasize that the building envelope must remain closed and impermeable to the passage of both fire and smoke.

The roof is a critical component of the structure designed to channel water and stay dry. The hollow interior of the roof, intended for airflow, becomes also a potential conduit for flames and embers. This design makes it particularly vulnerable during a forest fire,

Figure 12. An open window renders any structure vulnerable. This is an example where a brick and concrete building, constructed from non-combustible materials, has been completely destroyed due to the entry of fire and embers during the wildfire. Many such cases were witnessed during the Mati wildfire in Greece in July 2018.

especially if constructed with wood. Addressing these vulnerabilities, be it through the choice of roofing materials or other protective measures, becomes imperative in fortifying structures against the challenges posed by wildfires.

Traditionally, roofs are adorned with tiles, forming structures with two or more slopes. Other configurations include flat roofs, layered with asphalt fabric and other materials for water insulation and heat control.

The accumulation of vegetation debris on the roof poses a potential risk in the event of a forest fire. Pine needles, twigs, and other elements gather on the convex and flat parts of the roof, igniting due to the effects of flames or embers. A roof without proper maintenance is more prone to allowing fire to penetrate the structure, leading to its total destruction.

Figure 13. In this instance, poor roof maintenance and the presence of flammable materials inside have led to the combustion and collapse of the structure.

Roof eaves are particularly exposed to radiation, flame contact, and convective currents, all of which can incite ignition. The gutters lining the eaves can accumulate vegetation debris, serving as an effective ignition point that affects the entire roof. These aspects become pivotal in the design of passive protection for residences.

While a home may withstand the passage of fire and its consequences—flame contact, radiation, convection, and embers—it doesn't guarantee that it can always serve as a shelter in times of need. Certifying the habitability of the house in an environment filled with fire and smoke is also essential. Incorporating resilient roofing materials, regular maintenance practices, and strategic design considerations, such as protected eaves and gutter management, become critical components in fortifying homes against the multifaceted threats of wildfires.

2.3.3. Defensible space and home ignition zone

The ignition zone of a residence pertains to the first 10 m around the facade, where potentially flammable materials may exist, capable of initiating combustion during ember showers. This zone is crucial for ensuring the survival of buildings and falls entirely under the responsibility of the homeowner.

As previously mentioned, the presence of lightweight residential fuels or inflammable plants, laden with dry fine fuel, complicates defence efforts and significantly reduces the likelihood of a house's survival. Effective defence requires proactive measures within this ignition zone, such as clearing combustible materials and implementing fire-resistant landscaping practices.

Expanding the scope, the defensible area encompasses the first 30 meters around the dwelling and often involves neighbouring

Figure 14. Another example where a low-intensity flame front, spreading through herbaceous fuels, ignites materials and objects in an unmaintained plot, creating a situation of higher energy combustion and emission of toxic gases. These situations can be avoided with good prevention practices by the property owner.

plots. Collaborative planning with neighbours becomes paramount, necessitating joint designs and strategies to fortify the collective resilience of the community.

In this cooperative effort, the presence of usable water resources, such as tanks, cisterns, or pools, enhances defence possibilities and streamlines the operations and manoeuvres of intervention teams. Having readily available water sources not only increases the chances of successfully defending the area but also facilitates the strategic deployment of resources during firefighting efforts.

To ensure the survivability of homes in fire-prone regions, homeowners, with the support of their neighbours, must actively engage in creating defensible spaces. This involves not only eliminating potential ignition sources within the immediate vicinity but also

Figure 15. Toward a defensible space: in this case, both property owners have agreed to gradually transform their gardens into a design that reduces the load of vegetative fuel, minimizes the presence of objects and materials, and enhances accessibility for intervention measures.

fostering a collaborative community approach to enhance overall resilience against the challenges posed by wildfires.

The WUIVIEW (https://wuiview.webs.upc.edu/) project has pioneered a self-assessment method for gauging the potential danger and vulnerability of properties. This method is tailored for property owners, enabling them to conduct a self-assessment of the factors that play a significant role in evaluating the vulnerability and risk of their properties.

The assessment is georeferenced, allowing for the grouping of the entire urban development. This not only aids in understanding the collective risk but also facilitates the formulation of collaborative prevention strategies. The aim is to empower homeowners to take an active role in safeguarding their properties and to foster a collective approach to wildfire prevention within the entire community. By harnessing georeferenced data, the project encourages a comprehensive understanding of the shared risks and the implementation of coordinated strategies for enhanced resilience.

Exploratory techniques for characterizing the microscale

As underscored, the collaboration of property owners is indispensable in safeguarding WUI areas, creating defensible spaces, and providing opportunities for effective firefighting. However, achieving success in this endeavour is challenging without a populace that is both convinced and educated about the wildfire risk in the WUI. Traditional awareness and education campaigns have seen only partial success, primarily targeting older segments of the population that may be more resistant to adopting new measures and initiating changes on their properties.

This is where the incorporation of innovative technologies, such as virtual reality, becomes particularly compelling. Virtual reality offers a unique avenue for presenting wildfire scenarios in the urban-forest interface in a manner that is realistic, immersive, and interactive. Unlike traditional campaigns, which may struggle to engage certain demographic groups, virtual reality provides an inclusive approach that transcends age-related resistance and fosters a more profound understanding of the wildfire risk.

By immersing individuals in lifelike scenarios, virtual reality not only captures attention but also allows for a more visceral and memorable experience. This technology has the potential to bridge the gap in awareness and education by reaching a broader audience and instigating a deeper appreciation for the importance of proactive measures in the WUI.

This approach stands out as a direct and highly effective method for integrating messages and instructions regarding best practices for wildfire prevention. In the contemporary landscape, digital game development engines have evolved to a point where they facilitate the incorporation of intricate numerical models and photorealistic visual simulations. These simulations not only capture the essence of typical elements found in an interface scenario—such as buildings, vegetation, vehicles, furniture, tools, and more—but also vividly portray the intricate processes associated with combustion, including flames, smoke, and embers, as well as domino effects like a jet fire in an LPG tank.

The current capabilities of digital game engines allow for the seamless integration of complex numerical data, creating a visually stunning and immersive experience. This extends beyond the mere representation of static objects to the dynamic visualization of processes, making it an ideal medium for conveying the nuances of fire behaviour and the cascading effects that can occur in wildfire scenarios. The utilization of these advanced technologies not only enhances the realism of the presented scenarios but also provides a powerful tool for educating and raising awareness about the intricacies of fire prevention.

The WUICOM-BCN project has recently pioneered immersive experiences aimed at raising awareness and sensitizing communities in the vicinity of Barcelona, Spain. These experiences span three scales: landscape, community, and property, offering a comprehensive understanding of the wildfire interface. Notably, the project encountered two significant challenges during its development, focusing on the representation of vast tree masses and the volumetric rendering of smoke and fire.

Addressing these challenges required the application of specialized techniques. Specifically, the project utilized rendering methods capable of handling highly intricate scenarios, incorporating several million polygons. This approach allowed for the creation of visually stunning environments with photorealistic lighting and the seamless integration of non-geometric elements such as smoke, fire, and embers.

The technological intricacies involved in rendering large tree masses and volumetric representations of smoke and fire underscore the commitment of the WUICOM-BCN project to delivering an authentic and impactful experience. By employing cutting-edge techniques, the project not only overcame these challenges but also succeeded in creating immersive scenarios that vividly portray the dynamics of wildfires in the urban-forest interface.

These experiences serve as a testament to the potential of advanced technologies in conveying crucial information about wildfire risks and prevention. By offering realistic and visually compelling simulations across different scales, the WUICOM-BCN project sets a benchmark for future initiatives seeking to enhance public awareness and understanding of the complex dynamics associated with wildfires.

The experiences were fully immersive, achieved using virtual reality headsets, necessitating the rendering of these intricate scenes at a high frame rate of 70 to 90 frames per second. This demanding frame rate ensured a seamless and realistic virtual environment for users.

Given that numerical simulations of smoke and fire were conducted using computational fluid dynamics models, the project prioritized the development of approaches that allowed for real-time volumetric rendering of smoke and fire. This emphasis on real-time rendering was crucial in ensuring that the visual representation of smoke and fire mirrored the dynamic nature of these phenomena as captured by the numerical models.

In the landscape scenarios, the integration of geographical reference elements was a key aspect. This included roads, cadastral plots, toponyms, contour lines, and more, superimposed onto a digital terrain model. To enhance realism, this model was further enriched by overlaying it with orthophoto texture, creating a lifelike representation of the terrain.

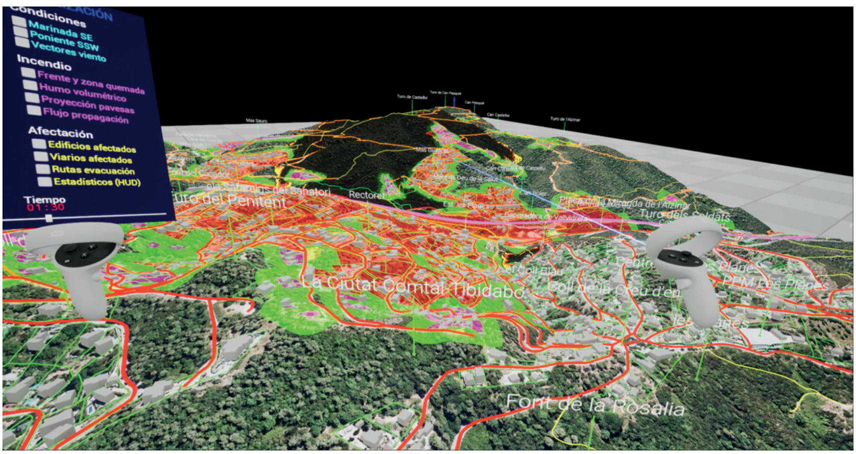

Figure 16. Immersive representation of a landscape depicting a forest fire threatening a populated area in Rectoret (Barcelona). Various GIS layers, including roads, cadastral plots, and toponyms, have been overlaid for enhanced context. Additionally, preventative measures such as perimeter firebreaks (in light green), actions on plots (in red), and interventions on isolated houses (in pink) are delineated. Users can access these functionalities through a wrist menu and interact with elements using two handheld controllers.

Simulations of fire spread have been conducted on this model, capturing the fragmented movement through residences in intermix zones. Transitioning to the community scale, a three-dimensional photogrammetric model of buildings and trees has been seamlessly integrated, enhancing the overall realism of the simulation.

At the community scale, a three-dimensional photogrammetric model of buildings and trees has been seamlessly integrated, thereby enhancing realism. Additionally, the project has focused on modelling the production and dispersion of volumetric smoke columns. These simulations provide a detailed understanding of how wildfires might unfold in various settings, offering insights into the dynamics of ignition, fire spread, and the volumetric aspects of smoke dispersion.

At the property scale, a meticulously designed scenario unfolds, featuring a complete structure replete with all its architectural components, glazing, doors, and even interior lighting and furnishings.

Figure 17. The 3D photogrammetric model of an entire neighbourhood has been generated from drone-captured photos, providing a highly realistic and up-to-date environment. The scenario includes the photo-realistic representation of volumetric smoke, externally calculated using computational fluid dynamic models.

This attention to detail extends to the outdoor space, where the garden is adorned with ornamental elements, hedges, as well as typical items like vehicles, garden furniture, an LPG tank, and other commonplace objects.

Within this simulated environment, various neighbouring plots have been strategically arranged to offer a diverse representation. One parcel remains undeveloped and unmanaged, allowing for a contrast with a forested area devoid of vegetation treatment. Another plot showcases a different structure, standing alone without any additional elements.

This comprehensive scenario at the property scale serves as a dynamic and immersive setting where users can actively engage. By including various elements typical of residential properties and their surroundings, the simulation not only captures the diversity of potential scenarios but also allows users to make informed decisions regarding vegetation management, object placement, and the operation of doors and windows. The realism achieved at this

Figure 18. At the property scale (microscale), typical elements found in a plot are incorporated: forest vegetation, landscaping, buildings, vehicles, garden furniture, LPG tanks, etc. Users can firsthand experience the passage of a forest fire and witness the consequences of their decisions.

scale contributes to a more authentic and impactful experience, enhancing the educational and training aspects of the simulation.

The user can immerse themselves in this true-to-life 1:1 virtual scenario, actively making decisions regarding vegetation management, object placement, and the operation of doors and windows. Subsequently, they have the opportunity to experience firsthand the progression of a forest fire and witness the consequences of the decisions they make.

This preliminary experience undoubtedly opens up significant possibilities for development, not only in terms of raising public awareness but also for training intervention teams. The interactive nature of the simulation allows users to engage with critical decision-making processes, providing a realistic and impactful learning experience. Beyond its educational value, the scenario holds immense potential for enhancing the preparedness and response capabilities of intervention teams, offering a valuable training tool in navigating the complexities of wildfire scenarios.

Figure 19. Simplified depiction of the combustion of objects and materials inside and outside the house, resulting from the owner's decisions regarding their placement and the opening of windows and doors.

2.4. Remote sensing applications to WUI fuel management assessment

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Portugal has been devastated by recurrent wildfires, destroying lives, ecosystems, natural resources, and property. The extreme wildfires have occurred in areas of aged population dispersed in small villages, or in isolated areas, in highly forested and mostly disorganized areas. The Portuguese government has defined stringent legislation defining fuel breaks which cover the whole territory and measure hundreds of thousands of kilometres and must be kept clean and are yearly verified by the authorities. In order to have a global picture and up to date of the status of the fuel breaks, essential for all the stakeholders, remote sensing-based methods can be employed to track and, by resorting to machine learning techniques, even classify their state. This is only possible due to the now widely available remote sensing datasets, like the ones provided by Sentinel-2 and LANDSAT programmes, and cloud tools like Google Earth Engine, and has been addressed in the recent literature (Badola *et al.*, 2022; Pereira-Pires *et al.*, 2020; Pereira-Pires *et al.*, 2021). However, the case of WUI fuel breaks has been less studied.

In this Section, we overview the techniques and rational of the approach being followed by the *Floresta Limpa*[2] team in what regards the assessment of fuel breaks using Sentinel-2 data, with special focus on the wildland-urban interface: roads, isolated houses, and populated places. These fuel breaks have different topologies, dimensions, and rules governing the allowed vegetation, that make each case a different problem requiring different techniques to address it.

The objective of the section is to provide a bird's eye view to the use of remote sensing data for monitoring fuel breaks and attempt to make the case for its adoption and its wide use and fostering further development. We present the several types of fuel breaks for the Portuguese case, and their characteristics. Next, the datasets employed are introduced and described. A major part of the work consists in the segmentation of the fuel breaks according to their type; the width of the fuel breaks can be very small, and therefore it is necessary to construct segments to reduce error in the analysis and interpretation of satellite signals. Finally, we describe a set of use cases regarding the WUI fuel breaks, depicting the timeseries of fuel breaks that were intervened versus the ones which were not. For some of the fuel break types we have already published results or preliminary results showing the effectiveness of the approach

[2] This work is supported by FCT.IP under project Floresta Limpa (PCIF/MOG/0161/2019 - https://florestalimpa.di.fct.unl.pt/) and NOVA LINCS (UIDB/04516/2020 - https://doi.org/10.54499/UIDB/04516/2020, and UIDP/04516/2020 - https://doi.org/10.54499/UIDP/04516/2020).

when combined with machine learning classifiers (Afonso *et al.*, 2020; Silva, 2022). The section concludes with a general discussion and pointers to ongoing and future work.

2.4.1. Fuel breaks in Portugal

The fuel breaks correspond to areas in strategic locations, which intend to prevent the spread of fires, facilitate firefighting, as well as protect the infrastructures close to their locations. In order for the fuel breaks to fulfil their function, a set of criteria was stipulated in Portuguese Law (*Decreto-Lei n.º 82/2021, de 13 de Outubro, Da Presidência Do Conselho de Ministros*, 2021), that these must follow.

There are two main types of fuel breaks in Portugal, namely interruption and reduction fuel breaks. The interruption ones consist of areas where the entire vegetation is cut, while the reduction are areas where only the surface vegetation is removed, introducing a spacing between crowns, suppressing its lower part.

These fuel breaks form a network divided into three levels, according to the function each one represents. The primary network is composed of reduction and interruption fuel breaks, with the aim of reducing the area covered by large fires, facilitating direct intervention. Regarding the secondary network, it focuses on reducing the consequences of fires by passively protecting roads and other infrastructures. Finally, both the secondary and tertiary networks are intended to isolate potential sources of fire ignition.

The primary network fuel breaks are at least 125 meters wide, dividing the Portuguese territory into areas between 500 and 10,000 ha, and approaches for the assessment of interventions combining remote sensing data with machine learning methods have been proposed with very good results (Pereira-Pires *et al.*, 2020).

(a) Fuel break protecting a roadway *(b) Fuel break around a high voltage utility line* *(c) Fuel break near a house*

Figure 20. Examples of fuel breaks.

The secondary and tertiary network include several subsets of fuel breaks, classified in accordance with the infrastructures successfully extraction vegetation data timeseries (see Figure 20):

- Fuel breaks around roadways, which need to have a width of at least 10 meters on each side.
- Fuel breaks around electrical power transmission lines, which if they are high voltage or medium it is needed to establish a strip with the same width as the cables, plus a strip of at least 10 or 7 meters on each side, respectively. As for low voltage lines, it is only required a strip of at least 3 meters from the centre of the cables.
- Fuel breaks around the transport network of gas and oil products, where the creation of a lateral strip of at least 7 meters from the axis of the pipeline is imposed.

Finally, fuel breaks around buildings and population clusters are also specified by the Portuguese Law. In situations where buildings are present, a strip of 50 meters wide should be created if this strip covers forest areas, or 10 meters wide if it covers agricultural areas. For population clusters, this width should be at least 100 meters.

2.4.2. Remote sensing data and ground data

The Sentinel-2 Multispectral Instrument (MSI) has been widely used as one of the most reliable tools in regard to vegetation analysis by remote sensing (Astola *et al.*, 2019). To access its observations, data was obtained by using datasets available on Google Earth Engine (GEE)[3].

The GEE Sentinel-2 'COPERNICUS/S2_SR_HARMONIZED' dataset is already pre-processed, thus avoiding the need for further atmospheric and radiometric corrections. However, cloud masking and removal plays an important role in successfully extraction vegetation data timeseries. Images that were too cloudy were discarded, and the remaining ones were filtered using the GEE 'S2 cloud probability dataset', where the pixels identified as either belonging to a cloud, or to a cloud's shadow, were removed from the final images.

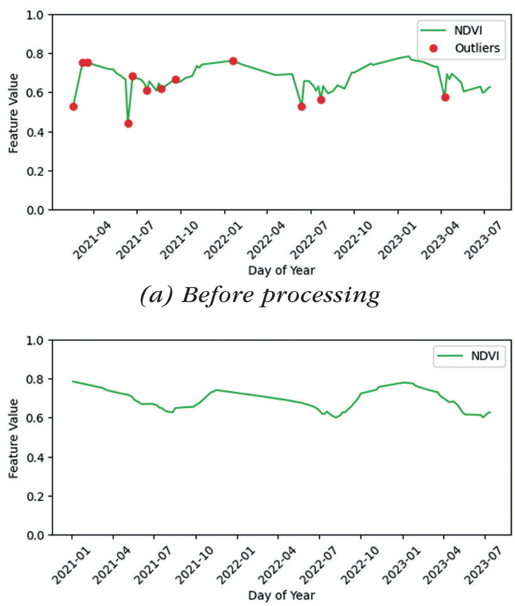
To analyse fuel breaks using remote sensed imagery, it is helpful to divide them into smaller objects, using a segmentation process. Using an object-based approach, with segments comprised of more than one satellite pixel, results in a smoothing of the noise that individual pixels can have due to the presence of small artificial structures or roads. The ideal size of a segment will depend on the specific problem, but the objective is to create homogeneous segments, that can accurately represent the area they are covering.

The segments were used to extract data from the Sentinel-2 images and obtain timeseries. The extracted Sentinel-2 bands were B4, B3, B2, B5, B6, B7, B8 and B11 and the extracted vegetation indexes were NDVI, NDWI, NBR, RENDVI, EVI, ARI1 and SRI (Puletti *et al.*, 2018). To reduce the pixels over each segment to a single value per satellite observation, the mean and the standard deviation reducer functions were used, resulting in a total of 30 features

[3] https://earthengine.google.com/

for each segment. Although all 30 features are usually fed into the machine learning classifiers for training, it is important to note that for simplification in the visualizations provided in the Use Cases of this Section, only the NDVI timeseries are shown, since it is one of the most important indices when working with vegetation data.

After extraction of the time series, it is extremely important to process them, to remove noise and better identify trends. Python libraries provided the tools for this processing. Outlier removal was achieved by using the 'Hampel' filter (Pearson, 1999), and noise was further cleared up by smoothing with the 'Savitzky-Golay' filter (Savitzky *et al.*, 1964). Finally, the timeseries are linearly interpolated on a 5-day interval to keep the observation frequency constant, so that changes between points are kept on the same time scale, and no large gaps without data exist. Figure 21 presents an example of a NDVI timeseries before and after processing.



(a) Before processing

(b) After processing

Figure 21. Example of a timeseries before and after processing: removal of outliers, smoothing and interpolation

2.4.3. Segmentation of fuel breaks

This Section describes the two different processes of segmentation of the fuel breaks. Two different processes are applied to different types of fuel breaks.

i. *Population Clusters and Isolated buildings*

The process of segmentation of these areas was divided into three phases.

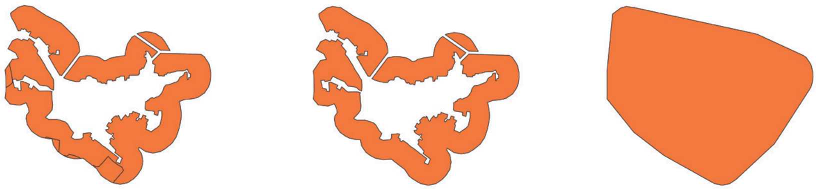
A. *Division according to the distance to the centre of geometry.*

Vegetation close to urban structures is generally agricultural and tends towards forest further away from cities and buildings, and so, to improve the segments homogeneity, the fuel breaks were divided into sections according to the distance to the centre of the geometry.

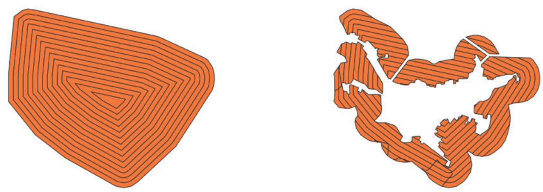
Figure 22 depicts the steps taken in phase A. In the first step, the original geometries were merged according to which fuel break they belong to (Figure 22b). Often, fuel breaks are composed of multiple polygons, due to being intersected by roads or other objects, and to join them, the algorithm Concave Hull was employed (Figure 22c). To each object, negative buffers were iteratively created, with 25 meters of width, in order to be able to fit at least 2 Sentinel-2 pixels, which have a size of 10x10 meters (Figure 22d). Finally, the buffers were intersected with original geometries to obtain the divided sections (Figure 22e).

B. *Division into smaller similar sized objects.*

Phase B consisted of dividing the previously created section into smaller similar sized segments. Since the segments are being created to work mostly with Sentinel-2 images, it is advantageous to take the placement of Sentinel-2 pixels into account and create the borders of the objects to surround full pixels.



a) Original fuel break *b) Merged geometries* *c) Concave Hull*



d) Negative buffers *e) Divided fuel breaks*

Figure 22. Process of dividing fuel breaks according to the distance to the centre of the geometry.

The process can be observed on Figure 23. First, a squared grid aligned with the limits of pixels of Sentinel 2 was created for the full area of the fuel brakes. Then, the grid was intersected with each of the sections created in the previous phase (Figure 23b). The algorithm K-means was used to create clusters of similar size from the grid squares, each with 25 Sentinel-2 pixels (Figure 23c). Then, the grid squares were merged based on the clustering (Figure 23d) and intersected with the original sections (Figure 23e).

C. *Dissolving small segments*

Phase C in the segmentation process was dissolving any small objects. Segments with less than 700 m^2 of area were merged with the neighbour with the smallest area belonging to the same fuel break.

ii) Road network, Electrical power transportation network and Gas transportation network

In these types of fuel breaks, it is not expected that vegetation follows any sort of pattern, and so only the last two steps described in the previous subsection were applied: B. Division into smaller similar sized objects and C. Dissolving small segments. Figure 24 presents examples of the segmentation produced.

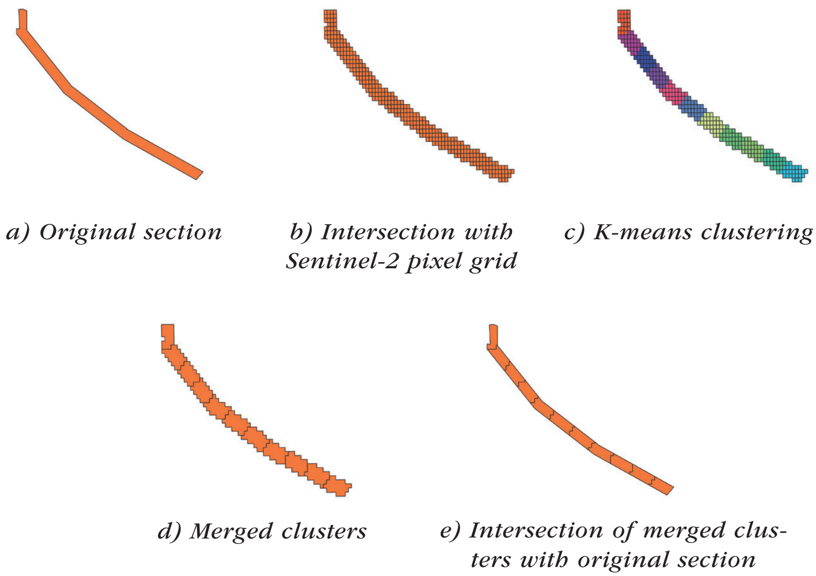


Figure 23. Process of dividing sections of fuel breaks into smaller similar sized objects.

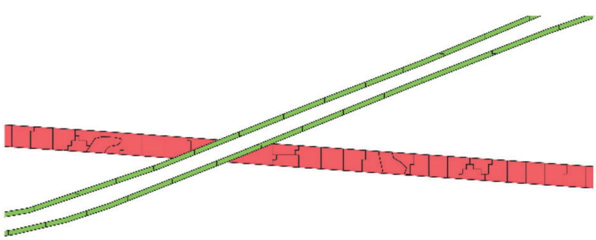


Figure 24. Examples of segmentations produced for fuel breaks along roads (green) and along electrical lines of very high voltage (red).

2.4.4. Case study — roads

One approach to gauge whether an intervention was conducted on a fuel break is analysing the difference in vegetation in the fuel break and in the area exactly outside of it. Fuel breaks that have had interventions will show a decrease in the NDVI value, while the outside area is expected to remain stable.

This approach works particularly well in fuel breaks along roads, due to their typical rectangular and small width geometry. Nonetheless, it could also be used in other types of fuel breaks.

To test this approach, a case study was conducted using the fuel breaks along roads in the region of Mação, a municipality in the Santarém district in Portugal.

Exterior segmentation of Fuel breaks

In order to perform the vegetation comparison between the inside and outside of the fuel breaks, it was necessary to create geometries contiguous to the previously created segments.

The full process can be observed in Figure 25. For each road fuel break, a buffer of 20 meters was created (Figure 25b). To obtain only the outside of the fuel breaks, the difference between the buffered polygon and the original fuel break was performed (Figure 25c). Since the exterior polygons can be intersected by other types of fuel breaks, the difference among them is also performed. The exterior polygons can also be intersected by roads, and to remove these zones vector information of the Portuguese roads was used, obtained through OpenStreetMaps4 (Figure 25c). Finally, the exterior polygons were divided into smaller segments, using a similar process to the one described in the Segmentation section (Figure 25e).

[4] https://www.openstreetmap.org/

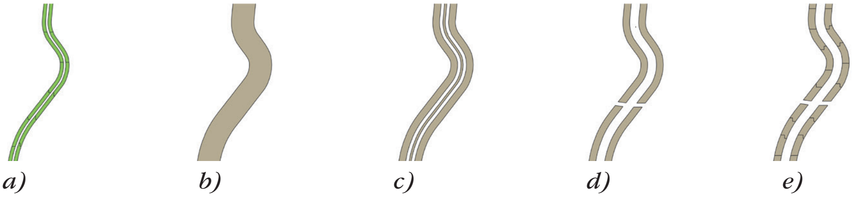


Figure 25. Process of creation of exterior segments.
a) Original fuel break
b) 20 meter buffer
c) Difference between buffer and original geometry
d) Removal of other types of fuel breaks and roads
e) Final exterior segments

Experiments

The city council of Mação provided ground truth data detailing the fuel breaks in which interventions were conducted in 2021. Using this, a subsection of road fuel breaks segments in Mação were chosen, 10 within fuel breaks with interventions, and 10 within sections without interventions. The NDVI values of all segments were analysed over the course of the year 2021, using Sentinel-2 imagery.

The average NDVI values of inside the segments was compared with the average NDVI value on the outside of the segment. To obtain the value on the outside of the fuel break, each inside segment was matched with the exterior segments that touched its exterior border, as can be seen in Figure 26, and the average of their NDVI values was used.

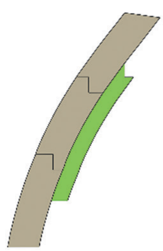


Figure 26. Example of a fuel break segment (green) with the corresponding exterior segments (grey).

Observing Figure 27, which shows the NDVI values of the segments where no interventions took place, it is possible to see that the behaviour of the NDVI indices inside and outside the breaks do not show any major discrepancies.

On the contrary, in the segments that were marked as having interventions, the inside NDVI values decreased sharply in July 2021, which was not accompanied by a decrease in the NDVI value of the exterior segments, as can be seen in Figure 28.

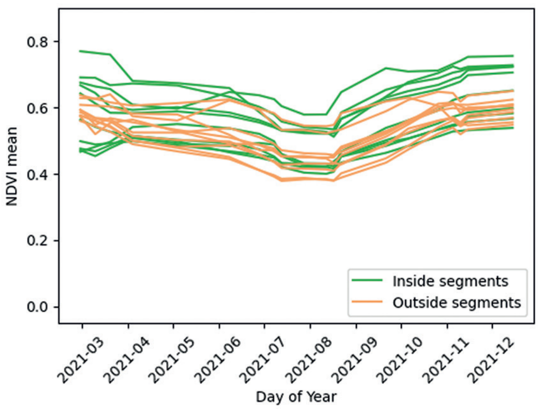


Figure 27. NDVI values of ten segments belonging to fuel breaks without interventions, during the year 2021.

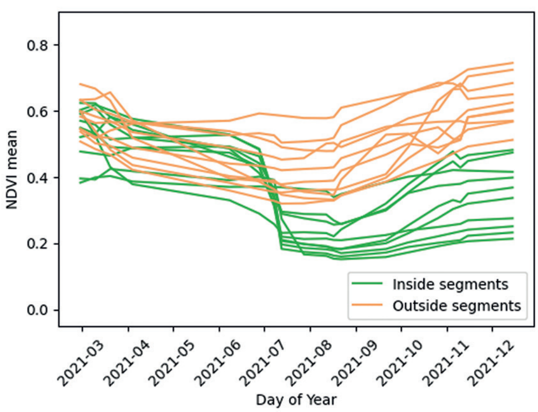
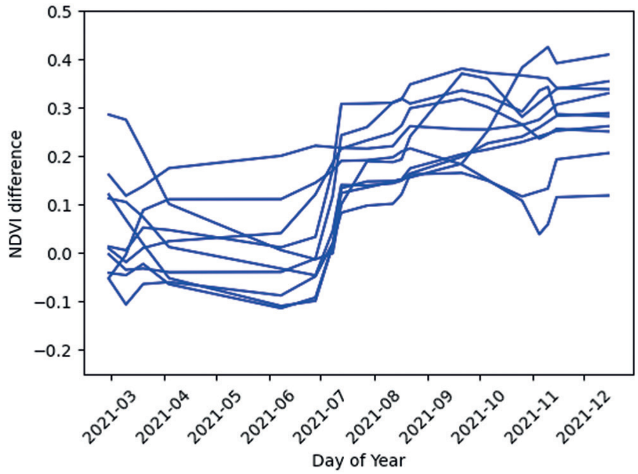
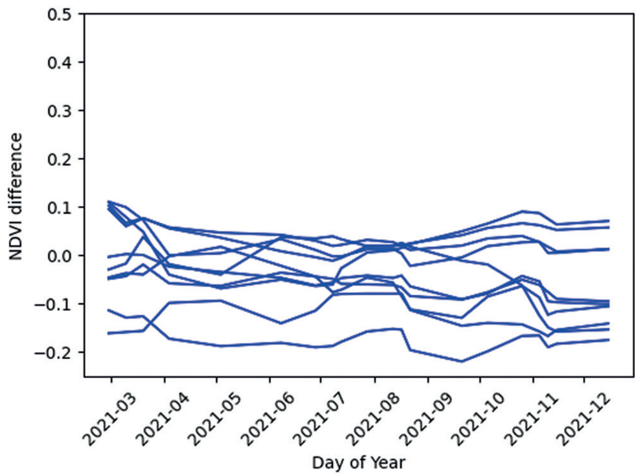


Figure 28. NDVI values of ten segments belonging to fuel breaks with interventions, during the year 2021.

The difference between NDVI interior and exterior segments was plotted for both groups, as can be seen in Figure 29. Again, it is possible to observe that the two groups of segments follow very different patterns.



(a) With intervention



(b) Without intervention

Figure 29. Difference in NDVI values for interior and exterior segments, in fuel breaks with and without interventions.

These experiments show that this approach is feasible and that information about the exterior of fuel breaks can provided useful information. If more ground truth data could be acquired, in particular information about the specific days in which interventions took place in 2021, a machine learning classification model could be trained and used to detect whether an intervention was performed on a fuel break, and when that intervention took place. A study using this approach in combination with several machine learning classifiers has been published, with very good and promising results (Afonso *et al.*, 2020).

2.4.5. Case study — population clusters

In order to create machine learning algorithms that can accurately predict the instants where interventions have taken place, it is important to add extra temporal features, namely for capturing the change of NDVI signal in a 30 days' time window.

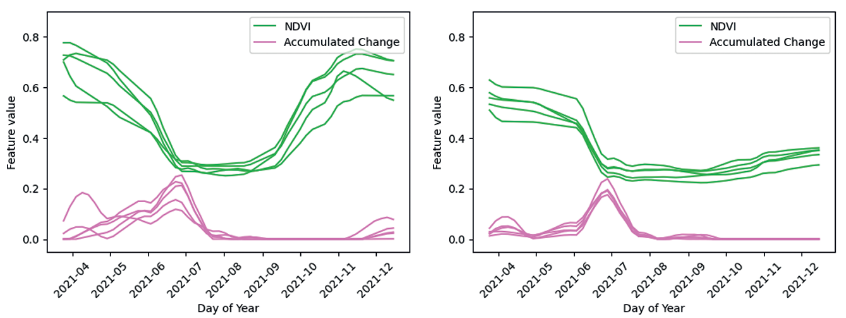
In this case study, the new temporal feature, Accumulated Change, is illustrated using the fuel breaks around urban conglomerates, again in the region of Mação. For each segment, the Accumulated Change was calculated by subtracting the NDVI value of each date and the maximum NDVI value of the previous 30 days. With this new attribute, context about the trend of the NDVI in the previous weeks is added to each date, which can be useful when detecting changes that occur over a longer period, as is the case with some intervention processes. In general, higher values of Accumulated Change hint at a bigger likelihood of some kind of event having occurred, such as fires or interventions.

Experiments

Fuel breaks surrounding urban conglomerates tend to be more heterogeneous in the type of vegetation than in the previous use case. As such, to test the usefulness of Accumulated Change, it is important to observe its behaviour in segments of the most common types in Mação, such as agricultural and areas of spontaneous vegetation.

Using the previously mentioned ground truth, a subsection of fuel break segments surrounding urban conglomerates were chosen for illustration purposes: 10 within fuel breaks with interventions, and 10 within sections without interventions. Of each group of 10 segments, 5 represent predominantly agricultural land, and 5 areas of spontaneous vegetation. Accumulated Change was calculated for each of the segments and analysed in conjunction with the NDVI, over the course of the year 2021, through Sentinel-2 imagery.

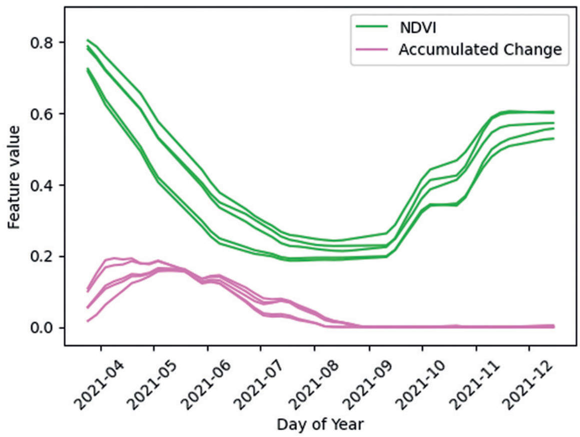
Observing the behaviour of the NDVI index in Figure 30, an intervention was conducted in this area around June/July of 2021, when there is a sudden decrease. The peak of the Accumulated Change appears to coincide with the lowest value of NDVI, effectively detecting the final part of an intervention. This happens in both types of segments.



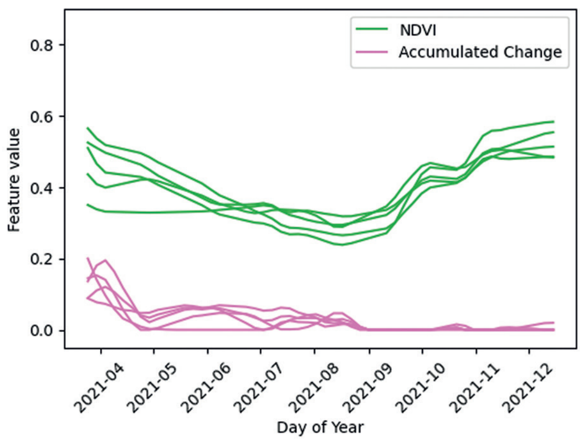
(a) Agriculture *(b) Areas of spontaneous vegetation*

Figure 30. NDVI and Accumulated Change values of segments belonging to fuel breaks with interventions pertaining to two different types: agriculture and areas of spontaneous vegetation.

The Accumulated Change in segments in zones without interventions has a different behaviour, as can be seen in Figure 31. In these segments, the rise and decrease of the values in this feature is slower, creating a more elongated curve with a softer peak.



(a) Agriculture



(b) Areas of spontaneous vegetation

Figure 31. NDVI and Accumulated Change values of segments belonging to fuel breaks without interventions pertaining to two different types: agriculture and areas of spontaneous vegetation

These experiments show the usefulness of the temporal feature Accumulated Change to detect interventions, particularly the end of a multi-stage process. The use of a combination of this feature and Sentinel-2's bands to train machine learning classifiers is in process, with a preliminary test having obtained very good results in predicting the date of interventions (Silva, 2022).

In this Section, we have shown that remote sensing-based methods can be employed to track fuel breaks, even the more difficult cases of narrow fuel breaks and with some vegetation, and potentially identify instances where an intervention took place. Notwithstanding, their utilization has always a certain degree of uncertainty, and it is important to identify its challenges.

The work in this Section focuses on the utilization of the satellite Sentinel-2, which despite all its merits, has some important limitations. Sentinel-2 instruments are passive sensors, meaning that its products are affected by the weather, specifically clouds which highly influence the spectral values. In our pre-processing, images that are too cloudy are discarded and some are filtered, resulting in a significant loss of information. This loss of information also impacts outlier removal, since instances can only be classified as an outlier, if they have at least one other instance in the last 15 and the following 15 days. This loss could be mitigated using Synthetic Aperture Radar data like Sentinel-1, whose instruments are not affected by the weather, but its lower resolution would make the analysis of narrow fuel breaks challenging. Alternatively, commercial satellites with better spatial and temporal resolution may be employed.

Through the Use Cases presented, we have shown that it is possible to create features that can be used to train machine learning models to be able to pinpoint when vegetation has been impacted in some form, with some results having already been published. The major bottleneck in the progress and development of these methods is the inexistence of information about the exact date of the interventions, or the state of the fuel break, that could be used as ground truth. The Floresta Limpa project is concluding the development of a mobile application to which municipalities, authorities and the general public can contribute to with information about the state of the fuel break, in order to improve the already existing classifiers.

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3.

Classification of vulnerability on the property scale

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3.1. Introduction to the classification of vulnerability on the property scale

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Vulnerability has, until recently, been one of the less-explored facets of risk. However, the IPCC conceptual model of risk, encompassing hazard, vulnerability, and exposure (IPCC 2014), as well as various other authors (Verde & Zêzere, 2010; Verde, 2015; Bachmann & Allgöwer, 1999; Miller & Ager, 2013; Castillo Soto *et al.*, 2013), emphasizes that while there is no risk without a hazard, there is also no risk without vulnerability. Vulnerability is the critical factor that transforms a natural event into a disaster, a concept traditionally examined by social sciences due to the inherently human nature of disasters (Pastor *et al.*, 2022). In a metaphorical shift, vulnerability is increasingly applied to any system, whether man-made or natural, including all elements affected by forest fires, such as the forest itself and other natural and anthropogenic values.

Conducting a vulnerability assessment at the property level is a pivotal strategy for managing fire risk in WUI areas. This approach aims to raise homeowners' awareness of fire risk by identifying significant problematic conditions on their property and in its immediate surroundings.

Research focusing on characterizing vulnerability at the plot scale seeks to identify building-related and external parameters contributing to interface vulnerability, classifying them into levels of risk where possible. Considered building elements include roofs, gutters, vents, semi-confined spaces, facade materials, glazing systems, shutters, etc. The built environment at the plot scale comprises elements varying in flammability, with ornamental vegetation being a primary concern.

Several tools are available for assessing property-level vulnerabilities in WUI areas: checklists, expert opinions, questionnaires providing a scoring system for vulnerability levels, and more sophisticated methods like quantitative index-based tools.

The first article delves into the role of ornamental vegetation in property-scale risk, examining flammability and combustibility levels while stressing the importance of considering spatial vegetation organization, horizontal continuity, other fuel types, and aggravating factors like slope and wind exposure. The second article, after reviewing main vulnerability factors, proposes two indices integrating these parameters, comparing and applying them to a case study for fire vulnerability assessment. Finally, the third article describes a multi-criteria approach used to objectify expert opinions and presents a web service tool.

3.2. Ornamental vegetation: a key factor in vulnerability level at the property scale

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Residents who choose to reside in wildland-urban interfaces are often drawn to close contact with nature, as it provides various services such as aesthetics, privacy, shade, and biodiversity (Driscoll *et al.*, 2010; Nelson *et al.*, 2005). This natural environment consists of native vegetation combined to varying degrees with ornamental plants in gardens. Consequently, vegetation in wildland-urban interfaces is defined as a heterogeneous fuel source comprising native and exotic species, consisting of individual plants, clusters, or hedges commonly used for property delineation (Ganteaume, 2018).

Despite the fact that this vegetation is the primary source of fuel contributing to the vulnerability of homes, residents may not always be aware of the fire risk at the property level. The characteristics of vegetation in proximity to houses are strongly correlated with house loss during wildfires. The examination of vegetation flammability and combustibility allows for a better understanding of fire behaviour in these diverse environments. The more flammable and combustible the vegetation, the higher the likelihood of a powerful fire approaching the house, thereby increasing its vulnerability.

The type of plant (flammability), its combustible biomass (combustibility), and its distribution within a garden collectively influence the probability of ignition and the spread of fire, determining the overall fire risk at the property level. Fire propagation relies on both flame properties and the characteristics of the fuel in its path (Catchpole, Hatton, & Catchpole, 1989). While fire behaviour in natural settings is relatively well-documented, the fire behaviour of ornamental vegetation has been less explored.

The objective of this subchapter is to focus on ornamental vegetation, present findings on its flammability and combustibility levels, and identify additional parameters contributing to fire risk at the property level.

3.2.1. Inflammable and combustible vegetation: definition

According to Anderson (1970), the flammability of a plant is characterized by the combination of four components:

- Its ability to ignite when subjected to a heat source (ignition delay)
- Its ability to continue burning once ignited (flame duration)
- Its ability to release energy and burn quickly (propagation, temperature, flame height)
- Its ability to consume during burning (rate of consumed material)

Flammability is evaluated for different plant levels, from the finest level (usually the leaf) to the level of a set of particles (usually litter or branch), and also for living fuel (e.g., fresh leaves) and dead fuel (e.g., litter). Combustibility is evaluated by the proportions of different types of particles (fine and coarse, dead and living) in the plant, as well as by the water content of fine particles.

The physical and chemical characteristics of the plant influence flammability, and the plant's structure affects combustibility. It is important to know the factors that make a plant more or less inflammable and produce more or less combustible biomass to select species wisely for planting in a garden and thus reduce the risk of fire. Some species are more flammable than others, but all plants, whether living or dead, provide fuel for fire when the required conditions are met. The flammability of a plant can varies during a forest fire where conditions are often unpredictable. The flammability of a plant will vary depending on:

- The water content of the plant
- The age, health, physical structure, and chemical content of the plant
- Daily and seasonal climatic variations
- The plant's location in relation to other combustible plants or objects
- The part of the plant concerned, with some parts being more flammable than others.

3.2.2. How to characterize inflammable and combustible vegetation?

To characterize flammability, different methods are used (Ganteaume, 2017) from the finest scale (particle = leaf) to a larger scale (branch), passing through an intermediate scale (litter composed of a set of particles).

The vegetation particles (fresh leaves) are burned on a radiant disk or a radiative burner, emitting heat of 500W (Figure 32a). At the litter scale (Figure 32b) or branch scale (Figure 32c), a burning

(a) (b) (c)

Figure 32. Devices for measuring flammability.

bench is used (equipped with devices to record temperature variations, flame height, and mass loss, with or without wind, using a linear ignition source (cotton wick) or a point ignition source (incandescent or flaming ember).

Other authors as Wyse *et al.* (2016) quantified terminal shoot flammability of 60 indigenous and exotic species in New Zealand. Alam *et al.* (2019) compared the flammability of plant species at the leaf-level (most used in flammability studies) and shoot-level (which retains aspects of plant architecture). Kraaij *et al.* (2022) used large plant shoots to facilitate a more realistic assessment of canopy flammability.

In order to quantify combustibility, the Cube method can be used (Cohen *et al.*, 2002). It allows evaluating the spatial distribution of different classes of plant particles (leaves or needles, twigs less than 2 mm, 2 to 6 mm, or more than 6 mm) living and dead in the plant and their proportions at different levels of the plant (at the base, centre, and periphery of the plant) by taking vegetation cubes from each species. The more fine and dead particles (thus dry), the higher the combustibility.

It involves taking fuel cubes at different levels of the plant canopy: top, centre, base (cf. Figure 33).

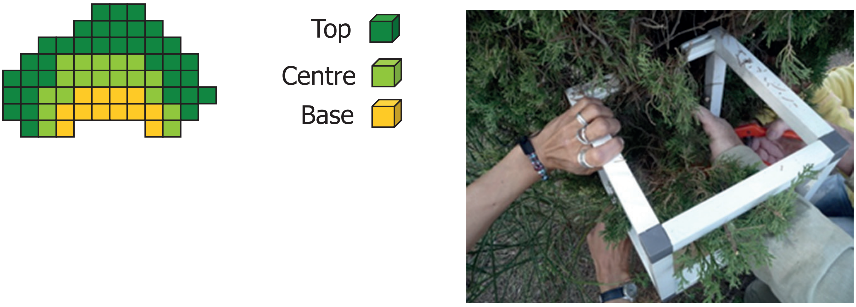

Figure 33. The cube method combined with moisture content measurement allows evaluating combustibility.

3.2.3. Indicator of vulnerability: the flammability and combustibility level of a plant

Previous studies have offered lists of recommended plants for gardens, categorized by their fire-related characteristics. Typically, authors assess, and rank species based on their flammability (Long *et al.*, 2006). The findings of these studies, which evaluate the flammability of various species, can be valuable in selecting plants with lower flammability for cultivation in fire-prone areas (Murray *et al.*, 2018). However, it's important to note that several authors emphasize that the burning of small plant components does not accurately reflect the overall flammability of the entire plant (Fernandes & Cruz, 2012; Schwilk, 2015 in Kraaij, 2022).

For a specific species, the level of flammability may vary depending on whether we are assessing the fresh leaves or the litter. The classification, which takes into account all components of flammability (variables recorded during burnings), can then establish groups of species with similar flammability characteristics. Caution should be exercised in underestimating flammability, as the classification is determined by the most severe fuel type (either leaf or litter), providing the overall flammability level of the species.

Regarding combustibility, the classification, based on the proportions of fine elements and dead elements and on the water content, produces groups of species with the same type of combustibility. The Leyland Cypress has the highest combustibility: lower water content, high dead biomass, and high biomass in fine elements. Species with the lowest combustibility have low biomass in fine and dead elements and low to medium water content. High combustibility combined with low water content leads to high fire spread and increased fire risk at the parcel level.

Ganteaume (2017) worked on a species selection key based on the risk level. This selection key is a practical tool developed to help choose suitable species for landscaping gardens in wildland-urban interface areas where fire risk is high, at the parcel level. This key, adapted from the CFA report ”Landscaping for bushfire,” takes into account the plant characteristics presented in the previous paragraph and provides an overall rating of flammability/combustibility level and corresponding fire risk, as well as maintenance advice. Ultimately, this key allows an opinion on the appropriateness of using ornamental species in wildland-urban interface areas in the Mediterranean region. It is important to note that different species belonging to the same genus may not have the same flammability; it is necessary to evaluate each species individually.

This key allows assigning to each species:

-  alert points
-  negative points

A single negative point classifies the plant in the ”extreme fire risk” category. The plant should be avoided in habitat-forest interfaces.

Three alert points or more classify the plant as a high fire risk. The plant should be avoided in the garden. It can be planted outside the 50 m perimeter around the house.

One or two alert points classify the plant as a medium fire risk. The plant can be used in the garden but requires regular maintenance.

With no alert points, the plant is classified as low fire risk. It can be used in the garden without any particular restrictions.

An example is given in Figure 34.

To complete this key, fact sheets describe certain ornamental species among the most frequently listed in the south of France or presenting particular characteristics. These species have been the subject of experiments related to flammability and combustibility. Each sheet presents the characteristics of the species used in the selection key above, a rating in four classes for the flammability of

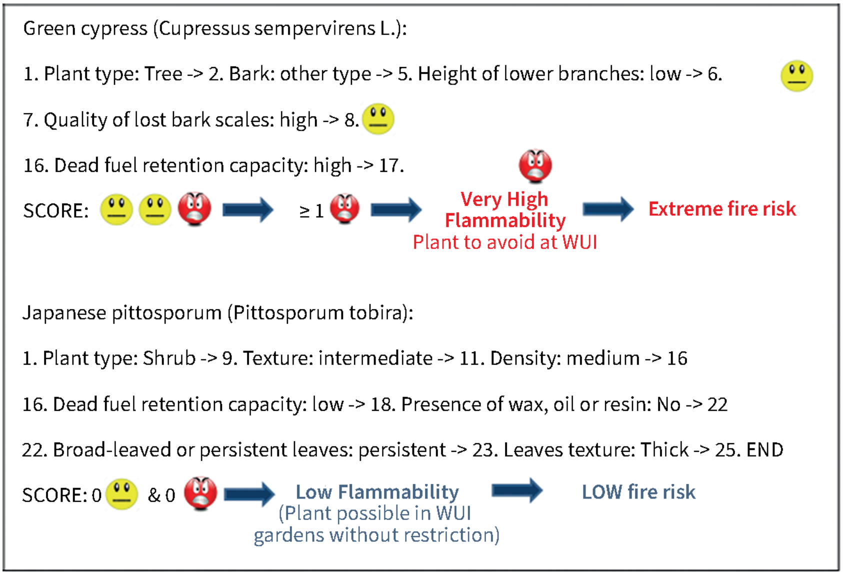

Figure 34. Example of risk level determination for two ornamental species.

different fuels, and the general combustibility of the plant. It also includes information about the origin of the species and its sensitivity to certain environmental conditions and diseases.

3.2.4. Other criteria to consider in the vulnerability of interfaces at the plot level

In addition to selecting less flammable species, the arrangement of vegetation in the garden will impact how fire spreads and increase the vulnerability of buildings. This propagation can occur through direct contact between flames and combustible wood decks or siding when plants are in contact with the building or growing very close to it. It can also occur through radiant heat produced by burning vegetation (Ganteaume, 2018). Creating a defensible space around the house reduces fire risk by increasing the level of self-protection. The concept of defensible space inherently defines the interfaces between human habitat and the forest (Jonhstonn *et al.*, 2019). It involves carefully managing vegetation, reducing the presence of flammable materials, and implementing fire-resistant landscaping practices. By maintaining a clear and well-maintained space around homes and structures, residents can significantly decrease the likelihood of a fire rapidly advancing and threatening their property. Scientific literature proposes some criteria that indicate a lower level of risk, such as landscaping options around the house or maintenance of vegetation:

- Acting on the structure of vegetation can decrease house vulnerability (Mell *et al.,* 2010).
- Risk posed by trees and shrubs near houses is reduced where they are arranged as many discrete patches as possible (Gibbon, 2018). Breaking the horizontal and vertical continuity will decrease the risk (Ganteaume 2018). This spacing between trees and shrubs depends on the species. Zhou *et al.* (2018) found that the flame height significantly increases as the spacing decreases for dragon juniper tree.
- Maintaining fuels at a distance from the house
- Avoiding ladder fuel
- Maintaining 'green' vegetation provides houses with additional protection during wildfires, decreasing fire risk. Vegetation with high moisture content requires more energy to ignite than cured vegetation. Fuel moisture plays an important role in the self-extinction of fires (Wilson, 1985).
- Trees and shrubs in the upwind direction from which wildfires arrive represent a greater risk to houses than trees and shrubs in the downwind direction (Gibbons *et al.*, 2018).

To better quantify the impact of these criteria on the vulnerability level, an adapted modelling of fire propagation in the wildland-urban interface is needed. This modelling would help take into account the complexity of ornamental vegetation around the house.

There are other combustible elements besides vegetation in interfaces. For example, wood and gas piles, oil tanks, and garden furniture are all combustibles that contribute to making interfaces more vulnerable. There is limited information on the real scale burning behaviour of these types of fuels, but recent literature gives some quantitative data. For example, Vacca *et al.* (2022) performed real-scale tests on different fuel packs commonly present on WUI properties. The results indicate that the most hazardous fuel packs among the four tested include those containing pallets, cardboard, paint, foam mats, and garden furniture, consequently elevating the vulnerability level. Ricci *et al.* (2021) conducted an assessment to determine the safety distances between storage tanks and vegetation susceptible to wildfire influence. The methodology they employed offers guidelines for establishing safety distances, which can be implemented in designing zones with reduced fuel density around the industrial facility.

Finally, in addition to vegetation and other combustibles, there are also other criteria playing a role in the vulnerability level at the plot scale. In particular, extreme conditions intensify the risk: rugged topography, extreme weather conditions (strong wind, high temperature, low relative humidity, long periods of drought), a high fuel load in the area adjacent to the plot, isolated and difficult-to-access housing, and the recurrence of large fires in the area.

All these criteria are cumulative. There is no specific flammability or combustibility model per se. However, they are taken into account in some quantitative vulnerability indices, such as those presented in the following two articles.

3.2.5. Conclusion

In summary, the in-depth study of the flammability of various plant components, such as litter, leaves, and branches, reveals the complexity of flammability and combustibility levels within the same species. It is evident that providing general recommendations on the flammability of a specific part of a species can lead to significant biases. To address these biases, innovative solutions are currently being explored. It is necessary to build databases on flammability that encompass the widest range of possible fuel types. Additionally, burning entire trees, as demonstrated in experiments conducted in large fire laboratories in the past (Mell *et al.*, 2009), is a viable approach. These experiments go beyond merely calibrating fire behaviour models through burning; they also involve correlating the results with observed damages.

Additionally, beyond species flammability, it is crucial to consider vegetation management to reduce the vulnerability of built-up areas by creating defensible space.

The current lack of physical fire models adapted to the plot scale and these highly heterogeneous environments constitutes a major gap in our ability to estimate risk levels at the property scale. A research priority should be given to the development of such models, enabling a more accurate assessment of risks and the design of management measures tailored to each context. Field experiments, for example those developed in the Interreg France-Italy Medstar Program, emerge as important tools to assess risk levels under real conditions.

3.3. Methodologies for vulnerability assessment at the property level

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Vulnerability assessment at the property level (microscale) is a key approach for fire risk management at the WUI. It can help to increase homeowners' fire risk awareness by identifying major problematic conditions present on their property and in its surroundings. However, there is a lack of specific WUI microscale legislation and quantitative tools in the most wildfire-prone European countries (Àgueda *et al.*, 2023). Table 1 presents an overview of building and property elements for which risk reduction strategies or suggestions are outlined in codes, standards or guidelines focused on addressing microscale concerns within the WUI. Among these elements, the concept of defensible space surrounding the dwelling emerges as a common theme across all references. In contrast, roof maintenance stands out as less frequently highlighted, being mentioned only in Canada, the USA, France, and in regional areas of Spain (i.e. Catalonia and Valencia).

Table 1. Building and property elements for which risk reduction strategies/suggestions are mentioned in codes, standards and guidelines that address WUI microscale risks. DFS: Defensible space; MAT: Roof Materials; MNT: Roof Maintenance; GUT: Gutters; VNT: Vents; SCS: Semi-confined space; FÇM: Façade materials; GLS: Glazing systems; SHU: Shutters. Adapted from Àgueda et al. (2023).

Standards and Guidelines	**DFS**	**ROOF**		**GUT**	**VNT**	**SCS**	**FÇM**	**GLS**	**SHU**
		MAT	**MNT**						
International WUI Code (International Code Council, 2021)	X	X		X	X[A]	X	X	X	X
AS 3959 — Australia (Australian Standards, 2018)	X	X		X	X	X	X	X	X
FireSmart — Canada (Government of Alberta, 2013)	X	X	X	X	X	X	X	X	X
Firewise — USA (NFPA, 2022)B	X	X	X	X	X	X	X	X	X
France (Ministère de l'Écologie et du Développement Durable, 2002)	X	X	X		X		X		X
Portugal (Autoridade Florestal National, 2008)	X								
Piemonte, Italy (Regione Piemonte, 2021)	X								
Sardegna, Italy (Regione Autonoma della Sardegna, 2022)	X								
Generalitat Valenciana, Spain (Manca et al., 2014)	X	X	X	X	X	X	X	X	X
Generalitat de Catalunya, Spain (Generalitat de Catalunya, 2019)	X	X	X	X	X	X	X	X	X

[A] *Requirements for vents refer to ignition-resistant Classes 1 and 2.*
[B] *Guideline for homeowners based on NFPA Standards such as NFPA 1140 (NFPA, 2022)*

Several tools are available for the assessment of property-level vulnerabilities in WUI areas. Table 2 presents a selection of straightforward options, among which the simplest is a checklist. An example of this category is the 'Home Ignition Zone Checklist' introduced by NFPA (2023), where a list of items required to make homes safer at the WUI is outlined.

Table 2. Selection of straightforward options for evaluating the vulnerability of properties at the Wildland-Urban Interface (WUI). C: Checklist; Q: Questionnaire; N: No; Y: Yes.

Reference	Type of tool	Scoring system	Number of questions / checkpoints	Maximum score and scoring levels
NFPA (2023)	C	N	8	-
FireSmart Canada (2020)	Q	Y	23	Maximum score = 412 (worst); Levels: < 21 points; 21-29 points; 30-35 points; > 35 points
Préfet des Bouches-Du-Rhône (2018)	Q	N	27	-
Manca et al. (2014)	Q	Y	28	Maximum score = 28 (worst); Levels: -
Generalitat de Catalunya (2019)	Q	Y	10	Maximum score = 20 (best); Levels: < 8 points, 8-16 points; > 16 points

There are also questionnaires that provide a scoring system to determine the vulnerability level of a property to the incoming fire (e.g., FireSmart Canada, 2020; Generalitat de Catalunya, 2019). FireSmart Canada (2020) provides an in-depth scoring system, dividing the defensible space into three different zones and assigning different weights to different categories (although the rationale behind these weightings is not justified). For example, the characteristics of the home and its attachments account for approximately 34% of the total score, while the different zones (0–1.5 m,1.5–10 m, 10–30 m and 30-100 m) account respectively for 7%, 29%, 15% and 15% of the total score - based on the latest version of the Home Ignition Zone assessment score card (FireSmart Canada, 2020). The final scoring in the questionnaire is divided in four different levels: low, moderate, high, and extreme. Attaining a low level requires a total score below 21 points, while an extreme level is reached with a total score exceeding 35 points (even though the maximum attainable score is 412 points). In the questionnaire of Catalonia (Generalitat de Catalunya, 2019) each response is assigned a score (0, 1 or 2; where 0 indicates the highest vulnerability). Then, these scores are aggregated to derive an overall value, linked to a specific vulnerability level. Nevertheless, there is here also a lack of explanation regarding the rationale behind the designated thresholds for each level. Additionally, certain questionnaires base their scoring on whether the answer to each question is affirmative or negative (i.e., the more affirmative answers, the more the house is vulnerable) and do not establish distinct levels of vulnerability (e.g., Manca *et al.*, 2014). Alternative questionnaires shift the emphasis away from scoring and focus only on identifying the weak points in the property, prompting the homeowners to take measures to address all of them (Préfet des Bouches-Du-Rhône, 2018).

More sophisticated advancements on the assessment of the vulnerability of WUI properties to wildfires include two quantitative index-based tools developed for Mediterranean environments. The first tool is the Physical Vulnerability Index (PVI) developed by Papathoma-Köhle *et al.* (2022) and the other one is the Vulnerability Assessment Tool (VAT) developed by Àgueda *et al.* (2023). Both works aim to address the limitations identified in the aforementioned tools, particularly the need to establish vulnerability indices and levels based on scientific knowledge. Another elaborate methodology based on a multicriteria analysis exists at a French level. This approach began to be developed about 10 years ago (Maille *et al.*, 2014) and the level of development reached to date is higher than that of the two previously mentioned tools, as the model has already been implemented as a decision support tool on a web service.

Next, details about the tools from Papathoma-Köhle *et al.* (2022) and Àgueda *et al.* (2023) are described and a case study is presented to compare both. Additionally, another recent effort made by Dossi *et al.* (2022) to evaluate the level of vulnerability specifically associated to constructive elements of dwellings located at the WUI is briefly outlined. The approach by Maille *et al.* (2014) is described in another section within this chapter.

3.3.1. Physical Vulnerability Index (PVI)

Papathoma-Köhle *et al.* (2022) undertook a comprehensive literature review to establish a set of 56 indicators associated with WUI buildings' susceptibility to wildfires. The authors categorized the indicators into four groups. They took into account those pertaining to the building envelope (e.g., window glass type, window size, protected vents, stored materials), the interior of the building (e.g., curtain material, upholstery), and the surroundings of the building (e.g., timber deck or porch, garage, slope of land, neighbouring buildings). Additionally, they included emergency response factors, such as the distance to fire stations and accessibility.

The index introduced by Papathoma-Köhle *et al.* (2022) is based on the systematic post-fire analysis of more than 400 dwellings impacted by the wildfire event which occurred in July 2018 in Mati (Greece). During this post-fire investigation, it was feasible to gather only 13 indicators out of the original set of 56. The limitations arose due to either the inapplicability of certain indicators within the context of Greek architecture or the impracticality of obtaining data for elements already destroyed by the fire.

A statistical methodology (Boruta feature selection) was employed to further select 8 relevant indicators from the pool of 13 collected indicators, and to weight them based on the importance of each indicator in explaining the observed degree of damage. The index was constructed as a composite of the 8 relevant indicators, which were scored (1-5; 5 = worst in terms of vulnerability) and added according to their relative importance (see Equation (1)).

$$PVI = \sum_{b=1}^{B} \left(w_b \cdot I_b\right) \qquad (1)$$

Where PVI indicates the Physical Vulnerability Index, I_b represents the indicator used, w_b its weight, and B is the total number of indicators (i.e., 8).

The eight relevant indicators were related to building characteristics and surroundings. These indicators, along with their corresponding weights and scores, are comprehensively listed in Table 3.

Table 3. Relevant indicators considered in PVI calculation, their weights and their scoring. Source: Papathoma-Köhle et al. (2022).

Indicator	**Weight**	**Scoring**				
		1	**2**	**3**	**4**	**5**
Roof material	33%	Concrete slab with tiles	Concrete slab	Metal roof with ceramic or metallic tiles (“helenit” type)	Wooden roof with ceramic tiles	Wooden roof with metal tiles
Structural type	23%	Stone construction with load-bearing masonry	Reinforce concrete structure	Light metal frame and plasterboard in gaps and mixed materials	Wooden structure	Mobile home (contianer)
Slope (terrain)	14%	Mild (0-5%)	-	Average (5-25%)	-	Intense (> 25%)
Vegetation	8%	No vegetation	Vegetation within 20 m	Bushes within 20 m	Tangent bushes and trees within 20 m	Hanging trees and tangent trees
Roof-leaf accumulation (see Table 4)	6%	1	2	3	4	5
Shutter material	6%	-	-	Aluminium	Mixed	Wood and plastic
Main ground covering	5%	Bricks	Slate slab and pebbles and chipping	Concrete	-	Natural soil without coating
Roof type	4%	-	-	Tireless flat and shed	Dual, three- or four-pitched roof (gable hipped)	Layered (combines different designs according to the floor plan of the building)

Table 4. Potential leaf accumulation on roof. Source: Papathoma-Köhle et al. (2022).

Roof type	Roughness of roof material	
	Concrete	Metal and ceramic tiles
Tireless flat and shed	1	2
Dual-, three- and four-pitched roof (gable, hipped)	2	4
Layered (combines different designs according to the floor plan of the building)	3	5

3.3.2. Vulnerabilty Assessment Tool (VAT)

In the work from Àgueda *et al.* (2023) the causes of fire entrance inside a dwelling located at the WUI were summarized considering two main intermediate events, as indicated in yellow in the fault tree shown in Figure 35: one involving the exposure conditions (lower main branch) and the other involving structural vulnerabilities typical of Mediterranean constructions (upper main branch). For the fire to enter a dwelling, both of these events should occur. The different paths leading to these two intermediate events in a Mediterranean environment were explored further to develop the complete sketch model shown in Figure 35.

The paths considered were based on the revision paper from Vacca *et al.* (2020). More specifically, when it comes to fire exposure of the dwelling, two areas around the structure were identified: Zone 1 included the area in a radius of 10 m from the dwelling, while Zone 2 consisted of a 10–30 m ring around the dwelling. In both of the selected zones, three types of fuels were considered: ornamental vegetation, artificial fuels (e.g. liquefied petroleum gas (LPG) tanks, garden furniture, sheds) and wildland vegetation. For each zone, a set of fuel management rules that can reduce the

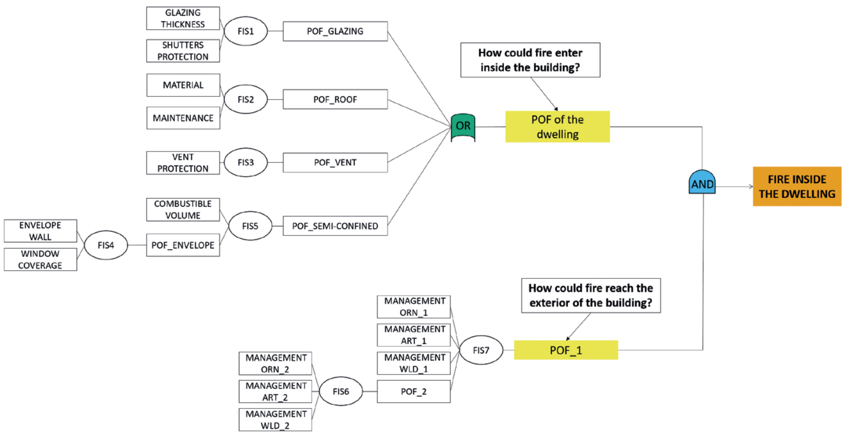

Figure 35. Scheme for vulnerability assessment to wildland fires for dwellings at the WUI. FIS: Fuzzy Inference System; POF: Probability Of Failure; ORN: Ornamental vegetation; ART: Artificial fuels; WLD: Wildland vegetation; _1: Refers to zone 1 (area within a radius of 10 m from the dwelling); _2: Refers to zone 2 (a 10 m to 30 m ring around the dwelling). Source: (Àgueda et al., 2023)

probability of the fire reaching the dwelling was established (detailed in Àgueda *et al.*, 2023). Failure occured when compliance with these rules was not met. Structural vulnerabilities of the dwelling were identified based on the different paths through which fire could enter. According to Vacca *et al.* (2020), there are four main paths, which are associated to either gaps that already exist in the dwelling due to bad maintenance, or that can be caused by the fire itself. These pathways involve glazing systems, roof, vents and structural damage to the dwelling's envelope due to heat accumulation in semi-confined spaces. The failure sequence for each one of these elements is identified as shown in Figure 35: the failure of a glazing system depends on the thickness of the glass pane (the considered type is annealed glass, given it is the most common in residential windows) and the type of shutters, with different degrees of protection depending on the material; the failure of the roof depends on the material of the roof covering, as well as the maintenance level of the roof itself; the probability of fire entrance through vents is determined by the material and conditions of their protection; the failure of the envelope of a semi-confined space is determined by the percentage of glazing systems present in the envelope, the amount of combustible materials stored in the space, and the material and thickness of the envelope, which allows to maintain the load bearing capacity of the structural element exposed to fire (Vacca *et al.*, 2022).

The impact of firebrands on the different types of fuels was indirectly integrated through the rules for fuel management. It was assumed that firebrand attack was likely to be an ignition source for fuels present in Zones 1 and 2. If any well managed fuel were to be ignited due to firebrands, it would not cause fire spread to other fuels or impact the dwelling's vulnerable elements. Furthermore, concerning structural vulnerabilities, the presence of firebrands was given significant consideration by considering that they can enter the building through gaps that exist either due to the building's characteristics or that result from poor maintenance of the building itself.

Following this reasoning, the vulnerability assessment tool (VAT) comprises two primary components: 1) a checklist for gathering the necessary inputs (available in Vacca (2023)); 2) a mathematical model to compute the probability of fire entrance into a building.

The mathematical model was formulated using a combination of expert knowledge-based fuzzy logic approach and classical logic approach, and it was implemented using Python programming. WUI fire experts were required to parametrise the seven fuzzy inference systems (FISs) outlined in the model (refer to Figure 35). To achieve this, a survey was formulated to gather insights from them regarding the consequents of the rules defined within each FIS, as well as to delineate membership functions. Details about the procedural aspects for configuring a FIS can be found in Àgueda *et al.* (2023).

3.3.3. Comparative analysis of VAT and PVI methodologies

A comparison of the VAT and PVI methodologies is presented next. First, general differences observed between each methodology based on the considered indicators are highlighted. Afterwards, the vulnerability of four specific properties located in the same Mediterranean WUI settlement is evaluated using both methodologies in order to effectively underscore the distinct results obtained from each index.

When it comes to the type of constructive elements included in both tools, it is observed that, although all of the eight relevant indicators considered for the PVI calculation are included in the events considered for the VAT index calculation, indicators for glazing thickness, vents presence and maintenance, and semi-confined spaces presence and management are missing in the PVI calculation. Additionally, the maintenance level of the roof is not taken into account in the PVI, while the shape of the roof is.

In terms of fuel availability near the dwelling, only vegetation within 20 m from the structure is considered in PVI calculation. Artificial fuels (commonly found in WUI properties as well) are not considered, and neither is the fire spread through the different types of fuels due to poor fuel distancing. In addition, the indicators used to develop the index are “only those relevant to the dominant architectural style of the area” and those that were possible to collect after the fire, when “many features were already destroyed”. This methodological step prevents the PVI tool from being a priori applicable to other Mediterranean areas where construction styles might differ greatly.

Four properties located in the Mas Sauró settlement of the Collserola Natural Park of Barcelona (Spain) are analyzed following the two methodologies (Figure 36). On April 24 and 26, 2023, they were visited and, in collaboration with the homeowners,

Figure 36. Monitored WUI properties (PR#) from the Collserola Natural Park in Barcelona (Google Earth, earth.google.com). Red line: 10-m around the dwelling; yellow line: 30-m around the dwelling. A) PR1; B) PR2; C) PR3; D) PR4.

the VAT questionnaires were filled out. Subsequently, after reviewing the marked responses, the VAT model was executed, which allowed inferring the vulnerability of the houses based on the VAT index. The characteristics of the properties and the results obtained for the 4 analyzed houses are shown in Table 5 and Table 6, respectively.

Table 5. Characteristics of the properties analyzed. O/A/W: Ornamental/Artificial/Wildland fuels. SCS: Semi-confined space. PR#: monitored property according to Figure 36.

Characteristics	**WUI dwellings**			
	PR1	**PR2**	**PR3**	**PR4**
Shutters	Wood	No shutters[B]	Wood	No shutters[B]
Glazing thickness[A]	14 mm	14 mm	14 mm	14 mm
Roof material	Combustible	Non-combustible	Non-combustible	Non-combustible
Roof maintenance	Good	Good	Good	Good
Vents	Combustible	Combustible	Combustible	Non-combustible in good conditions
Windows coverage in semi-confined space	-	-	-	-
Envelope type in SCS	-	-	-	-
Combustible material coverage in SCS (% in volume)	-	-	-	-
Fuel management compliance in zone 2 O/A/W (%)	25/50/25	100/50/25	100/50/25	0/100/25
Fuel management compliance in zone 1 O/A/W (%)	100/0/50	57/67/100	63/33/100	29/33/100

[A] Glazing thickness was assumed to be 14 mm (4 glass + 6 air + 4 glass) if there were double panes and 4 mm if the glazing pane was single.
[B] Several windows were protected with aluminium or PVC shutters, but not all of them.

Table 6. Probability of fire entrance in the properties characterized in Table 5 according to the elements identified in the scheme for vulnerability assessment to wildland fires presented in Figure 35. FIS: Fuzzy Inference System; POF: Probability Of Failure; _1: Zone 1 (10-m around the dwelling); _2: Zone 2 (10-m to 30-m ring around the dwelling).

Variables	**WUI dwellings**			
	PR1	**PR2**	**PR3**	**PR4**
POF_GLAZING (%)	39.2	70	39.2	70
POF_ROOF (%)	64.8	13.9	13.9	13.9
POF_VENT (%)	64.8	64.8	64.8	13.9
POF_SEMI-CONFINED (%)	0.0	0.0	0.0	0.0
POF of the dwelling (%)	92.5	90.9	81.6	77.8
MANAGEMENT_ORN_2 (%)	25	100	100	0.0
MANAGEMENT_ART_2 (%)	50	50	50	100
MANAGEMENT_WLD_2 (%)	25	25	25	25
POF_2 (%)	86.9	78.6	78.6	87.9
MANAGEMENT_ORN_1 (%)	100	57	63	29
MANAGEMENT_ART_1 (%)	0	67	33	33
MANAGEMENT_WLD_1 (%)	50	100	100	100
POF_1 (%)	78.6	53.6	72.8	84.9
Probability of fire entrance (VAT index) (%)	72.7	48.7	59.4	66.1

The PVI was also calculated according to the characteristics of the dwellings, as shown in Table 7. Shutter material scores presented in Table 7 appear to conflict with information given in Table 5. This discrepancy arises from the fact that dwellings may have both shuttered and unshuttered glazing systems. Unlike the VAT methodology, which accommodates the option for non-shuttered glazing systems, the PVI methodology does not allow a score for such. Consequently, for PVI calculation the materials used in specific shutters installed in PR2 and PR4 dwellings were considered, namely aluminium and PVC respectively.

Table 7. PVI results for properties characterized in Table 5.

Indicators	Weight	WUI dwellings			
		PR1	**PR2**	**PR3**	**PR4**
Roof material	0.33	3	1	1	1
Structural type	0.23	1	1	1	1
Slope (terrain)	0.14	3	3	3	3
Vegetation	0.08	4	4	4	4
Roof-leaf accumulation	0.06	4	5	4	4
Shutter material	0.06	5	3	5	5
Main ground covering	0.05	5	3	3	5
Roof type	0.04	4	5	4	4
PVI		**2.91**	**2.13**	**2.15**	**2.25**

Both indexes arrange the properties according to their vulnerability in a consistent manner. Nevertheless, while VAT values exhibit more pronounced distinctions across each property (ranging from

48.7 to 72.7, resulting in a margin of 24%), PVI outcomes reveal values within a narrower span (ranging from 2.13 to 2.91, yielding a difference of 16% only).

3.3.4. Wildfire Resistance Index (WRI)

Dossi *et al.* (2022) introduced the Wildfire Resistance Index (WRI) (Equation (2)), which takes into account only building features and somewhat refers to the opposite of a vulnerability index. In essence, a high WRI corresponds to a low vulnerability index for the structure. They used data from two past large fires, i.e., the CAL FIRE (DINS) database and the Pedrógrão Grande Fire Complex database, aiming to establish a correlation between building vulnerability and fire damage.

Due to variations in post-fire data collection methods, uniform indicators (or building features) were not available (see Table 8). Additionally, they assumed that all building features were contributing equally (according to Equation (2)).

$$WRI = \frac{\sum_{i=1}^{I} C_i}{I} \tag{2}$$

WRI indicates the Wildfire Resistance Index, C_i is the coefficient assigned to the building feature i (1 corresponding to higher fire protection, −1 to lower fire protection, and 0 to unknown or intermediate characteristics), and I is the total number of features (i.e., 6 or 4 depending on whether the CAL FIRE or the Pedrogão Grande database was used).

The work from Dossi *et al.* (2022) was challenging, specially because of the limited data on the pre-fire building characteristics.

Table 8. Coefficients (-1, 1, or 0) for WRI calculation assigned to CAL FIRE and Pedrogão Grande building features.

Indicator	CAL FIRE	Pedrogão Grande
Roof material	(-1) Combustible (1) Non-combustible (0) Unknown	
Windows	(-1) Single pane (1) Multiple areas (0) Unknown	-
Exterior	(-1) Combustible material (1) Non-combustible material (0) Unknown	(-1) Wood metal (1) Masonry stone (0) Unknown
Deck	(-1) Wood (1) Masonry no deck (0) Composite unknown	(-1) Wood (1) Masonry no deck (0) Unknown
Vent screens	(-1) Not present (1) Present (0) Unknown	-
Eave design	(-1) No eaves unenclosed (1) Enclosed (0) Unknown	-
Preservation level	-	(-1) Poor (1) Good (0) Unknown moderate

After reviewing various methodologies for assessing property--level vulnerability, it becomes evident that establishing a connection between vulnerability and damage is complex and requires the consideration of multiple factors; for instance, factors such as firefighter actions (Yes/No), evacuation/stay-and-defend procedures, and the positioning of the house relative to the advancing front may also play an important role in specific events. Additionally, pre-fire and post-fire data collection is key to validate this type of tools.

3.4. Toward a decision support tool to mitigate buildings vulnerability at WUI: the VUL'INTERMED model

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Decision support tools aiming at supporting decision-makers in their risk mitigation activities, may take various forms. Models for risk assessment, at different space and time scale levels, implemented as software platforms, are among the most operative, althought not the only ones. Such tools may be designed either for a global risk evaluation, or focuse more specifically on one or several of the risk components. Vulnerability assessment based on spatially explicit models is a key support for land management and planning decisision making for risk mitigation. At the scale of a whole territory, such tools provide supports for a more secure global land management ; at the scale of the setlements and land tenure units (micro-local scale) such tools can provide vulnerability diagnosis useful for optimising individual choices.

As it was underlined previously, specifying the models underlaying the software requires long research works and large databases in order to identify the main factors of damaging, taking into account both the temporal (conditions of spread) and spatial (relationship between fuel and the damaged value) contexts of the of events. Expert knowledge represent an alternative way for vulnerability assessment. Operational staff (firefighters, foresters, land managers, etc.) cumulate great experiences of damaging processes in their area of action, that may be used to specify formal models of vulnerability. Because it is subjective and contextualized, expert knowledge modelling requires formal elicitation. One way for such a formal elicitation of expert knowledge is multi-criteria analysis. However, all experts-opinion based models should be cross-validated with statistic models specified with damage data collected on the field after fire events.

In this chapter, we relate an experience of specification of an expert knowledge-based model designed to assess vulnerability of interface buildings to wildfires at local scale in an Euro-Mediterranean context. The aim was to develop a tool aimed at supporting house owners and local decision-makers in reducing WUI vulnerability and prioritize mitigation actions to be carried out for each of the houses. The model was implemented as a decision support tool developed on a web service.

3.4.1. Multicriteria analysis for vulnerability assessment

Multi-criteria analysis is indicated when the evaluation must take into account a large number of heterogeneous, quantitative, ordered or unordered qualitative criteria, or simply textual (Greene *et al.* 2011, Department for Communities and Local Government, 2009). It makes it possible to take into account the absence of linearity of the effect of the values of some criteria on the quantity to be evaluated, the existence of optimal values, as well as the threshold effects. It is therefore very suitable for the formalization of expert judgments. Multi-criteria analysis also proposes tools for the aggregation of judgments and therefore the pooling of knowledge and experience of experts from different backgrounds.

The analysis takes place in three main steps: i) structuring, ii) criteria and modalities assessment by experts and iii) criteria weights and modalities scores calculation.

A. Structuring the criteria tree

The multi-criteria analysis is based on an organization of the criteria in a semantic tree structure. The semantic tree groups the criteria and sub-criteria according to their nature and in no case according to the importance in relation to the quantity to be evaluated. For example, the class of criteria “Accessibility” can group together the sub-criteria “width of the road”, “nature of the road”, “distance to a main road”, etc.

Only the elementary criteria, i.e., the lowest level of the tree structure, take on a “value”. It is always a class (qualitative) value, ordered or not. We call “modalities” (or indicators) the different possible values taken by the elementary criteria. For example, the elementary criterion “nature of the road” has two modalities (“track” or “road”) whereas the elementary criterion “width of the road” takes classes of width (for example: “narrow” or “medium” or “wide”) as modalities.

Experts also evaluate modalities through pairwise comparisons, in order to calculate their relative score. Scores of modalities (or indicators) represent the value taken by the lowest level criteria (elementary criteria). These are the only quantities that characterize the object (building), which vulnerability is assessed.

In practice, the structuring of the tree of criteria and the specification of the modalities are done collectively within groups of experts from various backgrounds. (Vincke 1986, Tacnet *et al.* 2012). It is concerted and aims at reaching a consensus. The realization of the tree structure of the vulnerability criteria as well as the classes of values of the elementary criteria for the definition of the methods were carried out during a day of work which brought together a dozen national experts (France).

Figure 37 illustrates an extract of the resulting criteria tree.

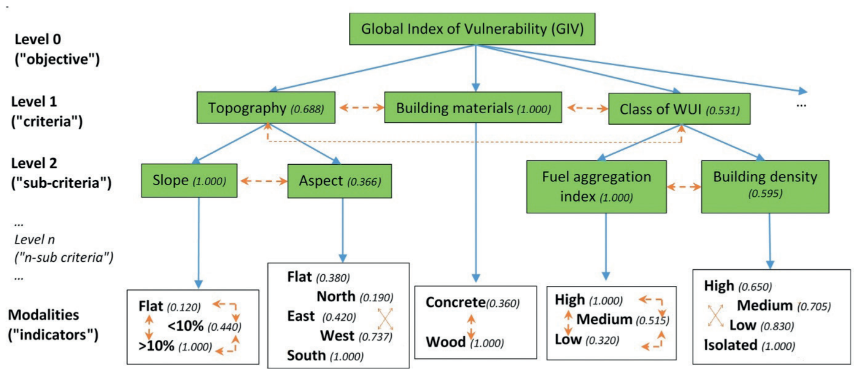

Figure 37. Extract from the criteria hierarchy (the orange arrows represent main pairwise comparisons. Weights are given in parentheses).

B. *Criteria and modalities assessment*

Unlike the phase of structuring the hierarchy tree of criteria, the objective of the criteria evaluation phase is to acquire the personal judgments of the experts. It is therefore not collegial, and is carried out by each expert independently. Experts should not influence each other.

The formalism used for experts knowledge elicitation is the Ascendant Hierarchy Process (AHP, Saaty, 1986). This formalism was initially specified as a decision support tool, for decision optimization in relation to criteria (multi-criteria decision support). It is however currently used for expert opinion based evaluation.

The principle is an assessment of criteria weight by comparison two by two in the same branch of the tree structure, level by level. On Figure 37, pairwise comparisons are shown wutg orange dotted arrows). In the same way, the weights of the modalities are also evaluated.

According to the AHP formalism, all the criteria of the same branch of the tree structure are compared two by two by the expert using a cursor, on a scale with two times nine levels (Figure 38):

the expert is asked to position the cursor on the side of the most important criterion, in proportion to its relative importance.

In practice, the survey may be either carried out by direct interview or on-line. Figure 39 is a screenshot of the implemented web-service (French version).

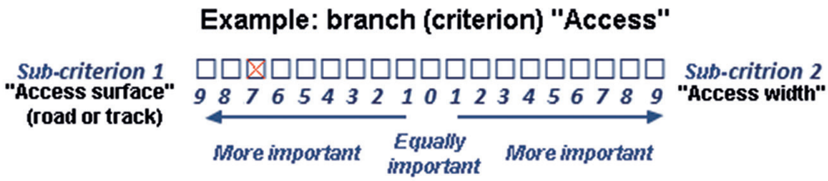

Figure 38. Collection of experts' judgement comparing two sub-criteria on a bilateral 9 degrees scale.

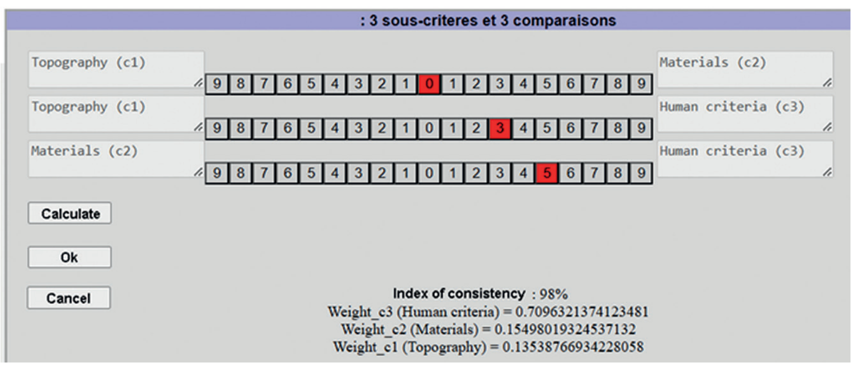

Figure 39. The survey website interface for criteria pairwise comparisons by experts.

C. *Criteria weights and modalities scores calculation*

Criteria weights and modalities scores are calculated exactly in the same way: they are of the same nature. The calculation of weights and scores is carried out in two main phases: i) calculation of weights and scores for each expert judgments and test of consistency iii) aggregation of the judgments.

i. *Calculation of criteria weights and modalities scores based on expert judgments, and tests of consistency*

Based on the evaluations provided by the various experts, the treatments make it possible to obtain weights assigned to each of the criteria, sub-criteria and modalities with the AHP algorithm. This one was implemented using R software. This one tolerates a certain level of inconsistency of the judgments (10% maximum), ie default of cardinal or ordinal transitivity. Indeed, it was demonstrated that a low level of inconsistency might reflect further expert knowledge that is not captured by the criteria hierarchy as specified in step 1 (Merunka, 1987).

The level of inconsistency calculation, based on eigenvalues calculation and comparison to random matrixes requires quite a lot of computing resources. The need to generate random grids of the dimension of the Cartesian product of the number of criteria in a given level of the hierarchy requires relatively large computing capacities and times as soon as the number of criteria in a branch increases (over five or seven sub-criteria).

The sum of the weights for criteria or modalities in the same branch of the tree is always equal to one. In order to avoid the weights to depend on the number of criteria in the branch, these are normalized, so that the weight of the criteria or modality with the strongest contribution to vulnerability is equal to 1.

ii. *Aggregation of expert judgments*

The weights of the calculated criteria are in fact "scores" or "notes" assigned by the experts, and not measured physical quantities. These are "judgments" having both a qualitative and subjective origin. The aggregation of these expert judgments cannot be done by a usual arithmetic average. The literature proposes several modes of aggregation of expert judgments. Two main solutions are to be considered: the deterministic solutions, based on the calculation of geometric averages, and the solutions based on fuzzy logic, allowing taking into account the uncertainty of judgments linked to subjectivity. It is this last way of aggregation based on fuzzy logic that is used in this work. The algorithm used was implemented by Pugnet (Pugnet 2015).

D. *Application of the model for vulnerability assessment*

The criteria hierarchy endowed with criteria weights and modalities scores is an executable model allowing calculating vulnerability for any WUI house, in the context the model was specified for. The score of vulnerability is obtained by calculating the linear combination of the criteria weights by the modality score of the building. The resulting index takes discrete values regarding the discrete modalities scores.

A vulnerability index can be calculated for any criteria or sub-criteria: these are called "specific vulnerability indexes" (SVI). The resulting index relative to the top of the hierarchy (level 0) represent to global vulnerability of the house: it is called the global vulnerability index (GVI).

$$GVI = \left(Wc_x \times Wc_{xx} \times Wc_{xxx} \times ...\right) \times SmC_{xxx...i} + \ (Wc_x \times Wc_{xx} \times Wc_{xxy} \times ...) \times SmC_{xxy} \quad (3)$$

Where :

Wc_x: weight of criterion Cx
Wc_{xx}: weight of sub-criterion Cxx (Cxx is a sub-criterion of Cx)
$Sm_{Cxxx...i}$: score of modality i of elementary sub-criterion C_{xxx}
$Sm_{Cxxy...i}$: score of modality i of elementary sub-criterion $C_{xxy...}$ of C_{xxy}

A possible formula to calculate specific vulnerability index of a criteria Cxx (level 2) is:

$$SVIc_{xx} = \left(Wc_{xx} \times Wc_{xxx} \times ...\right) \times SmC_{xxx...i} + \ (Wc_{xx} \times Wc_{xxy} \times ...) \times SmC_{xxy...k} \ + \ ... \quad (4)$$

Because vulnerability indexes have all a maximum possible value (the case of a given theoretical instance (building), where all the elementary criteria have the modality with the maximum score 1.000) and a minimum value (all the elementary criteria have the modality with the minimum score), the indexes can be expressed as percentages.

3.4.2. Results

The model for vulnerability assessment specified par the multicriteria analysis based on AHP can be presented in a table of criteria weights and modalities scores, which are the parameters of equations (3) and (4).

A. The table of criteria weights and modalities scores

Some weights and scores calculated for the different criteria of the hierarchy are given in the following table (extract). The hierarchy consists of five root (‘level 1’) criteria (C1. ”Contextual exposure and defendability ", C2. "Micro-local arrangements of the plot land unit", C3. "Topography", C4. "Constructive properties of the main building", and C5. "Human Factors of Vulnerability"). The main contributor to the overall vulnerability is criterion II: "Micro-local structure of the plot land unit" (weight equal to 1).

The model allows the implementation of cumulative criteria (they appear on a light blue background in Table 9). In this version, these are the sub-criteria "External elements or equipment at risk" and "Elements of ornamental vegetation" (sub-criteria of criterion II. "Micro-local development of the land unit") and the sub- - criterion "People living permanently on the site" (sub-criterion of criterion V. "Human factors of vulnerability").

Table 9. Extract (with blank dotted cells representing further developments of the hierarchy) of the criteria table with their weights (some modalities may be affected to criteria through queries on geodatabase (in green), while most of them (in red) require direct inquiries (interviews) of residents. The light blue background indicates "cumulative" criteria.

Criteria	Sub-criteria (level 1)	Sub-criteria (level 2)	Modalities («indicators»)
C1: Contextual exposure and defense infrastructures (0.696)	c11: Proximity of a rescue of firefighting center (0.321)		>30km(1.000) 10-30km (0.525) 3-10km (0.245) <3km (0.126)
	c12: surface of the forest threatening the WUI (0.848)		>100ha(1.000) 1-100ha (0.824) <1ha (0.215)
	c13: Quality of the firefighting and protection infrastructure of the forest threatening the WUI (1.000)		Good (tracks, hydrants, fuel breaks (0.130) Medium (0.560) Insufficient (0.933) None
…	…	…	…

Criteria	Sub-criteria (level 1)	Sub-criteria (level 2)	Modalities («indicators»)
C2: Micro-local spatial arrangements of the plot land unit (1.000)	c21: Accessibility (0.712)	c211: Way surface (0.430)	Road (0.300) Track (1.000)
		c212: Way width (1.000)	<4m (0.300) 4-6m (0.404) >6m (0.368)
	c22: Clearing (1.000)	c221: Clearing width (0.806)	<30m (0.262) Not cleared (1.000) 30-50m (0.212) >50m (0.204)
		c222: Clearing quality (0.100)	Good (Tree, shrub and grass strata…, 0.250) Medium (Grass and shrub, trees pruned…, 0.313) Insufficient (0.583) Not cleared (1.000)
C3: Topography (0.833)	…	…	…
C4: Constructive properties of main building (0.873)	…	…	…
C5: Human factors (0.592)°	c51: People living permanently on the site (1.000)	c511 Age(0.846)	0-3 (0.978) 4-12 (0.895) 12-17 (0.349) 18-65 (0.235) 66-85 (0.954) >86 (1.000)
		c512 Gender (0.100)	Female (1.000) Male (0.900)
		c513 Disability (poor health, reduced mobility..) (1.000)	Yes (1.000) No (0.333)
	c52: hospitality activities (guest house, bed and breakfast, etc.) (0.269)	…	…
	c53: risk knowledge & culture	…	…

The cumulative criteria make it possible to cumulate the vulnerability of each of the elements of the same class of entity (for example, several wooden annexes present on the site).

However, for the constructive elements, the contribution to vulnerability of each of these elements is not cumulated, but different methods are used to associate a level of contribution to the vulnerability of the criterion with classes of number of this element (for example, for the ”windows” criterion).

B. *Implementation: the VULN'INTERMED web service*

The model was implemented as a web-service software in the framework of the Intermed projet of the France-Italy Interreg Maritimmo European program (Maillé *et al.*, 2023).

The tool is designed to address two main standard use cases: i) literal quantitative vulnerability diagnosis of a single WUI land plot unit (not spatial mode) and ii) vulnerability mapping of an interface, by calculating vulnerability of a sample of buildings within this interface.

From a functional point of view, the various modules of the a-spatial version (literal quantitative diagnosis) of the system are supplemented by modules for managing the sample of buildings used for mapping, and modules for cartographic management themselves (Figure 40).

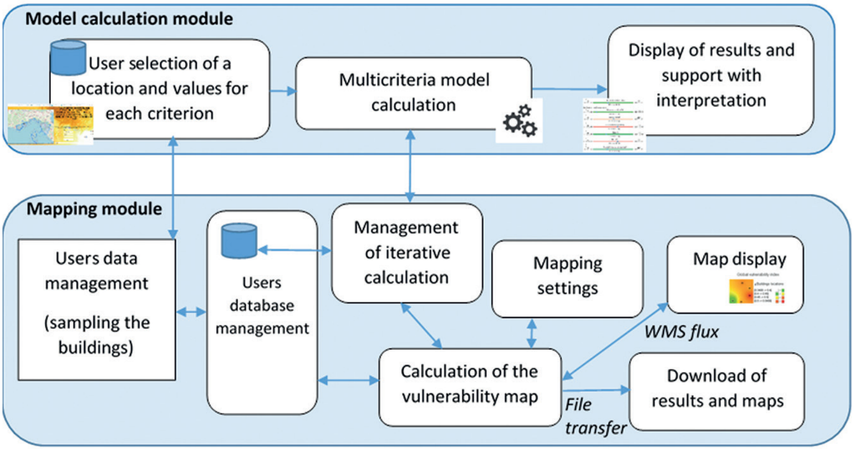

Figure 40. General modular architecture of the spatial decision support tool (SDSS).

C. *Literal quantitative vulnerability diagnosis: Specific indices and global indices*

The results sheet offers an overall vulnerability index and the specific vulnerability indexes for the six main classes of level 1 criteria. The percentage values measure the possible margin of progress. The absolute indices are comparable for the same level of criteria (Figure 41). A semantic color gradient from green to red is applied to the results sheet in order to emphasize on the most critical criteria (on which action must be taken as a priority).

It is of course easier to act on certain criteria than on others. For example, the slope of the terrain of a residential building cannot be modified. The results sheet therefore proposes a list of critical criteria that can be improved, while other criteria are listed separately (Figure 42).

Figure 41. A results sheet offered to the end user showing the most critical criteria to improve in order to mitigate vulnerability.

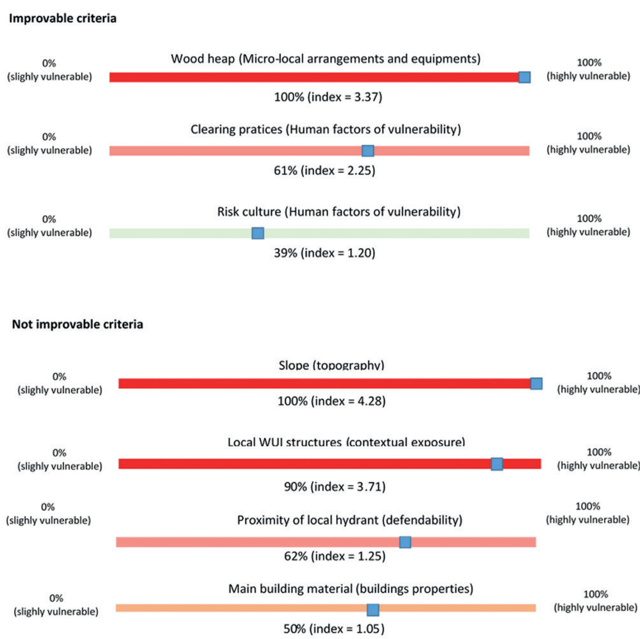

Figure 42. Hierarchized list of improvable and not improvable criteria provided to end user.

D. *Mapping vulnerability at local scale*

As many experiences show, like the Paradise city destruction during the Camp Fire in 2018 (19500 houses destroyed - CAL FIRE 2018), vulnerability, assessed through damages mesured after a fire event, presents a spatial correlation: vulnerability of one particular house increases the contextual vulnerability of the neighborhood. It is so possible to map the vulnerability of a WUI, by interpolating the vulnerability of the houses it is composed. Data collection for vulnerability mapping may require considerable resources for mapping large areas. Considering that criteria of vulnerability are also spatially correlated (geographical context: topography, natural vegetation, buildings rules, local regulation, cultural practices, social and economic classes spatial segregation, etc.), it is possible to sample the houses with a high sampling ratio in order to map WUI vulnerability.

It is possible to map the global vulnerability index, one of the specific vulnerability indexes assigned to particular elementary criterion (for example the "clearing" criterion) or the vulnerability linked to a class of criteria ie. a whole branch of the hierarchy, for example the criteria relating to the building accessibility.

For a particular criterion, the maps produced allow evaluating the relative spatial distribution of the contribution of this criterion, but in no case its relative importance in relation to the other specific criteria. Thus, for a given criterion, an area with a high value for one of the criteria does not mean a strong absolute contribution of this criterion to the overall vulnerability of the location, but an area where its contribution is stronger, in relation to the rest of the map.

The application allows choosing to map either the vulnerability rate or the index absolute value.

The rate map represents the distance from an ideal value. On a chromatic scale going from green to red, the red zones are the ones that present a greater margin of progress.

The absolute vulnerability indexes allow comparing the different maps obtained within the same class of criteria, for example, the maps of the family of criteria related to buildings' accessibility. They so allow comparing the maps of the five major classes of so-called root criteria (C1 to C5). This comparison requires drawing as many maps as there are criteria within a branch of the hierarchy (children of a given node).

A wide range of map types is available. It is possible to produce a map of continuous vulnerability (default), according to ranges of continuous values (Figure 43), or a map of vulnerability classes (discrete colors). A maximum of 10 classes or 10 ranges of continuous values can be defined. In any case, all values will be represented, from the minimum to the maximum of the zone.

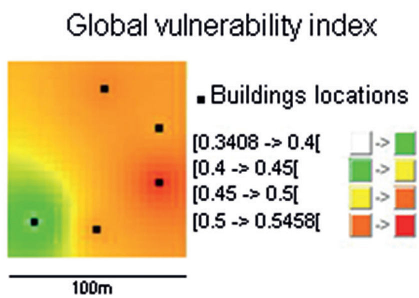

Figure 43. An example of a continuous representation of the calculated Global Vulnerability Index at local scale at 1m resolution (thresholds are automatically determined to optimize the representation).

3.43. Conclusion/Discussion

In order to help land management, planning decision-makers and home owners to better design and carry out actions for structural fire risk mitigation at local scale, we propose a spatial decision support tool which is aimed at providing vulnerability diagnoses of any house of the WUI. By interpolating the diagnoses of all or a sample of houses, the tool allows mapping the vulnerability of the whole interface itself, in order to identify locations where mitigation actions are urgently required.

Morever the residents themselves, the targeted users are any decision-makers likely to intervene in local land management and planning: representatives and technicians of local collectivities, urban planners, forest planners, firefighters services in charge of fire risk planning, etc.

Experts' opinion based modelling presents many limitations: it is based on subjective expert knowledge, acquired through uncontrolled experiences, in a precisely delimited geographical context. The multicriteria paradigm is aimed at formalizing the knowledge the experts have of the process, rather than formalizing the process itself. In order to specify a general model of vulnerability, statistical studies on damages occurrences must be carried out. Both approaches may allow ”cross-validation”, notably in contexts where damages data collection is not very much advanced.

This prototype can produce vulnerability maps from a sample of buildings described within the interface that the user wishes to analyze. Each building in the sample must be the subject of a field survey as well as a ”resident” survey to enter all the criteria of the vulnerability model. Although some of the data may be found in local scale databases (notably natural criteria, like topography and vegetation), many criteria require direct enquiries. For large areas, data collection and capitalization may be a great effort for the users, but must be considered as an investment for future land management decisions making.

A perspective for the continuation of this work is a scale transfer from local to 'territorial' scale, ie. the scale of several administrative entities (municipalities for example). This transfer cannot be done using the methods developed in this work, because this would suppose a very costly sampling effort, since the extension of the area studied is important. Scale transfer should be considered based on available geographic information, either raw (remotely acquired images) or interpreted and available in geographic standard databases. A study of the relationships between the values of the criteria and the global and specific vulnerabilities on the one hand, and the spatial variables available in the standard geographic information databases or derivable from other tele-acquired images on the other hand, is to be conducted to achieve this result.

In this work, we took into account the only WUI buildings class of value to assess WUI vulnerability. At territorial scale, a global assessment of vulnerability must take into account all values of the different classes present on the area, including human, infrastructures, production units, natural spaces, etc. Different methods, including economic contingent analysis or expert opinion based multicriteria analysis, may be used in order to specify territorial vulnerability models taking into account a wide range of classes of values present on the zone.

Finally, the increase of vulnerability, notably due to land cover change, is cumulated to the increase of fire hazard, notably due to climate change, so that the global risk might raise at an exponential rythm. The assessment, monitoring and simulation of WUI spread and densification becomes key decision support elements for land management and risk mitigation.

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4.
Structure ignition mechanisms in wildland-urban interface fires

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4.1. Chapter introduction

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The International Organization for Standardization (ISO) defines large outdoor fires as an urban fire, tsunami-generated fire, volcano-generated fire, wildland-urban interface fire, wildland fire, or informal settlement fire, where the total burnout area is significant (ISO TR24188:2022). Of all the large outdoor fires, it is wildland fires that spread into urban areas, known as wildland-urban interface fires, that attract the most attention. The term bushfire has a similar meaning to wildland fire (ISO TR24188:2022). In 2023, WUI fires in Hawaii resulted in the death of more than 90 people and the destruction of over 2,000 structures.

WUI fires continue to occur throughout the Americas, Australia, Europe, the Middle East and in Asia. The 2022 WUI fire season across Europe was unprecedented. It is important to distinguish WUI fires from wildland fires (Manzello and Suzuki, 2022); WUI fires include the burning of both vegetative fuels and communities whereas wildland fires include the burning of vegetative fuels and occur in uninhabited areas. Estimates place at least 70,000 communities, nearly 46 million structures at risk from WUI fires, which amounts to nearly 120 million people in the USA (Manzello *et al.*, 2018). Studies have linked climate change to increased WUI fire hazards (Abatzoglou *et al.*, 2016).

The growth of densely populated urban areas has also seen the development of large urban fires. The most recent of these occurred in the winter of 2016 in Niigata, Japan. The USA has also experienced major urban fires, such as the Great Chicago Fire in 1871 and the Baltimore Fire in 1904. Informal settlement communities in Southeast Asia, Africa, and the Americas continue to result in large outdoor fires capable of great destruction. There exist important similarities in the flame spread processes in informal settlement fires, urban fires, and WUI fires. As a wildland fire reaches an urban area, structure-to-structure fire spread processes will occur via the same mechanisms as those in informal settlement fires and urban fires: radiant heat, direct flame contact, and firebrands (Manzello and Suzuki, 2022). Once ignited, vast amounts of gaseous and particulate emissions are produced that may be inhaled by both humans and animals.

4.1.1. Fires confined to buildings — foundation of current fire safety regulations

Fire safety science research first focused on how to understand fire growth inside buildings. While these approaches have been very successful, it is important to grasp that fires that spread outside of a building are not confined to well-defined boundaries, and these complexities render understanding large outdoor fires a very complex endeavour (Manzello *et al.*, 2018). At the same time, vegetation and other human made fuels found outdoors may not be so easily made to be more ignition resistant (Manzello and Suzuki, 2023).

4.1.2. The need to address WUI fires

Several years ago, the state of California in the United States recognized the need to develop an approach to make infrastructure in communities more ignition resistant to WUI fire exposures. WUI fires have also been addressed by other key organizations, including the NFPA, ICC, ASTM International, and the Australian National Construction Code. Developing test standards for outdoor fire exposures presents significant challenges. It is important to note that the exposure conditions used in all the published test methods are best guess estimates of what exposure conditions would be in a WUI fire and were developed with the best available information at the time. It is argued that WUI fires represent the next frontier in fire safety science (Manzello, Presentation to the National Academies of Science, Engineering, and Medicine, 2021).

4.1.3. Current progress to develop globally harmonized test methods

ISO TC92/Task Group (TG) 03 (Large Outdoor Fires and the Built Environment) was formed to advise ISO TC92 (Fire Safety) on a path forward for the topic Large Outdoor Fires and the Built Environment. As a result of ISOTC92/TG03 activities, the task group proposed the formation of a new working group (WG) under TC92. This new working group (WG), entitled ISO TC92/WG14 (Large Outdoor Fires and the Built Environment) has been formally approved by global ballot (ISO TC92). The first completed task of ISO TC92/W14 was the publication of ISO/TR 24188:2022 Large Outdoor Fires and the Built Environment –Global Overview of Different Approaches to Standardization. Important basic knowledge of large outdoor fire propagation mechanisms is provided, following ISO/TR 24188:2022

(2022). Large outdoor fires differ from fires inside buildings in several ways; most notably the fire spread processes are not limited to well-defined boundaries, as is the case in traditional building fires or fires inside buildings. Large outdoor fires must consider the interaction of topography, weather, vegetation, and structures. Ignition could occur by three ways (and in combination) (Figure 44).

Direct flame contact refers to the situation where a structural component is in direct contact with flaming burning from an adjacent combusting fuel source. Thermal radiation is a form of electromagnetic radiation that is emitted from any object whose temperature is above absolute zero. Due to the burning of vegetative and structural fuels in WUI fires, any fuel type in proximity to these burning processes will experience radiation. Firebrands are the production or generation of new, far smaller combustible fragments from the original fire source. Firebrands are produced or generated from the burning of vegetative and structural fuels.

Figure 44. Schematic of fire spread mechanisms in large outdoor fires (Top: Direct flame contact, middle: thermal radiation, bottom: firebrands) (taken from Manzello and Suzuki, 2023).

Firebrand processes include generation, transport, deposition, and ignition of various fuel types, leading to fire spread processes at distances far removed from the original fire source. Clearly a combination of any of the above mechanisms is possible. Direct flame contact and thermal radiation act in combination as a flame exists and emits thermal radiation.

4.1.4. Sections of this book chapter

In this chapter, three contributions are presented. Dr. B Guillaume. and Dr. E. Guillaume provide an over of the direct flame contact structure ignition mechanism. Prof. K. Zhou discussed thermal radiation as a structure ignition mechanism. Prof. Suzuki and Prof. Manzello closed the chapter with a discussion of firebrands as a structure ignition mechanism. It is hoped these efforts will bring about an improved understanding of the differences between WUI fires and traditional fires that occur inside buildings.

Interested readers are referred to a recent review on the most current progress to develop globally harmonized international testing standards for WUI fires (Manzello, 2024)

4.2. Direct flame contact

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Direct flame contact, together with convection of hot gases present in the gas plume over the flames, is one of the three exposure mechanisms of structures to wildfire in the wildland-urban interface, the two other mechanisms being radiative exposure and firebrands' exposure.

ISO/TR 24188:2022 defines direct flame contact as refers to flames impinging on building systems and materials. The flames can come either from the main wildfire flames, from burning elements, and ornamental vegetation surrounding structures, or from adjacent structures.

The different ignition sources in the vicinity of the structure, namely the neighbouring forest, the adjacent ornamental vegetation, and manufactured fuels, can be close enough to the structure to allow heat transfer by direct contact (heavy convection and intense radiation from flame) or by associated convection (hot gases). Most recent scientific findings on exposure to flame and convection at WUI are reviewed in Filkov et al (2023).

The present section details the physical characteristics of exposure to flame and convection in the WUI context, then the physical characteristics of structure vulnerability, and finally the different structure hardening strategies against wildfire are detailed.

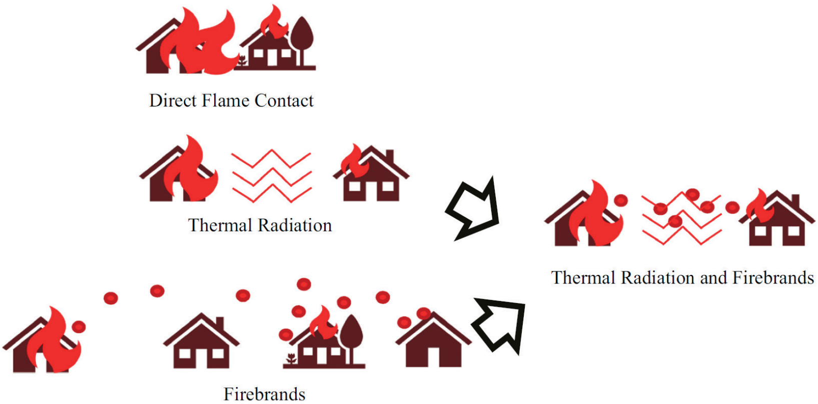

Figure 45. Fire propagation modes in large outdoor fires, from Suzuki and Manzello (2021).

4.2.1. Physics of exposure to flame and convection in the WUI

The wildfire typical exhibit one or many different phases, depending on the vegetation that is encountered: the surface fire, the passive crown fire, the active crown fire, and very rarely the independent crown fire (Scott and Reinhardt, 2001). The surface fire is the most rapidly part of the fire, spreading first to the unburnt fuels ahead, burning herbaceous matter, litter, and low shrubs. When trees are present and sufficient heat can ignite the low branches, the fire transits to a passive crown fire (several isolated trees do burn). This transition depends on the surface fire intensity, the height of the low branches above the surface fuels and the canopy moisture (Rothermel, 1991). When the burning canopies can contaminate one each other, the fire transits to an active crown fire. Very rarely, the active crown fire can become totally independent from the surface fire. To anticipate wildfire propagation for suppression activities (hazard mapping), the fire behaviour is assessed as a surface fire even if it has transitioned to a passive crown fire, since the fire will spread at the speed of the surface fire. In the WUI context, the crown fire in passive phase needs to be assessed, since the building can be vulnerable to a fire of an isolated tree in its vicinity.

A typical direct flame contact scenario occurs in three phases: pre-heating, flame contact, post-fire effects. Strong post fire effects do very rarely occur, where they are essentially due to a fire re-growth in the upstream remaining patches of unburnt fuels; and even more rarely in conjunction with a large wind direction change (see Figure 46).

Concerning the pre-heating phase, essentially composed of radiative heating and firebrands, the assessment of exposure to flame contact and convection requires to take it into account since it can contribute significantly to the heat accumulation on the structure before the strong heat impact of the flame contact. The duration and intensity of the pre-heating phase will largely vary depending on the upstream environmental conditions: forest type, water content, orography (slope effect), weather parameters (strong winds, drought), that can range from some seconds for a fire progressing very rapidly on a continuous light grass meadow up to 30 min for a fire progressing quite slowly but with very strong intensity on large woody fuel forests (Leonard *et al.*, 2011 — see Figure 46).

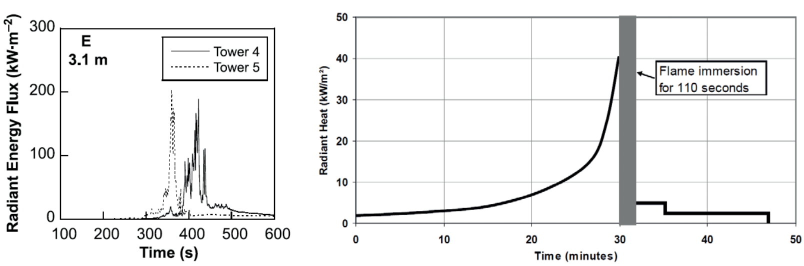

Figure 46. Left: real case of wildfire exposure during time (Butler et al, 2004), Right: schematized wildfire exposure during time (Leonard et al. 2011).

The flame contact with a structure is reached when temperature of around 700°C reaches the structure, or when the structure receives a heat flux of about 50 kW/m^2. The flame contact means seconds to minutes for distant scenarios, the range of this duration will be explored hereafter. The flame contact phase largely varies both in duration and intensity. The flame contact phenomenon is characterized in terms of residence time, flame temperature, flame length (or flame height, when the flame is tilted by wind or attached to a slope) and burning rate (or alternatively mass-loss rate or heat release rate), while convection in the hot gases above the flame is characterized in terms of received heat flux and surrounding air flow.

Fire residence times for vegetation fuels vary from some seconds for light fuels to some minutes and extends for manufactured fuels to several tens of minutes (adjacent wood pile, etc.) or hours (adjacent secondary structure).

Table 10. Typical residence times for different adjacent fuels in the WUI — residence times from (a) Scott and Reinhard (2001) and (b) NIST TN 2235.

	Residence time
Herbaceous material[a]	10 s
Shrubs (diameter <=6 mm) [a]	2 min
Garden woodshed[b]	20 min

Flame temperatures are reported mainly from measurements in laboratory experiments to be on average 700°C, with peaks up to 1000°C (Filkov et al 2023). More exceptional peaks have been estimated in extreme fires, like the 1100°C average temperature during the downburst phase of the Yarnell Hill Fire in 2013 or 1300°C during the ICFME (Butler *et al.* 2004). The flame temperature is highly dependent on the oxidant term in the combustion, namely oxygen brought by wind in the outdoor fires.

The flame length of a surface fire can range from few tens of centimetre in low grass to lengths of 4-6 m for dense and 1-2 m high shrubs (ex. in Northern America: chaparral; in Europe: molinie, gorse, etc.). For canopy fires, flame length is often reported as 2 times the tree heights (Butler, 2014). Wind has a strong effect on flame tilt in grasslands, in sparse shrublands and in open forests, while in closed forests wind is poorly penetrating and flame is not strongly tilted in large canopy fires. The hot gases from convection will be largely propagating close to the ground when flame is tilted, while they will be injected at higher levels when the flame is poorly tilted.

Wildfire exposure has more often been characterized for fire--fighting objectives (ex. fire suppression) rather than for structure exposure in the WUI. Therefore, the main parameter used classically to characterize the fire intensity in line with these objectives is the fireline intensity, with unit kW/m. Some slight differences are found in the number and values of these fireline intensity levels (FILs) chosen at national levels between Australia, Canada/USA, and Europe. The Canadian version (Alexander and Cruz, 2019) is shown in Figure 47. The fireline intensity (kW/m) I_B is obtained as defined by Byram (1959):

$$I_B = H \times \omega \times r \qquad (5)$$

where H is the fuel heat of combustion (MJ/kg), ω is the amount of fuel consumed in the active flame front (kg/m^2) and r is the fire rate of spread (m/s). Grassland fires can propagate at much higher rate of spreads than shrubland and canopy fires, and thus gain in fireline intensity sometimes close to shrubland fires. Canopy fires extend in fireline intensity from 4 000 kW/m for passive canopy fires up to 100 000 kW/m for fully developed independent canopy fires. Burrows (1984) suggested that fires below 500 kW/m can be attacked directly by hand tools, with 2000 kW/m as a limit for direct attacks using bulldozers and tankers, and finally fires in the range 2 000-5 000 kW/m can be controlled by indirect attacks.

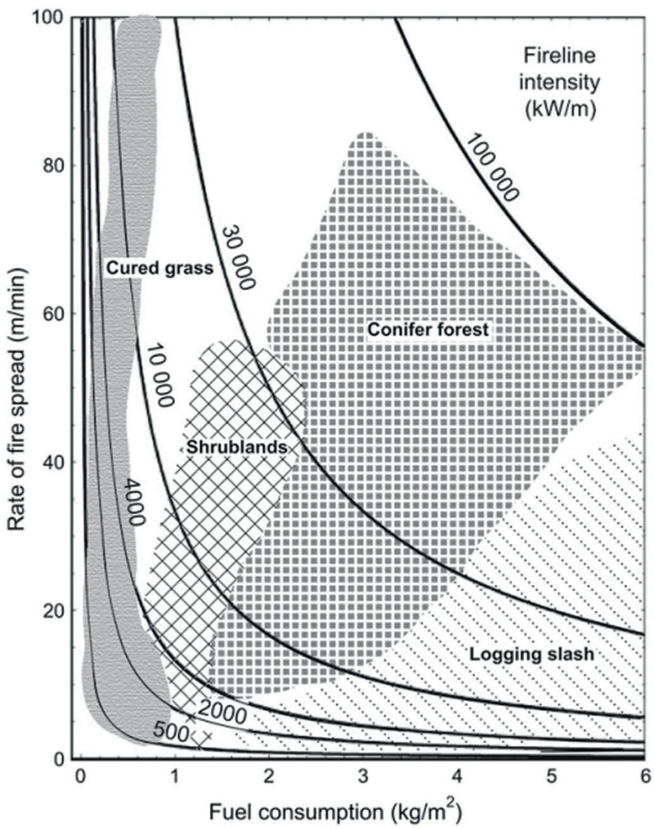

Figure 47. Representation of 5 different FILs in the Canadian methodology, as a function of rate of spread and of fuel consumption, assuming a constant fuel heat of combustion of 18 MJ/kg.

The fireline intensity is not a directly observable through measurement but can be related to the flame length that can be visually estimated. Several empirical relationships have been issued through the years to relate these two parameters. An example, based on Equation (6), the Byram (1959) formula, and Equation (7), the Thomas (1963) formula, is shown in Figure 48 (Scott *et al.*, 2013). Alexander and Cruz (2012) provide a thorough review of these experimental relationships.

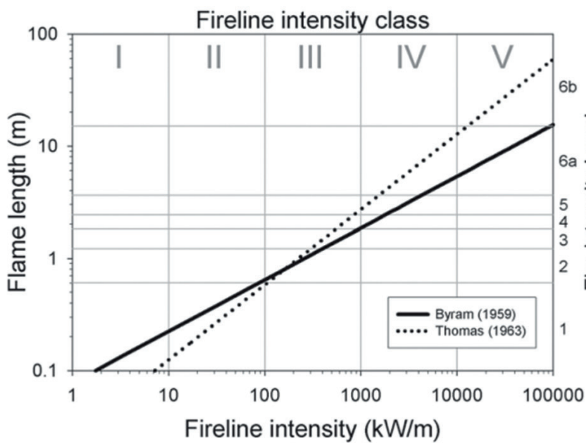

Figure 48. Representation of link between fireline intensity and flame length.

A parameter better indicated for fire analysis in the WUI context is the heat release rate, which can be an input to complex thermal exposure models to infer received heat flux. The heat release rate (or combustion rate) Q_a (kW/m²) can either be inferred from the Byram formula:

$$Q_a = \frac{I_B}{r \times t_R} \qquad (6)$$

where t_R is the residence time (s), or, in the case where the source can be modelled as a pool fire shape (this is particularly the case for surface fuels: herbaceous fuels, litter, and low shrubs), it can be inferred from the Heskestad (1983) formula, linking Q (W) and L (m) as:

$$L = 0.0148Q^{0.4} - 1,02D \quad (7)$$

where D is the equivalent diameter (m) of the vegetation fuel bed.

It has also been shown that the flame intermittency outdoor largely impacts the hot gases convection, intermittency induced by the flame intermittency itself or forced from the intermittent wind gusts.

Concerning the surrounding air flow, the complex air vortices (downdrafts of cold air and updrafts of hot gases) created by the fire are amplified by topography and can lead fires of high intensity to generate fire-induced wind, that can lead temporarily the fire in a different direction than simply pushed in the direction of the ambient wind. Therefore, exposure assessment of a structure cannot be reasonably limited to the main local wind directions knowing from the site climatology, and unless having very good reasons to discard some particular directions of fire arrival to the structure (ex.: absence of fuel reaching close to the structure in some specific wind directions), the exposure shall better assume an isotropic distribution of the fire arrival directions.

The exposure of structures to flame and convection, among the other fire effects, is a challenging modelling task which is still at exploratory phase in fire science. It requires modelling the vertical extension of the fire propagation on the isolated ornamental or artificial fuels collocated to the structure, to account for the differentiated effect on the different building stages. Only physics based CFD models are currently tailored for such assessment. Fine modelling of flame radiative emission and parietal heat transfers at relatively high flame velocity is requested. Currently, such exploratory studies are found with models WFDS (Meerpoel-Pietri et al, 2023), FDS (Vacca et al, 2020; Ganteaume *et al.*, 2023) or FIRESTAR2D (Fayad *et al.*, 2023).

4.2.2. Physics of structure vulnerability in the WUI

The structure envelope constitutes the last protection against wildfire before the occurrence of the major structure damages.

The direct flame contact and convection can generate several exterior damages, by burning fully the secondary structures, adjacent to or in the vicinity of the structure or burning partially the envelope itself. These exterior damages on structures due to flame contact are generated during the short duration of the three stages of the wildfire passage on site: the pre-heating, impact, and post-fire stages.

If the fire comes to penetrate the envelope, it transforms into a damaging interior fire, with potential structure ruining (roof collapse, or structure collapse...), with no chances for locked down people to survive. The interior damages are generally generated on higher intensity and longer duration. A significant time can also exist (sometimes hours) between the passage of the exterior wildfire and the setup of the interior fire, especially when hot spots of smouldering fires are disseminated inside the structure, that are hardly seen from the fire-fighting crews just after the wildfire passage, even with thermal-IR cameras, that would then eventually lead to ignition.

Therefore, there is a high need to prevent the envelope failure, particularly when direct flame contact is possible (Vacca et al, 2020). Wildfire possible pathways need to be identified (Westhaver, 2017 on Fort McMurray 2016 fire) leading to eventual direct flame contact on structure.

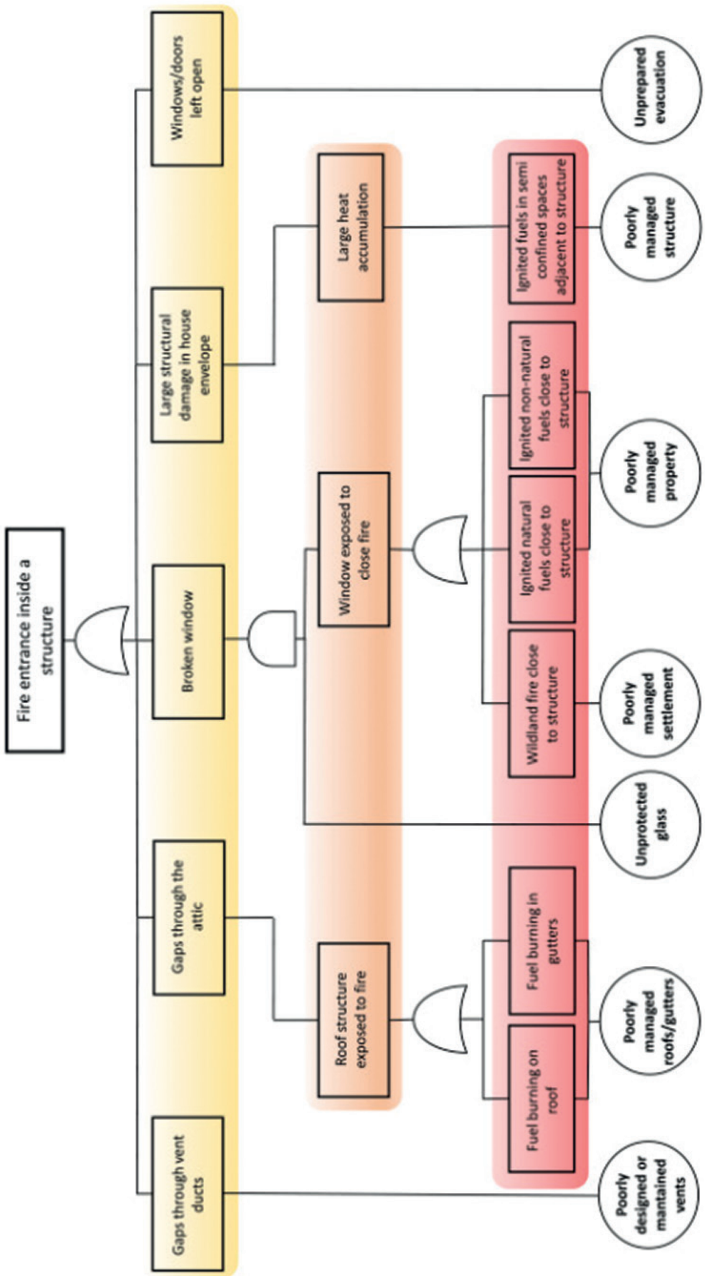

Figure 49. Envelope failure scheme (source: Vacca et al 2020).

All types of vent ducts can act as fire penetration zones, as well as the attic and the interface between walls and roof.

Glazing has been seen to be eventually vulnerable to direct flame contact, especially single-glaze with thermal-sensitive frame (Leonard *et al.*, 2011). A tree or swimming-pool deck in fire close to glazing are often seen in post-fire analysis as the source of a glazing failure.

Wildfire can ignite and propagate flames on the exterior walls, which opaque pat around the glazing systems can be composed of combustible elements in facade.

The effect of direct flame contact to structures, among other fire effects, are experienced on the "One House" platform by CSIRO and insurance and architect partners (Australia), as well as in the SPE laboratory in Corsica (France) on their EXPLORII platform (Tihay-Fellicelli et al, 2023).

4.2.3. Structure hardening against direct flame contact

Structure hardening is the complementary protection means to natural and artificial fuel reduction around the structure.

Protection performance needs to be defined in compliance with the desired objectives. Against wildfires, first protection objective can be people security, for civilians in a 30 min lockdown in the structure and for fire-fighters in protected clothing in intervention near the structure during the fire passage. Second protection objective is a longer-term protection to preserve the goods from ruining.

The critical threshold of people exposure to direct flame contact has been evaluated in a 2005 French regulation (Arrete ICPE, 2005).

The structure longer-term protection has been assessed in terms of time-to-ignition by several methods (Janssens, M. ,1991; Cohen and Butler, 1996; Wang and Dowling, 2007; Reszka *et al.*,2012). Among these methods, the Flux-Time-Product method (Silcock and Shields, 1995) has been largely employed, and is used here in Table 11 to provide critical thresholds for woody material.

Table 11. Typical time to ignition or to damage for flame contacts during wildfire attack.

	Time to ignition/ time to damage
Irreversible effect on people skin in direct flame contact	3 s at 50 kW/m^2
Ignition of woody material in direct flame contact	17 s at 50 kW/m^2 12 s at 60 kW/m^2 8 s at 70 kW/m^2 5 s at 80 kW/m^2

Note that the lockdown situation can lead to the following concomitant effects: a good performance of people protection behind interior wall, while the exterior wall is on fire. This situation is to avoid, since it has all chances to generate a panic effect when people locked down see the wall in flames through the windows, eventually the panic urging them instinctively to run outside the building.

People locked down additionally exhibit vulnerability to smoke and hot gases able to penetrate through all kinds of openings in the structure envelope, and to expose them to toxic gases (Guillaume 2020, Guillaume 2024). Protection can only be obtained by closing temporarily these vents, either through a system of smoke hatch either manually or electrically closed, or when the vents are small by obstruction with wet or incombustible objects.

4.3. Thermal radiation

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The thermal radiation is one key heat transfer mode that dominates the fire spread from wildland fire to the community in WUI. The radiation could be, essentially, viewed as the propagation of electromagnetic waves. Its ray holds both a wavelength and a speed. The wavelength of approximately 0.1-100 μm, across the visible light and infrared, is the spectrum of the thermal radiation. Obviously, the spectral nature of thermal radiation is one important feature. The second feature relates to its directionality. The two features complicate the quantitative description and modelling of thermal radiation from wildland fire.

In addition, there is a distinct difference of radiation emission and absorption between gas and solid/liquid. In most solids and liquids, the radiation emission and absorption are due to the molecules that are within a distance of about 1 μm from the exposed surface, for which the radiation is a surface phenomenon. However, the radiation emitting from or absorbed by a finite volume of gas is the integrated effect of local emission or absorption throughout the volume, for which the radiation is a volumetric phenomenon. In wildland fire, the fire front contains different gases, carbon particle, aerosols, smoke particles, etc. The glowing embers behind the fire front also radiates thermal energy. Some components show the volumetric phenomenon of the thermal radiation, while the other components hold the surface phenomenon. The reductive assumption of a volumetric phenomenon to be a surface phenomenon could result in a significant error, for the modelling of wildland fire radiation.

In this section, the radiative characteristics is firstly discussed including the combustion product (polar molecules, carbon particle, smoke particle, glowing ember, etc.), the measured radiant heat flux and radiative fraction of typical wildland fires. Then the classical modelling methods and their limitation are reviewed for the thermal radiation from wildland fires, finally followed by the effect of thermal radiation on the building structure in WUI.

4.3.1. Radiative characteristics of wildland fires

In wildland fires, the hot glowing embers and the high-temperature fire front can emit a large amount of thermal radiation to the surrounding objects. The glowing ember can be treated as a grey body whose emissivity coefficient approaches one, i.e. that of blackbody. The individual carbon particle alone behaves also nearly like the true blackbody, but the small carbon particles are so little in the flame volume (approximately 1 g per cubic meter of gas (Taylor et al, 1975)). In addition, the polar molecules inside the flame volume can also radiate thermal energy. Accordingly, the burning flame holds an apparent flame emissivity (ε) as a function of flame thickness (*l*). It can be estimated by:

$$\varepsilon = 1 - e^{-k \times l} \qquad (8)$$

Where k is the absorption coefficient. Equation (8) tells that a large flame in wildland fires holds a higher emissivity than a small flame. Using the emissivity model for CO_2-H_2O-soot mixture of Taylor and Foster (1974), flames beyond 3 m in thickness radiate nearly like a black body.

According to the Stefan-Boltzmann equation and Planck's law, the radiant energy intensity or emissive power (E) is proportional to the flame temperature (T) raised to the power of *4* multiplied by the emissivity coefficient,

$$E = \varepsilon 6 T^4 \qquad (9)$$

Where σ is Stefan–Boltzmann constant, i.e., 5.67x10-8 $W/m^{-2}.K^{-4}$. A large wildland fire front with a typical temperature of 1100 °C results in an emissive power of 202 kW/m^2, while the glowing ember with a surface temperature of 600 °C leads to that of 33 kW/m^2, assuming an emissivity of unity. Comparison shows that the contribution of thermal radiation could not be ignored from the glowing ember in wildland fires. Equations (8) and (9) also indicate that the emissive power is nonuniform over the whole flame surface, if the flame thickness and/or flame temperature varies throughout the flame volume.

A lot of studies have measured the radiant heat flux from the wildland fire front. Butler *et al.* (2004) measured the radiant heat fluxes and temperatures at five locations in a boreal forest crown fire. In detail, the peak radiant heat flux reached 290 kW/m^2, and the average radiant heat flux from the flames across all tests was approximately 200 kW/m^2, and the equivalent radiometric temperatures calculated from the radiant heat flux exceeded thermocouple-based temperatures. Morandini *et al.* (2006) experimentally studied the effect of wind on the flame properties of fire spread across the Mediterranean shrub. For the radiative property, the maximum radiant heat fluxes were 7.8 kW/m^2, 2.2 kW/m^2 and 1 kW/m^2 at 5 m, 10 m and 15 m away from the 7.2 m long flames, respectively. In the four field tests of upslope fire spread, the peak radiant heat fluxes were measured to be 25-51 kW/m^2, for the vegetative fuels ranging from pine needle to shrub (Silvani and Morandini, 2009). In 13 natural and prescribed wildland fires, the radiant heat fluxes beneath two crown fires peaked at 200 kW/m^2 and 300 kW/m^2, while the peak radiant heat fluxes reached 132 kW/m^2 and 100 kW/m^2 for the shrub and surface fire spreads, respectively (Silvani and Morandini, 2009). Moreover, the fire radiative energy, defined as the time integration of the measured radiant heat flux, is proportional to the consumed fuel load (Silvani and Morandini, 2009). In short, the radiant heat flux from actual wildland fires ranges from hundreds to tens of kilowatt per square meter, depending on the wildland fuel type and the distance between sensor and fire front.

A few studies concern the radiative fraction of wildland fire front and glowing ember. In a surface fire spread over a 2 m long and 1 m wide bed of pine needles (Morandini *et al.*, 2013), the radiant fraction emitted by the fire front was measured to be 9.7%, and decreases with increasing fuel loads. However, the radiative fraction of glowing ember increases with increasing fuel loads, and the total radiative fraction of both ranged from 17.3% to 22.4%. In the work of Morandini *et al.* (2013), the burning intensities were within 40-171 kW/m. However, Kremens *et al.* (2012) argued that the radiative fraction increases from approximately 0.1 to 0.2 and then decreases to 0.1 as the burning intensity increases from approximately 200 kW/m to 1000 kW/m. Obviously, the radiative fraction of wildland fire is much less than that of liquid pool fires reported in Yang *et al.* (1994).

4.3.2. Modelling of thermal radiation from wildland fires

In the wildland fire radiation model, the fire front is assumed to be a plate or a cylinder of uniform temperature and emissivity with specified height, width and tilt angle (Zárate *et al.*, 2008;

Billaud *et al.*, 2011). Obviously, the solid plate approach converts a volumetric phenomenon to a surface phenomenon for the flame radiation energy emission. The reduction is attractive because it addresses the complex physics associated with CO_2-H_2O-soot mixture as required for the volumetric determination of flame radiation. In the solid flame radiation model, the radiant heat flux received by a target away from the fire front, can be expressed by:

$$\dot{q}'' = E\ F\ \tau \quad (10)$$

in which E is the emissive power of flame that can be determined by equations (8) and (9). Another method to calculate E is written as $E = \frac{(x_r \times \dot{Q})}{A_f}$, in which, x_r, $\dot{Q}$ and A_f are the radiative fraction, total heat release rate and total surface area of fire front, respectively. Here, F is the view factor that depends on the fire front shape and the spatial relative position of the target against the fire front, and τ is the transmissivity, defined as the fraction of the thermal radiation that is transmitted through the atmosphere. The transmissivity is determined by the atmospheric humidity, the concentration of carbon dioxide and the distance between the target and fire front. For example, Frankman *et al.* (2008) examined the attenuation of radiation transfer from wildland flames by the atmospheric humidity, and pointed out that the water vapor reduces the radiant heat flux by 9%-16% for the 1 m-10 m long flame of 1000 K in temperature in the scenario of 100% relative humidity. Anyway, the flame emissive power and atmospheric transmissivity can be calculated using semi-empirical equations, and thus the calculation of view factor is the key point.

For a single crown fire, a cylinder is often used to model the flame shape, and thus the thermal radiation is considered to be emitted from the cylindrical surface. For vertical and horizontal target orientations, expressions for estimating the view factor from a right cylinder are written as equations (11) and (12), respectively (Mudan, 1987).

$$F_{\text{flame}\rightarrow\text{VT}} = \frac{1}{\pi S}\tan^{-1}\left(h\big/\sqrt{S^2-1}\right) - \frac{h}{\pi S}\tan^{-1}\sqrt{\frac{S-1}{S+1}} + \frac{Ah}{\pi S\sqrt{A^2-1}}\tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \quad (11)$$

$$F_{\text{flame}\rightarrow\text{HT}} = \frac{B-1/S}{\pi\sqrt{B^2-1}}\tan^{-1}\sqrt{\frac{(B+1)(S-1)}{(B-1)(S+1)}} + \frac{A-1/S}{\pi\sqrt{A^2-1}}\tan^{-1}\sqrt{\frac{(A+1)(S-1)}{(A-1)(S+1)}} \quad (12)$$

where $A=(h^2+S^2+1)/2S$, $B=(1+S^2)/2S$, $S=2L/D$ and $h=2H/D$ in which L is the distance from the cylinder centre to the target, and H and D are the height and diameter of the cylinder, respectively. Figure 50a shows the illustration of the nomenclature.

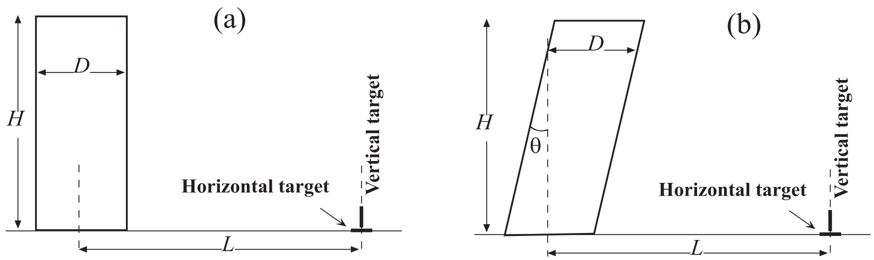

Figure 50. View factor calculation: geometries for (a) right and (b) tilted cylinders.

The flame is tilted under the wind effect, and thus it is modelled by a tilted cylinder. The view factor for the tilted cylindrical flame with a circular base is (Mudan, 1987).

$$\pi F_{\text{flame}\to\text{VT}} = \frac{a\cos\theta}{b - a\sin\theta} \times \frac{a^2 + (b+1)^2 - 2b(1 + a\sin\theta)}{\sqrt{AB}}\ tan^{-1}\sqrt{\frac{A\,(b-1)}{A\,(b+1)}}$$
$$+ \frac{\cos\theta}{\sqrt{C}} \times \left[tan^{-1} \frac{ab - (b^2-1)\sin\theta}{\sqrt{b^2-1}\ \sqrt{C}} + tan^{-1} \frac{(b^2-1)^{½}\sin\theta}{\sqrt{C}} \right] - \frac{a\cos\theta}{b - a\sin\theta}\ tan^{-1}\sqrt{\frac{b-1}{b+1}} \quad (13)$$

$$\pi F_{\text{flame}\to\text{HT}} = tan^{-1}\sqrt{\frac{b+1}{b-1}} - \frac{a^2 + (b+1)^2 - 2(b + 1 + ab\sin\theta)}{\sqrt{AB}} \times tan^{-1}\sqrt{\frac{A\,(b-1)}{A\,(b+1)}}$$
$$+ \frac{\sin\theta}{\sqrt{C}} \times \left[tan^{-1} \frac{ab - (b^2-1)\sin\theta}{\sqrt{b^2-1}\ \sqrt{C}} + tan^{-1} \frac{(b^2-1)^{½}\sin\theta}{\sqrt{C}} \right] \quad (14)$$

where a=2H/D, b=2L/D, A=a^2+(b+1)^2-2a(b+1)sinθ, B=a^2+(b-1)^2-2a(b-1)sinθ, C=1+(b^2-1)cos^{2}θ. See Figure 50b for the illustration of the nomenclature.

For a straightly linear fire front, a plate can well simulate the flame shape. The emitting plate holds a rectangular area that relates to the flame length and width of fire front. The emitting plate is right under no wind conditions, while it is tilted under the background wind influence. For the right plate under no wind scenario, Zárate *et al.* (2008) summarized the analytical equations to calculate the view factor from a plate to a horizontal or vertical target, for two geometrical arrangements. One arrangement is the right plate that is vertical and parallel to a differential target located in front of one of the emitting surface corners, while the other is that in front of its centre. For the inclined plate due to the wind influence, some analytical equations are also available to calculate the view factor for a target at a certain position (Rossi *et al.*, 2010; Rossi *et al.*, 2011). In particular, Rossi *et al.* (2010) made a comparison between the predictions of the solid flame radiation model and the model derived from Radiative Transfer Equation. The second model assumes a volumetric flame, as compared to a radiant plate in the solid flame radiation model. They found the emissivity of 0.2

for the solid flame radiation model to well agree with the second model and the measured radiant heat flux.

In addition to the analytical equations (11) to (14), the contour integral approach (Sparrow, 1963) or the direct numerical integration (e.g., the compound Simpson method (Zhou and Wang, 2019)) can also help to determine the view factor from a cylinder or a plate to any nearby target. However, a cylinder or a plate is a simple geometry, and sometimes fails to model the more complex geometry of an irregular fire front. In other words, the simple geometry assumption causes significant errors or uncertainties of the thermal radiation model, but the complex geometry assumption leads to a huge trouble for the mathematical calculation.

Therefore, the Monte Carlo method is proposed to estimate the thermal radiation from irregular flame volume. The academic viewpoint that the radiation is the propagation of a collection of particles named photons or quanta, is the theoretical foundation of the Monte Carlo method used for the thermal radiation calculation. The Monte Carlo method helps to trace the history of a statistically meaningful random sample of photons from the emission points to the absorption points. The emission points are on fire front surface, while the absorption points constitute the target surface. Billaud *et al.* (2011) made a comparison of the radiant heat fluxes predicted by the Monte Carlo method and the solid flame radiation model, for the simple geometry of wildland fire front, and finally used the Mente Carlo method to calculate the thermal radiation from the curved and irregular fire front. There is no doubt that the Monte Carlo method can well agree with the solid flame radiation model but holds a bigger capacity than the latter.

Three key limitations should be stressed in the available radiation models, including the solid flame radiation model and the Monte Carlo method. One question is that the models assume all thermal radiation emitting from the burning flame. However, the buoyant plume containing smoke particles can considerably contribute the thermal radiation in the large wildland fire. Up to 40% of the total radiant energy may be contributed by the hot plume of a line fire with burning intensity exceeding 600 kW/m (Wang, 2009). Moreover, the thermal radiation is also ignored from the glowing embers behind the fire front. The second limitation results from the application of the mean flame length in the description of flame shape. The turbulent flame of wildland fire front significantly pulsates and holds a considerable ratio of the intermittent flame length to the overall flame height. As summarized by Rossi *et al.* (2010), the turbulence-radiation interaction should be considered for a more accurate and realistic modelling of thermal radiation in wildland fires. The last one is caused by the constant emissive power or the constant photon emitting capacity over the whole flame surface. As stressed in Section 4.3.1, the emissive power is not uniform over the whole flame surface for the spatial variation of the flame emissivity and/or flame temperature. The measurement shows the significant variation of the flame emissive power with the height for linear fire fronts of surface fire spread, and data fitting gave $E(z)=150\left(1-\exp(-0.75\times(H-z))\right)^{2.89}$, in which z is the vertical distance (Wotton and Martin, 1996). Sullivan *et al.* (2003) reviewed the thermal radiation model used in bush fires and concluded that the third limitation leads to a poor predication of radiant heat flux from bushfires.

4.3.3. Thermal response and ignition of structure under radiant heat

In WUI, the house and infrastructure are often made up of flammable materials like wood and plastic and incombustible materials like steel and brick. The radiant heat exposure could ignite the structure materials and reduce the mechanical integrity of structure. The vulnerability of structure components to thermal radiation can be estimated by different thermal radiation threshold values with diverse consequences. Table 12 shows consequences of structure materials and mechanical integrity caused by diverse thermal fluxes. The application of the threshold in Table 12 into the estimation of structure damage requires the constant radiant heat flux. However, the radiant heat flux received by a structure in WUI varies with the time, for the distance between it and fire front could increase or decrease during the wildland fire spread.

The integration of the radiant heat flux with time is used to evaluate the effect of time-varying radiant heat on structure. Cohen (2004) and Cohen and Butler (1998) proposed the concept of the flux-time integral (FTP). FTP can be derived from the measured or calculated radiant heat flux, which is expressed by:

$$\mathrm{FTP} = \int_{t_0}^{t_f} \delta(\dot{q}'' - \dot{q}''_{cr})^{1.828} dt \quad (15)$$

where $\dot{q}''_{cr}$ is the minimum incident heat flux for ignition depending on material type, and equals 13.1 kW/m^2 for wood, t_0 and t_f are the initial and final heat exposure times, respectively, and the coefficient δ equals 0 for $\dot{q}'' \leq \dot{q}''_{cr}$ or 1 for $\dot{q}'' > \dot{q}''_{cr}$. Obviously, the FTP increases as the time goes if $\dot{q}'' > \dot{q}''_{cr}$. The ignition occurs when the FTP increases to reach the minimum FTP for ignition (FTP_{ig}), and the ignition time is also determined. FTP_{ig}=11,501 kJ/m^2 for wood. The prediction of Equation (15) was well compared to the no ignition phenomena and the measured ignition time in seven field tests of home ignition by crown fires (Cohen, 2004). The limitation of Equation (15) is the requirement of $\dot{q}''_{cr}$ and FTP_{ig} for different materials.

Table 12. The effects of radiant exposures on typical structure materials (Zárate et al., 2008; Cohen and Butler, 1998).

Radiant heat flux (kW/m^2)	**Effects**
10	Certain polymers can ignite
11.7	Thin steel (partly insulated) can lose mechanical integrity
12.6	Wood can ignite after a long exposure
20	Piloted wood ignition after more than 5.5 minutes
25	Thin steel (insulated) can lose mechanical integrity
37.5	Damage to process equipment and collapse of mechanical structures

4.4. Firebrands

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4.4.1. Introduction

Firebrands are one of the three fire propagation mechanisms in wildland-urban interface fires, along with direct flame contact and thermal radiation. ISO/TR 24188:2022 defines firebrands as an "airborne object capable of acting as an ignition source and carried for some distance in an airstream" (ISO/TR 24188:2022). Firebrand processes include generation, transport, deposition, and ignition of various fuel types, leading to fire spread processes at distances far from the original fire source (Manzello 2019). Because of this nature, firebrands are considered a driving force in WUI fire spread. Several reviews on firebrands can be found elsewhere (Manzello et al 2020, Manzello and Suzuki 2023). As this chapter is focused on the risk management in WUI at a structure scale, firebrand generation, and deposition and ignition of fuels will be discussed.

4.4.2. Firebrand generation

Firebrands are produced or generated from burning vegetative (trees, shrubs etc) and structural fuels (homes, sheds etc) in WUI area. In general, it is still difficult to obtain the information (size, mass, temperature, combustion state) of firebrands during real WUI fires. The information on firebrands generated during real WUI fires may be obtained afterwards (Manzello and Foote 2014, Rissel and Ridenour, 2013). Other approach to investigate characteristics of firebrands are 1) experiments in laboratory settings, or 2) prescribed fires. Both approaches have advantages and disadvantages, as the former can be performed many times, in the same condition, at a more controlled environment, but may be considered too ideal. The latter can be performed only in the forest without involving structures, can be considered more realistic as a wildland fire situation than the former, but prescribed burns usually are performed in less severe condition than actual fires for safety and cannot obtain the same condition twice, so the results are not repeatable.

4.4.3. Firebrands generated from trees

Firebrands from vegetation (such as trees and shrubs) have a cylindrical shape, mostly made from branches, or a flatter shape, made from bark slices (Manzello et al 2007, El Houssami et al 2016). Early experiments focused on generation of firebrands from trees were performed under no wind with different size of Douglas-fir trees (Manzello et al 2007). Since then, different tree species were burned for this purpose. There is no conclusive trend which species produce the most firebrands due to the difference of collection methods and experimental condition. Manzello and Foote investigated the size of firebrands generated in Angora fires by measuring holes of trampolines located in that burned area (Manzello and Foote 2014). This method was used to investigate the firebrand generated in the Bastrop Complex Fire (Rissel and Ridenour 2013). A series of investigation of firebrand generation in prescribed fire in the Pinelands National Reserve, NJ, USA supported the size and mass of firebrands within the same range of firebrands produced from tree burn experiments or those found in investigation (El Houssami *et al.*, 2016).

Some theoretical studies to understand the generation of firebrands were also performed. A shape of tree could be mathematically described, then one can model mechanical strength of tree branches, and degradation of the mechanical strength over time. This was the first attempt to model firebrand generation from tree (Barr and Ezekoye 2013).

4.4.4. Firebrands generated from houses

Firebrands from structures tend to be flatter than the those from vegetation and to have more variety of shapes, this is because of structure firebrands break off from building materials while vegetative firebrands break off from branches. Research on structure firebrand attack has been focused on measuring the size and mass of firebrands, along with distance from a structure if possible.

In some research, an entire house was burned, and firebrands were collected. In others, components of a house (building materials) were burned for the experiments. The series of experiments (Suzuki *et al.*, 2012, 2013, 2013, 2019) provided the methods to investigate the firebrand generation from houses by burning the components of a house (building materials) by comparing the characteristics of firebrands at each stage of experiments, also with the ones from real urban fires where most of firebrands can be expected from structures, not vegetations. Overall, the generated firebrands can be considered small, less than 1 g mass and 10 cm^2 projected area.

4.4.5. Firebrand deposition and ignition of fuels

It is known that majority of structure ignition is caused by firebrands in real WUI fires. For example, more than 65 % of burned houses were ignited by Wicth fire (Maranghides and Mell 2009). In news, the name “ember shower” is used often- while the term “embers” has a different meaning from firebrands, as embers are any small, hot, carbonaceous particles and firebrands are airborne particles which are able to start new fires (spot fires), this name explains well how firebrands look like (like showers) in real WUI fires.

4.4.6. Development of firebrand generator (Dragon) technology

To address firebrand exposure required the development of entirely new experimental methodologies. The Firebrand Generator (called Dragon) was developed in 2006 (Manzello et al 2007). Originally the Dragon has the capability to produce firebrand showers limited for a certain duration, now with continuous-feed system, the Firebrand Generators have the capability to produce firebrand showers for a desired duration in a repeatable way (Manzello and Suzuki 2014). The full-scale Continuous Feed Firebrand Generator consists of two parts: the main body and the continuous feed component. The feed system is connected to the main body and is equipped with two gates to prevent fire spread. A blower is connected to the main body to vary the combustion state of the generated firebrands from either glowing combustion or flaming combustion. Douglas-fir wood pieces are used to produce vegetative firebrands and Japanese Cypress wood chips may be used to simulate firebrands from burning structures. Firebrands generated from the combustion of these various wood types in the Dragon have been shown to be consistent with sizes measured from full-scale burning trees, size distributions obtained from actual WUI fires, and firebrands produced from burning structures. The number flux and mass flux of generated firebrands may be adjusted by varying the feeding rate of wood pieces into the device. Many experiments were performed in the Building Research Institute (BRI) in Japan as BRI maintains one of the only full-scale wind tunnel facilities in the world designed specifically for fire experimentation; the Fire Research Wind Tunnel Facility (FRWTF).

4.4.7. Decking assemblies

Experiments using the Dragon have demonstrated the dangers of the dynamic process of continual, wind-driven firebrand showers landing onto decking assemblies for the first time (Manzello and Suzuki 2014, 2017, 2019). For each wood decking assembly type tested (cedar, Douglas-fir, and redwood), the accumulation of glowing firebrands resulted in flaming ignition of the deck boards. It was also observed that ignition of the deck boards produced smouldering ignition in the support members under the decking assembly. Additional experiments have shown decking assemblies, once ignited, can result in a fire spreading to adjacent building components (Manzello and Suzuki 2017).

4.4.8. Roofing assemblies

Post-fire studies have identified a building ignition mechanism where small firebrands penetrate under non-combustible tile roof coverings (Manzello et al 2010). Experiments conducted using the Batch-Feed Dragon have provided experimental confirmation of this ignition mechanism for ceramic tile roofing assemblies (see Figure 51).

In follow-up experiments, concrete tile roofing assemblies (flat and profiled tile), as well as terracotta tile roofing assemblies (flat and profiled tile), were exposed to wind-driven firebrand showers (Manzello 2013). Underlayment or sarking, in the form of a layer of aluminium foil laminate bonded with a fire-retardant adhesive to a polymer fabric, was placed under the tile battens. The results showed that firebrands penetrated the tile gaps and subsequently melted the sarking material for both types of concrete tile roofing assemblies (flat and profiled tile) and the profiled tile terracotta roofing assembly.

Figure 51. Images of experiments conducted using oriented strand board/ceramic tile (OSB/CT) without bird stops installed (Manzello et al 2010). Intense smouldering ignition (SI) was observed within the OSB base layer and eventually flaming ignition (FI) was observed. The wind tunnel speed was 7 m/s and the Firebrand Generator was located 2.0 m from the CT roofing assembly. The dimensions of the roof assembly were 122 cm by 122 cm.

4.4.9. Building vents

For building ventilation, common vents include gable vents, foundation vents, and eave or soffit vents. The 2007 California Building Code of Regulations, Title 24, Part 2, Chapter 7A, desired to mitigate firebrand penetration through building vents by recommending a metal mesh of 6 mm is placed behind building vents. This mesh size was not based on any scientific testing since no test methods were available at that time. Therefore, the Firebrand Generator was used to study the penetration of firebrands into building vents. It was found that firebrands were not quenched by the presence of the mesh and would continue to burn on the mesh until they were small enough to pass through the mesh opening (Manzello et al 2012).

4.4.10. Mulch located adjacent to structures

Buildings are often surrounded by vegetation that, when ignited, can produce intense, localized firebrand showers, and provide direct flame contact with building elements, leading to the ignition of buildings. Experiments showed that it is possible to ignite the wall assemblies, when adjacent mulch was ignited by firebrands (Manzello et al 2017).

4.4.11. Developing laboratory scale test methods for firebrand exposure

The full-scale experimental results have led to significant improvements in understanding firebrand structure ignition vulnerabilities. Yet, more cost effective, reduced scale test methods are required to provide the scientific basis for standard test methods. The reduced-scale continuous feed firebrand generator has been developed. The continuous feed Baby Dragon is able to produce similar results to the continuous feed Dragon (see Figure 52, Suzuki and Manzello 2017).

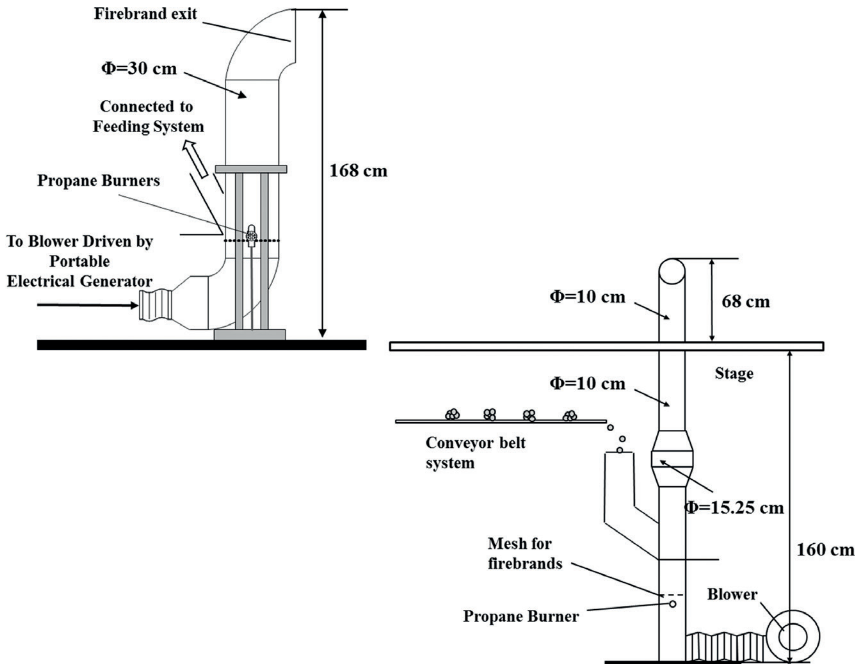

Figure 52. The full-scale firebrand generator and the reduced-scale firebrand generator (Suzuki and Manzello 2017).

4.4.12. Codes and standards related to firebrands

It is important to have science-based standard test methods to harden communities appropriately to WUI exposure. While NFPA 1140, AS 3959, 2021 IWUIC deal many test standards focus on direct flame contact or thermal radiation, less test standards exists due to the lack of data on firebrand exposure compared to those two. Developing test standards for WUI exposures presents significant challenges.

4.4.13 Need for globally harmonized test methods

Each country or region has different standards and codes to WUI fires. ISO TC92/WG14 (Large Outdoor Fires and the Built Environment) has published the technical report ISO/TR 24188:2022: Large Outdoor Fires and the Built Environment –Global Overview of Different Approaches to Standardization (ISO/TR 24188:2022).

Test methods for firebrand exposure have been identified as a key missing component in global large outdoor fire standards. Currently an ISO standard firebrand generator, based on the Dragon design described above, has been published (ISO 6021:2024, Firebrand Generator).

Interested readers are referred to a recent review on the most current progress to develop globally harmonized international testing standards for WUI fires (Manzello, 2024)

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5.
Fuels management in the structure surroundings

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5.1. Introduction to fuels management in the structure surroundings

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The area surrounding a building, often referred to as the "defensible space[5]" (DS), plays a crucial role in managing wildfire risk. This zone acts as a buffer between the fire-prone wildlands and the building itself. Effective fire risk management in this zone can significantly reduce the chances of a building igniting as a result of a wildfire. The dimensions of the DS vary across different organizations, regions, and countries. For instance, the National Fire Protection Association (NFPA) in the United States recommends a 200 ft zone (~61 m), Canada uses a 30 m zone, and European countries typically prescribe a 50 m zone. In this book, a 50 m zone surrounding the structure is considered. This distance is based on the potential for direct heat transfer to the building by radiation and convection from a fire front reaching the DS's outer edge and gradually reducing its intensity as it approaches the building.

Increasing the DS distance also lowers the probability of ignition by spotting, a significant mechanism in the ignition of structures

[5] Sometimes referred as "home ignition zone" (HIZ)

during wildfires (chapters 2 and 3). Spotting distances can span several kilometres, making fuel management zones around buildings somewhat limited. However, as described in this chapter, an appropriate fuel break management can substantially reduce the risk of building ignition from firebrands, even those produced at distances much larger than 50 m.

Effective fire risk management in the DS must consider at least the following characteristics related to the building implementation area:

- *Regional characteristics:* factors such as the region's susceptibility to fires, fire regime, dominant vegetation, fire history (e.g., number of ignitions or large fires registers), and climate.
- *Site-specific characteristics:* these include the types of fuels present near the building and the topography of the terrain/property.
- *Building characteristics:* it involves the construction materials and practices used in the building itself.

Other fire risk management factors include the self-protection needs of the building occupants, such as their physical and mental abilities, and the local civil protection capabilities and resources. Local and regional policies also play a significant role in determining the level of fire risk management required.

Fire risk management can be achieved through various means, addressing any of the components or factors mentioned above. This chapter primarily focuses on managing the fuels around the building. These fuels can be natural (Section 5.2), usually vegetation, or man-made (Section 5.3), including various materials and equipment typically found around buildings (e.g., cars, LPG tanks, complementary constructions, decks, awnings). Knowledge of flammability characteristics allows for a good selection of vegetation and man-made fuels that can be close to buildings, thus reducing the risk of building ignition. Nevertheless, effective fire risk management involves more than just selecting and using low--flammability species and materials or separating them to prevent fire from spreading horizontally to the building or vertically to taller elements like trees. As will be discussed in Section 5.4, the arrangement of vegetation, equipment, auxiliary constructions, and other elements around the building plays a critical role in reducing local atmospheric turbulence, thereby potentially minimizing the probability of building ignition.

Beyond fuels managing around the building, other significant measures include adopting fire-resistant construction practices and implementing self-protection systems. Effective integration of these strategies ensures a holistic approach to mitigate the risk of wildfires and to protect structures in fire-prone areas.

5.2. Natural fuels

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Forest fires are considered one of the serious threats to human lives, structures, and wildlife. Due to climate change, the number of fires, their area, and frequency of occurrence increase significantly each year. One of the solutions for fire management is fuel treatment with full knowledge of fuel properties and efforts to classify them. Wildland fuels and natural fuels can be defined as species that grow and spread naturally by ecological processes, i.e., vegetation development, deposition, decomposition, and disturbance, (Keane, 2015), with no direct human interventions, such as timber harvests, tree thinning, surface fuel treatments, and prescribed fires, or land management operations. The accumulation of natural fuels is the consequence of development, which is the result of the establishment, growth, and mortality of vegetation. Productivity, defined as the biomass accumulation rate, is the result of the vegetation environment, i.e., weather, hydrology, topography, and soil and its erosion rates, and interactions.

Considering the wide range and diversity of natural fuels, one of the approaches that can be proposed for fire management and ecosystem control is the classification of live fuels and dead biomass, (Keane, 2013, 2015). One of the advantages of fuel classification is detecting the potential fire behaviour, (Wagner, 1983), mapping the fire hazards, (Fernandes, 2009; Keane *et al.*, 2001), and identifying fire-prone areas (Beverly *et al.*, 2021; Shang *et al.*, 2020) to allocate suitable fire response systems, (Taylor *et al.*, 2013), and proactive fuel reduction strategies, (Pais *et al.*, 2021).

The fuel classification is a mean to have an inventory of species for robust fire behaviour prediction models and to associate the fire behaviour and fire danger index locally. The classification of the natural fuels is performed based on layering and this includes the level from the ground up to the treetops. The fuels of the lowest layer, ground, start from the soil, containing the plant's roots, and include the duff in the upper layer. Surface fuels from the top include large logs, small shrubs, grass, leaves, and low vegetation. Finally, crown (aerial) fuels include trunks, branches, leaves of living trees at higher levels, and standing snags. Crown fuels encompass dead trees including the mosses. In most forest fires, ground and surface fires are the most fire-feeding fuels, and on some occasions such as crown fires, extreme weather conditions, steep slopes, and higher fuel loads all layers can be involved. Natural fuels, based on their chemical characteristics, can have different behaviours when dealing with fire. For example, resinous species such as eucalyptus, pine, and black spruce are highly flammable, and conversely, some such as poplars can be resistant to fire. Other factors associated with physical properties e.g., size, shape, depth, load, bulk density, moisture content, continuity, and vertical or horizontal arrangement can alter the flammability characteristics, (Duff *et al.*, 2017; Gould *et al.*, 2011; Keane, 2013, 2015). Compact fuels, due to lack of air/oxidizer penetration have slow fire propagation, while in sparsely dispersed fuels, fire can evolve much faster. Fuel moisture is one of the prominent factors that can impede fire spread rate in its high contents. Other factors such as topography (i.e., slope steepness, aspect, elevation, and configuration of the land), and weather variables (i.e., wind, atmospheric humidity, and temperature) can affect the fire spread. This section is meant to give a summary of natural fuels and vegetation classification with its application in fire modelling and fire danger index practices, as illustrated in Figure 53.

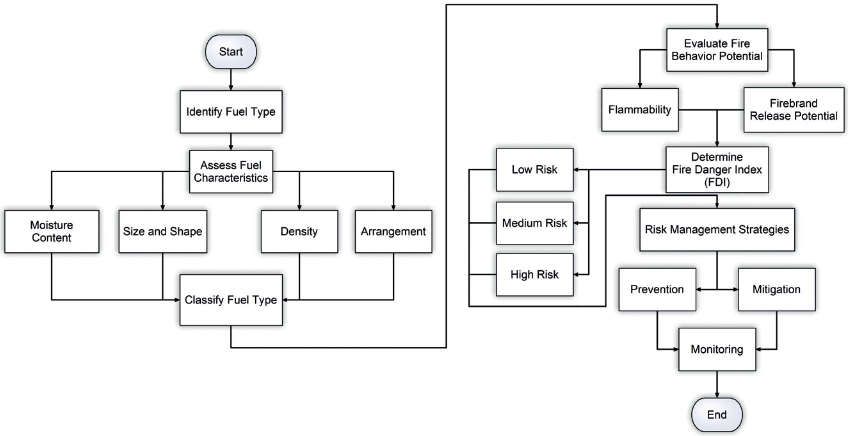

Figure 53. The flowchart representing fuel classification as a basis for fuel and risk management and fire danger indexing.

5.2.1. Classification of natural fuels

Natural fuels in forests are categorized based on their vertical arrangement in the forest structure: ground fuels, surface fuels, and crown fuels. Each category has distinct characteristics and plays a different role in fire behaviour.

Vertical Fuel Layers

As illustrated in Figure 54, natural fuels are often categorized into three main vertical layers:

1. *Ground fuels* include all combustible materials lying beneath the surface litter, such as roots, duff, and decomposed organic matter. These fuels are often compact and have high moisture content, which can slow down fire spread but can sustain smouldering fires for long periods.

2. *Surface fuels* consist of materials lying on or immediately above the ground, including leaves, needles, twigs, bark, logs, and small shrubs. These fuels are typically the primary carriers of fire in forest ecosystems. Their flammability is influenced by factors such as moisture content, size, and arrangement.
3. *Aerial or crown fuels* are located in the upper canopy of the forest, including branches, moss, leaves, and needles of living trees, as well as standing dead trees (snags). Crown fires can be particularly dangerous as they spread rapidly and can leap from tree to tree, driven by wind and topography.

The density and arrangement of vegetation cover significantly influence fire behaviour. Dense vegetation can provide continuous fuel for fire spread, while sparse vegetation can create gaps that slow down or stop the fire. The characteristics of the vertical fuel layers are described in Table 13.

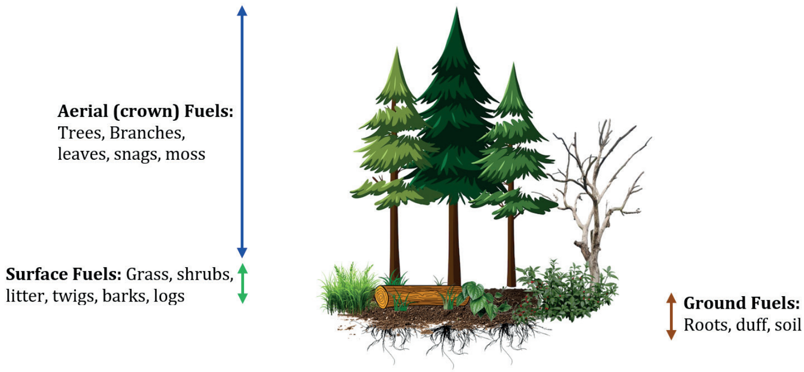

Figure 54. Classification of the natural fuels: Aerial, Surface, and Ground fuels.

Table 13. Characteristics of Vertical Fuel Layers (Forestry Canada Fire Danger Group, 1992; Rothermel, 1972; Wotton et al., 2005).

Fuel Layer	Level	Fire Behaviour
Ground	Below surface	Smouldering, slow spreading
Surface	0-2 m above ground	Rapid spread, intense
Crown	Tree canopies	Extreme intensity, fast spreading

5.2.2. Vegetation types and flammability characteristics

Various vegetation types, as in **Table 14**, exhibit different fire behaviour due to their unique structural and chemical properties.

1. *Grasslands* are characterized by rapid fire spread but lower intensity compared to forested areas. They are dominated by fine fuels that dry quickly and support frequent, fast-moving fires, (Cheney & Sullivan, 2008).
2. *Shrublands*, including chaparral ecosystems, often experience high-intensity fires due to their dense structure and flammable oils. These ecosystems are adapted to periodic fires, (Keeley & Fotheringham, 2001).
3. *Coniferous forests*, particularly those dominated by species like eucalyptus, pine or spruce, are prone to intense crown fires due to their resinous content and often dense canopy structure, (Alexander & Cruz, 2013).

- *Eucalyptus trees,* such as *Eucalyptus globulus* (Blue Gum), *Eucalyptus citriodora* (Lemon-scented Gum), and *Eucalyptus camaldulensis* (River Red Gum) are species known for their high flammability due to the presence of volatile oils in their leaves. These oils can ignite easily and contribute to the rapid spread of fire.

- *Pine trees,* such as *Pinus sylvestris* (Scots Pine), *Pinus ponderosa* (Ponderosa Pine), and *Pinus radiata* (Monterey Pine) are those with resinous wood and are highly flammable. The resin can act as fuel, and the needle litter on the forest floor can facilitate fire spread.

4. *Deciduous forests* generally have lower fire risk compared to coniferous forests, especially during the growing season when leaves have high moisture content. However, they can still experience surface fires, particularly in the dormant season, (Pausas *et al.*, 2008).
5. *Poplar trees, such as Populus tremuloides* (Quaking Aspen), *Populus nigra* (Black Poplar), and *Populus deltoides* (Eastern Cottonwood) are less flammable compared to eucalyptus and pine. Their higher moisture content and lower concentration of flammable compounds make them more resistant to fire.
6. *Mixed forests* combine characteristics of both coniferous and deciduous trees, leading to complex fire behaviour that can vary depending on the specific composition and structure, (Sturtevant *et al.*, 2009).

Table 14. Vegetation types and flammability characteristics.

Vegetation types	**Flammability characteristics**
Grasslands	Rapid fire spread but lower intensity; dominated by fine fuels that dry quickly and support frequent, fast-moving fires.
Shrublands	High-intensity fires due to dense structure and flammable oils; adapted to periodic fires.
Coniferous forests	Prone to intense crown fires due to resinous content and dense canopy structure.
Deciduous forests	Lower fire risk during the growing season due to the high moisture content in leaves; can experience surface fires, especially in the dormant season.
Mixed forests	Complex fire behaviour due to a combination of coniferous and deciduous trees; varies with specific composition and structure.

5.2.3. Fuel properties and fire behaviour

Fuel Size

Forest Fuels are categorized into different size classes based on their diameter, which significantly influences their moisture content and combustion characteristics. Understanding these classifications is crucial for fire management and predicting fire behaviour. The main fuel size classes are:

1. *1-Hour Fuels:* These are fuels with a diameter of less than 0.6 cm. Due to their small size, 1-hour fuels, such as fine twigs and small branches, dry out quickly and respond rapidly to changes in moisture. They are highly flammable and contribute to the spread of fires by igniting easily and burning intensely over a short period, (Anderson, 1982).
2. *10-Hour Fuels:* Fuels in this category have diameters ranging from 0.6 to 2.5 cm. Examples include small branches and larger twigs. These fuels have a moderate drying rate and can sustain combustion longer than 1-hour fuels, but not as long as the larger classes. Their moisture content is less responsive to short-term weather changes compared to 1-hour fuels, (Brown, 1974).
3. *100-Hour Fuels:* With diameters between 2.5 and 7.6 cm, 100-hour fuels include medium-sized branches and small logs. They take longer to dry out compared to 1-hour and 10-hour fuels, which means they have a slower response to changes in moisture. These fuels contribute to the fire's intensity and duration, as they can smoulder and sustain a fire over a longer period, (Scott & Reinhardt, 2001).
4. *1000-Hour Fuels:* Fuels larger than 7.6 cm in diameter fall into this category, such as large logs and stumps. These fuels have the longest drying times and can retain moisture for extended

periods. Although they are less susceptible to rapid changes in moisture, once ignited, they can burn for prolonged periods and contribute significantly to the fire's longevity and intensity, (Burgan & Rothermel, 1984).

Fuel Moisture Content (FMC)

Fuel moisture content is a critical factor in determining ignition probability and fire spread. Live fuel moisture varies seasonally and among species, while dead fuel moisture responds more rapidly to environmental conditions, (Chuvieco *et al.*, 2004).

Surface Area to Volume Ratio

The surface area to volume ratio of fuels affects their drying rate and ignitability. Fine fuels with high surface area-to-volume ratios ignite more easily and promote rapid fire spread, (Rothermel, 1972).

Fuel Load

Fuel load, or the amount of available fuel per unit area, directly impacts fire intensity and duration. Higher fuel loads can lead to more intense and longer-lasting fires, (Ottmar *et al.*, 2007).

Fuel Bulk Density

Fuel bulk density, the weight of fuel per unit volume, influences fire spread rates. Lower bulk densities often promote faster fire spread due to better oxygen availability, (Scott & Burgan, 2005).

5.2.4. Vegetation cover properties and fire behaviour

Vegetation cover properties play a crucial role in determining fire behaviour in forest ecosystems. These properties influence various aspects of fire dynamics, including ignition probability, fire spread rate, intensity, and the potential for crown fires. Understanding these relationships is essential for effective fire management and risk assessment.

- *Canopy cover* affects fire behaviour by influencing fuel moisture, wind speeds, and the potential for crown fire initiation. Dense canopies can promote crown fires but may also reduce surface fuel drying, (Scott & Reinhardt, 2001), primary carriers of fire and respond quickly to changes in moisture content. Crown fuels, found in the upper canopy, can lead to high intensity, rapidly spreading crown fires.
- *Density of understory vegetation* impacts fire spread rates and intensity. Dense understories can lead to more intense fires and increase the likelihood of crown fire initiation, (Agee & Skinner, 2005).
- *Fuel continuity*, both horizontal and vertical, plays a crucial role in fire spread. Continuous fuels promote fire spread, while gaps or discontinuities can act as natural firebreaks, (Finney, 2001).
- *Leaf Area Index (LAI)*, which measures the total one-sided leaf area per unit of ground surface area, impacts fire behaviour by affecting how much moisture fuel retains, the amount of wind that can penetrate through the canopy and the overall distribution and load of fuels. Typically, higher LAI values suggest denser vegetation, which can result in more intense fires if ignited, while also potentially maintaining higher levels of fuel moisture (Keane, 2020).
- Fuel age significantly affect fire behaviour. Young, dense stands are often at higher risk for intense fires because of their substantial fuel loads and continuous vertical growth. Mature stands, with their well-developed vertical layers, can be vulnerable to crown fires. Old-growth forests, characterized

by their intricate structures, can exhibit diverse and unpredictable fire behaviours (Spies *et al.*, 2018).

5.2.5. Natural fuels' flammability and hazard index

To classify forest species by their flammability traits, various experiments were conducted on different Mediterranean species at LEIF (Laboratório de Estudos sobre Incêndios Florestais) in Coimbra, Portugal. Thermal tolerance for unprotected individuals and objects is determined according to Table 15, (Modarres *et al.*, 2024).

Table 15. Heat flux thresholds (Ψ_{th}) and effects on different elements.

Ψ_{th} (kW/m^2)	Effects and damages
1.6	No discomfort, long exposure
4.0	Pain after 20 s exposure. Blisters/burns after 20 s exposure
4.7	Injuries after 25 s exposure
7.0	Max exposure for firefighters: minutes
12.5 – 15.0	Wood ignition with flame Plastic tube melting (lethal)
18.0 – 20.0	PVC insulation degrades
25.0	Wood burns with prolonged exposure
35.0 – 37.5	Damage to steel tanks and equipment

According to the results from the empirical analysis of different species, plants can be categorized based on their heat generation potential, which originates from each plant's physical characteristics, age, and chemical contents. Maximum heat flux values, q_{max} (kW/m^2), for each species for the laboratory samples with the corresponding crown heights, are detailed in Table 16.

Table 16. Maximum heat flux values for different natural fuels and the corresponding hazard indexes.

Species	Scientific name	Crown height (m)	qmax (kW/m2)	Hazard index
Kiwi	*Actinidia deliciosa*	0.7	1.1	Low
Hydrangea	*Hydrangea macrophylla*	1.2	2.1	
Blackthorn	*Prunus spinosa*	1.8	2.6	
Holly	*Ilex aquifolium*	1.6	3.3	
Fig tree	*Ficus carica*	1.5	4.7	
Grapevine	*Vitis vinifera*	0.2	5.1	Moderate
Acacia	*Acacia dealbata*	1.8	5.9	
Cherry laurel	*Prunus laurocerasus*	1.7	6.0	
Cherry tree	*Prunus avium*	1.6	6.2	
Gum rockrose	*Cistus ladanifer*	1.5	6.6	
Oleander	*Nerium oleander*	1.8	6.7	
Ivy	*Hedera helix*	0.8	7.2	High
Apple tree	*Malus sylvestris*	2.1	7.8	
Leyland cypress	*Cupressocyparis leylandii*	2.3	8.0	
Loquat	*Eriobotrya japonica*	1.6	8.9	
North. white cedar	*Thuya occidentalis*	2.0	9.0	
Olive tree	*Olea europaea*	1.9	9.7	Very High
Arizona cypress	*Cupressus arizonica*	2.7	10.0	
Bramble	*Rubus ulmifolius*	0.3	10.6	
Lindens	*Tilia tomentosa*	1.9	10.8	
Madrone	*Arbutus unedo*	1.7	11.5	Extreme
Sumac	*Rhus typhina*	1.2	11.6	
Laurel	*Laurus nobilis*	2.0	31.8	

Based on q_{max} values, the species can be categorized into four different fire hazard levels.

- Low: $q_{max} \leq 5$ kW/m²
- Moderate: 5 kW/m² < $q_{max} \leq 7$ kW/m²
- High: 7 kW/m² < $q_{max} \leq 9$ kW/m²
- Very High: 9 kW/m² < qmax ≤ 11 kW/m²
- Extreme: $q_{max} > 11$ kW/m²

In this classification, Low and Moderate flammability classes are less fire-prone due to their lower hazard index ratings, making them suitable for planting in wildfire-prone areas and gardens where fire safety is a concern. It's important to create fire breaks or reduce fire risks around homes and buildings.

Although plants with lower fire hazard ratings are safer for these areas, they can still ignite in extreme conditions. Factors like drought, high winds, and fuel buildup can significantly raise the fire risk. Thus, maintaining good landscaping practices, such as removing flammable materials and establishing defensible space, is crucial. When choosing plants, consider not only their fire resistance but also climate, soil conditions, and water needs to ensure a healthy, sustainable landscape.

5.2.6. Conclusion

Understanding the classification and characteristics of natural fuels is essential for effective fire management and prediction. Fuels in forests are categorized into ground, surface, and crown layers, each with distinct properties that influence fire behaviour. Ground fuels, such as roots and duff, typically burn slowly and sustain smouldering fires. Surface fuels, including leaves and twigs, are primary carriers of fire and respond quickly to changes in moisture content. Crown fuels, found in the upper canopy, can lead to high intensity, rapidly spreading crown fires.

Different vegetation types exhibit varied flammability characteristics, which are determined by their structural and chemical properties. Grasslands, with their fine fuels, are prone to rapid fire spread but lower intensity. Shrublands, particularly chaparral ecosystems, experience high-intensity fires due to their dense structure and flammable oils. Coniferous forests, such as those dominated by eucalyptus and pine, are highly flammable due to their resinous content and dense canopy, making them susceptible to intense crown fires. In contrast, deciduous forests generally have a lower fire risk during the growing season due to higher moisture content in leaves but can still experience surface fires. Mixed forests, combining both coniferous and deciduous species, present complex fire behaviours that vary with their specific composition and structure.

The size of fuels, ranging from 1-hour to 1000-hour fuels, also plays a critical role in determining fire behaviour. Smaller fuels, like 1-hour fuels, dry out quickly and contribute to rapid fire spread, whereas larger fuels, such as 1000-hour fuels, burn for longer periods and contribute to the fire's intensity and duration. Other factors, including fuel moisture content, surface area-to-volume ratio, fuel load, and fuel bulk density, further affect ignition probability, fire spread, and overall fire behaviour.

Vegetation cover properties, including canopy cover, understory density, and fuel continuity, significantly impact fire behaviour. Dense canopies can promote crown fires, while dense understories and continuous fuels can lead to more intense fires and an increased likelihood of fire spread. Additionally, the Leaf Area Index (LAI) affects fire behaviour by influencing moisture retention, wind penetration, and overall fuel arrangement, with higher LAI values generally indicating denser vegetation. The age and structure of forest stands also play crucial roles, with young, dense stands at higher risk for intense fires and mature stands being more susceptible to crown fires. Old-growth forests can display varied fire behaviours due to their complex structures.

Extensive laboratory experiments led to the classification of forest fuels into five categories: Low, Moderate, High, Very High and Extreme fire-prone species. This classification is defined based on heat flux values measured during combustion. The results identified kiwi as the least, while laurel emerged as the most flammable species.

Overall, a comprehensive understanding of flammability factors is crucial for developing effective fire management strategies and mitigating the impact of fires on various ecosystems. By considering the interactions between fuel types, size classes, and vegetation characteristics, fire managers can better predict fire behaviour and implement appropriate measures to manage and control wildfires.

5.3. Man-made Fuels

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Man-made or artificial fuels located within the surroundings of a building can vary significantly but are mainly composed out of plastic or wooden materials. Examples of man-made fuels (Figure 55) include sheds, outdoor furniture, vehicles, LPG tanks, stored materials, or even other buildings. These fuels can be ignited by firebrands, through direct flame contact or even due to radiant exposure (Caton *et al.* 2017) and they have potential to burn for long periods of time. This means that they are likely to create the most damage during the post-frontal combustion fire phase (Vacca *et al.*, 2020), as they can contribute to fire spread onto a property even after the passing of the main fire front.

(a) *(b)*

Figure 55. Examples of man-made fuels involved in WUI fire accidents: (a) metal shed, LPG tank and greenhouse and (b) vehicles ignited during the Mati fire (Greece, 2018) (Caballero and Sjöström, 2019).

Man-made fuels can also burn with significant intensity, possibly exposing homes to the risk of ignition and structural failure, should these fuels be located close enough to affect their weakest elements (Vacca *et al.*, 2022). The spacing of man-made fuels in relation to other man-made fuels, vegetation (may it be ornamental or wildland vegetation) or structures is therefore key to avoid further fire spread.

In the Fort McMurray fire of 2016, it was observed that there was a positive correlation between home survival and properties that had minimum amounts of materials, machinery, and general "clutter" stored in open areas and accessible to wind-driven embers. In this fire, the most common and significant sources of combustibles were general yard 'clutter', firewood, construction materials, recycling and compost storage, machinery and recreational vehicles, petroleum products, and patio furniture or amenities (Westhaver, 2017).

Man-made fuels can also be found to be stored in fuel packs, which are an accumulation of fuels that consist of different types of materials. An example of the hazard that is associated to fuel packs is given by the large heat accumulation due to their ignition in semi-confined spaces (e.g., porch, space under decks, garage, shed), which can lead to fire spread through a property due to the ignition of other surrounding elements (Vacca *et al.*, 2020). Figure 56 shows structural damage caused by the combustion of fuel packs in non-combustible semi-confined spaces.

(a) *(b)*

Figure 56. Consequences of the combustion of man-made fuels in semi--confined spaces: (a) shed containing tools and other materials destroyed during the Monchique fire (Portugal, 2018); (b) garage containing man--made fuels destroyed during the Mati fire (Greece, 2018) (Caballero and Sjöström, 2019).

Other man-made fuels that can cause fire spread on a property are aboveground domestic LPG tanks, which are used as an energy source for heating, hot water, or cooking in WUI settlements. When these tanks are exposed to flames coming from fuels located in their vicinity, they heat up and the pressure inside the tank will increase. If the tank pressure reaches the Pressure Relief Valve (PRV) set point, this will open, releasing LPG that will immediately ignite forming a jet fire. The jet fire will hence worsen the heat load to the tank and its surroundings. If no measure is taken in order to cool down the tank and/or extinguish the fire, the tank may fail, leading to a loss of containment (Scarponi *et al.*, 2020). Fourteen WUI accidents in which LPG reservoirs are involved are described

Figure 57. Domestic LPG tank in Benitatxell (Spain, 2016) damaged by a jet fire caused by the opening of the PRV due to the combustion of ornamental vegetation (Scarponi et al., 2020).

by Barbosa *et al.* (2023), reporting two fatalities and the partial destruction of three buildings related to the burst of LPG cylinders.

Existing WUI codes, standards and guidelines address the management of the defensible space around a building, although focus is placed on the distancing of vegetation from buildings and very few rules address the spacing between artificial fuels and structures. There is however no mention on the distancing between different man-made fuels in order to avoid fire spread through a property (Àgueda *et al.*, 2023), with the exception of the distancing between LPG tanks and other fuels, for which each country provides its own safety distances (Scarponi *et al.*, 2020).

It is therefore necessary to identify safety distances between man-made fuels in order to avoid fire spread throughout a property, along with safety distances between these fuels and structures, to avoid fire entering a building. A systematic and standardised field data collection methodology can help in identifying these distances (Mell at al., 2010). An example of this type of data collection is given by Maranghides *et al.* (2021), which identified the distance of 3 m between an ignited garden shed (8 m x 4 m) and a building to not be enough to avoid damage to the building, as the eaves started pyrolyzing.

There is however also a need for quantitative information of the burning behaviour of WUI man-made fuels in order to define and characterize the role of these fuels in a home's ignition process. This type of information is available for fuels that are located indoors (Babrauskas, 2016), and some of these fuels (e.g., wooden pallets, vehicles) can also be located in WUI environments, but very little information is known on the quantitative burning behaviour of other WUI man-made fuels and fuel packs. Recently, tests have been performed on four different WUI environment fuel packs, for which HRR, MLR, fire load, smoke concentrations, temperatures and heat fluxes were recorded (Vacca *et al.*, 2022). These tests showed that items made out of plastic materials such as polypropylene (e.g., outdoor furniture, children's outdoor toys) are very hazardous, as the melting of this material increased the flaming surface by almost doubling its width. The spacing between these types of fuels and others present on the property should therefore consider this flaming surface expansion in order to avoid fire spread through a property.

Further quantitative tests on other types of WUI man-made fuels and fuel packs are needed in order to understand not only the hazard that they pose to WUI structures, but also the role that they have in contributing to fire spread on a property as well as within a WUI settlement.

5.4. Aerodynamic turbulence in the building surroundings

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5.4.1. Introduction

According to several studies conducted by various authors (Ribeiro *et al.*, 2020) (Dossi *et al.*, 2022), the primary mechanism affecting infrastructures is spotting, followed by the convection mechanism resulting from flames impacting buildings. Consequently, buildings often ignite before the arrival of the fire front, causing surprise among individuals involved who are not always prepared to respond to early ignitions. On the other hand, the falling of firebrands onto flammable components of structures may result in late ignitions, i.e., hours, or even days after the flame front has gone. This also surprises people because, at that stage, it is common for individuals to relax in their vigilance and house protection activities, assuming that the danger has already passed.

Hence, the spotting mechanism assumes great relevance concerning the exposure of houses to wildfires. Although the occurrence of spot fires can have various origins (e.g., material rolling down a versants or ignition caused by running animals that were caught by the fire), the aerodynamic transport of firebrands is undoubtedly the most common. Therefore, in addition to factors related to the fuels generating firebrands and the fuel bed where firebrands land, which is explored in Section 4.4, the probability of spotting is highly influenced by the wind characteristics and the turbulence generated, in this case, at the buildings' surroundings.

It is commonly observed that the arrival of the fire front at the edge of a forest triggers the release of several firebrands and, likely, promote the potential appearance of several spot fires downstream. This phenomenon can be explained by the increased turbulence created at the forest's periphery, which is frequentely observed.

The following text aims to explore and describe the turbulence that can arise in the vicinity of a building, which can promote the release, transport, and fall of firebrands onto vulnerable building components, such as the roof. The classic wildland-urban interface scenario in which the continuous forest and the built environment are clearly separated and distinguished will be considered as the reference scenario.

5.4.2. Origin of air flows in wildfires

The Sun is the most import energy source on Earth. Its most obvious energy form is radiation. When an object is directly exposed to it, it warms up and its temperature increases. The heating rate depends on various factors, such as the characteristics of the material exposed and the angle of incidence of solar radiation. The air in contact with a heated surface warms up, expands, becomes lighter relatively to the surrounding colder air layers. The hot air tends to rise, pushing cooler layers and dragging air from the surroundings. This elementary movement (known generally as convection) gives rise to the air circulation commonly known as wind. Therefore, wind is the natural movement or air, and it can be classified as a local breeze or a large-scale atmospheric circulation.

Based on the similar convection phenomenon, other local air flows can be created due to heating processes. For example, in wildfires, an identical phenomenon gives rise to hot air pockets due to the heat released in the combustion process.

5.4.3. Boundary layer fundamentals

All fluids, including air, are characterized by their viscosity. When the air is moving, its viscosity imposes a zero velocity to the air in contact with stationary solid walls (no-slip condition). Such means that the air flow has a zero velocity in the layer touching the solid boundary. However, as the distance from the wall increases, the air stream maintains the so-called undisturbed speed ($V\infty$), implying there is a region, known as boundary layer, where the flow velocity (V) increases from zero (at the wall) to $V\infty$ (far away from the wall surface).

If the air stream takes place inside a converging channel (see Figure 58), the flow remains always attached to the duct wall as the cross section is decreasing gradually in the flow direction. The mass conservation law (Equation (16)), assuming incompressible conditions (i.e., constant density,ρ), applied at sections A and B, indicates that $V_B > V_A$, when the cross-section area (A) decays ($A_B < A_A$). The energy conservation principle, expressed by the Bernoulli Equation (17) (White, 2011), implies that $p_B \leq p_A$, being p the static pressure. Therefore, as the pressure decreases gradually in the flow direction, the flow tends to speed up, creating a favourable pressure gradient region ($dp/dx<0$), as the flow is in the direction of higher to lower pressure zones.

$$V_A A_A = V_B A_B \quad (16)$$

$$p_A + \frac{1}{2}V_A^2 + gz_A = p_B + \frac{1}{2}V_B^2 + gz_B \quad (17)$$

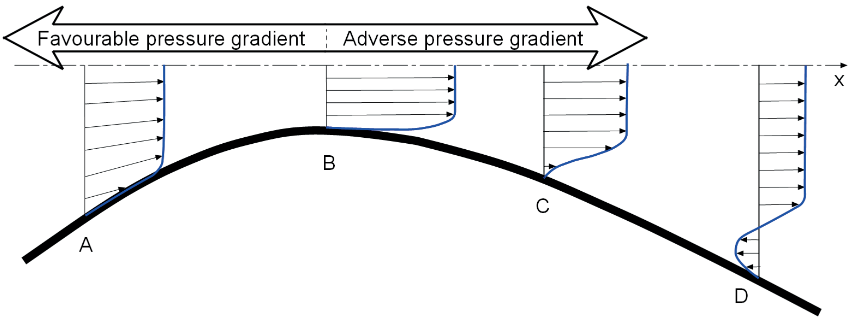


Figure 58. Flow inside a duct of variable cross section.

The opposite occurs in diverging regions. As the cross-sectional area enlarges gradually in the streamwise direction ($A_C>A_B$), the mean velocity decreases and, therefore, pressure increases, creating a region characterized by an adverse pressure gradient ($dp/dx > 0$). Such pressure augmentation hinders the flow and so, flow separation can occur, inducing the appearance of recirculation zones (see location D in Figure 58). As the designation suggests, those regions are characterized by fluid flowing in the reverse direction, contrary to the undisturbed flow orientation.

The flow separation zones are characterized by turbulent eddies, whose largest dimension is identical to size of the recirculation region. The larger eddies give origin to gradually smaller swirls through a cascade process, transferring energy between different scales, due to fluid viscosity (see Figure 59 in a fire situation).

Figure 59. Visualization of a wide range of turbulent vortices scales in a fire.

5.4.4. Wind flow in the vicinity of buildings

As mentioned in section 5.4.3 for internal flows, flow separation is expected in the case of external flows when the surface curvature is pronounced as illustrated in Figure 60. Indeed, the undisturbed streamlines act as an ideal wall (without friction) and, due to the pronounced ground slope, if the cross section enlarges, a flow speed reduction occurs.

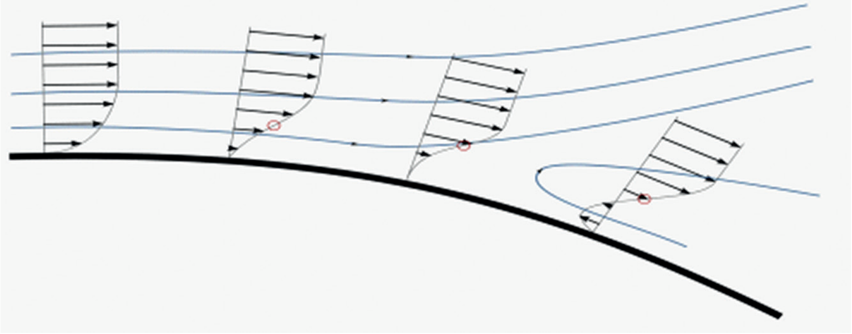


Figure 60. Flow separation near a sloped wall (Source: Olivier Cleynen, https://upload.wikimedia.org/wikipedia/commons/c/c7/Boundary_layer_separation.svg).

Recirculation zones are commonly observed in wind flows around buildings or similar obstacles (see Figure 61). The air flowing along the upper wall has difficulty to remain attached to the surface after a sharp edge due to its inertia. Owing to the blockage induced by the obstacle, the wind flow is forced to accelerate over the top of the obstruction. After the sharp edge, in the leeward side of the obstacle, there is a sudden area expansion where the fluid velocity decreases quickly, and flow separates from the surfaces. A recirculation region is established where the swirling vortices created are strongly turbulent and instable.

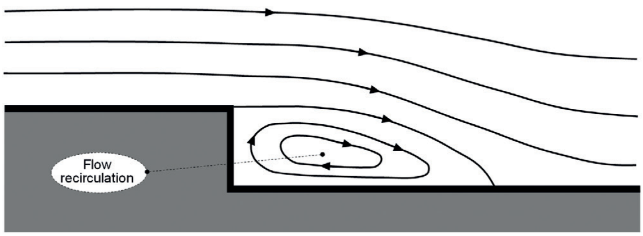


Figure 61. Flow separation and bubble recirculation in the leeward of obstacles.

As mentioned before, the dimension of the largest three-dimensional turbulent structures (vortexes) created is of the order of the height (H) of the obstacle or of the extent of the gap (D) between the obstacles (see Figure 62).

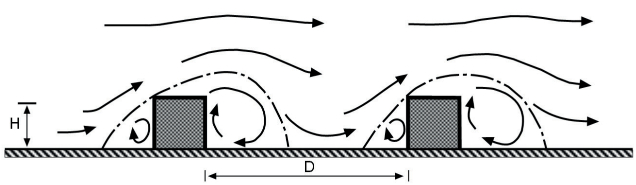


Figure 62. Illustration of the recirculating turbulent eddies in the vicinity of obstacles.

The presence of an obstacle in the path of a flow creates a phenomenon similar to the duct flow. Obstructions of low porosity force the flow to accelerate due to the reduction of the cross-section and, afterwards, to slowdown owing to the sudden cross-section increase (as exemplified in Figure 62). On the leeward side of the obstacles, a flow recirculation zone (also known as "wake") is established, where non-stationary vortices are formed and continuously released/ transported by the main flow field. The local flow is characterized by strong instability due to vortex shedding. The larger eddies give rise to smaller vortexes, through the cascade phenomenon, resulting in eddies of intense vorticity that can drag and lift small particles.

As an example, hatchback cars (with two volumes), contrarily to sedans (three volumes), commonly come equipped with rear windshield wipers. Due to the flow recirculation on the wake of the car, local vortexes raise dust and water particles from the ground, dirtying the back glass. Similarly, in wildfires, the strong swirling eddies, originated in recirculation zones after a low-porosity barrier of trees, are susceptible to induce the release and transport o firebrands prone to start spot fires.

5.4.5. Wind flow and fire risk at WUI

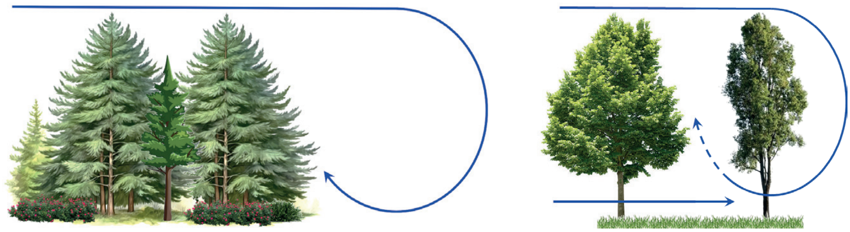
To better analyse the flows generated around buildings situated in a forested environment, a scenario of a construction near a forest with a fuel management strip separating them will be considered. If a dense forest abruptly ends, without a gradual reduction of the fuel height, the forest edge will behave similarly to the leeward side of a solid obstacle as described earlier, favouring the creation of a wake zone (Figure 63a).

The strong turbulence of the recirculation zone, primarily occurring near the edge of the forest, facilitates the release and uplift of firebrands. These embers are then carried toward the building by convective flows and by the wind. Depending on their inertia and characteristics, firebrands may fall within or after the recirculation cell. However, it is in the downward flow region of the recirculation cell, or immediately after, where those airborne particles' deposition is more likely to occur.

Nevertheless, it is well known that the forest is not a solid block, exhibiting some porosity that depends on the spacing between trees and the type of canopy, which can be more or less dense. This porosity mitigates the effect of horizontal vorticity production since recirculation is disrupted because it does not meet the opposition typical of a dense forest and so the reverse vortex flow penetrates the forest's peripheral area (see Figure 63b). However, for simplification purposes, a sufficiently dense and extensive forest is considered, that will prevent airflow from penetrating its periphery, acting similarly to a solid block.

If the forest acts like a solid body, large turbulent eddies are created in the leeward of the forest, which will promote strong turbulence between the forest's periphery and a construction. As mentioned, the largest size of the eddies is limited by the height of the trees and by the wind velocity. Therefore, if the forest's density, especially in its outermost and under layer (shrub), is low, there will be smaller and instable vortices. On the other side, if the forest edge does not abruptly terminate in height but features vegetation with a gradual reduction in height, vorticity creation is attenuated, resulting in less turbulence and consequently, fewer firebrands are generated (Figure 64).

Considering the scenario of a dense forest, where high vegetation abruptly ends at its periphery, behaving like a solid body, vorticity structures will promote upward flows releasing firebrands. If the fuel management strip is free of obstacles such as vegetation, the turbulence remains, with slight attenuation depending on the width



(a) *(b)*

Figure 63. Scheme to explain the horizontal vorticity formed in the boundary of a forest.

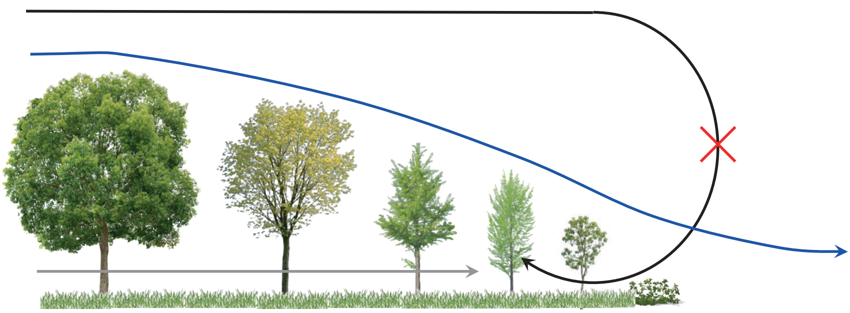
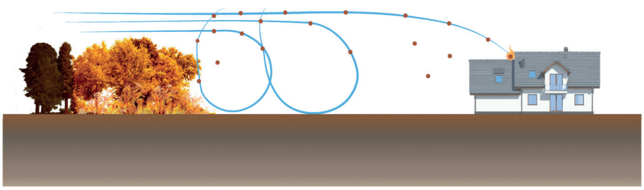


Figure 64. Scheme of the effect of a leader fuel management in the turbulence.

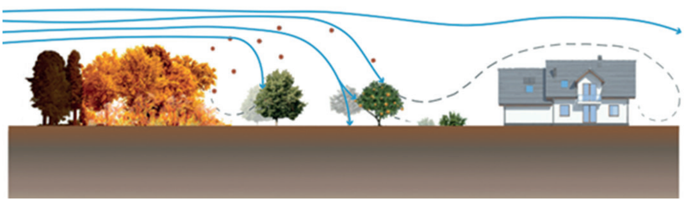
of the defensible space zone[6] (Figure 65a). Thus, the transport of firebrands is facilitated. On the contrary, if there are obstacles (e.g., vegetation) in this separation zone between the forest and the building with sufficient height and density to disrupt vorticity, turbulence will decrease more intensely (Figure 65b). Therefore, the presence of obstacles or flow attenuators in the fuel management strip, such as vegetation or other man-made materials, reduces turbulence, decreases the likelihood of firebrands being released and aerodynamically transported, and thus, mitigates the possibility of

[6] Considered zone around the building, with about 50 m width, composed by the structure ignition zone, firebreak zone and reduced fuel zone.

downstream ignitions. It is important to understand, however, that the distance between these flammable obstacles should be sufficient to prevent flames from propagating from one element to another, allowing the direct spread of flames to the building — this topic was discussed in Section 5.2.



(a)



(b)

Figure 65. Scheme of the wind turbulence in defensible space without vegetation.

5.4.6. Conclusions

As described, the wind flow over a solid obstacle, like a building, usually results in the formation of a recirculation zone. The size of the wake is identical to the height of the construction, and the turbulent vortices formed are characterized by strong instability. The intense vorticity of the eddies is capable of dragging and lift particles, prone to be transported by the main wind flow.

Dense forests behave similarly to solid bodies. Thus, at the periphery of dense forests, in both the canopy and surface strata (e.g., shrubs and herbaceous), there is usually a significant release of firebrands when the fire front arrives. These firebrands are transported over distances that depend on several factors, including atmospheric turbulence beyond the forest's edge. The presence of clear terrains downstream, i.e., free of obstacles, facilitates the transport of firebrands, as the attenuation of both turbulence and wake zone is slight, potentially driving the firebrands to the building, which in this scenario, would be the first obstacle in the defensible zone.

A proper management of fuels surrounding a building can reduce the number and size of firebrands released at the forest's edge and mitigate the formation of vorticity and turbulence, making it more difficult for firebrands to be aerodynamically transported to the structure. Some of these techniques include: 1) thinning vegetation and pruning trees at the forest's periphery to increase porosity and reduce the formation of the wake zone — conversion to less flammable species and vegetation with low potential to produce firebrands (cf. Section 5.2) is also a good measure; 2) gradually reducing the height of vegetation at the forest's edge to lessen the formation of the wake zone; 3) placing obstacles in the defensible space, such as trees, to dampen the turbulence created in the area, thereby promoting the early fall of firebrands.

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6.

Self-protection systems against wildfires

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6.1. Introduction to self-protection systems

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Forest fires pose great threats not only to forests, but also to villages and facilities adjacent to forests and to houses within forests. Many reports warn that the occurrence and severity of forest fires will increase due to climate change, and many cases of forest fires supporting these warnings are appearing around the world. The occurrence of such forest fires not only affects areas that have not been invaded by humans, such as Alaska, the frozen soil regions of Siberia, and the Amazon, but also poses threats to many cities where people are living in areas near forests. In cases of forest fires in South Korea, the maximum forest fire spread rate was found to be 8.8 km/h, and the distance of forest fire spread by spotting was found to be 2 km (Donghyun, 2005). In the case of the forest fires in Portugal in 2017, the maximum rate of spread was at least 9 km/h and the maximum spotting distance was at least 21 km

(Viegas *et al.*, 2021). In the United States, a maximum fire spread rate of 13 km/h and a distance of forest fire spread by spotting of 3.2 km were observed in the Wallace Greece Forest fire in 2003.

The extreme wildfire events, which are becoming increasingly frequent, lead to situations where public civil protection means are insufficient to respond to all the rescue requests made by citizens. On many occasions, activities to suppress the main fire front are interrupted due to the need to protect property and people as the fire enters or threatens to enter the WUI. Given the expected trend of increasing extreme wildfires worldwide, the standards for fire risk management must address not only the reduction of fire danger by preventive measures (cf. Chapter 5) but also increasing citizens' capacity for self-protection, which is the main purpose of Chapter 6. This means that effective methods to make the WUI space into more fire-resistant and safe areas must be devised. The methods to improve safety conditions include removing fuels and taking actions to prevent fuels from burning. FireSmart and FireWise designate zones 1, 2, and 3, and install on-site firefighting equipment to protect houses along with a manual on fuel removal providing information on water supply to prevent fire spread from a forest fire by spraying water on the roof and around the house. In the case fuel removal, damage to forests or nature should be accepted. Additionally, it is difficult to judge how much fuel should be removed to assure a safe space considering the severity of forest fire spread rates and intensity, and it is challenging to create reliable barricades as buffer zones to stop forest fire spread due to the amount of work required for fuel removal and management problems. Methods to prevent fuels from burning include the use of water sprays and sprinklers, fire foam, and retardants, or preventing and extinguishing fires when they spread.

In this chapter, various self-protection systems are described, aimed at enabling citizens and communities to respond to fires more independently. However, the self-protection capacity should always be integrated with and seen as complementary to the public civil protection system, which will always serve as a backup when self-protection capacity is insufficient. Throughout the chapter, in addition to this introductory text, Section 6.2 provides an overview of advancements in self-protection systems, industrial applications, and associated challenges, with a special focus on sprinkling systems. In Section 6.3, two water sprinkling systems for protecting exposed elements from fire and for hindering fire spread in forested areas are presented. In Section 6.4, self-protection systems based on the use of fire-resistant screens to protect exposed elements from fires are described, addressing other solutions that are based on heat transfer reduction to protect exposed elements.

6.2. Advancements and challenges in fire self-protection systems

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Water sprinkler systems are frequently set up in buildings to offer an economical way of reducing the potential hazards to both life safety and property damage, among other things. Since the 1960s, studies have extensively focused on municipal and residential water demand, while innovative solutions are emerging to meet this critical resource's needs, which, as emphasized by Marshal (1879), play a pivotal role in community development. Inefficient water usage, particularly in irrigation and gardening, constitutes a significant source of wastage, often underestimated due to the minor impact of water bills on income (Rahman *et al.*,2014); however, addressing this issue through advanced sprinkler technology becomes crucial for substantial water and energy conservation across agricultural, industrial, and residential domains.

Water sprinkler systems play a vital role in wildfire management as they offer a proactive approach to containing and extinguishing fires. These systems help create firebreaks, protect critical infrastructure, and safeguard communities by applying water directly to areas needing protection. They are particularly valuable in areas where traditional firefighting methods might be challenging or insufficient. Ongoing research efforts are dedicated to evaluating the effectiveness of this fire protection system (Hua *et al.*, 2002).

The purpose of the present section is to provide a comprehensive overview of water sprinkler systems used in wildfire management, aiming to explore the academic research conducted to develop different types of water sprinkler systems, as well as the recent technologies in the commercial market. Additionally, the challenges and limitations of these systems will be described, just like their integration with other wildfire management techniques, and their environmental impact. By doing so, this section seeks to present the state-of-the-art knowledge on water sprinkler systems for wildfires, fostering a deeper understanding of their significance and potential for further advancement in wildfire management strategies.

6.2.1. Academic research on water sprinkler systems for wildfires management

With the increasing fires and rising cost of suppression, there is a growing challenge of insufficient human resources to safeguard all threatened infrastructure and settlements. Therefore, it becomes crucial to empower the citizens with effective tools to defend their belongings and properties, as these play a vital role in forest fires management (Beighley and Hyde 2018).

Limited scientific research was carried out on wildfire sprinkler system effectiveness, resulting in an unclear understanding of how water sprinkles reduce wildfire damage to buildings and the extent of protection provided, besides the effect of extern factors such as temperature, dryness and wind on the performance on sprinklers. Green (2019) worked on his PhD thesis on “the sprinkler systems for the protection of buildings from wildfires”. This thesis highlighted that a proper design of wildfire sprinkler systems can offer significant protection to buildings during wildfires and underscored the importance of factoring in wind effects to accurately evaluate the performance of these sprinkler systems. The tools and techniques developed in this research provide a simple, yet effective, way to measure sprinkler performance under the challenging conditions of hot and windy wildfire scenarios. With further refinement and application to a wider range of sprinkler setups, these tools have the potential to establish a robust quantitative foundation. This foundation could then guide the design of effective wildfire sprinkler systems and promote the meaningful use of sprinklers as a measurable and valuable strategy for mitigating wildfire risks (Green, 2019).

Other investigations were also focused on the development of self-protection water systems. Viegas *et al.* (2021) have combined water spray systems with fire-resistant fiberglass fabrics to cool the exposed surface during a fire event. The results have revealed the proposed system can successfully sustain the progress of a fire front while simultaneously protect the integrity of the fire screen. Thus, this combination of a protective solution with physical barriers and misting has two positive consequences. On one hand, the evaporation of the water that runs down the screen reduces the temperature near the screen, mitigating its degradation from heat. On the other hand, the water falling at the base of the screen promotes the moisturizing of the vegetation at the bottom, which is often the weakest zone through which the fire passes due to the screen being placed over grasses or small shrubs and consequently not being properly grounded.

A technical note (Green and Kaye, 2019) demonstrated an initial assessment of using water sprays to intercept and extinguish airborne firebrands for building protection during wildfires, where the authors created an analytical model to estimate collision probabilities between firebrands in intersecting streams, applied to scenarios involving firebrands and water droplets. This analysis suggests that this method could safeguard buildings from firebrand threats, with two conditions: using high water flow rates (~1 L.s^{-1} per meter of building perimeter) or employing small droplets (~0.1 mm) at moderate rates (~0.1 L.s^{-1}.m^{-1}). As a perspective, Green and Kaye (2019) provided a foundation for future exploration of these spray systems and their quantitative comparison to other wildfire sprinkler types.

Fire protection sprinkler systems for structures have been used in Canada and Australia for several years, whereas their adoption in the United States was not so frequent (Merson, 2006). Johnson *et al.* (2008) published a report of lessons learned from the Ham Lake Fire and the Gunflint Trail, specifically about external sprinkler systems and defensible space. The Ham Lake Fire experience in northeastern Minnesota illustrated the high efficacy of external wildfire sprinkler systems in safeguarding structures and their surrounding vegetation from wildfire destruction, contingent upon specific conditions. Although these systems are valuable, they require consistent testing and upkeep. Ultimately, while sprinkler systems stand as a noteworthy addition, the significance of other good WUI fire management practices remain, positioning these systems as a complementary tool.

Water has emerged as the most used firefighting agent due to its unparallel availability, cost and effectiveness in suppressing fires. Its thermal properties make it well-suited for extinguishing various types of fires by getting heat from flames, combustion products, and fuel surfaces. The transition from liquid to vapor (steam) efficiently absorbs thermal energy, and the copious steam production aids fire suppression by lowering oxygen levels in the confined atmosphere, especially in cases of limited space (Grant *et al.*, 2000).

Pre-moistening nearby flammable surfaces can reduce the fire spread by acting as a heat-absorbing barrier. Water sprinklers' capacity to absorb thermal radiation has additionally been utilized as an 'indirect' firefighting tactic to shield personnel or property (Grant *et al.*, 2000). ADAI (www.adai.pt) is working on the optimization of the use of water sprinkler systems for self-protection during a wildfire (Almeida *et al.*, 2024). Specifically, the main objectives of this study are to explore possible solutions for reducing the intensity of the fire front and rate of spread by moisturizing the biomass by sprinkling water, seeking to determine the minimum amounts of water required for different fuel loads or expected fire intensity. The water absorption and adsorption rate of forest fuels, namely herbaceous and shrubs, is being analysed varying the sprinkling duration and flow, in order to determine the most efficient water sprinkled when the minimum water should be used to extinguish the fire. The tests were carried out in the laboratory, in an environment where the environmental temperature is practically constant, and which guarantees that the results obtained are consistent and better controlled. However, in a fire scenario, the conditions are more complex and unpredictable. The conclusions obtained through these experimental program were the following: (i) the fuel moisturizing before the arrival of fire to the area to humidify has been shown to have significant effects in reducing the fire intensity and rate of spread, (ii) with water sprinkling over the vegetation, its moisture content quickly rises to values above 50% in relation to the saturation content, falling less sharply after interruption, in a scenario without fire nearby. For the tested conditions, discontinued sprinkling allowed maintaining the moisture content of the biomass at values above 50% of the saturation point, and (iii) a Phase 1 of fuel moisturizing, starting before the arrival of the fire front and lasting for 5 to 10 minutes depending on the type and load of vegetation, followed by Phase 2 of direct sprinkling on the fire front for as long as necessary or possible, proved to be the most efficient procedural algorithm.

The thesis published by Barnes (2017) examined the sprinkler effectiveness in reducing fuel hazards to prevent wildfires, particularly in the context of climate change's impact on fire patterns. The study focuses on altering fuel moisture using sprinklers to lower fire risk. Experimentation in Alaskan forests shows positive results, with recommended sprinkler distribution of 10-20 mm equivalent rainfall to prevent ignition. This prevention approach is safer and more cost-effective than suppression, highlighting indirect response tactics like fuel management and sprinkler protection for wildfire preparedness (Barnes 2017).

J. Hua et al (2002) carried out an investigation on fire extinguishing mechanisms within such systems remains a challenge due to intricate physical and chemical interactions between water spray and fire plumes. Quantitative approaches for assessing water spray system efficacy were stated to be lacking, hindering optimized design for diverse environments and fire types. This research introduced a numerical simulation method to quantitatively analyse complex interactions between water spray and fire plumes. Key factors such as spray pattern, droplet size, and flow rate were investigated for their impact on fire suppression. Simulation outcomes reveal that solid cone patterns with smaller droplets are more effective in extinguishing fires compared to hollow cone patterns with larger droplets.

6.2.2. Commercial market of water sprinklers systems

Regarding the commercial market of sprinkler systems, according to the RAD Fire Sprinklers Ltd, recent advancements in fire suppression technology include intelligent fire sprinkler systems and the utilization of unmanned aerial vehicles (UAVs), or drones. Intelligent fire sprinkler systems employ sophisticated sensors and software to monitor building environments, swiftly alerting authorities to potential fire hazards. Integration with other building systems enhances overall functionality. UAVs equipped with fire suppression mechanisms offer rapid response capabilities, particularly in challenging locations like tall structures and remote industrial sites. These technologies hold promise for revolutionizing fire response, minimizing damage, and improving overall effectiveness in emergency situations. the system proposed by CLM Fireproofing (https://clmfireproofing.com) generates droplets considerably smaller than those from traditional sprinklers. This not only conserve water but also augments the dispensed water's surface area. Fires thrive on oxygen, and mist suppression systems, by substituting oxygen with steam, expedite temperature reduction. However, mist suppression systems offer more than this advantage. By coating affected walls with a fine water layer, they curtail the fire impacts.

Furthermore, Electrically Activated Sprinklers (EAS) produced by Complete Pumps and Fire Company (https://completepumpsandfire.com.au), commonly known as "smart sprinklers", diverge from traditional sprinklers in their operational mechanism. Instead of being triggered solely by a thermal component, such as heat or smoke, these systems utilize various detection methods to identify fire presence and electronically activate the sprinklers accordingly. The distinguishing factor lies in the size of the fire upon detection, which tends to be much smaller compared to what would activate a conventional sprinkler's thermal element. The early initiation of sprinklers during the initial stages of fire development leads to reduced overall damage, making it a potentially suitable approach for scenarios that are not effectively covered by traditional sprinklers.

6.2.3. Challenges of water sprinklers systems

Farrell *et al.* (2023) reported on the challenges and issues surrounding sprinkler systems, examining advancements and usage of water mist fire suppression technology. Their study delves into the methods of generation, suppression mechanisms, applications, and key parameters. The challenges associated with mist systems include operation and maintenance, design and standardization, application limitations, and economic factors.

Water mist systems generate small droplets via high-pressure discharge and tiny nozzle orifices, which pose technical concerns such as plugging due to corrosive products. While twin-fluid systems at lower pressure offer an alternative, they increase operational costs. Maintenance frequency, flushing, cleaning, and inspection are significant concerns, and adherence to existing guidelines are recommended. Design complexity arises from factors like droplet size, spray momentum, and vegetation/fuels' characteristics, necessitating a performance-based approach due to a lack of theoretical basis. Application challenges involve restricted use in residential and commercial buildings due to limited performance data. Economic challenges stem from system complexity and costs compared to alternatives like gaseous systems. Future research should address these challenges to enhance the feasibility and affordability of water mist fire suppression systems (Farrell *et al.*, 2023).

Other challenges related to supplying water for fire suppression were reported when centralized water sources or hydrants are absent. These challenges highlight the potential issues of reduced water pressure during fires, underscoring the significance of private local water supplies in extreme situations. Moritz and Butsic (2020) emphasize the importance of adhering to water supply regulations in new residential developments, including interior and exterior sprinkler systems. The enhancement of water-related requirements is advocated as a beneficial measure for the safety of residents and firefighters (Moritz and Butsic, 2020).

6.3.4. Conclusion

In conclusion, water sprinkler systems have evolved from basic building safety tools to multifaceted solutions for various challenges. They conserve water through advanced technology and play a pivotal role in wildfire management by creating firebreaks and protecting structures. Research emphasizes the importance of well-designed systems, even considering complex scenarios like wind effects.

Efforts to intercept airborne firebrands and optimize sprinkler performance are ongoing. Challenges include complexities in water mist systems and the need for consistent testing in external fire protection. Water's unmatched suppression properties, from cooling to oxygen displacement, contribute to their effectiveness.

Advancements include intelligent systems and drone utilization in the commercial market, showing potential for revolutionizing fire response. Overall, water sprinkler systems have transformed into versatile tools addressing modern fire protection needs across various domains, from water conservation to wildfire management.

6.3. A water sprinkler system for establishing fire protection lines and protecting large areas

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6.3.1. Introduction

In this section, contents regarding the Crown Water Spray Equipment for Forest Fires Protection (CWSEFFP) are presented, intended to expand the water screening capacity of sprinklers on houses adjacent to forests as presented in FireSmart and FireWise to more aggressively suppress wide-area fire spread and protect WUI communities from forest fires. Here, through indoor experiments to prevent the spread of surface fire flames, the sprinkling rate per unit area necessary to extinguish or prevent the spread of flames from pine coniferous forest surface fuels has been shown to be at least 100 mL.m^2. The required minimum watering amount to prevent the spread of forest fires can vary significantly depending on various circumstances, such as forest fire intensity and weather conditions. In fact, the owner of a house that survived the 2017 Kansas wildfire said that he turned on the sprinklers before evacuating, and when he returned, his house and cows were alive. (https://weather.com/news/news/kansas-wildfire-home-spared).

As shown in the photos of Figure 66, the effect of the sprinkler system that spreads water from the roof for the prevention of damage to buildings due to forest fires can be observed. Therefore, as with the drainage work carried out at the village level to make drainage ditches and waterways to prevent flooding, it is now necessary for each village to introduce powerful wide-area water screen facilities to sprinkle water or fire extinguishing agents, thereby blocking radiant heat and reducing spotting effects. This is a critical time when it is necessary to introduce and operate aggressive forest fire prevention facilities in order to protect the WUI village community from more dangerous and stronger forest fires. Therefore, in this chapter, the crown water sprinkler equipment for the prevention of wide-area forest fire spread at the village community level is introduced. In South Korea, Naksan Temple, which is a thousand-year-old temple, 22 assets of state-designated cultural properties were destroyed by the Yangyang forest fire in 2005. , To protect temples, which are cultural properties and recreational facilities, in the forests from large-scale forest fires that occur every year, the author of this section designed the "Crown Water Spray Equipment for Forest Fires Protection — CWSEFFP" that can sprinkler water in an area of about 200x80 m^2 by installing large nozzles that can rotate 360 degrees over a radius of 40 m at a height above the trees. The CWSEFFP 1 began to be installed in earnest in 2012. Thereafter, through engineering calculations and system improvements, a "Village-level crown water spray equipment to prevent forest fires" that can sprinkler water in an area of up to 2,000 m x 80 m with one pressurized water supply device was designed (CWSEFFP 2).

(a) *(b)* *(c)*

Figure 66. (a, b) Sprinkler system working on fireproof, (c) A photo posted to Facebook by the Kansas National Guard (Resource: a Photo from KDRV.com homepage, B Photo from Canadian Firefighters homepage).

The Crown Water Spray Equipment for Forest Fires Protection v1 — CWSEFFP 1 is a facility that sprinklers water from a position higher than the trees to protect cultural properties and forest recreation facilities such as houses and temples in small villages located near forests from forest fires or to extinguish fires when they spread. CWSEFFP 1 consists of a pressurized water supply device, piping parts such as water supply pipes and selection valves, towers, large sprinkler nozzles, and a control device that can remotely activate the system. Regarding the operation of this facility, when a forest fire breaks out, the pump, which is a pressurized water supply device, starts to supply water to a large nozzle that sprinklers water with a radius of about 42.5±7.5 m from one nozzle. The pump can be designed according to the conditions of the site to adjust the watering amount and and sprinkler distance.

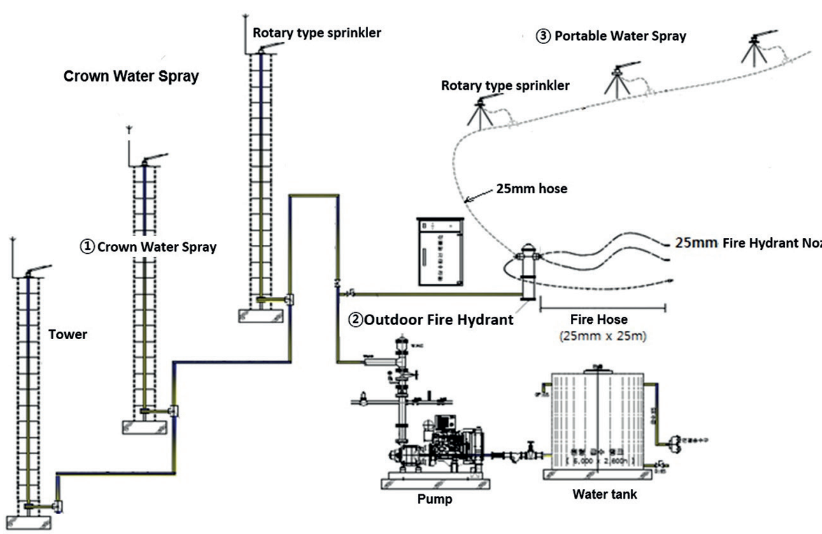


Figure 67. Facility schematic for CWSEFFP 1.

As shown in the facility schematic diagram in Figure 68, the CWSEFFP 1 enables the use of three types of water sprinkler equipment: (a) sprinkling water from three crown water towers, (b) sprinkling water by connecting a fire hose from an outdoor fire hydrant, and (c) sprinkling water by installing a mobile water sprinkler equipment.

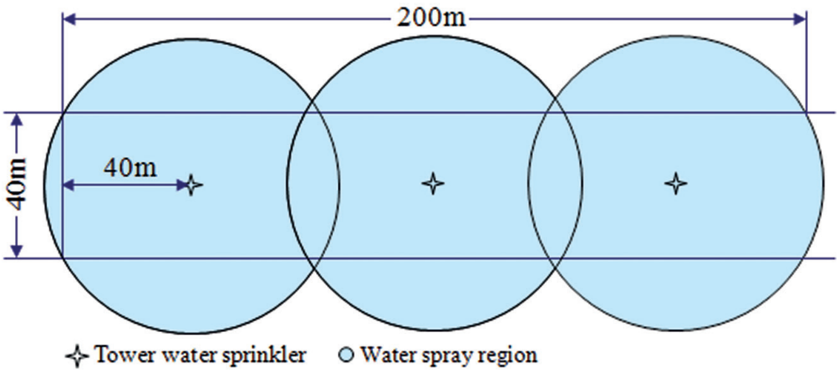


Figure 68. Schematic diagram of the use of in-line sprinkler systems.

In the case CWSEFFP 1, three crown water sprinklers towers operate simultaneously so that water can be sprinkled over an area of approximately 200x80 m^2, depending on the radius of sprinkling, as shown in Figure 69. To strengthen the forest fire extinguishing performance of the CWSEFFP 1, additional foam or gel fire extinguishing agents can be mixed into the water being sprinkled utilizing a proportioner method, which involves installing a chemical mixing device on the discharge side of the pump so that a certain concentration of the chemical is diluted and sprinkled with water. The CWSEFFP 1 in areas where people do not live permanently can be operated by a fire sensor, or the pump can be operated remotely by the manager through a smartphone app. Additionally, as shown in Figure 70, a certain pattern of sprinkling radius and the water sprinkled flow rate can be designed according to the performance of the nozzle, and in the case of certain areas where water should be intensively sprinkled as shown in Figure 70, the performances of individual nozzles can be set differently to adjust the sprinkling radius and water flow rates. Thus, the CWSEFFP 1 can be designed to fit the field situation through performance-based design.

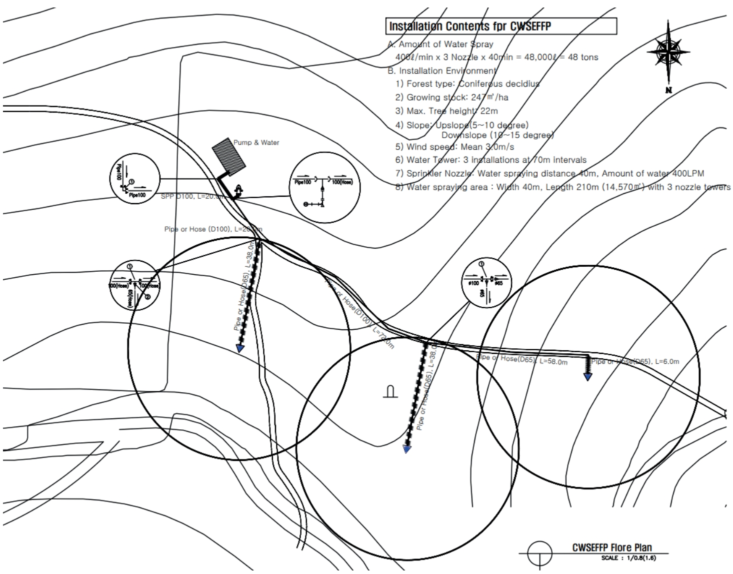


Figure 69. CWSEFFP 1 Floor plan for protecting forest recreation facility.

Figure 70. CWSEFFP 1 operation scene that has been installed in South Korea since 2012.

6.3.2. CWSEFFP 1

Main functions of the CWSEFFP 1

As for the main functions of the CWSEFFP 1, when a forest fire spreads, the CWSEFFP 1 can sprinkler water to the areas adjacent to the forest in advance to wet house facilities and the surrounding forest with water thereby indirectly extinguishing fire by preventing ignition from heat flux or firebrands, or sprinkle water to the areas where flames are spreading, thereby directly extinguishing the fire. The reasons why damage to houses and facilities near forests occurs due to the spread of forest fires not only in South Korea but also throughout the world, can be summarized as follows:

a) Forest fire environment

- A lot of fuels that would lead to high forest fire intensity, such as pine forests that are vulnerable to forest fires, is distributed in areas near forests.
- Fuel continuity is maintained because fuels in the surroundings of areas near forests are not managed.
- Rapid spread of forest fires due to dry weather along with strong winds

b) Forest fire prevention and firefighting environment

- Use of self-protection systems is poor;
- In the case of villages in areas near forests, the roads are narrow and existence of situations where the entrance or exit of fire trucks is challenging occur, hindering firefighting activities.

- Firefighting helicopters are mainly used for head fire suppression because they cannot bu used during night periods and houses can be damaged as result of aerial water drops.

Therefore, if water is sprinkled at rates not lower than 400 L/min to areas of a radius exceeding 40 m per nozzle through the installation of the CWSEFFP 1, as shown in Figure 71, at least 0.08 $l.m^{-2}.min^{-1}$ of water can be distributed in a maximum area of 5,024 m^2 with a maximum length of 200 m when three circles are combined, so that forest fires can be extinguished or the fire spread to houses can be prevented. Figure 71 shows the amounts of water sprinkled by each individual sprinkler per unit area according to the rotation speed per minute for water flows of 300 to 450 L/min, from a nozzle sprinkling with a radius of 40 m. The selection of the amount of water sprinkled per unit area from the CWSEFFP 1 should vary with the fire intensity expected for the fuel load in the surroundings. For example, in the case of grasslands with low fire intensity, the amount of water sprinkled per area can be lower than that of pine forests with high fire intensity.

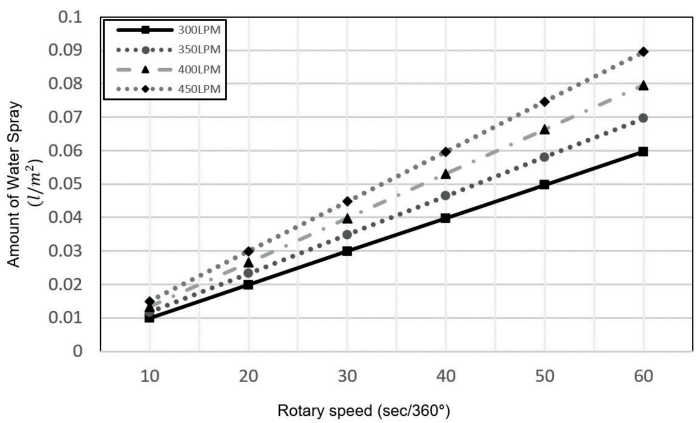


Figure 71. Water sprinkle per unit area according to nozzle rotation speed.

Calculation of the amount of water sprinkled necessary to prevent the spread of forest fires.

In order to directly extinguish a forest fire or prevent the spread of a forest fire, an appropriate amount of water should be sprinkled so that the heat flux per unit area will not reach the ignition temperature, achieving a cooling fire extinguishment effect using the latent heat of water. In a study on the forest fire risk based on the 2005 Yangyang Forest Fire, Donghyun (2010) found the maximum heat flux to be 561.35 kW/m², the average heat flux to be 252.64 kW/m², and the heat flux according to the separation distance during crown fire (Figure 72).

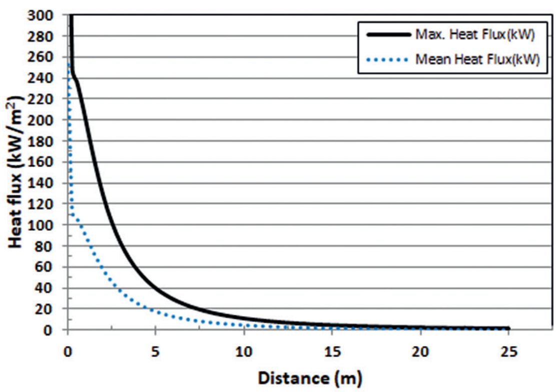


Figure 72. Heat flux over distance in the case of 2005 yangyang forest fire (Donghyun, 2010).

Regarding changes in the enthalpy of water, the energy necessary to increase room temperature to 100°C is 4.18 $kJ.kg^{-1}.K^{-1}$. The energy needed to convert liquid water to water vapor at 100°C is 2,257 kJ/kg. Therefore, the latent heat required to vaporize water at room temperature is approximately 2,590 kJ/kg. When 1 kg of water at 20°C is converted to steam at 300°C, 718.8 kcal/kg of heat can be absorbed, as shown in Equation (18).

$$Q_{\text{net}} = Q_{\text{sensible heat}} + Q_{\text{latent heat}} + Q_{\text{specific heat of water vapor}} \qquad (18)$$

where,

- Q_{net} = *entire absorbed energy (kcal)*
- $Q_{\text{sensible heat}} = mC\Delta T = m\times 1(kcal/kg°\text{C})\times(100\text{-}20)°\text{C} = 80\ kcal/kg$
- $Q_{\text{latent heat}} = 538.8\ kcal/kg$
- $Q_{\text{specific heat of water vapor}} = 0.5\ kcalkg°\text{C}\times(300\text{-}100)°\text{C} = 100\ kcal/kg$.

Therefore, depending on the amount of water per unit area, the quantity of water necessary to prevent the flame from spreading or to extinguish the flame can be calculated. In this respect, Donghyun (2011) used the latent heat of water to calculate the amount of water necessary to prevent reaching the ignition temperature from the Heat Release Rate (HRR) using Equation (19), with the heat flux value in Table 17. The amount of water (Q_{water}) required for the direct extinguishment to prevent its spread can be calculated using Equation (19).

$$Q_{water} = \frac{Q_{fires}}{Q_{net}} = \frac{Q_{fires}(kcal/㎡\cdot s)}{718.8(kcal/kg)} \qquad (19)$$

Table 17. Heat flux in the case of 2005 yangyang forest fire (Donghyun, 2010).

	Items	Result
Conditions	Max. Heat Flux of Crown Fire	561.35 kW/m^2(134.26 kcal.m^{-2}.s^{-1} kcal/m^2·s)
	Mean Heat Flux of Crown Fire	252.64 kW/m^2 (60.34 kcal.m^{-2}.s^{-1} kcal/m^{2}s)
	Max. Heat Flux at 5 m separation distance	64.75 kW/ m^2 (15.469 kcal.m^{-2}.s^{-1} kcal/m^2·s)

Therefore, the quantity of water per unit area required to prevent a flame from spreading or to extinguish it can be calculated. In this context, Donghyun (2011) used the latent heat of water to calculate the necessary amount of water to prevent reaching the ignition temperature from HRR, using Equation (19) and the heat flux values provided in Table 17. The amount of water (Q_{water}) required for direct extinguishment of a forest fire and for indirect extinguishment to prevent its spread can be calculated using the following Equation (19).

According to Equation (19), the amount of water required for direct fire extinguishment based on the maximum heat flux and the average heat flux of a crown fire is 0.187 $kg.m^{-2}.s^{-1}$ and 0.084 $kg.m^{-2}.s^{-1}$, respectively. Additionally, 0.022 $kg.m^{-2}.s^{-1}$ of water is necessary to prevent fire spread in areas 5 m away from the crown fire under the maximum heat flux. In practice, the amount of water applied in advance to prevent the fire from spreading is significantly less than the amount of water required for direct fire suppression. For instance, while 0.187 $kg/.m^{-2}.s^{-1}$ is necessary for the direct extinguishment of crown fire under the maximum heat flux, only 0.022 $kg.m^{-2}.s^{-1}$ of water is needed at a separation distance of 5 meters from the crown fire. This indicates that indirect extinguishment can be achieved with a smaller amount of water, approximately 1/8 of that required for direct extinguishment. In Kida's (1973) experiment on flame extinguishment on wood surface, the critical water sprinkler flow rate was measured at 0.0025 $L.m^{-2}.s^{-1}$. Similarly, in Tamanini's (1976) experiment on thin wood pieces, the critical fire extinguishing water amount was measured at 0.0013 $L.m^{-2}.s^{-1}$. Rickard (2012) presented the critical water application rate (, $kg.m^{-2}.s^{-1}$) needed to prevent the spread of surface flames due to radiant heat flux as 12.9E-3 $kg.m^{-2}.s^{-1}$. Figure 73 plots the critical water flow rate per unit area in the active combustion zone, assuming a steady-state heat release rate of 500 kW/m². When calculating the external heat flux, it is assumed that flame radiation will dominate, and other components will not be accounted for. This assumption is valid for low-wind conditions. Here, 500 kW/m² represents the heat release directly reached by virgin fuel. Therefore, the critical water flow rate may vary depending on the intensity of the heat flux from the fire source. Depending on the flame length, critical water sprinkler flow rates of up to 0.01to 0.05 $L.m^{-2}.s^{-1}$ have been presented.

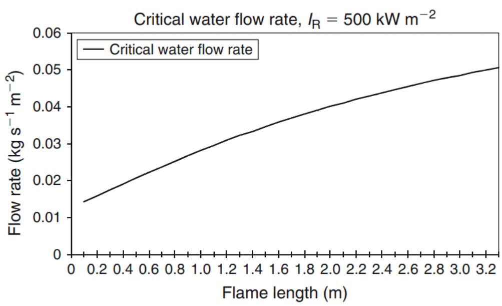


Figure 73. Critical water application rate as a function of the flame length.

U.S. NFPA-13, (2007) provides five density/area curves on a graph. These curves correspond to the hazard classifications: Light Hazard, Ordinary Hazard Group 1, Ordinary Hazard Group 2, Extra Hazard Group 1 and Extra Hazard Group 2. These curves stipulate the required minimum densities and coverages that establish the minimum water requirements for sprinkler systems. In this classification system, forests or wood-related hazards fall under Extra Hazard Group 1. Therefore, as shown in Figure 74, the water sprinkler rate per minute per unit area presented in NFPA 13 has a maximum value is 0.053 $mm.m^{-2}.min^{-1}$.

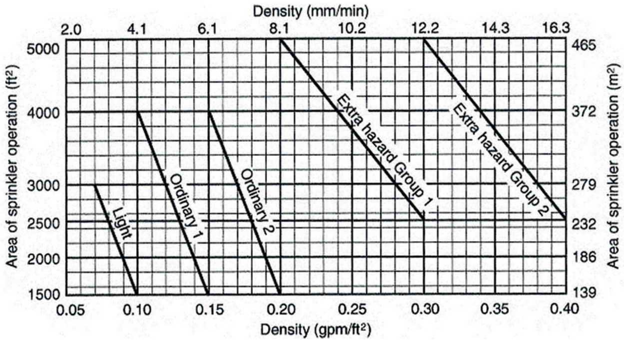


Figure 74. Water density/area curves (nfpa 13 figure 11.2.3.1.1).

In conclusion, it can be seen that sprinkling a sufficient amount of water to a flame can either extinguish it or prevent its spread. Based on data from various studies on the water quantities required to stop flame spread or to extinguish flames, South Korean water sprinkler equipment designed to prevent forest fires was engineered with a sprinkler rate of 0.08 $L.m^{-2}.s^{-1}$ to effectively prevent flame spread.

Equipment configuration

Water source

The water source of the CWSEFFP must provide an adequate supply of water based on the number of nozzles installed and the required flow rate. The amount of water needed in the source is calculated using the Equation (20). For example, with three nozzles operating at a flow rate of 400 L/min for 40 minutes, the total water required is 48 tons.

In South Korea, where many forest fires occur in winter, it is essential to implement measures to prevent the water source and the supply system from freezing. These measures include: (a) maintaining the water temperature above 0°C, (b) constantly circulating the water in pipes, (c) installing pipes and facilities below the frost line, (d) adding antifreeze agents, and (e) using insulating materials and heating wires.

$$Q_{water} = \frac{L/min}{N} \times N \times T = 400L/\times 3ea \times 40min = 48,000L \quad (20)$$

where,

$Q_{water}(m^3, l)$: water storage capacity of the water source

N(ea): Number of nozzles installed.

T(min): Operating time

A water source located above the installed nozzles has the advantage of enhancing reliability and facilitating the pressurization of the water supply system. If the location of the water source provides adequate pressure for watering, there is no need for a mechanical pressurized water supply system, such as a pump.

To secure the required amount of water, a dedicated fire extinguishing water tank is commonly installed. However, if the water source is also used for other facilities, it is essential to ensure that the effective water volume for the CWSEFFP is maintained. When calculating the effective water storage volume, it should be included the water volume between the hood valve and intake port of both the CWSEFFP and other facilities. The locations of the foot valve and the intake port within the water tank must be separate to prevent interference.

The foot valve (Figure 75) is installed when the water source is located below the pump impeller. It features a filter net attached to prevent foreign substances from entering the pressurized water supply system by suction. If foreign substances obstruct water intake, it can cause cavitation, leading to pump failure and reduced performance. The grid size of the filter net should not exceed 12.7 mm to avoid both the entering of foreign substances and interfering with the water supply volume.

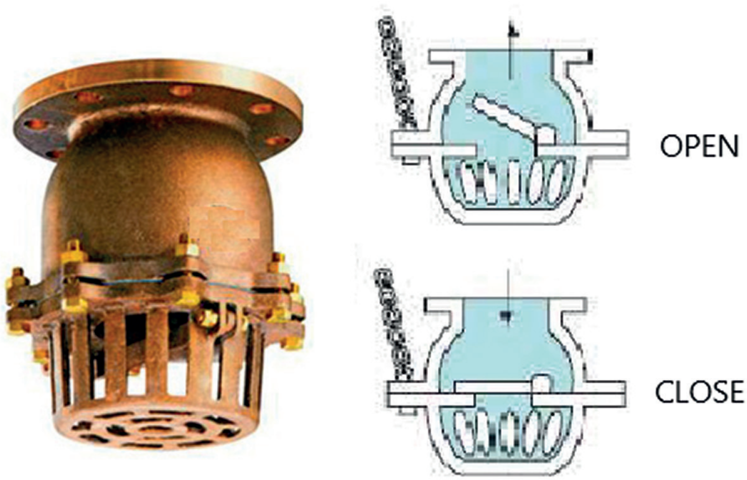


Figure 75. Example of foot valve structure.

Sprinkler nozzle

As shown in Table 18, the standard design of the CWSEFFP is a system that sprinklers water up to 200 m by operating three large nozzles, each capable of sprinkling at least 42.5 ± 7.5 m, for a water sprinkler flow rate of 400 L/min. The sprinkling distance and flow rate depend on the characteristics of the nozzles and the performance of the pump. The large sprinkler nozzles used in the CWSEFFP must be able to rotate 360 degrees, and the rotation speed must be adjustable. Additionally, the angle of the nozzles must be adjustable to avoid direct hits on trees or facilities during rotation which could prevent achieving the desired distance. The height of the nozzles should be adjusted automatically for sprinkling within a specific section of the 360° rotation radius. Alternatively, the angle should be set to not be smaller than the maximum angle at which the nozzles avoid obstacles (Figure 76). Figure 77 shows various forms of large sprinkler nozzles, which have various functions such as rotation angle adjustment, sprinkler angle adjustment, and sprinkler timer.

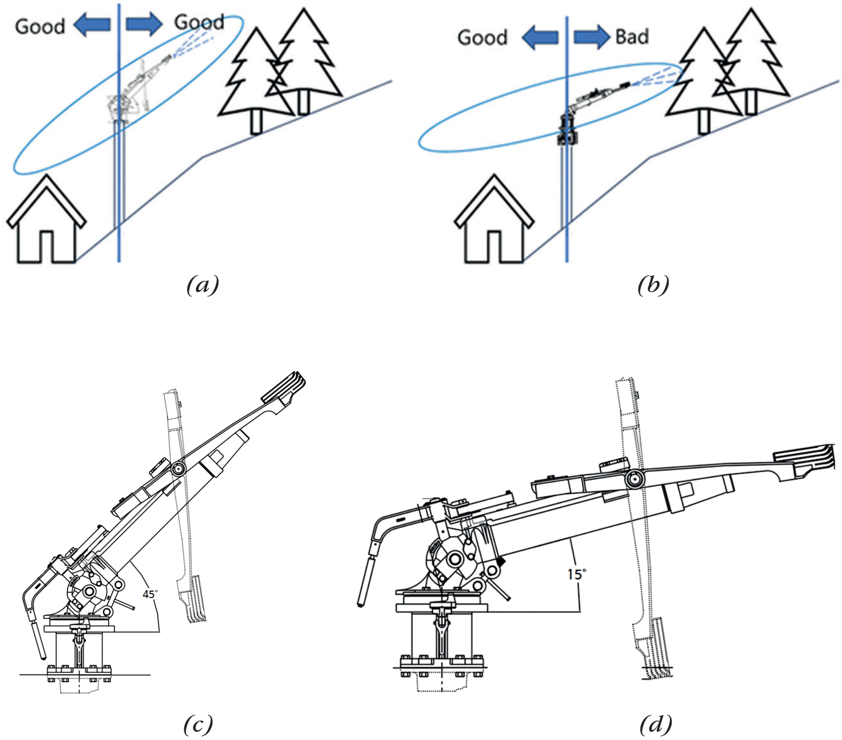


Figure 76. Appropriateness of sprinkle radius depending on nozzle location and angle; (a)a good example of not being an obstacle to trees and buildings, (b)example of bad sprinkling distance due to wooden obstruction, (c)nozzle angle 45°, (d) Nozzle angle 15°.

Figure 77. Various large sprinkle nozzle product examples.

Table 18 shows the values of the sprinkling distance, watering amount, and sprinkling pressure according to the specifications of the CWSFFP nozzle product. The actual nozzle pipe diameter and watering pressure and distance, based on the sprinkling pressure at the end of the nozzle, match the measured values presented in Table 19. Therefore, the actual measured values of the nozzle product, based on the basic design and calculation formula, are important. The sprinkling distance can be calculated according to the law of conservation of potential and kinetic energy, depending on the sprinkling angle, or it can determined through actual testing. The relationship between watering pressure and watering amount, in relation to the pipe diameter of the nozzles, can be obtained using the following equation.

$$Q_n = 0.067 \times D^2 \times \sqrt{p} \qquad (21)$$

Q_n: Flow rate of water from nozzle (L/min)

D: Nozzle diameter (mm)

p: Pressure at nozzle (KPa)

(Example) Calculation of watering amount

When the nozzle diameter is 16 mm and the nozzle's watering pressure is 506.6 kPa, the watering amount becomes 386.05 L/min, using Equation (21).

Table 18. Cwseffp nozzles and water spay characteristics.

Specifics	Data
Water input female BSP (mm)	50~65
Nozzle diameter(mm)	Nozzle diameter for max. sprinkling distance (14 to 32)
Watering pressure (KPa)	320 to 680
Watering amount (L/min)	350 to 1,000
Water shooting radius (m)	35 to 50
Sprinkle angle (º)	Application angle for max. sprinkling distance (Normally 25 to 43°)

Table 19. Actual test values of sprinkling performance according to nozzle diameter and sprinkling pressure.

Nozzle diameter	Pressure		Jet length	Water sprinkle capacity	Values for a single sprinkler	
					Irrigated area	Rainfall per hour
mm	*atm*	*KPa*	*m*	*l/min*	*m^2*	*mm/h*
14	3	304.0	30	283.3	2461	6.9
14	4	405.3	31	325.0	2826	6.9
16	3	304.0	32	350.0	2826	7.4
18	3	304.0	33	433.3	3017	8.6
14	5	506.6	35	366.7	3215	6.8
16	4	405.3	35	400.0	3419	7.0
20	3	304.0	35	500.0	3630	8.3
18	4	405.3	36	508.3	3630	8.4
16	5	506.6	40	450.0	3846	7.0
20	4	405.3	40	608.3	4298	8.5
18	5	506.6	40	566.7	4298	7.9
22	4	405.3	40	683.3	4298	9.5
20	5	506.6	43	666.7	5024	8.0
22	5	506.6	44	766.7	5024	9.2
22	6	608.0	47	850.0	5805	8.8

Pressurized water supply device

The pressurized water supply device is designed to apply pressure to firefighting water, delivering it to the required location with sufficient pressure through piping, thereby imparting kinetic energy. The pressurized water supply device, which can sprinkler an appropriate watering amount in the CWSEFFP's nozzle sprinkler radius simultaneously through three nozzles, can be classified into several types: those that use the natural head of an elevated water tank, a pressure water tank, an electric starter or internal combustion engine pump operation method, a pressurized water tank method, or a mixed method (Figure 78).

These devices must be installed at a location where the water source is higher than the watering nozzle to allow for water supply through the natural gravitational drop pressure.

Devices that use the elevated water tank method can supply water under the sprinkling conditions specified for the CWSEFFP by using natural head pressure generated by the tank's height. These devices must be installed at a location where the water source is higher than the watering nozzle to allow for water supply ca through the natural gravitational drop pressure. A pressure water tank facility uses a large pressure tank to supply water under the sprinkling conditions specified for the CWSEFFP. It pressurizes water into the tank and supplies it using the pressure of the compressed air. Since only about 2/3 of the tank's capacity can be filled with water, and the water pressure decreases as watering occurs, not all of the tank's volume can be considered effective water available to be used. Therefore, it is crutial to secure a water source with a sufficient amount of water during the design phase. The most common type of pressurized water supply device uses a pump operation method, employing a pump to supply water under the specified sprinkling conditions for the CWSEFFP 1.A pump with a rated discharge appropriate for the design flow rate must be selected to ensure effective operation.

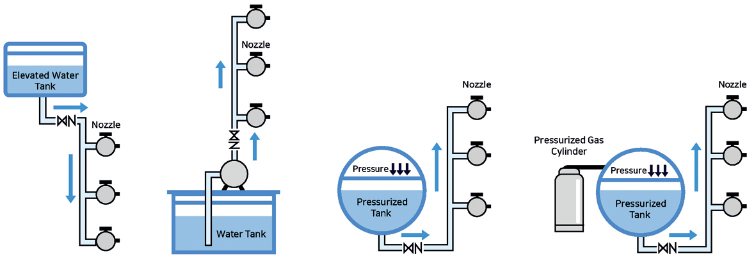


Figure 78. Various pressurized water supply device examples.

Rated discharge volume refers to the discharge volume of the pump at the rated discharge pressure. If the discharge volume is reduced by adjusting the pump's discharge side valve, the discharge pressure will increase, and conversely, if the discharge volume is increased, the discharge pressure will decrease. Figure 79 illustrates the relationship between discharge pressure and discharge volume, showing the pump performance (head/flow) curve. A pump with a rated discharge volume higher than the design flow rate of the CWSEFFP must be selected.

Centrifugal pumps, which use centrifugal force, are generally used as fire pumps. These pumps must exceed the specified water pressure and watering amount required for the CWSEFFP. Therefore, a pump with a rated discharge pressure (rated head 100%) close to the design pressure when operating at the rated load should be selected. Additionally, a maximum flow performance test must confirm a flow rate of 150% of the rated flow rate at 65% of the rated discharge pressure. A static operation test should also be conducted to ensure that there is no cavitation in the pump and that the relief valve operates correctly to prevent excessive water pressure (Figure 79).

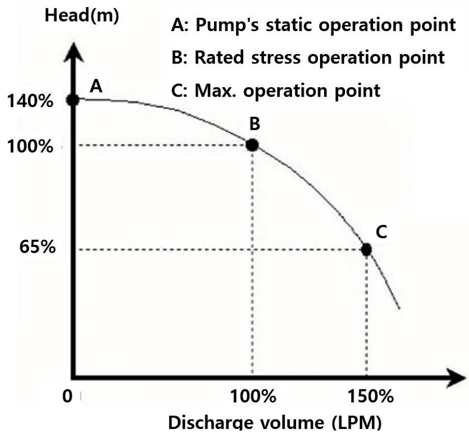


Figure 79. The flow of the pump vs. the head pressure performance curve.

The relief valve should be installed between the pump and the check valve to allow a portion of the pump's discharge volume to be released, preventing damage due to the pump's static operation.

When installing a pressurized water supply device, attention must be paid to the following points.

1. It should be installed so that performance tests, repairs, and checking are easy.
2. I should be installed in a place where there is no damage due to disasters such as fire and flooding.
3. Measures to prevent freezing should be taken, or it should be installed in a place where there is no risk of freezing.
4. The pump should be designated for exclusive use.
5. A compound pressure gauge or a vacuum gauge should be installed on the suction side of the pump, and a pressure gauge should be installed on the discharge side; however, a compound pressure gauge or a vacuum gauge may not be necessary if the water level of source is higher than the position of the pump or if a vertical pump is used.

6. A water hammer arrestor should be installed to prevent issues such as pipe fixation in case of impact due to pump water supply on the suction and discharge sides.
7. A performance test pipe to test the performance of the pump should be installed. The diameter of the performance test pipe can be calculated using the following Equation (22).

$$Q = uA = u \times \frac{\pi}{4} D^2, \quad \therefore D = \sqrt{\frac{4Q}{\pi u}} \qquad (22)$$

where,

Q=*Amount of water*(m^3/s)

u=*Flow speed*(m/s)

A= *Cross-sectional area of the pipe*(m^2)

D= *Inner diameter of the pipe*(mm)

(1) Cavitation

The operation of the pump without discharging firefighting water is called "static operation". During static operation, cavitation can occur, where the temperature inside the pump rises, causing noises and vibrations that damage the impeller or casing of the pump. To prevent cavitation, circulating piping or a relief valve must be installed.

(2) Primer

If the pump is installed higher than the water source, a primer should be installed to ensure water is always supplied to the pump and suction side piping. The purpose of the primer is to supply water to the pump's suction piping, and it is connected to the pump's discharge side piping. The primer consists of a priming tank, a drainpipe, an overflow drainpipe, a priming pipe, a low water level alarm device, and a device that can automatically supply water to the priming tank. The priming tank should have a capacity of at least 100 L.

(3) Rated discharge pressure of the pressurized water supply device

The discharge pressure of the pump, which acts as a pressurized water supply device, must ensure that the pressure at the tip of the distal nozzle provides the appropriate sprinkling distance and water sprinkling flow rate. Since this equipment requires a minimum watering amount of 400 L/min and a sprinkling distance not shorter than 40 m, the rated discharge pressure of the pressurized water supply device must support at least 1,200 L/min when three nozzles are sprinkling water simultaneously.

(4) Pump performance

The discharge volume of the pump in the pressurized water supply devices must satisfy the sprinkle pressure requirements that ensure the water sprinkling flow rate and sprinkling distance of the three installed nozzles. The pump must supply at least 400 L/min per nozzle x 3 Nozzles, totalling at least 1,200 L/min. The power of the pump can be calculated by determining the total head as follows:

1. Calculation of total head

$$\text{Total head } (H, m) = h_1 + h_2 + h_3 + h_4 + h_5 \qquad (23)$$

h_1: Friction head loss of piping (m)

h_2: Friction head loss of connecting hose (m)

h_3: Friction head loss of pipe fittings (m)

h_4: Actual head (m)

h_5: Nozzle sprinkle pressure (m)

Here, the friction loss pressure per 1 m of pipe can be obtained using the friction head loss ata provided by the pipe manufacturer or calculated using the Hazen-Williams formula. The actual head (h4) is the sum of the height of the suction side of the pump and the height of the nozzle at the highest position.

$$\Delta P(MPa) = \frac{6\times10^4\times Q^2}{120^2\times d^5} \qquad (24)$$

where, Q=Pipe flow rate (LPM), d=Inner diameter of the pipe(mm)

2. Pump power calculation

$$P(KW) = \frac{\gamma\times Q\times H\times K}{102\times \eta} \qquad (25)$$

where, γ = specific weight (1,000 kg/m^3), Q = total flow rate (m^3/min), H = total head (m), K = allowance rate, η = efficiency of the pump

(Example) Calculation of the pump power in case of three crown water sprinkler facilities sprinkle water simultaneously.

<*Conditions*>

1. Nozzle pipe diameter 16 mm, watering 400 L/min of water per nozzle at a 5.0atm pressure;
2. The friction loss of head of the piping (h1, m) is 15% of the actual head, the friction loss of head of the connecting hose (h2, m) is 20% of the actual head, and the friction loss of head of pipe fittings (h3, m) is 5% of the actual head, the

actual head (m) is 40 m, nozzle sprinkle pressure head (h5, m) is 51.66 m
3. The efficiency (E) of the pump is 0.55, and the allowance rate o (K) is 1.1

<Explanation>

1. Q = 400 LPM × 3 ea = 1,200 LPM = 1.2 m^3/min = 0.02 m^3/sec
2. H(m) = h1 + h2 + h3 + h4 + h5 = (40×0.15) + (40×0.2) + (40×0.05) + (40) + (51.66) = 107.66 m
3. $P(KW) = \frac{\gamma \times Q \times H \times K}{102 \times \eta} = \frac{1{,}000 \times 0.02 \times 107.66 \times 1.1}{102 \times 0.55} = 42.22kW$

The installation of a pump that is a pressurized water supply device should consider the following.

1. Should be installed so that performance tests, repairs, and checking are easy.
2. Should be installed in a place where there is no damage due to disasters such as fire and flooding.
3. Measures to prevent freezing should be taken or should be installed in a place where there is no risk of freezing.
4. The pump should be designated for exclusive use.

Pressure gauges and valves, etc.

Vacuum gauges, compound pressure gauges, and pressure gauges must be installed on the suction and discharge sides of the pump. The pressure gauge should be installed on the discharge side of the pump, where a positive pressure higher than atmospheric pressure is always applied. The vacuum gauge is a measuring instrument that is installed on the suction side of a pump to measure pressure below atmospheric pressure. The compound pressure gauge is a measuring instrument that can measure pressures both below and above atmospheric pressure and combines the functions of a pressure gauge and a vacuum gauge. When installed on the suction side, it functions as a vacuum gauge, and when installed on the discharge side, it functions as a pressure gauge.

Piping has various valve devices for water supply and drainage. An opening and closing valve is a valve that opens and closes to start or stop water supply. A solenoid valve is a valve device that can open and close automatically by an electrical signal. A drain valve is a device that removes water by opening the valve at the lowest point to drain water from the pipe. It is installed for inspection or to prevent freezing or bursting in the pipe during winter.

Water Tower

The water tower installed in the CWSEFFP is basically a facility that elevates the CWSEFFP above the trees to secure the designed maximum sprinkling distance while ensuring that the water sprinkled from the nozzle does not hit any obstacle. The tower installation types include a circular rod type, a trust structure type, and a mixed type as shown in Figure 80. Matters that must be considered when installing a tower are as follows:

It must be designed to prevent the tower from shaking due to the operation of the nozzle and the influence of wind depending on the height of the tower, or it must be fixed with wires to supplement the prevention of shaking.

A lightning rod must be installed to prevent equipment failure due to lightning.

1. It must have a structure that allows people to safely climb up for inspection and maintenance or provide conditions to allow inspection using a ladder truck, or similar.
2. A pressure gauge must be installed on the pipe that branches off from the main water supply pipe to the nozzle of the tower so that the watering pressure can be identified.
3. A drain valve must be installed on the pipe that branches off from the main water supply pipe to the nozzle of the tower to drain water from the pipe when not in operation.
4. A solenoid valve must be installed on the pipe that branches off from the main water supply pipe to the nozzle of the tower so that the valve can be automatically opened or closed by an electrical signal.

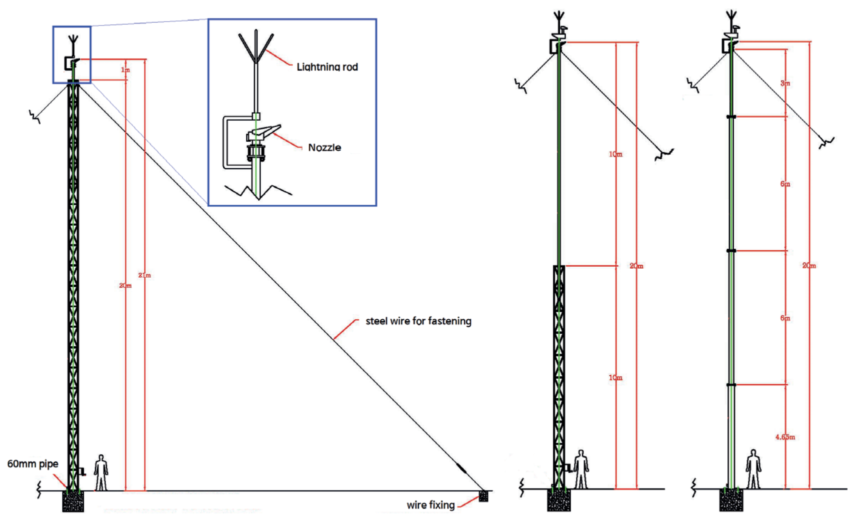
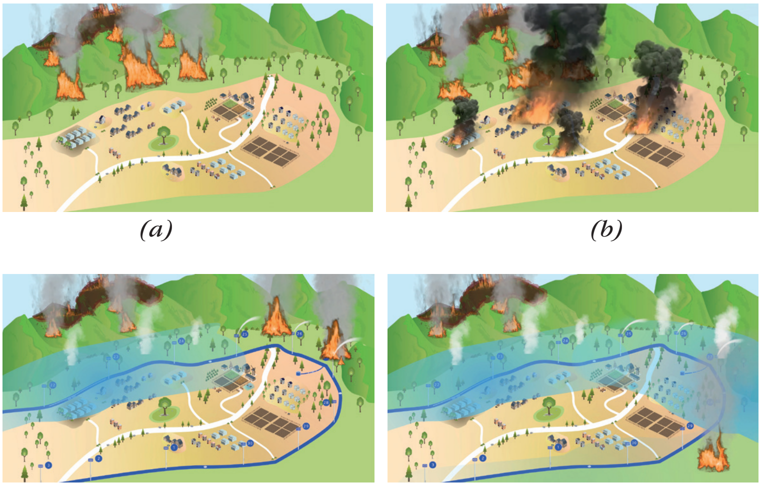


Figure 80. Type of towers: (left) truss tower, (middle) mixed tower (right) pipe tower.

6.3.3. CWSEFFP 2

CWSEFFP 1, described earlier, uses three large sprinkler nozzles installed in the form of a tower to sprinkler water over an area of approximately 200x80 m^2 to protect facilities near forests from forest fires. This is very effective for the protection South Korean recreational facilities and major temples in forests. However, there are limitations to the sprinkling area's ability to protect residential areas near forests in large scale at the village level or to cover large areas within forests to prevent the spread of major forest fires.

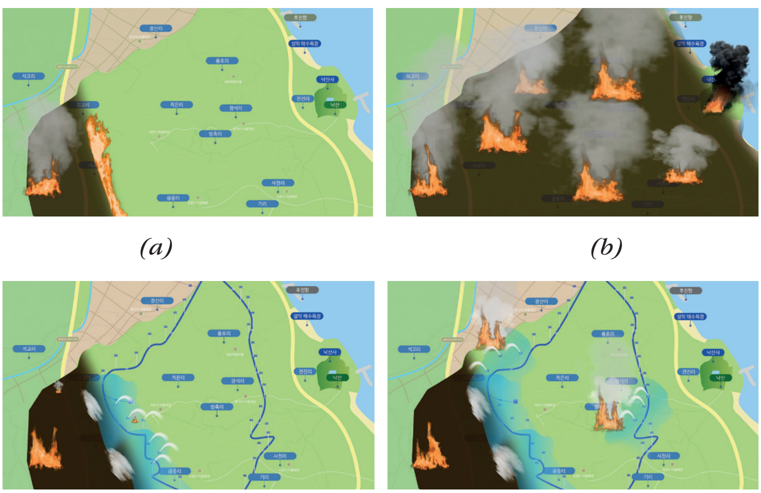
CWSEFFP 2 operates multiple water sprinkler units for forest fire by differential sprinkling and has dramatically expanded the sprinkling area of the existing CWSEFFP 1 through selective control of sprinkling from large nozzles or remote control. Across the world, forest fires that continue to spread for several dozen days and cause large-scale damage to villages and facilities in areas near forests are frequent. Therefore, this section describes a system that expands the sprinkling distance of CWSEFFP 1, which is 200 m, by 10 times to 2,000 m, using differential sprinkling technology. Figure 81 is a conceptual diagram of protecting a village by installing the CWSEFFP 2 system 2 km from the boundary of the village Figure 82 is a conceptual diagram of the CWSEFFP 2 system directly installed in the forest used to avoid the spread of forest fires. In South Korea, entire villages were destroyed by forest fires, as shown in Figure 81, and there is a case where a thousand-year-old temple was lost in the 2005 Yangyang Forest Fire (South Korea) due to the spread of forest fires in forest areas, as shown in Figure 81. Therefore, a plan to install the CWSEFFP 2 system starting in 2024 has been established.



(a) (b)

(c) (d)

Figure 81. Conceptual diagram of cwseffp 2 system operation (protection of village units in areas adjacent to forests); (a) Forest fire spread to areas adjacent to forests, (b) Village destruction by fire after forest fires spread to areas adjacent to forests, (c) Protection of areas near forests after CWSEFFP 2 operation, (d) Spotting fire suppression after CWSEFFP 2 operation.



(a) (b)

(c) (d)

Figure 82. Conceptual diagram of cwseffp 2 system operation (prevention of spread and extinguishment of forest fires in forests); (a) spread of forest fires in forests, (b) after spread of forest fires in forest areas, (c) forest fire extinguishment after CWSEFFP 2 operation, (d) Spotting fire suppression after CWSEFFP 2 operation.

The basic system CWSEFFP 1 is installed to sprinkle water from three large sprinkle nozzles simultaneously, delivering more than 400 L/min of water from the nozzles at the end over a radius of 40 m. The amount of water sprinkled in advance to prevent the spread of an eventual forest fire is deemed sufficient if it is more than 0.08 $L.m^{-2}.min^{-1}$, as explained in Section 6.3.2. Accordingly, since CWSEFFP 1 is designed to operate for more than 40 minutes, it sprinkles a total of 3.2 $L.m^{-2}$ for 40 minutes. CWSEFFP 2 consists of 10 sets of three fire tower nozzles per set, totalling 30 nozzles. Each set is configured to sprinkle 0.08 $L.m^{-2}.min^{-1}$ every 10 minutes, so that 0.32 $L.m^{-2}.min^{-1}$ of water can be sprinkled over 40 minutes, with each set sprinkling water four times at a sprinkling length of 2 km. CWSEFFP 2 is designed so that each fire tower nozzle can be opened and closed selectively, and N pieces of fire tower nozzles are arranged to cover approximately 2 km of the protected area. Automatic opening and closing valves are installed on the pipes of fire tower nozzles no. 1 through no. N, respectively. The system is designed so that the opening and closing of automatic valves of no. 1 through no. N fire tower nozzles can be sequentially controlled or selectively controlled automatically by fire detection to open or close valves located near the ignition point of the forest fire. The control system of CWSEFFP 2 was designed to control each automatic opening and closing valve. At least three fire tower nozzles among no.1 through no. N must be operational to ensureat least 200 m of sprinkling coverage. A conceptual diagram of CWSEFFP 2 is as shown in Figure 83. CWSEFFP 2 can be controlled remotely through a computer or smartphone app and can be equipped with a function to check operational status through CCTV installation.

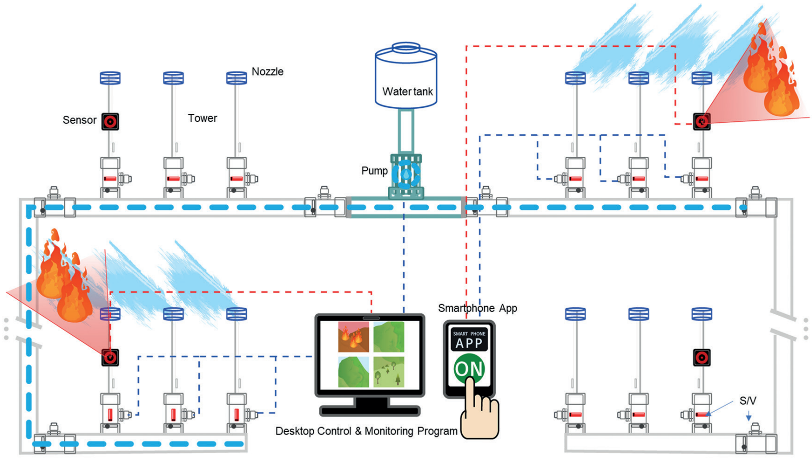


Figure 83. Schematic diagram of CWSEFFP 2.

The simpler installation details and operation stages of CWSEFFP 2 are as follows:

<CWSEFFP 2 installation details>

1. The total number of fire tower nozzles installed is 30.
2. The number of nozzles operating simultaneously is 3, which is considered 1 set.
3. The 30 nozzles installed are set as 10 sets.
4. When 1 set is in operation, if the nozzles rotate 360° per minute, a sprinkling distance of 200 m is secured.
5. Therefore, 10 sets have a sprinkling coverage of up to 2 km.
6. The control system remotely and automatically controls the supply of water to the automatic opening and closing valves by set.
7. The watering amount of the fire tower nozzle located at the farthest end of the pump, which is a pressurized water supply device, must be able to secure a watering amount of 400 L/min and a watering distance of 40 m.

8. In principle, the pressurized water supply device and water source should be located at the centre of the 2 km sprinkling coverage and so that water is supplied for approximately 1 km on each side. However, depending on the altitude difference of the actual head, the installation location may vary under the condition that the performance of the terminal sprinkle tower nozzle is secured.

<CWSEFFP 2 operation stages>

1. With the operation of the pressurized water supply device, Set 1 of the fire tower rotates 360 ° for about 1 minute to sprinkle water. At this time, the water pipe valves to Set 1 are open, and the water pipe valves of Set 2 and subsequent sets are closed.
2. One minute later, the water pipe valves of Set 2 open, and it rotates 360° for 1 minute to sprinkle water. At this time, the water tower nozzle branch pipe valves of Set 1 are closed, and the water pipe valves of Set 3 and subsequent sets are also closed.
3. The above process is repeated so that 30 water pipe towers of Set 10 sprinkle water once every 10 minutes.
4. After 10 minutes, the processes from ① to ③ are repeated. Depending on the amount of water available in the water source, which allows operation for 40 minutes, the process is repeated at 10-minute intervals for the entire 40 minutes.
5. If water is continuously supplied at a rate of 1,200 L/min, processes ① to ③ will be repeated.
6. In cases where water is sprinkled intensively in a certain area due to the spread of forest fire, the water pipe valve of fire tower N, which can sprinkle water in that area, is opened to start operating.

Here, the calculation for the pressurized water supply device to operate the CWSEFFP 2 system is the same as that of CWSEFFP 1, and the performance of the pump can be determined by considering the length of the pipe and the actual head. In particular, the pressure loss due to the equivalent length of the pipe can be obtained through the Hazen-William's formula.

6.4. Heat transfer resistance systems — fire screens

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Wildfires have become increasingly devastating in recent years, posing significant threats to both human lives and the environment. As traditional firefighting methods struggle to keep up with the escalating intensity and frequency of these fires, alternative strategies such as heat transfer resistance systems have gained attention.

The global rise in wildfire events has prompted researchers and engineers to explore novel techniques to combat the destructive nature of these fires. Heat transfer resistance systems, a relatively new field within wildfire management, aim to hinder the heat transfer originated by a fire front to surrounding vegetation, structures, and ecosystems. Unlike traditional firefighting methods that focus on directly suppressing flames, heat transfer resistance systems address the fundamental heat transfer mechanisms involved in wildfire spread.

These systems operate on the principle of creating a barrier between the advancing fire front and the vulnerable elements at risk. These barriers are designed to either reflect, absorb, or dissipate the radiant heat produced by the fire, thereby reducing its impact on adjacent areas. By manipulating the properties of materials, coatings, and structures, heat transfer resistance systems aim to slow down the rate of heat transfer and inhibit fire progression (Vines 1968) (Opolot *et al.* 2022).

6.4.1. Academic research on heat transfer resistance systems for wildfires and industrial applications

Physical thermal barriers are among the proposed solutions for protecting structures and preventing the spread of fires. Pereira *et al.* (2022) introduced a one-dimensional heat transfer model to predict temperature distribution in fire-resistant fiberglass blankets with aluminium coating. This model accounts for radiant and convective heat on one side of the barrier, and the heat transfer to the other. The conversion from Laplace to Fourier domain is achieved using a Padé Approximant. Validation through numerical methods and experiments demonstrates accurate results, with deviations of 14.0% and 8.7% on the respective sides of the barrier. Imperfect thermal contact during experiments is noted as a potential error source (Pereira *et al.*, 2022). Another study highlights the critical role of fire curtains in maintaining the integrity of fire-engineered designs by ensuring operational deployment. Fire curtains serve as a vital fire separation measure when other protection systems fail, even in scenarios like power outages. Automated systems for curtain activation exhibit a failure probability of 0.99 though some systems, which exclude electro-mechanical parts, enhance reliability. Fire curtains offer effective fire protection in civil engineering, preserving aesthetics while utilizing fire-resistant materials for structural safeguarding (Nedryshkin *et al.*, 2016).

A thesis on "Field Testing Wildland Fire Shelters", reported new prototypes designed to withstand convective and radiant heat. Compared to the M2002 standard model, these prototypes, tested across various North American locations, showed superior performance. Enhanced insulation layers in the new prototypes effectively mitigate convective heat transfer, outperforming the M2002 model (Williams, 2017).

Baranovskiy and Malinin (2021) focused on the detrimental effects of forest fires on railway operations, developing a mathematically model to predict heat transfer in passenger carriages exposed to radiation from a fire front. This model, implemented using RAD Studio using Delphi, involves non-stationary heat conduction equations and is solved using finite-difference and locally one-dimensional methods. It provides insights into temperature distribution in carriage walls and identifies safe and dangerous fire exposure scenarios, paving the way for fire safety software development for railway systems.

Advancements in materials science, nanotechnology, and engineering have led to the development of sophisticated heat transfer resistance systems. Innovative fire-resistant coatings, aerogels with ultra-low thermal conductivity, and smart materials that respond to temperature changes are being explored for their potential to revolutionize wildfire mitigation strategies. One study developed a heat-transfer model for flame-resistant fabrics (Nomex® IIIA and Kevlar®/PBI) exposed to high heat fluxes. The model incorporates thermochemical reactions by using apparent heat capacity, considers radiation absorption, variable thermal properties, and heat transfer in the air space. The finite element method is used to solve equations. The predictions closely match measurements, with temperatures within 4% of infrared thermometer readings and burn criterion times within 6% of actual test results (Torvi and Dale, 1999).

A method was demonstrated for evaluating the fire resistance of intumescent coatings, a leading form of passive fire protection for steel structures. Due to their unique behaviour at high temperatures, existing standard test methods designed for traditional fireproofing materials are inadequate. The proposed procedure employs the concept of equivalent constant thermal resistance, offering a practical approach. It utilizes an approximate formula to predict the maximum temperatures for protected steel components under standard fire conditions. By calculating the equivalent constant thermal resistance using both small-scale and full-scale test data, the procedure accurately estimates steel temperatures in the range of 400°C to 600°C. This simple yet effective approach avoids complex computations and is recommended for practical application. The concept of equivalent constant thermal resistance has the potential to quantitatively assess the insulation capacity of intumescent coatings (Li *et al.* 2012).

An investigation carried out by Hendawitharana *et al.* (2021) addressed post-wildfire damage assessment, highlighting the limited impact of past assessments on property damage reduction. Existing simulations often overlook factors like architectural design, construction materials, and other elements that influence wildfire house ignition. To improve wildfire risk assessment, this research introduces a novel approach utilizing heat transfer modelling and ground/airborne LiDAR point cloud data. This method accurately models building structures and surroundings, enabling detailed heat transfer models in Fire Dynamics Simulator (FDS). A case study comparing the proposed approach with a simplified model demonstrates its effectiveness in identifying vulnerable building areas during bushfires. This innovative approach holds promise for enhancing bushfire planning and damage mitigation strategies.

Another paper focused on developing a heat transfer model for firefighter protective clothing, offering versatile applications in evaluating protection, burn injury, and heat stress of fabric assemblies. The initial stage of the model assumes dry fabrics, temperatures below thermal degradation points, and a planar fabric geometry with one-dimensional heat transfer. Radiative heat transfer is addressed using a forward-reverse model. Model accuracy is assessed by comparing time-dependent temperatures within and on the fabric assembly to experimental values. The model performs well overall, displaying discrepancies of around 5°C inside the garment and up to 24°C on the outer shell, possibly due to unaccounted-for fabric-specific optical properties. The study sets the foundation for a comprehensive heat transfer model for analysing firefighter protective clothing (Mell and Lawson, 2000). Moreover, aiming to create an inexpensive protection system, magnesium oxide fiberglass-reinforced panels were used to protect outdoor infrastructures like telecommunication stations from forest fires. The research highlights the social, environmental, and economic impacts of such fires and proposes a cost-effective solution for protection. The developed system was tested in a wind combustion tunnel and proved effective in preventing fire damage to structures (Vaz *et al.*, 2022).

Interestingly, a study presented a thermally adaptive aerial robot designed to address the challenges posed by extreme environments, where traditional robot operation is hindered by factors like high temperatures. The robot incorporates both structural thermally insulating material and a phase change material cooling system inspired by natural thermal regulation mechanisms. The research focuses on the concurrent development of materials and design, resulting in a thermally adaptive system. The use of polyimide aerogel as a structural material and glass fibre reinforcement with silica aerogel particles contributes to the robot's ability to withstand extreme temperatures. The developed high technology-readiness-level drone prototype demonstrates its capacity to function effectively across a wide range of ambient temperatures. The proposed technology has the potential to revolutionize aerial robotics in various industrial and research applications (Häusermann *et al.*, 2023). Additionally, other researchers investigated the use of a high thermal conductivity heat pipe (HP) to mitigate coalfield wildfires. The HP effectively dissipates heat and prevents heat accumulation in coal piles. Experimental results show significant initial cooling impact near the HP. The HP maintains coal temperatures below 80 °C, inhibiting spontaneous combustion. The research proposes the HP as a technology to control coalfield wildfires and details its practical implementation pathway (Li *et al.* 2018).

6.4.1. Conclusions

The escalating intensity and frequency of wildfires demanded the exploration of innovative strategies such as heat transfer resistance systems for effective mitigation. Traditional firefighting methods have struggled to keep pace with the destructive force of these fires, prompting researchers to develop alternative approaches. Heat transfer resistance systems represent a new field in wildfire management, focusing on preventing the heat transfer from the fire front to vulnerable elements. Unlike conventional firefighting techniques, which primarily target flame suppression, these systems address the fundamental heat transfer mechanisms involved in wildfires. By creating barriers that reflect, absorb, or dissipate radiant heat, these systems aim to minimize the impact of fires on exposed elements.

Advancements in materials science and engineering have enabled the creation of sophisticated heat transfer resistance systems. These systems leverage new fire-resistant coatings, ultra-low thermal conductivity aerogels, and responsive smart materials to revolutionize wildfire mitigation. Research efforts have resulted in mathematical models and physical prototypes that improve fire-resistant fabrics, protective clothing for firefighters, and building materials to withstand extreme temperatures. Furthermore, heat transfer resistance technologies extend to the realm of robotics, with thermally adaptive aerial drones designed to operate in extreme environments.

These developments hold great promise for applications in diverse sectors, including wildfire management, infrastructure protection, and energy storage.

However, challenges persist in integrating these advancements into practical wildfire management strategies. While significant progress has been made, further research is needed to refine and expand the capabilities of heat transfer resistance systems. This includes addressing higher temperature and pressure applications, optimizing materials for varying conditions, and refining modelling approaches. Ultimately, the interdisciplinary collaboration between materials science, engineering, fire ecology, and robotics is vital in shaping the future of wildfire mitigation and protection against extreme fire events.

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7.
Modelling fire impact at WUI – property scale

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7.1. Introduction

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The assessment of fire impact on an asset within the WUI, an integral risk component alongside fire likelihood, requires the evaluation of three types of data: fire exposure, defined as the thermal insult experienced by the asset, the resultant effects of this exposure, dependent on the susceptibility of the assets at risk, and a valuation of the corresponding impacts (Johnston, *et al.*, 2020).

From a fire engineering perspective, the examination of fire exposure and its effects has been explored through experiments, fire observations and fire modelling approaches. Experimental and observational data can provide tangible information on how fire behaves in real-world; however, they are often constrained by practical limitations and safety concerns. In contrast, fire modelling allows for a cost-effective and safe means of simulating a wide array of scenarios, offering valuable insights into fire behaviour that can inform design and mitigation strategies, provided the models are validated and verified.

In this context, the scientific community already has access to modelling frameworks that can effectively handle the intricate details of WUI property-scale scenarios, demonstrating a strong level of reliability. These tools rely on physics-based Computational Fluid Dynamics (CFD) by which WUI fire ignition pathways (i.e., firebrands, radiation and flame contact) can be represented, enabling the analysis of their effects on building sub-systems or entire properties.

This chapter is divided into three sections that compile different state-of-the art examples of CFD modelling. These simulation exercises can be conducted using current technology to analyse different aspects of fire impact at the WUI property scale. The first section is dedicated to firebrand exposure, the main responsible of building ignitions in WUI areas. In this section, recent research using Fire Dynamics Simulator (FDS), the most widely used CFD software in fire safety engineering, is examined to gain an understanding of how simulations are parameterized to simulate firebrand wind-driven transport and deposition. Subsequently, the modelling approach employed by FDS to simulate firebrands as Lagrangian particles is explained, and a case study involving firebrand exposure modelling around varying solid obstacles is presented in detail.

The second section is devoted to analysing fire exposure associated to WUI defensible spaces, areas around WUI structures and communities where fuel reduction is generally required. Clearing vegetation within defensible spaces lowers the chances of structures igniting directly from flames or radiant heat. Additionally, reducing fuels around WUI communities decreases the generation of firebrands mitigating the overall fire impact. In this second section, an overview on typical requirements for defensible spaces and recent modelling efforts is provided, followed by a detailed example. This example employs WFDS (Wildland Fire Dynamics Simulator), an extension of FDS designed specifically for simulating wildfires in WUI environments. The study investigates the effects of varying defensible space configurations on fire behaviour and heat exposure.

The final section is dedicated to analysing the fire effects of burning residential fuels (both man-made and natural) on exposed building sub-systems using FDS. Initially, current approaches to characterizing the combustion of residential fuels are reviewed, with a special emphasis on the modelling requirements within FDS. Following, the framework for vulnerability analysis is introduced, relying on performance-based criteria for materials and sub-systems when facing exposure to fire. Lastly, two case studies are presented in which the combustion of residential fuels is modelled to identify vulnerabilities in building sub-systems. In the first case, framed windows are exposed to residential man-made (i.e., a stack of wooden pallets) and natural (i.e., Douglas Fir ornamental trees) fuels. In the second case, a concrete semi-confined storage area attached to the main envelope of a building is exposed to a fuel-pack burning made of non-natural domestic items.

With these three topics, the reader will gain a significant overview of several key aspects related to fire impact modelling at WUI property scale. The diverse range of scenarios covered in this chapter contributes to a comprehensive understanding of WUI fire dynamics and emphasizes the importance of exploiting advanced modelling techniques to ensure resilient and fire-safe communities.

7.2. Modelling firebrand attack

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Firebrands are aerodynamically transported burning fragments of fuel which can ignite fuels at far distances away from flames (Manzello, *et al.*, 2020). Firebrand ignition has been often recorded as the leading cause of WUI building ignitions, both in post-fire inspections and experimental studies (e.g., Blanchi, *et al.*, 2006; Hakes, *et al.*, 2017; Ribeiro *et al.*, 2020; Potter and Leonard 2010). Simulating firebrand exposure on structures is therefore essential to mitigate and prevent wildfire damage.

Firebrand exposure is a complex phenomenon characterized by several interrelated subprocesses. Firstly, firebrands are generated when flaming fuel, either natural or man-made, break down due to thermal degradation, creating burning fragments of various sizes and shapes. The fragments are then lofted by the fire plume or directly transported by the local wind flow, and aerodynamically transported in the wind until they land, and possibly accumulate, on target fuel (Wadhwani *et al.*, 2022). The material properties and geometry of both the source fuel and of generated particles, the fire intensity, as well as the local wind flow and fire-induced flow influence these mechanisms. Spotting occurs if target fuel ignites, creating secondary fires, which may spread independently progressing. These processes, related to firebrand exposure on buildings, are schematically illustrated in the Figure 84 diagram.

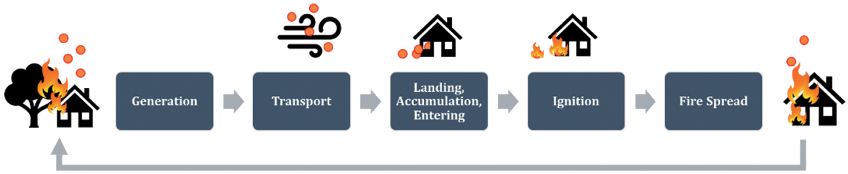


Figure 84 Schematic diagram of firebrand exposure and ignition subprocesses on buildings: firebrand generation, wind-driven transport, landing and accumulation, ignition and fire spread

Firebrands can ignite buildings either directly, by igniting external components or by entering the structure through openings; or indirectly, by firstly igniting nearby fuel and subsequently igniting the building structure through flaming exposure (Caton *et al.*, 2017). In both indirect and direct ignition pathways the amount of burning firebrand fuel, their temperature, the sorrounding wind speed, and contact time with target fuel, are significant in determining ignition.

In this section we summarize research advances in estimating firebrand exposure to buildings using FDS. An overview of the FDS Lagrangian particle model, which is used to simulate firebrand particles is provided along a reflection on the software limitations to simulate this exposure process. Lastly, a case study presenting FDS simulation results of firebrand landing and accumulation around solid obstacles is presented.

7.2.1. Recent research: modelling firebrands with FDS

To model firebrand exposure in FDS, realistic firebrand particle sizes and material densities should be selected for the scenario of interest. Numerous field and experimental firebrand generation studies present firebrand particles distribution measurements for different generating fuels. Hedayati *et al.* (2019) developed a methodology for accurate post-fire firebrand analysis, concluding the minimum sample size for collected particles is 1,400 firebrands. For urban fuel firebrand generation, Manzello *et al.* (2019) recorded firebrand properties generated in wind tunnel experiments, conducting full scale experiments of burning roofing assemblies, and Suzuki and Manzello (2018) analysed firebrands collected from the 2016 Itoigawa city fire in Japan. In both studies, geometry of particles was analysed. Most recent versions of FDS include drag models for cylindrical and spherical particle; literature includes approaches which modify the available FDS drag model to consider cuboid particles, and particle shape irregularity.

Table 20 summarises relevant literature studies which have applied FDS to model different aspects of firebrand exposure subprocesses. FDS has been most often used and applied to simulate firebrand wind-driven transport, and firebrand deposition. Firebrand generation flux data can be extracted from field and experimental studies, and firebrand heat exposure and ignition has not been directly physically calculated from CFD simulations. To simulate firebrand wind-driven transport, various research applying different empirical and computational models are available (Koo *et al.*, 2010) however not discussed in this section.

7.2.2. FDS Lagrangian particle model and use for firebrands' simulation

FDS simulates firebrands as Lagrangian particles (McGrattan, *et al.*, 2023). Lagrangian particles are modelled through a force term ($\vec{f_b}$) included in the gas phase conservation of momentum equation of the software. This term is calculated by Equation (26) and computes the force transferred from the particles to the surrounding fluid flow in a given grid cell. This constitutes the assumption that

Table 20. Literature studies modelling firebrand exposure processes using FDS.

Study objective	Overview of FDS simulation parameters
Firebrand short-range transport, validation to original experimental results (Wadhwani et al., 2017).	Experimental investigations are used to validate the FDS Lagrangian particle transport model simulations of non-burning cubiform and cylindrical firebrand particles. Drag model for cuboid particles is added to FDS model. Cuboid particles landing distributions agree with experimental results with a smaller error compared to cylindrical particles landing distributions.
Firebrand deposition patterns around varying cubic structure (Mankame and Shotorban, 2021)	Firebrand deposition around a cuboid obstacle of varying dimensions is modelled. FDS Lagrangian particle model is modified to include translational and rotational motions of particles and particle pyrolysis and charring thermal degradation. Firebrand particles are simulated as cylinders. The computational domain is 0.8 × 0.4 × 0.4 m with mesh grid size of 0.0025 m and cube height of 0.08 m. Deposition distributions are characterized for varying cuboid dimensions, the leeward side of the cuboid is always found to be protected from firebrand contact.
Quantifying firebrand generation flux from a single tree and from a forest fire (Wickramasinghe et al., 2022)	An inverse analysis approach is applied to simulations to recreate published firebrand generation data. Interpolation technique then is added to calibrate wind velocity, relative humidity, and vegetation species (for a single Douglas-fir tree, and a forest fire) effects. For the single tree a cone shape with 2.6 m height and 1.5 m girth is simulated, in an 8 × 8 × 10 m computational domain with 50 mm grid size. For the forest a plot of 336 × 162 m is simulated, with a stationary fireline.
Quantifying relationship between firebrand flux, FFDI and radiative heat flu; focus on AS3959 (Wickramasinghe et al., 2022)	A eucalyptus forest fire is simulated under three different wind speeds to model varying fire intensity. The firebrand size, shape, and quantity are based on published generation study. Computational domain size used is 336 × 102 × 90 m; finest mesh grid size is 0.75 m. Fuel density and distance from exposed buildings is based on Bush Attack Level (BAL) of AS3959 (Australian Standards, 2018)

particle-particle interactions are negligible. The force term is related through Newton's second law of motion to the particle acceleration. Each particle position is therefore resolved using Equation (27). V is the grid cell volume, ρ is the gas density, C_d is the drag coefficient, A_p is the particle cross-sectional area, $\vec{u}_p$ is the particle velocity, $\vec{u}$ is the gas velocity, m_p is the particle mass, and $\vec{g}$ is the gravitational acceleration.

$$\vec{f}_b = \frac{1}{V}\Sigma[\frac{1}{2}\rho C_d A_p\left(\vec{u}_p - \vec{u}\right)\left|\vec{u}_p - \vec{u}\right| - \frac{dm_p}{dt}\left(\vec{u}_p - \vec{u}\right)] \quad (26)$$

$$\vec{a}_p = \frac{d\vec{u}_p}{dt} = \vec{g} - \frac{1}{2m_p}\rho C_d A_p\left(\vec{u}_p - \vec{u}\right)|\vec{u}_p - \vec{u}| \quad (27)$$

FDS currently includes drag models for spherical and cylindrical particles. Firebrands are often assumed to have cylindrical shape; however, the complexities of cylinder aerodynamics include the significant influences of rotational and lift forces which are neglected in the FDS Lagrangian particle model (McGrattan, *et al.*, 2023).

The particles size, shape, and material properties are defined in the FDS simulation input file. Lagrangian particles can be introduced to the computational domain either through a solid surface with a defined normal inlet velocity, or through a volume; particles can be introduced at the start or periodically throughout the simulation. An example FDS input file called 'dragon_5a' which roughly models the NIST Firebrand generator experimental apparatus can be found in Manzello *et al.*, (2008).

The change in particle mass over time is included in Equation (27), influencing the force transferred from particles to surrounding fluid and the resulting density of the particles. The combustion kinetics and thermal degradation of Lagrangian particles cannot be directly introduced in FDS simulations, however a modified code with this capability can be found in Mankame and Shotorban (2021).

Once the particles come to contact with a solid boundary, the default FDS mode continues solving force term, moving the particles along the solid boundaries. If the *Adhere to solid* mode is set to true, FDS adheres the particles to the solid boundaries; velocities at which the particles move can be defined.

Lagrangian particle coordinates over simulation time, as well as related numerical parameters (including temperature, diameter, mass, velocity, acceleration, age, drag force) are recorded in FDS output FORTRAN file ending in '.prt5'. Publicly available scripts, created by the FDS developers, can read and convert these data files to other programming languages (e.g., MATLAB).

7.2.3. Case study: modelling firebrand exposure around varying solid obstacles

Aim of Study

This work computationally investigates the interaction between varying solid obstacle geometry with airborne particle exposures (Dossi, 2023). Three obstacles mimicking common WUI building component shapes (i.e., a vertical wall, re-entrant corner and single horizontal step) are simulated under 4, 8, 10, and 12 m/s ambient wind speed. Steps and re-entrant corners are often present on the external walls, and around decks and windows of buildings; all components identified as vulnerable to wildfire ignition (Dossi *et al.*, 2022).

FDS modelling parameters and methods

Spherical particles with 50 kg/m^3 density and normally distributed diameters between 2.5 mm and 7.5 mm are introduced. The density is selected based on the density of Douglas-fir wood density (500 kg/m^3) and the literature suggestion to estimate char density as 10% of unburnt wood density (Ragland *et al.*, 1991). Normally distributed diameters aim to introduce a range of particle weights and sizes mimicking wooden particle weights at various stages of combustion, to address the limitation of simulating firebrands as non-burning particles. The particle parameters match the final firebrand weight distribution reported in experimental studies (0.01 g – 0.1 g).

Figure 85 shows two computational domain schematic diagrams alongside relevant dimensions and features. The domain size is 10 m × 10 m × 6 m. Mesh grid sensitivity analysis resulted in average 7% error of final particle position with chosen grid size δ = 5 cm, compared to grid size of 2.5 cm. All domain boundaries are open except the solid ground floor boundary which is an inert non-slip boundary (shown in yellow in the schematic diagram) and the inlet wind flow boundary (the boundary with the firebrand inlet vent shown in pink in the schematic diagram), which introduces wind with a specified speed.

The firebrand inlet vent is located 1.6 m above the ground, with a width length of 6 m. The inlet is extended past the obstacle width in the y direction to enable observation of how the particles interact around the obstacle lateral edges.

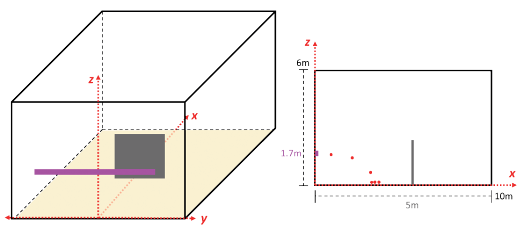
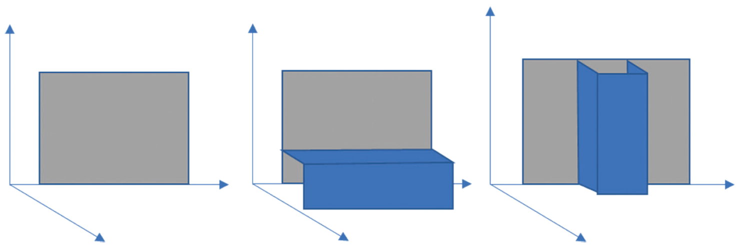


Figure 85. Schematic of computational domain shown in 3D (left) and in at the y=0 plane (right) — firebrand inlet shown as pink rectangle, and the solid obstacle location as grey square. firebrands are depicted as red dots

The obstacles are located at 5 m from firebrand inlet, at x=5, and centred at y=0. The obstacle shapes are shown schematically in Figure 86: a vertical wall with dimensions 2.4 m × 2.4 m, a single horizontal step, and a re-entrant corner. The latter two shapes are added to a wall with the same dimensions as the vertical wall, their additional features are both 0.5 m × 0.5 m in cross-sectional dimensions.

Figure 86. Schematic diagrams of three solid obstacles tested in simulations. From left to right: vertical wall, step, and re-entrant corner



The simulations are conducted for a total time of 60 s to minimize computational resources; firebrand particles are introduced only once the flow in the domain is fully developed (t=10 s). Final particle position is visualized either as boxplot of particles x-coordinates, or as heatmaps showing the relative number of particles and time spent at a given coordinate location. For the heatmap visualization a bivariate histogram function is then applied to the particles x and y coordinates, for all simulation time steps conducted. This approach calculates the number of particles that pass within each bin in the given domain area. The results are normalized: 0 corresponds to no particles passing the location indicated throughout the simulation, and 1 corresponds to the highest number of particles spending the longest time.

7.2.4. Results

4 m/s wind speed is the lowest ambient speed tested and resulted in nearly identical particle path for each solid obstacle geometry tested. Boxplots and histograms showing particle distribution

along the x-axis of the computational domain ground floor for each obstacle tested at t=20 s and t=60 s are shown in Figure 87.

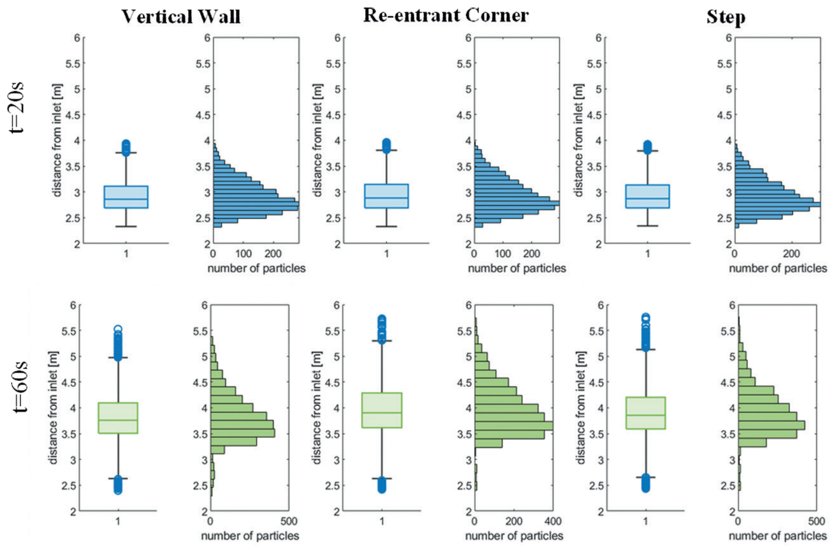


Figure 87. First particle deposition location at t = 20s (top) in blue, and particle location at t=60s (bottom) in green, of particle distribution on computational domain z=0 plane for each obstacle at 4 m/s wind.

Figure 88 shows the heatmaps generated for all obstacles tested at 8, 10, and 12 m/s wind speeds; each column shows simulations at a given wind speed and each row shows a different obstacle tested (top to bottom the matrix columns show the wall, step, and re-entrant corner results respectively). Colours correspond to relative number and time particles spent in each location, normalized over 0 to 1 range. At 8 m/s, simulations show the highest amount of firebrand contact occurring with the ground floor between firebrand inlet location and the obstacles windward recirculation zone; particles subsequently follow recirculation zone edge around the to the wake. The highest contact region is this windward recirculation zone edge. At 10 m/s and 12 m/s, particle paths and contact concentrate mostly at the intersection edge between the wall obstacle and ground floor. At 10 m/s the highest firebrand contact is at this intersection, with second highest contact traced at the edges of the leeward wake flow path. Firebrand contact is also recorded, at a lower extent, at windward recirculation zones edges. At 12 m/s, particle contact regions differ most significantly between each obstacle. For the re-entrant corner geometry, the particles concentrate in the corners. The second most exposed section of the re-entrant solid obstacle is the section perpendicular to the wind flow direction and firebrand inlet, this is the same highest exposed hazard region for the wall and step obstacle. Around the step obstacle, an additional high-risk region is observed above the step at $z = 0.5$ m, at the intersection with the vertical wall obstacle portion of the obstacle; firebrand particles only reach this region at highest wind speed (12 m/s) simulated.

7.2.5. Future work

This work provides a methodology and approach to estimate firebrand contact and exposure around more complex and specific solid obstacle boundaries on a single building spatial scale, providing insight into how increasing wind speed and varying obstacle geometry impacts firebrand exposure. Considering varying wind direction, and firebrand inlet heights are important parameters that need to be quantified in future work to more accurately simulate possible firebrand exposure scenarios. Finally future work can connect the identified hazard areas to expected firebrand heat exposure for a more comprehensive fire risk evaluation.

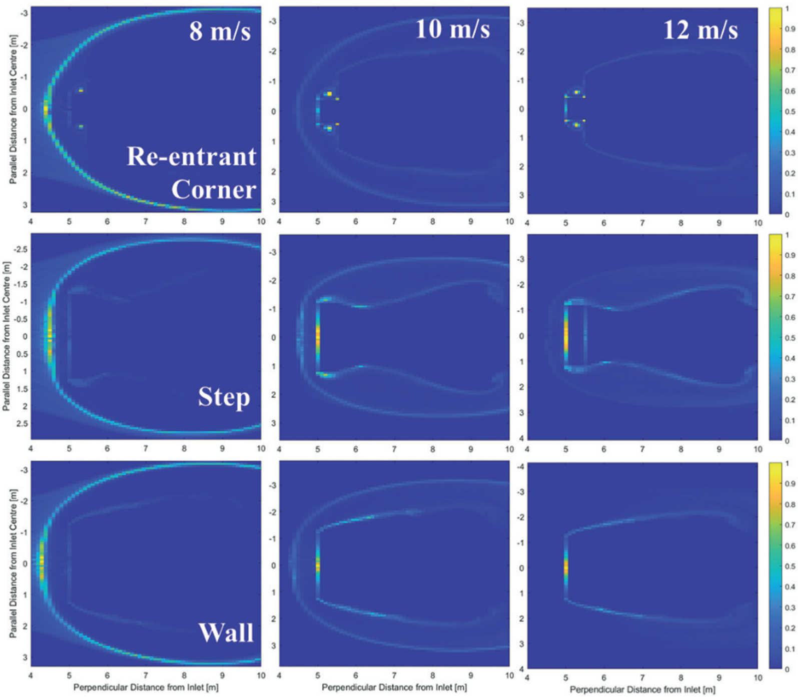


Figure 88. Heat maps of relative firebrand particle contact with solid boundaries for obstacle geometries (by rows, top to bottom: re-entrant corner, step obstacle, and wall obstacle), and wind speeds tested (by column, left to right: 8 m/s, 10 m/s, and 12 m/s).

7.3. Modelling of the effectiveness of defensible space fuel requirements

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The so-called defensible space refers to a buffer area between the structure and the immediate surroundings where fuels have been modified to reduce their overall amount and to disrupt the vertical and horizontal continuity in their arrangement. An adequate defensible space reduces the likelihood that the exposure to a wildfire will result in home damage or loss and provides firefighters with better and safer opportunities for wildfire response (Calkin *et al.*, 2014; Cohen 2000; Cohen & Stratton, 2003; 2008). Defensible space regulation requirements differ from one country to another, and while they are often issued from post-fire surveys (Laranjeira & Cruz, 2014; Intini *et al.*, 2020), they are poorly supported by scientific evidence and studies, particularly in European countries (Agueda *et al.*, 2023). Even if the fire exposure mechanisms or pathways leading to structures loss have been identified (Caton *et al.*, 2017), this is flame impingement or convection, radiant heat from burning residential fuels (ornamental vegetation or artificial fuels) and flying embers or firebrands, still, more efforts are necessary to understand how and why dwellings are damaged or completely destroyed under WUI fires exposure (Filkov *et al.*, 2023). In particular, there is a need to quantitatively assess the effectiveness of the current defensible space fuel requirements by characterizing fire behaviour and heat exposure levels in different conditions and configurations; and for different vegetation types (Mell *et al.*, 2010).

Moreover, regulations are difficult to enforce and little respected (Ganteaume *et al.*, 2023). Some of the barriers that homeowners face completing defensible space requirements include costs and/or time needed, underestimation or incomplete understanding of their home's ignition risk or inadequate motivation to comply (Petek, 2021). In this regard, the defensible space maintenance is an important consideration since some fuel treatments requirements enforce homeowners to take regular actions that can demotivate them, especially if their home's defensible space extends beyond their property limits and/or other homeowners do not maintain their defensible space. So, quantifying the effectiveness of defensible space fuel treatments and understanding how this effectiveness depends on how closely the principles of fuel management are carried out and on their maintenance over time, can help improve fuel treatment requirements and take the more appropriate actions to help homeowners break down some of the above-mentioned barriers.

7.3.1. Overview on the defensible space fuel requirements

The mitigation strategy of clearing vegetation around structures to reduce home ignition was firstly introduced by Cohen (2000) through the concept of the Home Ignition Zone (HIZ) following some experimental research into home's ignition due to the effects of radiant heat. The HIZ subdivides the defensible space into three different zones, each one with different fuel requirements to achieve different objectives. The immediate zone or non-combustible area aims to reduce the likelihood of the home's direct flame contact exposure. The intermediate zone aims to slow down fire spread and reducing its intensity by breaking vertical and horizontal fuel continuity. Finally, the extended zone intends to interrupt fire's path and constrain fire spread to the ground. The HIZ also considers the home itself and thus it includes home preparedness and hardening actions.

Based on the HIZ concept, most countries facing WUI fires have developed regulations or guidelines, addressing the characteristics of the defensible space (i.e., size, number of zones) and the fuel requirements in this space mainly in terms of tree/plant spacing, tree pruning and home structure/tree spacing. Fuel requirements are specific to each zone and in some codes also depend on the slope of the terrain. Table 21 summarizes the principal defensible space fuel requirements for some representative regions and countries, for illustrative purposes. For a more exhaustive compilation refer to Intini *et al.* (2020).

Table 21. Examples of defensible space fuel requirements.

Country* → Requirements ↓	**Corsica (France)**	**Catalonia (Spain)**	**Portugal**	**USA**	**Canada**
Defensible space radius (m) / Slope	50 / No	25 / Yes	50 /No	30 / Yes	30 / Yes
Number of zones	2	2	3	3	3
Zone 1 — Non-combustible (m)	3	2	2	1.5	1.5
Tree spacing (m)	2	3	4	5.4	3
Minimum tree's pruning height (m)	2	3.5	4 (trees > 8 m)	1.8	2

Notes:
*Corsica (Prefet de la Haute-Corse, 2022), Catalonia (Generalitat de Catalunya, 2019), Portugal (Autoridade Florestal National, 2008), USA (NFPA, 2002) and Canada (FireSmart, Government of Alberta, 2013)

As it can be observed in Table 21 there is a lack of standard guidelines concerning the defensible space characteristics and the associated fuel requirements. Even if in a particular case some requirements are more restrictive as is the case in Corsica for the size of the defensible space and the non-combustible zone, other requirements as the tree spacing are less restrictive. Thus, assessing the effectiveness of defensible fuel space requirement is a complex task due to the high level of detail in the requirements and the almost infinitely number of possible WUI scenarios. Furthermore, when comparing different regulations or guidelines, interactions (i.e., synergies or compensation effects) between different requirements values should be considered. In this regard, three-dimensional, time dependent, computational fluid dynamics fire behaviour models can be supporting tools to quantitatively assess the effectiveness of defensible space fuel requirements.

7.3.2. Using CFD tools for modelling the defensible space fuel requirements effectiveness

Modelling WUI fires is very challenging especially due to (i) the complexity of fuel types involved (wildland, ornamental, structural, fuel breaks as roads), which intermix forming heterogenous fuel arrangements across different scales, (ii) the variety of environmental conditions (weather, terrain) in which WUI fires develop, and (iii) the interactions between fuels (characteristics and arrangement), environmental conditions and the fire driving physical processes (ignition, combustion, heat transfer, flow, smoke transport) at a large range of spatial and temporal scales (Mell *et al.*, 2010). Accurately modelling environmental conditions and fuels is thus critical for the assessment of the fire exposure of a structure and thus for the assessment of the effectiveness of defensible space requirements. Three-dimensional, time-dependent CFD physics-based fire behaviour models allow for the modelling of spatially explicit 3-D residential fuel elements. Moreover, since they simulate combustion, thermal degradation of vegetation and fluid flow, they have the capabilities of providing heat exposure conditions and levels for different fuels and environmental conditions. For these reasons, and also due to the advances in computing capabilities, the use of this types of tools has progressively increased over the last decade.

However, studies found in the literature dealing with fuel management are mainly focused on the effect of wildland fuel treatments on fire behaviour and wind flow, where particular attention is mainly given to assess either the effects of the treatments increasing within-stand heterogeneity (Parsons *et al.*, 2017; Marshall *et al.*, 2020; Atchley *et al.* 2021; Ritter et al 2022) or the effects of the fuel breaks characteristics (size and vegetation left) (Pimont *et al.* 2011; Frangieh *et al.*, 2021). While these studies provide meaningful insights on the effect of vegetation stand characteristics of the treated areas on fire behaviour and/or flow dynamics, the types of vegetation considered, and their structure are not representative of those of the residential fuels which are commonly found close to the structures in the WUI settlements at the property scale, especially in the Mediterranean area. Moreover, in most of the cases building structures are not modelled. In this regard, Gadheri *et al.* (2021) found out that the building structure has an effect on the fire behaviour and the fire impact as it increases the plume's intermittency and local heat exchange at some locations upstream of the building. Studies which include WUI fires impact on structures are focused on how the thermal exposure changes due to wind and/or slope, paying little attention of defensible space fuel requirements (Khan *et al.*, 2019; Edalati-nejad *et al.*, 2021).

As a result, the literature focused on the investigation of the effectiveness of defensible space fuel requirements is very scarce. Ganteaume *et al.* (2023) tested the capabilities a CFD model to reproduce the impact of a past fire in terms of vegetation damage on different WUI scenarios cases at the property scale by comparing numerical results with post-fire surveys. For each case, two configurations of vegetation management were tested where regulation was either enforced or not. Numerical results of this study underline the relevance of fuel reduction at the defensible space for fire mitigation. Pérez-Ramirez *et al.* (2022) numerically characterized heat exposure conditions of a building structure in common Mediterranean WUI scenarios. Two different configurations of the defensible space were studied, corresponding to different spatial patterns for the canopy layer presenting different levels of aggregation. These configurations were conceived to test the allowed limits of the current regulations in Corsica but still enforcing them. Moreover, different conditions were tested in terms of ambient temperature, relative humidity and fuel moisture content. The results of this study highlight the importance of the effect of the spatial distribution of vegetation on the heat exposure conditions at property scale. While these studies reveal the potential of CFD models to assess the effectiveness of defensible space fuel requirements, still more efforts are necessary.

7.3.3. Case study: modelling defensible space fuel requirements with WFDS

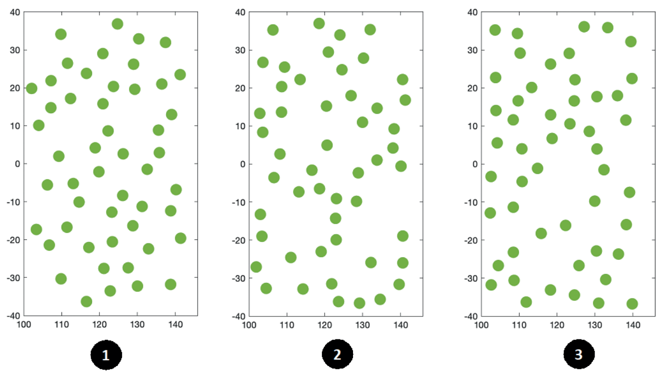
Aim of the study

The aim of this work is to numerically investigate the effects on fire behaviour, and heat exposure conditions of different configurations of the defensible space responding to the Corsican regulation requirements with WFDS (Mell *et al.*, 2007; 2009; Pérez-Ramirez *et al.*, 2017). Special attention has been given to the role of the amount and type of surface vegetation, which have been chosen to be representative for two different levels of maintenance of the prescribed fuel management requirements. Moreover, the coupled effect of the spatial distribution patterns of the raised vegetation has also been considered. The exposure mechanisms modelled include flame radiation and direct flame contact.

Scenarios Definition

The scenarios modelled consider the different zones that a fire must burn before the fire front might approach and reach the structure. This is a forested area and the defensible space around the dwelling. The forested area corresponds to a high-density cork oak forest composed by a canopy stratum of cork oaks, a shrub layer of plants of rockrose, tree heath and strawberry tree and a litter layer. Details on the modelling of this area can be found at Pérez-Ramirez *et al.* (2022). The defensible space is modelled by following the requirements of the current regulation in Corsica. In the zone I (0 – 3 m) there is a non-burnable deck in front of the house and everywhere else around the structure a grass layer. In the zone II (3 – 50 m) different configurations are tested. Concerning the surface fuel both a shrub layer (20 cm height) which might result from the resprouting of the clearing of the forest area are considered and a grass layer (10 cm height). Both configurations agree with the current regulations, but they are representative of two different levels of clearing maintenance. While the second case is the more restrictive in terms of fuel reduction, the first case reaches the upper limit of phyto-volume allowed. The raised vegetation in this area is composed by a hedge 1 m height and 1 m wide located at the limit with zone I, and a canopy layer of cork oak trees. Three different spatial distributions of trees in this zone are examined. These distributions respond to the same statistical spatial patterns since they are replicates of the same spatial point process model. Moreover, a case with only the surface fuel is considered. As a result, 8 different scenarios are modelled. Specifications for these scenarios are detailed in Table 22.

Table 22. Specifications of the different scenarios and conditions tested.

Defensible space — Zone I (0 m - 3 m)
In front of the structure: non-burnable deck *Everywhere else around the house:* Grass layer 10 cm height, 10% FMC
Defensible space — Zone II (3 m – 50 m)
3 m – 4 m: Ornamental hedge 1 m height x 1 m depth, 60% FMC *4 m – 7 m:* Surface vegetation (see hereafter). No other vegetation allowed in this area *7 m – 50 m:* Surface vegetation only or surface vegetation + Canopy stratum (see hereafter)
Surface vegetation
Configuration 1: Resprouting shrubland (shrubs + litter+ grass), mean FMC = 23 % *Configuration 2:* Grass layer 10 cm height, 10% FMC
Canopy stratum
3 different tree's spatial distribution patterns; CBH = 2 m; TH = 7 m, Leaves FMC = 60%; Distance between tree's canopies 2 m; Distance between trees canopy and the hedge 3 m (mandatory) 
Conditions
Wind: 35 km/h; *Temperature/Relative Humidity:* 32°C, 20 %; *FMC forest:* 52 % - 81 %
Notes: FMC: Fuel Moisture Content on dry basis; CBH: Crown Base Height; TH: Tree height

WFDS modelling

The computational domain size is 275 m x 80 m x 96 m (Figure 89). The domain is subdivided into two areas, the first one covering the area where combustion takes place up to 32 m height with grid cells of Δx=Δy=Δz=25 cm, and the second one covering the upper part of the domain with grid cells of Δx=Δy=Δz=50 cm. A 1/7th power law profile is used at the inlet of the domain to implement the wind condition. In addition, upwind and downwind areas are implemented to allow correspondingly the development of a proper wind profile and to resolve the vortex shedding to avoid boundary effects.

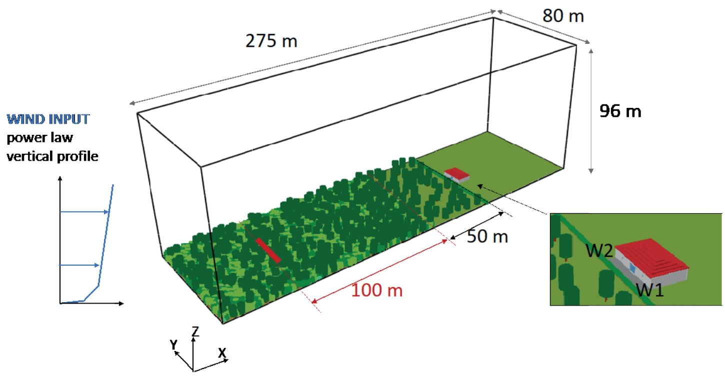


Figure 89. General scenario configuration as rendered by smokeview.

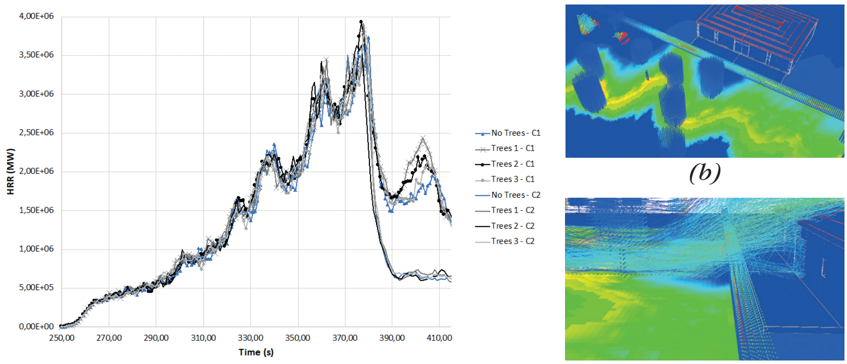
Surface fuels are modelled by using the fuel boundary model coupled with a linear pyrolysis sub-model for the thermal degradation of the solid phase. For raised vegetation elements (i.e., hedge and trees) the fuel element model combined to an Arrhenius type model for solid-phase degradation including char oxidation are used.

Different openings are implemented in the structure façade the most exposed to the fire where numerical devices are located to determine the thermal exposure (W1 and W2).

Results

Figure 90A presents the heat release rate (HRR) over time for the different scenarios considered where C1 refers to surface fuel configuration 1 (regrowth) and respectively C2 to configuration 2 (grass). As it can be observed, there are important differences depending on the surface fuel configuration. These differences can be explained by the differences in the tree's canopy and hedge consumption. For the worst case of configuration 1, trees presenting a total canopy consumption are at most 25 m from the structure, and those presenting a partial canopy consumption at 15 m from the structure. Correspondingly, trees presenting a total canopy consumption for cases with a surface fuel configuration type 2 are at most 35 m from the structure, and those presenting a partial canopy consumption at 25 m from the structure. The spatial distribution of trees on configuration 1 has a considerable impact on the combustion of the tree's canopy and thus on the HRR (Figure 90A). However, when considering configuration 2, fire intensity peaks at about 380 s (Figure 90A) and then drops significantly to an almost constant level. At this moment the fire front is located at 35 m from the structure, and all the trees damaged by the fire are between 50 m to 35 m from the structure. That explains why there are no notable differences in HRR due to the presence of trees when fire approaches the structure. Differences are observed in the peak value which is lower for the case with no trees. Concerning the hedge combustion in front of the structure for cases with a surface fuel configuration 2, the hedge is partially consumed both due to the lack of combustible fuel (non-burnable deck) ahead of the fire front and due to the complex flow interactions caused by the presence of the hedge and the house inducing recirculation instabilities (Figure 90b,c).

Figure 91 presents the results of radiant heat exposure at side windows (Figure 89) for cases with a surface fuel configuration type 1 (regrowth). These results highlight the differences already observed in the HRR, sustaining the fact that for this surface fuel configuration the trees spatial patterns play an important role on fire behaviour as well as on the flow dynamics that affect the flame position and thus the thermal impact of the structure. Consequently, the radiant thermal impact for the worst cases scenarios can double the radiant thermal impact of other cases. For configuration 2, in all cases the radiant heat flux received at side windows is lower than 5 kW/m² since the portion of the hedge in front of the façade where windows are located do not burn.



(a) *(b)* *(c)*

Figure 90. Fire behavior results. a) Heat release rate over time for studied scenarios. b) case c2 — trees 2, smokeview rendering of particles temperature and surface HRR per unit area. c) case c2 — trees 2, smokeview rendering of wind flow and surface HRR per unit area.

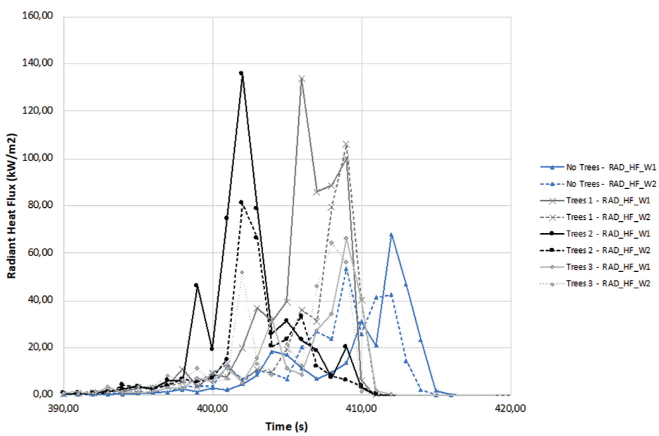


Figure 91. Radiant heat fluxes received at side windows for surface vegetation configuration 1 — regrowth.

7.3.4. Conclusions and future work

The results of this study illustrate the importance of the regular maintenance of surface fuels in order to keep a restricted amount of surface fuel since this minimizes the structure radiant heat exposure. Future work will be devoted to continuing this study with further investigations on scenarios with slope, as well as with other ambient conditions which might be closer of those expected due to climate change. The final aim is to define a framework to assess the effectiveness of defensible space fuel requirements including mass-ensemble based simulations.

Acknowledgements

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7.4. Modelling of the combustion of residential fuels for the analysis of building vulnerabilities

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The modelling of the combustion of residential fuels, which include wildland vegetation, ornamental vegetation and artificial fuels, can be performed by using the CFD tool FDS, which allows to model the many variables of WUI property scale scenarios. FDS has been validated in multiple fire engineering applications and it is used for Performance-Based Design (PBD) evaluations of complex building scenarios (Hurley and Rosenbaum, 2015). With the proper characterization of the fire source and building and property features, FDS can provide information on key variables of WUI risk management by quantifying the hazard associated to the combustion of residential fuels as well as the vulnerability of the analysed structure or structural sub-system (Vacca *et al.*, 2020).

Observations from past WUI fires (e.g., Blanchi *et al.*, 2006; Leonard *et al.* 2009; Maranghides and Mell, 2011) have highlighted that the likelihood of house loss is mostly related to the interaction of firebrands with surrounding combustible elements, which results in flames too close to the structure (with the exception of those cases where buildings are located close to the wildland, which might be directly exposed to the wildfire (Vacca, 2023). The threat posed by the combustion of vegetation depends on the residence time of the fire and on the flames' geometry, which varies greatly depending on the type of vegetation (e.g., grassland, shrubland, forest stand; Alexander *et al.*, 2007). When it comes to ornamental vegetation, the combustion intensity and the duration of the flaming phase depend on the specie and its level of maintenance (i.e., trimming, pruning, watering). Artificial fuels, mainly composed out of plastic and wooden materials, present significant variability both when it comes to Heat Release Rates (HRR) and burning time, and they have the potential to burn with significant intensity and duration (Vacca *et al.*, 2020).

7.4.1. Quantitative characterisation of the combustion of residential fuels

There are currently no frameworks, guidelines or standards for the modelling of the combustion of residential fuels of WUI property scale environments. When it comes to quantifying the hazard posed by wildland vegetation, the Australian Standard 3959 proposes a methodology that measures the severity of a building's potential exposure (Bushfire Attack Level (Australian Standards, 2018)) by accounting for the proximity to vegetation, the slope of the terrain, meteorological conditions, vegetation characteristics and the wildfire danger index. The fireline intensity (Byram, 1959) and the flame depth (Nelson and Adkins, 1988) can also be used as a way to quantify wildfire exposure. With respect to ornamental vegetation located at the property scale, little data is available on its burning behaviour, and many studies have been carried out at particle scale, not accounting for vegetation structure, flow dynamics, etc. (Meerpoel-Pietri *et al.*, 2022). FDS allows to model this type of vegetation in form of Lagrangian particles, which undergo a solid--phase thermal decomposition process. The pyrolysis is modelled based on inputs which include the moisture content and bulk density of the vegetation and its physical properties (density, conductivity, specific heat capacity). The simulation of the combustion of Douglas Fir trees using Lagrangian particles has been validated (Mell *et al.*, 2009), although efforts in validating the modelling of the combustion of other species are needed. When it comes to artificial fuels, the burning behaviour of common fuels that can be found indoors (e.g., pieces of furniture and small appliances) has been extensively analysed in small- and real-scale tests (Hurley *et al.*, 2016), and some of these fuels (e.g., wooden pallets, vehicles) can also be found in the surroundings of WUI structures. There is however a lack of quantitative information on the burning behaviour of the accumulation of different types of artificial fuels (i.e., fuel packs) in WUI environments. To obtain this type of data, some real-scale tests have been performed on several types of fuel packs that include items that are commonly present on WUI properties (Vacca *et al.*, 2022).

When simulating fire exposure of a building or a building sub--system with FDS, a simple pyrolysis model can also be used, which needs as input either the Heat Release Rate Per Unit Area (HRRPUA, in kW/m^2) or the Mass Loss Rate Per Unit Area (MLRPUA, in $kg.m^{-2}.s^{-1}$) of the ignited fuel or fuel pack (McGrattan *et al.*, 2023).

7.4.2. Using a quantitative approach for WUI vulnerability analysis

FDS allows for the analysis of a large number of scenarios and can cover the diverse fire safety needs of the WUI property scale (Vacca *et al.*, 2020). Through this tool, fire scenarios which involve vulnerability assessment of a building, or a building sub-system can be quantitatively analysed. These scenarios should represent fire and environmental conditions that are thought to be threatening to the analysed property and structure, along with building and/or property characteristics that are thought to be vulnerable to the selected fire exposure. When analysing a WUI scenario, to be conservative, it is recommended to simulate a full burnout, meaning that the fire is not suppressed, but decays according to the available fuel. Environmental conditions that should be considered within a scenario include the location of the property within the landscape along with meteorological information such as outdoor temperature, humidity and wind speed and direction (Vacca *et al.*, 2022). Property and/or building characteristics are to be included depending on whether the scope of the analysis includes the entire property and building or only a building sub-system. These include physical features (i.e., geometry and materials) that can affect fire spread or that can cause fire entrance inside the building (i.e., vulnerable elements).

Results from simulations can be compared to previously set performance criteria in order to obtain quantitative conclusions. Performance criteria are threshold values set to quantify the hazards posed by each scenario (Hurley and Rosenbaum, 2015). These criteria include structural requirements that should be met when the analysed building is to be used as a shelter as well as when the goal of the analysis includes property protection. Performance criteria must be set for the vulnerable structural elements of a building as well as for other vulnerable elements located on the analysed property.

7.4.3. Case study: modelling of the combustion of residential fuels to identify building sub-system vulnerability

The modelling of the combustion of residential fuels close to two different building sub-systems with the aim of identifying their vulnerability is here presented. The first analysed building sub-systems consists of framed windows. No standard or guideline proposes a performance criterion for glazing systems exposed to a fire in the WUI environment, therefore the chosen performance criterion for framed glazing systems is identified through a literature review as the critical temperature difference at cracking between the heated part of the pane and the shielded edge located below the frame ΔT_{cr} (Keski-Rahkonen, 1988; Pagni, 1988) with a value of 83°C (Vacca, 2023). Two fire scenarios are chosen: the first one involves the combustion of a stack of wooden pallets with an assigned HRR curve (Karlsson and Quintiere, 2000), while the second scenario involves the burning of three Douglas Fir trees, the combustion of which is simulated using Lagrangian particles. Both scenarios are analysed in windy conditions, with a wind speed of 30 km/h that pushes the flames towards the window. The fuels are located at several distances from the window in order to identify the distance at which the performance criterion is not met, and the scenario can therefore deem to be safe. The window size is 1.2 x 1.2 m, and it includes a PVC frame (performance criterion: melting point at 220°C, (Chen *et al.*, 2011)). Both double pane and single pane windows are analysed with the material properties given in Table 23. An example of the simulated domain and HRR curves for each scenario is shown in Figure 92. The domain size is 5.8 x 9.8 x 9.6 m³ for all scenarios, and the mesh size is 0.1 m.

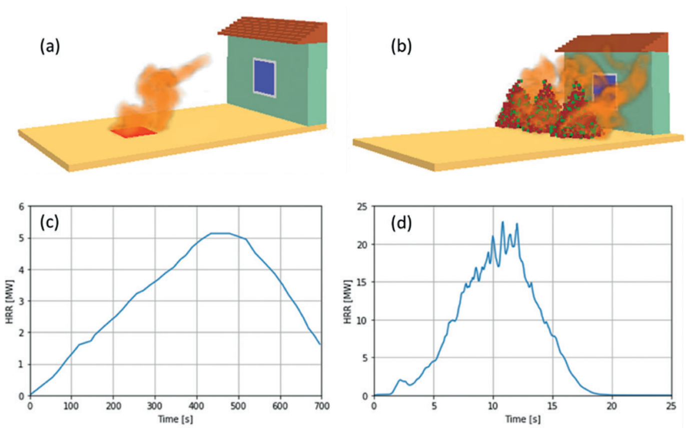

Figure 92. Simulation domain (a) and HRR curve (c) of the stack of wooden pallets located 5 m from the window; simulation domain (b) and HRR curve (d) of the three Douglas fir trees located 1 m from the window.

Table 23. Material properties for the glazing system scenarios.

Material	Specific heat capacity [kJ·kg^{-1}·K^{-1}]	Conductivity [W·m^{-1}·K^{-1}]	Density [kg/m^3]	Emissivity [-]
Float glass (Wang and Hu, 2019)	0.82	0.94	2,500	0.85
PVC (Thunderhead Engineering, 2022)	1.29 –1.59[A]	0.134 – 0.192[A]	1,380	0.95
Notes: A: The property varies with the temperature of the material				

Results from this analysis shows that the selected performance criterion ΔT_{cr} is not reached at a distance of 6.5 m for single pane and 5 m for double pane windows when exposed to the combustion of the stack of wooden pallets, and the same is valid for the performance criterion of the PVC frame, therefore these distances can be deemed to be safe. On the other hand, when it comes to the exposure to the combustion of the trees, the melting of the PVC frame is what causes failure of the glazing system, therefore the same safe distance is identified for double pane and for single pane glazing: this distance is 2 m (Vacca, 2023).

The second building sub-system that is here analysed is a concrete semi-confined space attached to the main envelope of a building which is used as a storage area. The performance criterion for a concrete wall is to maintain its load bearing capacity above the value of 74% (European Committee for Standardization, 2004a), in order to not sustain structural damage that could cause fire entrance inside the building. The chosen fire scenario consists of the combustion of a fuel pack containing 3 pallets, 4 small mattresses, 11 cardboard sheets, and 7 plastic buckets containing each 12 L of oil-based paint (Vacca *et al.*, 2022; HRR curve shown in Figure 93). The methodology for the calculation of the load bearing capacity entails three steps: (i) obtaining the adiabatic surface temperature (AST) as output of the FDS simulation (McGrattan *et al.*, 2023; the used mesh size is 0.1 m), (ii) identifying the temperature profile through the wall by using a finite difference method which uses the AST as input, (iii) calculating the load bearing capacity over time of the analysed wall cross-section according to Eurocode 2 EN 1992-1-1 (European Committee for Standardization, 2004b) and EN 1992-1-2 (European Committee for Standardization, 2004a). Concrete characteristics are those specified in Eurocode 2 (European Committee for Standardization, 2004a).

Results for the cross-section located at the back left corner of the semi-confined space (the corner where the fuel pack is located) at a height of 0.1 m (location where the highest AST is recorded) are shown in Figure 94, where temperature profiles through the cross section are plotted every 15 minutes and the load bearing capacity of the analysed cross section is plotted over the entire duration of the fire. In this scenario the load bearing capacity drops to 93%, remaining therefore well above the performance criterion of 74%. This scenario can therefore be deemed safe.

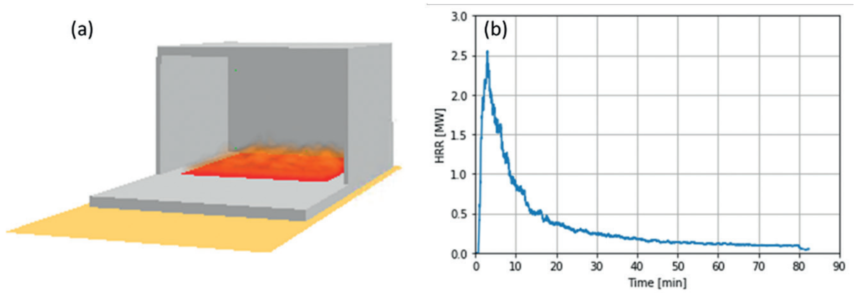

Figure 93. Simulation domain (a) and HRR curve (b) of the scenario involving fuel storage in a semi-confined space.

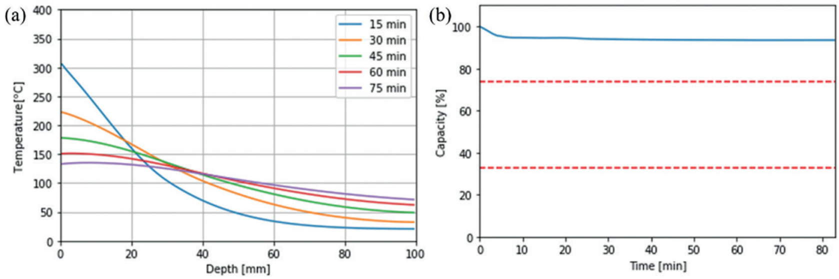

Figure 94. Results for the cross-section at 0.1 m: (a) temperature profile through the cross-section recorded every 15 minutes, (b) load bearing capacity of the analysed cross-section over time.

7.4.4. Future work

The presented methodology for the quantitative analysis of the vulnerability of selected WUI scenarios can be used as a baseline for the analysis of other scenarios that might include different configurations, fuels, building and property sub-systems and materials. When studying new scenarios, additional performance criteria must be identified depending on the sub-system or materials that will be analysed, and quantitative information of the chosen burning source must be obtained.

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8.

Policies, legislation and normatives in the context of WUI (property scale) fire risk

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8.1. Introduction to the normative regulation of the wildland-urban interface

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The present chapter aims to provide a brief overview on how the wildland-urban interface (WUI) in the pair house/surroundings is generally regulated by law, in view of preventing, reducing or repairing the effects of wildfires.

As differences of normative approaches between legal systems are frequent, mostly in domains — as is the WUI - where adjustment to national, regional and local specificities is paramount, our Introduction will focus on the main traits of such laws and regulations. Complementarily, Chapters 8.2 (Australian Regulatory Controls for Buildings at the Wildland-Urban Interface) and 8.4 (Land-Use Planning in the American Wildland Urban Interface: Avoidance or Compliance?) will detail legal systems — Australian and Californian –, showing how each deal with WUI challenges.

The methodology to perform such a normative analysis could be multifold. It could be centred in the selection of international standards and guidelines concerning fires in the Wildland-Urban Interface areas, taking into consideration specific regulatory fields (Intini, 2020), or it could be centred on specific tools of regulatory and non-regulatory nature (Miller, 2016 and Chapter 1.4. in this Part).

We will adopt an approach that mostly dwells around the several normative strategies adopted at different governance levels. Indeed, Law in its broader sense includes a wide set of normative instruments with different densities (from general principles to concrete decisions) and different legal effects (ranging from soft law instruments to harder sets of rules, that are binding, enforceable and whose violation is sanctionable).

Naturally these are not all or nothing dicothomies. In the in-between various normative options are possible, depending on several factors: the level of governance at stake (international, European, national, regional, local and transboundary), the scientific and technical knowledge or development achieved in the regulated field, the consensus reached in disputed areas and the nature and importance of the public interests involved.

8.1.1 Normative strategies related to the wildland-urban interface

At an international level, the importance of policy and, in a broad sense, normative instruments relevant to the WUI have been increasing, mostly after the Sendai Framework for Disaster Risk Reduction 2015-2030 (A/CONF.224/CRP.1), which lays down principles, priorities and concrete targets for action which should lead to a substantial reduction of disaster risk and losses. Together with the Sustainable Development Goals (mostly SDGs 13 and 15), the Sendai Framework reinforced the role of voluntary commitments and international efforts such as the Global Wildland Fire Network (GWFN) and the International Wildfire Preparedness Mechanism (IWPM). And although these are non-binding instruments their breadth and exemplary nature are one of the sources for legal changes applicable to the WUI in many legal systems.

Of course, some changes are easier to introduce than others; the case of mandatory fire risk insurances in the WUI is one of the examples of a legal measure that is seen by most as adequate and desirable (cf. Priority 3: Investing in disaster risk reduction for resilience of the Sendai Framework and Chapter 8.3. of this book), but has been seldomly put into practice, given given some hardships in defining concrete model risks.

At an international level, standardization efforts relevant to the WUI are also a beacon for better construction solutions from the point of view of reducing the vulnerabilities of buildings from large outdoor fire exposures - cf. ISO/TR 24188:2022(en) - Large outdoor fires and the built environment[7].

When confronted with the European Union level of regulation, it is abundantly clear that this international Entity has increasing powers in relation to both the prevention and the suppression of wildfires (Ponce, 2015). These powers are not only due to the European Union support competences in the civil protection field [article 6(g) of the Treaty of the Functioning of the European Union] but also due to the more profound competences related to the establishment and perfecting of the internal market. Indeed, this requires some level of harmonization of technical standards, for instance at the level of building requirements.

This is the case of Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonized conditions for the marketing of construction products, that is immediately applicable and binds public and private entities. Annex I of the aforementioned regulation states that fire safety is one of the basic requirements of construction works, which must be designed and built in accordance with certain fire safety requirements. However, these requirements essentially take into account fires originating within the

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[7] Available at: https://www.iso.org/obp/ui/en/#iso:std:iso:tr:24188:ed-1:v1:en

buildings themselves, specifically in terms of load/support capacity, the generation and spread of fire and smoke, limiting the spread of fire to adjacent works, ensuring adequate evacuation of occupants and safety levels for rescue teams. Notwithstanding the fact that the regulations are essentially geared towards the interior of the building, one should not forget the importance that some of these requirements have with regard to external ignition sources, particularly from forest fires. This is the case, for example, of the value of fireproofing products (such as fire doors) - particularly those that also face the outside of buildings, which prevent sparks or small embers from entering the inside of a building - and also the importance of fixed fire detection and firefighting systems inside buildings. These are, in fact, requirements that can mitigate damage if any incandescent material gets inside the building and starts a fire. Also, with a view to protecting buildings against the entry of sparks or incandescent embers, special attention should be paid to windows, chimneys and building ventilation systems.

This does not mean that Member States of the European Union cannot adopt their own construction regulations related to buildings in the WUI — this was recently the case in Portugal with Ordinance (Despacho) 8591/2022, of 13 July, adopted within the scope of the Rural Fires Integrated Management System, the most import piece of legislation regulating the WUI (Oliveira, 2023)[8]. However, the balance between formal and binding regulation and adaptability to new solutions and methodologies is still an issue within many European countries, traditionally based on formal and strict legal rules and not, for instance, in deemed-to-satisfy based solutions.

However, in other countries there is already abundant legislation on the construction of buildings at the WUI, such as Australia and the USA. In the US, the California Building Code regulates construction

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[8] For instance, in the neighboring Spain, the Spanish Building Code does not add any particular provision in terms of characteristics, materials and dimensions in the design and construction of houses at the WUI (.

in these areas and the respective safety aspects. In Australia, the National Construction Code (NCC) has sections designed to regulate construction in areas prone to rural fires, that are complemented by State and Territory legislation (in the form of Acts and Regulations) that give legal effect to the NCC in each concrete case.

A legal field of regulation that is "exclusive" to the WUI has to do with the establishment of defensible spaces, a concept that includes vegetation management (fuelbreaks and firebreaks) but can also involve other legal recommendations or obligations (for instance water infrastructures, adequate road access, etc.). In more serious cases, the legislator may provide for limitations or prohibitions on construction in fire risk areas, as to not to allow the creation of other wildland-urban interface or intermix areas or to avoid their sprawling. Given the recognized importance of these defensible spaces, but also the various factors that influence fire behaviour and therefore the technical requirements for fuel management, they may be found in several legislations but regulated in quite different modes, as the particularities of the place where management is carried out must be taken into consideration (Viegas, 2005; Lopes, 2002).

The regulation of these defensible spaces, however different in terms of the wildfire risk assessment criteria, is a generalized normative strategy — that according to the relevance of fire risk prevention in each State, may lead to severe legal consequences from civil, administrative and, even, criminal nature.

Another normative strategy not specifically linked to the WUI, but that should necessarily include the adequate consideration of the WUI areas, is related to the adoption of land use planning instruments. These are quite different from fire risk or forest use management plans, once they aim to regulate the use, occupation and transformation of the land, taking into consideration all relevant interests (public and private; urban and rural) and not only a specific interest (fire or forest management).

Nonetheless, not only do land use planning instruments already cover many States (in some States, at least one level of planning regulation is mandatory) but they also establish provisions that, taking into consideration — if plans are properly done — the risk assessment conducted and the environmental impacts analysed, are very stringent in allowing for new urban occupations that may further endanger communities, persons, animals and property. These plans could also redirect construction or impede growth in areas that have burned and are extremely likely to be hit again by fire.

Syphard *et al.* (2013) call land use planning as a measure "that represents a further shift in thinking, beyond the preparation of communities to withstand an inevitable fire, to preventing new residential structures from being exposed to fire in the first place". Although not a real alternative to specific tailored WUI measures (such as the defensible spaces), land use plans are indeed to be pursued further as instruments that may well contribute to contain WUI areas, at least when the interest in fire prevention is dully considered in their elaboration.

8.1.2. For an upgraded role of law within the wildland-urban interface

Despite all the efforts and normative strategies already at use, the problems posed by the WUI are not going away, given the increased population density in some areas, the pressure for a constant urban sprawl (and WUI growth) and even for the re(occupation) of burned WUI areas. Not forgetting the presence of more frequent and devastating fires under the current climate change conditions.

And, of course, law is also not going away, once its role as a regulator and a behaviour setter is particularly relevant even in times of environmental and social change (Bohman, 2021)

What we could anticipate or at least wish for is that law could be adjusted or upgraded to better regulate WUI areas and reduce the risk they encapsulate.

Indeed, if all legal systems, mostly the more complete one's at a State level, are a composite of several legal approaches or adopt hybrid normative strategies, it is important to monitor and evaluate if that "normative mix" is indeed working out. Or if, on the contrary, the approach taken should be adjusted, either to strengthen the binding nature of the rules and their enforceability, either to flexibilize the rules and to rely on other less stringent instruments, for instance giving a voice to community or citizens' initiatives. Law need not be and is not a straitjacket (Keiter, 2006), since it lives well with moments of lesser normative strength, as long as the applicable legal solutions are duly framed and predictable.

Besides adaptability, it is also important that technical knowledge and law go hand in hand. Today even, methods for identifying and classifying severity in WUI areas are regulated by law, with different levels of refinement, once they are linked to obligations or limitations imposed upon individuals (mostly under the defensible spaces framework).

However, in some cases, legal regulation is oversimplified, as is the case of Portugal, where only the type of activity at hand and the type of land (forest or agricultural) in the surroundings, and no other relevant factors as topography, climate and concrete vegetation, are relevant to determine the width and scope of those defensible spaces (Viegas, 2020). It is important, therefore, without over complexifying legal rules — which might render them virtually not understandable and, most probably, not respected — that they are attentive to technical knowledge and incorporate it into their core. This could indeed be the answer for better rules in what regards defensible spaces, building limitations and, even, insurance regulation.

8.2. Australian Regulatory Controls for Buildings at the Wildland-Urban Interface

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8.2.1. Introduction to Australian Regulatory Framework

The performance-based National Construction Code (NCC) is the primary set of technical design and construction provisions for buildings in Australia. The NCC sets the minimum required level for the safety, health, amenity, accessibility and sustainability for all buildings, with additional requirements applying in areas subject to specific hazard impacts such as wildfire. While the NCC is published by the Australian federal building regulator, the Australian Building Codes Board, it is State and Territory legislation (in the form of Acts and Regulations) that give legal effect to the NCC in each State and Territory of Australia. These State and Territory Acts and Regulations set out the legal framework and administrative mechanisms for the NCC to support the design and construction of buildings.

The NCC is published in three volumes, with the Building Code of Australia (BCA) being the NCC Volume One [ABCB, 2022a] and the NCC Volume Two [ABCB, 2022b], and the NCC Volume Three being the Plumbing Code of Australia[9]. Of most relevance to this

[9] The NCC Volume Three is not relevant to this chapter and is therefore not referred to again hereafter.

chapter, the NCC Volume One (one part of the BCA) primarily covers the design and construction of multi-residential, commercial, industrial and public assembly buildings, as well as some associated structures. In addition, the NCC Volume Two (the second part of the BCA along with NCC Volume One) primarily covers the design and construction of smaller scale buildings including houses, small sheds, carports and some associated structures.

Each volume of the NCC contains the following:

- Governing Requirements (mandatory); and
- Performance Requirements (mandatory); and
- Compliance options to meet the NCC requirements (optional); and
- State and Territory variations and additions.

Each volume of the NCC is split into two main sections:

- Administrative requirements contained within the Governing Requirements; and
- Technical requirements contained within the remaining sections of the volume of the NCC.

The Governing Requirements provide the rules and instructions for using and complying with the NCC and provide an understanding of how the technical requirements of the NCC should be applied to any particular situation. The over-arching principle of the performance-based NCC is that while the Governing Requirements and Performance Requirements are mandatory, i.e., the design and construction of every building must comply with these requirements, the NCC provides various compliance pathway options and does not prescribe which option should be used.

As shown in the upper half of Figure 95, each section of mandatory Performance Requirements in the NCC is preceded in a hierarchical framework by Objectives and Functional Statements, both of which act as guidance only.

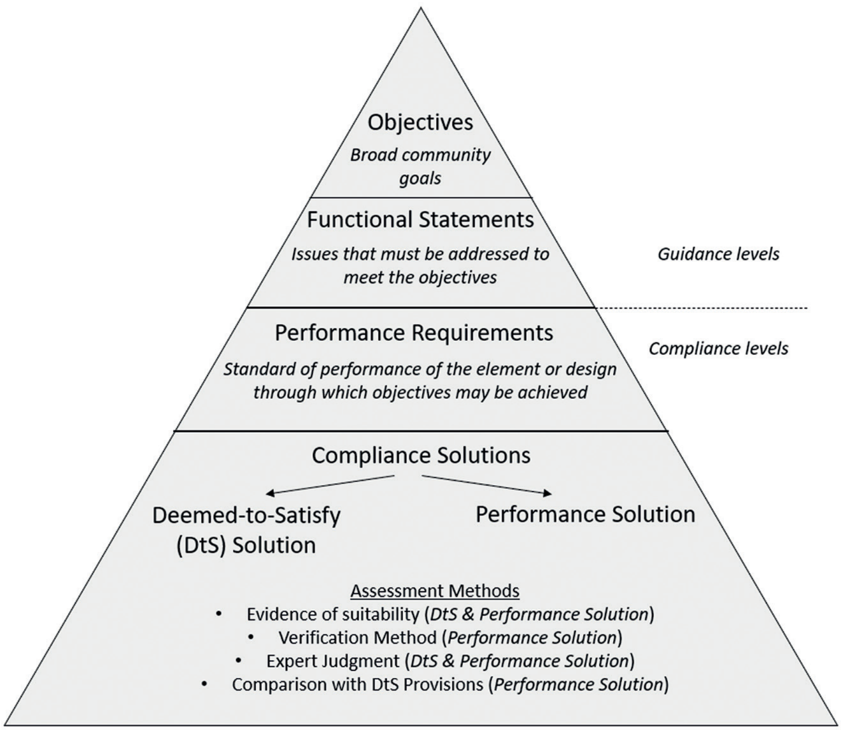


Figure 95. NCC compliance hierarchy.

Compliance with the NCC is achieved by complying with both the Governing Requirements of the NCC and the Performance Requirements. As indicated in the lower half of Figure 95, the Performance Requirements are satisfied by: (a) a Performance

Solution; (b) a Deemed-to-Satisfy Solution; or (c) a combination[10] of (a) and (b).

A Deemed-to-Satisfy (DtS) Solution is achieved by demonstrating that the design complies with the DtS Provisions, and hence the design is deemed to have met the Performance Requirements. A DtS Solution can show compliance with the DtS Provisions through one or a combination of two Assessment Methods: (a) Evidence of suitability; or (b) Expert Judgement.

A Performance Solution is achieved by demonstrating that the design complies with all relevant Performance Requirements, or that the design is at least equivalent to the Deemed-to-Satisfy Provisions. A Performance Solution must be shown to comply with the relevant Performance Requirements through one or a combination of four Assessment Methods: (a) Evidence of Suitability; (b) a Verification Method; (c) Expert Judgement; or (d) comparison with the Deemed-to-Satisfy Provisions.

'Evidence of Suitability' is a form of evidence which supports the use of a material, product, form of construction or design meets a Performance Requirement or DtS Provision, and may be in the form of formal certification, a laboratory test report, a certificate or report from a professional engineer, or another form of documentary evidence [ABCB, 2022a].

A 'Verification Method' is defined in the BCA as being "a test, inspection, calculation or other method that determines whether a Performance solution complies with the relevant Performance Requirements [ABCB, 2022a].

'Expert Judgement' is defined in the BCA as being "the judgement of an expert who has the qualifications and experience to determine

[10] A 'combination' means that part of the building design is a Performance Solution, and the remainder of the design is a DtS Solution.

whether a Performance Solution or DtS Solution complies with the Performance Requirements [ABCB, 2022a].

8.2.2. NCC Provisions Specific to Buildings at the WUI

The NCC uses building classifications to identify requirements for different intended purposes of buildings or parts of buildings, and the classification relates to the characteristics and intended use of the building. A building classification is a number between 1 and 10. In relation to the NCC volumes that contain the BCA, NCC Volume Two covers Class 1 and Class 10 buildings, while NCC Volume One covers Class 2 to Class 9 buildings. Table 24 provides a summary of the ten building classifications used in the BCA (NCC Volume One and NCC Volume Two).

The NCC defines a 'designated bushfire prone area' as "land which has been designated under a power of legislation[11] as being subject, or likely to be subject, to bushfires.". Designation of an area as bushfire prone is triggered through state planning policy and mapping of land within specified distances of vegetation deemed to constitute a potential wildfire hazard.

The NCC Volume One and the NCC Volume Two have slightly different provisions for buildings that are located in what are called 'designated bushfire prone areas', namely Part G5 Construction in Bushfire Prone Areas in the NCC Volume One, and Part H7 Ancillary Provisions and Additional Construction Requirements in the NCC Volume Two. Table 25 provides a comparison of the provisions from both the NCC Volume One and the NCC Volume Two.

[11] Typically, environmental planning legislation in the respective State or Territory.

Table 24. Building classifications in BCA.

NCC volume	Building classification	Description
Volume Two	Class 1	Building that is a dwelling. Class 1a is one or more buildings which together form a single dwelling, e.g.: (1) detached house; (2) Row house, terrace house, town house or villa, separated by fire-resisting wall. Class 1b is one or more buildings which together constitute, e.g.: (1) Boarding house, guest house, hostel or the like, accommodating less than 12 people and total floor area less than 300 m^2; (2) four or more single dwellings located on one allotment and used for short-term holiday accommodation
Volume One	Class 2	Building containing two or more sole-occupancy units
Volume One	Class 3	Residential building providing long-term or transient accommodation
Volume One	Class 4	Dwelling in a Class 5, 6, 7, 8 or 9 building if it is the only dwelling in the building
Volume One	Class 5	Office building used for professional or commercial purposes
Volume One	Class 6	Shop or other building used for sale of goods or supply of services, e.g., restaurant, supermarket, service station.
Volume One	Class 7	Storage-type building. Class 7a is a carpark. Class 7b is a building that is used for storage, or display of goods or produce for sale by wholesale
Volume One	Class 8	Process-type building
Volume One	Class 9	Building of a public nature. Class 9a is a health care building Class 9b is an assembly building Class 9c is a residential care building
Volume Two	Class 10	Non-habitable building or structure. Class 10a is a non-habitable building including a private garage, carport, shed or the like Class 10b is a structure that is a fence, mast, antenna, retaining wall, free-standing wall, swimming pool, or the like

Table 25. Comparison of provisions in NCC Volume One and NCC Volume Two.

Row	NCC Volume One	NCC Volume Two
1	**Objectives (first level in NCC Compliance Hierarchy — see Figure 95)**	
2	**G5O1 Objective** The Objective of this Part is to— (1) Safeguard occupants from injury from the effects of a bushfire; and (2) Protect buildings from the effects of a bushfire; and (3) Facilitate temporary shelter for building occupants who may be unable to readily evacuate the building prior to a bushfire."	**H7O1 Objective** The Objective is to— (4) Protect a building from the effects of a bushfire; and (5) Reduce the likelihood of fatalities arising from occupants of a Class 1[a] dwelling not evacuating a property prior to exposure from a bushfire event."
3	**Functional Statements (second level in NCC Compliance Hierarchy — see Figure 95)**	
4	**G5F1 Construction in bushfire prone areas** A building constructed in a designated bushfire prone area— (1) Is to provide a resistance to bushfires in order to reduce the danger to life and minimise the risk of the loss of the building; and (2) If occupied by people who may be unable to readily evacuate the building prior to a bushfire, is to be constructed so as to provide its occupants shelter from the direct and indirect actions of a bushfire."	**H7F4 Bushfire areas** A Class 1 building or a Class 10a building or deck associated with a Class 1 building constructed in a designated bushfire prone area is to provide resistance to bushfires in order to reduce the danger to life and reduce the risk of loss of the building. **** **H7F5 Private bushfire shelters** A structure designed for emergency occupation during a bushfire event must provide shelter to occupants from direct and indirect actions of a bushfire."
5	**Performance Requirements (third level in NCC Compliance Hierarchy — see Figure 95)**	
6	**G5P1 Bushfire resistance** A building that is constructed in a designated bushfire prone area must be designed and constructed to— (1) Reduce the risk of ignition from a design bushfire with an annual exceedance probability not more than 1:100 years, or 1:200 years for a Class 9 building; and (2) Take account of the assessment duration and intensity of the fire actions of the design bushfire; and (3) Be designed to prevent internal ignition of the building and its contents; and (4) Maintain the structural integrity of the building for the duration of the design bushfire. ****	**H7P5 Buildings in bushfire prone areas** A Class 1 building or a Class 10a building or deck associated with a Class 1 building that is constructed in a designated bushfire prone area must be designed and constructed to— (1) Reduce the risk of ignition from a design bushfire with an annual exceedance probability not more than 1:50 years; and (2) Take account of the assessment duration and intensity of the fire actions of the design bushfire; and (3) Be designed to prevent internal ignition of the building and its contents; and (4) Maintain the structural integrity of the building for the duration of the design bushfire. ****

Row	NCC Volume One	NCC Volume Two
6	**G5P2 Additional bushfire requirements for certain Class 9 buildings** A building that is constructed in a designated bushfire prone area and occupied by people who may be unable to readily evacuate the building prior to a bushfire must, to the degree necessary— (1) Reduce the risk of an untenable indoor environment for occupants during a bushfire event, appropriate to the— (a) Location of the building relative to fire hazards, including— (i) Classified vegetation; and (ii) Adjacent buildings, structures and movable objects; and (iii) Carparking areas and allotment boundaries; and (iv) Other combustible materials; and (b) Number of occupants to be accommodated within the building; and (c) Intensity of bushfire attack on the building; and (d) Duration of occupancy; and (e) Intensity of potential consequential fires; and (f) Occupant tenability within the building before, during and after the bushfire event; and (g) Combined effects of structural, fire exposure and other effects to which the building may reasonably be subjected; and (h) Provision of firefighting equipment and water supply to facilitate protection of the building; and (2) Be provided with vehicular access to the site to enable firefighting and emergency personnel to defend or evacuate the building; and (3) Have access to a sufficient supply of water for firefighting purposes on the site; and (4) Provide safe access within the site to the building (including carparking areas), as well as safe egress after the bushfire event."	**H7P6 Private bushfire shelters** A private bushfire shelter must be designed and constructed to provide a tenable environment for occupants during a design bushfire with an annual probability of exceedance not more than 1:200 years, appropriate to the— (1) Location of the private bushfire shelter relative to fire hazards including— (a) Predominant vegetation; and (b) Adjacent buildings and structures; and (c) Allotment boundaries; and (d) Other combustible materials; and (2) Occupancy of the private bushfire shelter; and (3) Bushfire intensity having regard for the bushfire attack level; and (4) Fire intensity from adjacent buildings and structures, allotment boundaries and other combustible materials; and (5) Ready access to the private bushfire shelter from the associated dwelling and occupant egress after the fire; and (6) Tenability within the private bushfire shelter for the estimated maximum period of occupancy; and (7) Generation of smoke, heat and toxic gases from materials used to construct the private bushfire shelter; and (8) Structural and fire loads and actions to which it may reasonably be subjected, appropriate to— (a) The topography between the private bushfire shelter and the predominant vegetation or other fire hazards; and (b) The distance between the private bushfire shelter and the predominant vegetation or other fire hazards; and (c) The size of the potential fire source and fire intensity; and (d) Wind loading; and (e) Potential impact from debris such as falling tree limbs; and (9) Degree of external signage identifying the location of the private bushfire shelter; and (10) Degree of internal signage identifying the design capacity and maximum period of occupancy; and (11) Degree of occupant awareness of outside environmental conditions; and (12) Degree of essential maintenance."

Row	NCC Volume One	NCC Volume Two
7	**Verification Methods**	
8	**G5V1 Buildings in bushfire prone areas** (1) Compliance with Performance Requirement G5P1 is verified if the ignition probability for a building exposed to a design bushfire does not exceed 10%. (2) Bushfire design actions must be determined in consideration of the annual probability of a design bushfire derived from— (a) Assigning the building or structure with an Importance Level in accordance with (3); and (b) Determining the corresponding annual probability of exceedance in accordance with Table G5V1. (3) A building or structure's Importance Level must be identified as one of the following: (a) Importance Level 1 — where the building or structure presents a low degree of hazard to life and other property in the case of failure. (b) Importance Level 2 — where the building or structure is not of Importance Level 1, 3 or 4 or is a Class 2 building accommodating 12 people or less. (c) Importance Level 3 — where the building is designed to contain a large number of people and is a— (i) Class 2 building accommodating more than 12 people; or (ii) Class 3 boarding house, guest house, hostel, lodging house or backpackers' accommodation; or (iii) Class 3 residential part of a hotel or motel; or (iv) Class 3 residential part of a school. (d) Importance Level 4 — where the building or structure is— (i) Essential to emergency management or post-disaster recovery; or (ii) Associated with hazardous facilities; or (iii) Subject to a necessary 'defend in place' strategy and is a— (A) Class 3 accommodation building for the aged, children or people with disabilities; or (B) Class 3 residential part of a health-care building which accommodates members of staff; or (C) Class 3 residential part of a detention centre; or (D) Building that operates in the event of a bushfire emergency, such as a public bushfire shelter or a bushfire emergency control centre.	**H7V2 Buildings in bushfire prone areas** (1) Compliance with H7P5 is verified if the ignition probability for a building exposed to a design bushfire does not exceed 10%. (2) Bushfire design actions must be determined in consideration of the annual probability of a design bushfire derived from— (a) assigning the building or structure an Importance Level in accordance with (3); and (b) determining the corresponding annual probability of exceedance in accordance with Table H7V2. (3) A building or structure's Importance Level must be identified as one of the following: (a) Importance Level 1 — where the building or structure presents a low degree of hazard to life and other property in the case of failure. (b) Importance Level 2 — where the building or structure is not of Importance Level 1 or 4 and is a Class 1a or 1b building accommodating 12 people or less. (c) Importance Level 4 — where the building is a Class 10c building and is subject to a necessary 'defend in place' strategy. (4) The ignition probability for a building must be assessed by application of the following: (a) An event tree analysis of relevant bushfire scenarios. (b) Design bushfire conditions that include combinations of the following actions appropriate to the distance between the building and the bushfire hazard: (i) Direct attack from airborne burning embers. (ii) Burning debris and accumulated embers adjacent to a building element. (iii) Radiant heat from a bushfire front. (iv) Direct flame attack from a bushfire front. (5) Applied fire actions must allow for reasonable variations in— (a) fire weather; and (b) vegetation, including fuel load, burning behaviour of vegetation (including the potential for crown fires); and (c) the distance of the building from vegetation; and (d) topography, including slopes and features that may shield; and (e) ignition of adjacent buildings, building elements, plants, mulch and other materials; and

Row	NCC Volume One	NCC Volume Two
8	(6) The ignition probability for a building must be assessed by application of the following: (a) An event tree analysis of relevant bushfire scenarios. (b) Design bushfire conditions that include combinations of the following actions appropriate to the distance between the building and the bushfire hazard: (i) Direct attack from airborne burning embers. (ii) Burning debris and accumulated embers adjacent to a building element. (iii) Radiant heat from a bushfire front. (iv) Direct flame attack from a bushfire front. (7) Applied fire actions must allow for reasonable variations in— (a) Fire weather; and (b) Vegetation, including fuel load, burning behaviour of vegetation (including the potential for crown fires); and (c) The distance of the building from vegetation; and (d) Topography, including slopes and features that may shield; and (e) Ignition of adjacent buildings, building elements, plants, mulch and other materials; and (f) Effective size of fire front; and (g) Duration of exposure; and (h) Flame height; and (i) Flame tilt; and (j) Flame adhesion to sloping land; and (k) The height of the building and its elements. (8) The assessment process must include consideration of— (a) The probability of non-complying construction of critical aspects of an approved design; and (b) The probability of critical aspects of an approved design being fully functional during the life of the building; and (c) Inclusion of safety factors; and (d) Sensitivity analysis of critical aspects of a proposed design."	(e) effective size of fire front; and (f) duration of exposure; and (g) flame height; and (h) flame tilt; and (i) flame adhesion to sloping land; and (j) the height of the building and its elements. (9) The assessment process must include consideration of— (a) the probability of non-complying construction of critical aspects of an approved design; and (b) the probability of critical aspects of an approved design being fully functional during the life of the building; and (c) inclusion of safety factors; and (d) sensitivity analysis of critical aspects of a proposed design."

Row	NCC Volume One	NCC Volume Two
9	**Deemed-to-Satisfy Provisions**	
10	**G5D1 Deemed-to-Satisfy Provisions** (1) Where a Deemed-to-Satisfy Solution is proposed, Performance Requirements G5P1 and subject to G5D2, G5P2, are satisfied by complying with G5D3 and G5D4. (2) Where a Performance Solution is proposed, the relevant Performance Requirements must be determined in accordance with A2G2(3) and A2G4(3) as applicable. **** **G5D2 Application of Part** The Deemed-to-Satisfy Provisions of this Part apply in a designated bushfire prone area to— (a) A Class 2 or 3 building; or (b) A building located in an area subject to a Bushfire Attack Level (BAL) not exceeding BAL—12.5, determined in accordance with AS 3959 that is— (i) A Class 9a health-care building; or (ii) A Class 9b— (A) Early childhood centre; or (B) Primary or secondary school; or (iii) A Class 9c residential care building; or (c) A Class 10a building or deck immediately adjacent or connected to a— (i) Class 2 or 3 building; or (ii) A building of a type listed in (b). **** **G5D3 Protection — Residential buildings** In a designated bushfire prone area, the following must comply with AS 3959: (a) A Class 2 or 3 building. (b) A Class 10a building or deck immediately adjacent or connected to a Class 2 or 3 building. **** **G5D4 Protection — certain Class 9 buildings** (1) In a designated bushfire prone area, the following must comply with Specification 43: (a) A Class 9a health-care building. (b) A Class 9b— (i) Early childhood centre; or (ii) Primary or secondary school. (c) A Class 9c residential care building. (2) In a designated bushfire prone area, a Class 10a building or deck immediately adjacent or connected to a building of a type listed in (1) must comply with S43C2 and S43C13."	**H7D1 Deemed-to-Satisfy Provisions** (1) Where a Deemed-to-Satisfy Solution is proposed, Performance Requirements H7P1 to H7P5 are satisfied by complying with H7D2 to H7D5. (2) Where a Performance Solution is proposed, the relevant Performance Requirements must be determined in accordance with A2G2(3) and A2G4(3) as applicable. (3) If a private bushfire shelter is installed, it must comply with Performance Requirement H7P6. **** **H7D4 Construction in bushfire prone areas** (1) The requirements of (2) only apply in a designated bushfire prone area. (2) Performance Requirement H7P5 is satisfied for a Class 1 building, or a Class 10a building or deck associated with a Class 1 building, if it is constructed in accordance with— (a) AS 3959; or (b) NASH Standard — Steel Framed Construction in Bushfire Areas."

Row	NCC Volume One	NCC Volume Two
11	**Ancillary provisions**	
12	**Specification 43 — Bushfire Protection for certain Class 9 buildings** **S43C1 Scope** (1) This Specification sets out bushfire protection measures for buildings described in G5D4. (2) Compliance with this Specification does not guarantee the safety of building occupants or the maintenance of tenable conditions within a building during a bushfire event. **** **S43C2 Separation from classified vegetation** (1) The building must be separated from classified vegetation— (a) by not less than the minimum distances specified in Table S43C2; or (b) such that radiant heat flux on exposed building elements will not exceed 10 kW/m^2. (2) For the purposes of (1), the term 'classified vegetation' has the meaning that it has in AS 3959. **** **S43C3 Separation between buildings** (1) The building must be located not less than 12 m from any other building. (2) The separation distance required by (1) need not be complied with if the building is constructed— (a) with external walls that have an FRL of not less than 60/60/60 when tested from the outside, including any openings protected in accordance with AS 3959 for BAL—19 or greater; or (b) for external walls and roof, using a material or system that satisfies the test criteria of AS 1530.8.1 for a radiant heat flux of 10 kW/m^2 or greater. **** **S42C4 Separation from allotment boundaries and carparking areas** (1) The building must be located not less than 10 m from any allotment boundary or open carparking area/spots. (2) The separation distance required by (1) need not be complied with if the building is constructed— (a) with external walls that have an FRL of not less than 60/60/60 when tested from the outside, including any openings protected in accordance with AS 3959 for BAL—19 or greater; or (b) for external walls and roof, using a material or system that satisfies the test criteria of AS 1530.8.1 for a radiant heat flux of 10 kW/m^2 or greater. ****	

Row	NCC Volume One	NCC Volume Two
12	**S43C5 Separation from hazards** The external walls and roof of the building must be protected from potential hazards on the site such as liquefied petroleum gas bottles, fuel storage, storage of combustible materials, waste bins, vehicles, machinery, and the like, by— (a) a separation distance of not less than 10 m; or (b) where within the 10 m separation distance described in (a), constructed with external walls that have an FRL of not less than 60/60/60 when tested from the outside, including any openings protected in accordance with AS 3959 for BAL—19 or greater; or (c) for external walls and roof, using a material or system that satisfies the test criteria of AS 1530.8.1 for a radiant heat flux of 10 kW/m^2 or greater. **** **S43C6 Non-combustible path around building** A non-combustible pathway directly adjacent to the building and not less than 1.5 m wide must be provided around the perimeter of the building. **** **S43C7 Access pathway** (1) Access pathways that lead to a road or open space must— (a) be readily identifiable; and (b) have an even surface; and (c) have a minimum clear width of not less than 1 m. (2) If the access pathway is an accessway that is required to comply with Part D4, the requirements of Part D4 override (1) to the extent of any inconsistency. **** **S43C8 Exposed external surfaces** An external area designed to hold people unable to be safely accommodated within the building, that may be exposed to radiant heat flux from a fire front during a bushfire event, must not be exposed to an incident radiant heat flux from the fire front exceeding 1 kW/m2 above background solar radiant heat flux. ****	

Row	NCC Volume One	NCC Volume Two
12	**S43C9 Internal tenability** To maintain internal tenability throughout the duration of occupancy during a bushfire event, the building must comply with the following: (a) An air handling system must be provided that is capable of— (i) being adjusted for full recycling of internal air for a period of not less than 4 hours to avoid the introduction of smoke into the building; and (ii) maintaining an internal air temperature of not more than 25°C. (b) The building envelope must be designed such that if an air handling system required by (a) fails, then— (i) internal air temperatures can be maintained below 39°C; and (ii) internal surface temperatures can be maintained below 60°C. (c) If the building is divided into separate compartments, then, for the purposes of (a), each compartment must have a separate air handling system. (d) Each air handling system required by (a) must be designed to account for the activation of smoke detectors from low concentrations of smoke from external sources, so as to ensure that air-conditioning and other essential systems remain operational. **** **S43C10 Building envelope** The building envelope must be constructed in accordance with AS 3959 — BAL 19 or greater, except that where the use of combustible materials is permitted by AS 3959, they are not to be used unless permitted by C2D10(4), (5) or (6). **** **S43C11 Supply of water for fire-fighting purposes** Water for fire-fighting purposes must be available and consist of— (a) a fire hydrant system complying with E1D2, or (b) a static water supply consisting of tanks, swimming pools, dams or the like, or a combination of these, together with suitable pumps, hoses and fittings, capable of providing the required flow rate for a period of not less than 4 hours, determined in consultation with the relevant fire brigade. ****	

Row	NCC Volume One	NCC Volume Two
12	**S43C12 Emergency power supply** (1) Emergency power must be provided to support, for not less than 4 hours before and 2 hours after the passing of the fire front during a bushfire event, the ongoing operation of— (a) air handling systems to maintain internal tenability; and (b) any pumps for firefighting; and (c) any emergency lighting and exit signs; and (d) any other emergency equipment listed in C3D14(6) and required to be provided. (2) Manual control for emergency back-up power supply must be provided to facilitate manual intervention where the power supply fails or runs out. **** **S43C13 Signage** Signage must be provided to warn building occupants against storing combustible materials under or adjacent to the building. **** **S43C14 Vehicular access** Vehicular access to the building must be provided in accordance C3D5(2), as if the building were a large, isolated building for the purposes of C3D4.	

8.2.3. Comparison of NCC Provisions

Comparing the various NCC provisions detailed in Table 25, at the top (Objectives) level of the NCC compliance hierarchy (see Figure 95), as detailed in Row 2 of Table 25 the focus in the NCC Volume One Part G5 is on safeguarding occupants, protecting buildings, and facilitating temporary shelter where evacuation does not occur. The corresponding Objectives in the NCC Volume Two Part H7 focus on protecting buildings and reducing the likelihood of fatalities where evacuation does not occur. This reflects the different occupancies of the buildings whereby people are more likely to leave a place of work as opposed to their homes to which they have greater emotional attachment.

At the second (Functional Statements) level of the NCC compliance hierarchy, as detailed in Row 4 of Table 25 the focus in the NCC

Volume One is providing resistance to bushfires so as to reduce the danger to life and minimise the risk of the loss of buildings, and to provide shelter from bushfire actions where evacuation does not occur. In the NCC Volume Two, the same 'providing resistance' Functional Requirement is stipulated, as well as a second corresponding Functional Requirement for private bushfire shelters.

At the first of the two compliance levels (the Performance Requirements section in the NCC compliance hierarchy at the third level in Figure 95), as detailed at Row 6 in Table 25, both the NCC Volume One and Volume Two have a probabilistic ignition reduction requirement, namely not more than 1:100 years or 1:200 years (depending on the Building Class) in Volume One, and not more than 1:50 years in Volume Two. In addition, Volume One and Volume Two have a further three identical requirements relating to duration and intensity of the design bushfire, prevention of internal ignition, and maintenance of structural integrity. The final type of Performance Requirement in both Volume One (for a certain Building Class) and Volume Two relates to the situation where evacuation is not possible or does not occur. For Volume One this addresses reducing the risk of untenable indoor conditions, and for Volume Two a private bushfire shelter when the probability of design bushfire exceedance being more than 1:200 years.

The second of two compliance levels (the Compliance Solutions section in the NCC compliance hierarchy at the fourth level in Figure 95), both Volume One and Volume Two provide a single Verification Method (G5V1 and H7V2, respectively) as well as various Deemed-to-Satisfy Provisions (Row 10 in Table 25). As stated previously, a Verification Method is one of four Assessment Method options to show that a Performance Solution (i.e., a performance-based design) complies with the relevant Performance Requirements.

With reference to Row 8 in Table 25, Verification Method G5V1 and H7V2 have six common elements, as follows:

1. The stipulation that compliance with relevant the Performance Requirement is verified if the ignition probability for the design bushfire does not exceed 10% - this is essentially what is called the 'performance criterion' in performance-based design.
2. The requirement that to determine the bushfire design actions consideration must be given to the annual probability of a design bushfire based on the Importance Level of the building or structure, and tabulated annual probability of exceedance (APE) thresholds.
3. An Importance Level 1 building/structure is one where there is a low degree of hazard to life and other property, while at the other end of the range, an Importance Level 4 building/structure is essential or critical or where there is a 'defend in place' strategy for occupants who are unable to evacuate. In Table 26, the APE data from Table G5V1 and Table H7V2 in Verification Method G5V1 and Verification Method H7V2, respectively, are reproduced.

Table 26. Annual probability of exceedance (APE) for design bushfire actions.

Importance Level	Complex analysis APE for bushfire exposure	Simple analysis APE for weather conditions (design bushfire)
1	No requirement	No requirement
2	1:500	1:50
3	1:1000	1:100
4	1:2000	1:200
Note: Complex analysis must consider the probability of ignition, fire spread to the urban interface and penetration of the urban interface coincident with fire weather conditions		

4. The requirement that the ignition probability be assessed using an event tree analysis (or other form of consistent probabilistic analysis) of relevant bushfire scenarios, and that the design

bushfire include various actions appropriate to the distance between the building/structure and the bushfire hazard.

5. The requirement that applied fire actions allow for reasonable variations in eleven variables, such as fire weather, vegetative fuel, etc.
6. Requirements for consideration of uncertainty in the analysis.

The Australian federal building regulator has also published a document entitled Handbook: Bushfire Verification Method [ABCB, 2021] which provides non-mandatory guidance for the use and application of both Verification Method G5V1 and Verification Method H7V2.

With reference to Row 10 in Table 25, Part G5 in the NCC Volume One, and Part H7 in the NCC Volume Two contains various Deemed-to-Satisfy Provisions.

In relation to the DtS Provisions in Volume One, buildings that are Building Class 2 to 9 in a designated bushfire prone area must comply with Australian Standard AS 3959 (Standards Australia, 2020). Class 9 buildings (health care facilities, early childhood centres, primary or secondary schools and residential care buildings) are required to comply with AS 3959 to BAL—12.5 as long as they are not subject to more than 10 kW/m^2 and also comply with the Ancillary Provisions in Specification 43 (refer to Row 12 in Table 25), and a Building Class 10a building, must comply with the Ancillary Provisions in Specification 43. Critically, should the building be subject to more than 10 kW/m^2 there are no DtS Provisions that are applicable, and the Verification Methods provided in the Bushfire Verification Handbook (ABCB, 2021) are also not applicable.

To compare AS 3959 and Specification 43, the former is a prescribed assessment methodology, while the latter is a series of prescriptive requirements that must be complied with. Specification 43 includes a range of requirements relating to various aspects for designing a building in a bushfire prone area, namely: a) separation of the building from classified vegetation (see specific requirements in Table 27, being Table S43C2 in the NCC Volume Two); b) separation between buildings; c) separation from allotment boundaries and carparking areas; d) Separation from hazards; e) non-combustible path around buildings; f) access pathways; g) exposed external areas; h) internal tenability; i) building envelope; j) supply of water for fire-fighting purposes; k) emergency power supply; l) signage; and m) vehicular access.

Table 27. Minimum distance of building to classified vegetation.

Vegetation classification	Slope	Minimum distance (m) of the building to classified vegetation
High risk	Upslope and flat land	60
High risk	Downslope max 20 degrees	110
Medium risk	Upslope and flat land	40
Medium risk	Downslope max 20 degrees	80
Low risk	Upslope and flat land	30
Low risk	Downslope max 20 degrees	50

Notes:
(1) Table values are based on a Fire Danger Index of 100 in accordance with AS 3959.
(2) High risk equates to vegetation classification of forest and woodland in accordance with AS 3959.
(3) Medium risk equates to vegetation classification of scrub and rainforest in accordance with AS 3959.
(4) Low risk equates to vegetation classification of shrubland, mallee/mulga and grassland in accordance with AS 3959.

In relation to the Deemed-to-Satisfy Provisions in Volume Two, buildings must either comply with AS 3959 (SA, 2020), or the National Association of Steel Framed Housing (NASH) standard NS 300 (NASH, 2021), and a private bushfire shelter must comply directly with Performance Requirement H7P6 (i.e., there are no Deemed-to-Satisfy Provisions for private bushfire shelters).

8.2.4. Deemed-to-Satisfy Provisions in Australian Standard AS 3959

The version of AS 3959 that is referenced in the NCC Volume One and the NCC Volume Two was published in 2018 and incorporates Amendment 2 in 2020 (SA, 2020). The Foreword to AS 3959 states that "the standard is primarily concerned with improving the ability of buildings in designated bushfire-prone areas to better withstand attack from bushfire thus giving a measure of protection to the building occupants (until the fire front passes) as well as to the building itself". The stated objective of AS 3959 is to specify "requirements for the construction of buildings in bushfire-prone areas in order to improve resistance to bushfire attack from burning embers, radiant heat, flame contact and combinations of the three attack forms".

The essence of AS 3959 is to (i) determine the bushfire attack level (BAL) that a building in a bushfire-prone area could be subjected to, and (ii) the corresponding construction required for the building (Baker *et al.*, 2020). The BAL is defined in AS 3959 as being "a means of measuring the severity of a building's potential exposure to ember attack, radiant heat and direct flame contact, using increments of radiant heat expressed in kilowatts per metre squared, and the basis for establishing the requirements for construction to improve protection of building elements from attack by bushfire".

The six BALs contained in AS 3959 are: BAL—LOW; BAL—12.5; BAL—19; BAL—29; BAL—40; and BAL—FZ. BAL—FZ[12] is defined in AS 3959 as "the highest level of bushfire attack as a consequence of direct exposure to flames from the fire front in addition to heat flux and ember attack". AS 3959 contains two methods for determining BALs; a simplified procedure (Method 1) and a detailed procedure (Method 2).

[12] The postscript 'FZ' stands for 'flame zone'.

Method 1 is a simplified procedure involving five steps to determine BALs. Step 1 involves determining the relevant fire danger index (FDI), which is a prescribed value between 40 (Northern Territory and Queensland) and 100 (Australian Capital Territory, and parts of New South Wales), depending on the jurisdiction and region, as shown in Table 28.

Table 28. FDI Values in different Jurisdictions and Regions (Data from Table 2.1 in AS 3959 (SA, 2020).

Jurisdictional and Regional Values for FDI[1]	
State/region	**FDI**
Australian Capital Territory	100
New South Wales	
(a) Greater Hunter, Greater Sydney, Illawarra/Shoalhaven, Far South Coast and Southern Ranges fire weather districts[2]	100
(b) NSW alpine areas[3]	50
(c) NSW general (excluding alpine areas, Greater Hunter, Greater Sydney, Illawarra/Shoalhaven, Far South Coast and Southern Ranges fire weather districts)	80
Northern Territory	40
Queensland	40
South Australia	80
Tasmania	50
Victoria	
(a) Victoria alpine areas[3]	50
(b) Victoria general (excluding alpine areas)	100
Western Australia	80
Notes: 1. The FDI values may be able to be refined within a jurisdiction or region where sufficient climatological data is available and in consultation with the relevant authority. 2. Refer to this link for an example for NSW: http://www.bom.gov.au/nsw/forecasts/fire-forecasts.shtml 3. Refer to NCC Volume Two for definition of alpine areas.	

FDI is a defined term in AS 3959, namely "the chance of a fire starting, its rate of spread, its intensity and the difficulty of its suppression, according to various combinations of air temperature, relative humidity, wind speed and both the long- and short-term drought effects". The notes associated with the FDI definition in AS 3959 indicate that FDI refers to the Forest Danger Index calculated by the McArthur Mk 5 Forest Fire Danger Meter using published equations (Noble *et al.*, 1980) while the Grassland Fire Danger Index values are calculated by the McArthur Mk 4 Grassland Fire Danger Meter using the published equations (Purton, 1982). It is worth noting that a limitation of AS 3959 with respect to the application of historical fire weather data was identified in the 2020 Royal Commission into National Natural Disaster Arrangements (Australian Government, 2020). However, this limitation only applies where Method 1 of AS 3959 (discussed in subsequent paragraphs) is applied, as the resultant tables rely on Fire Danger Indices from 2009 data. The limitation is easily addressed through use of the elevated Fire Danger Indices calculated using Annual Probabilities of Exceedance.

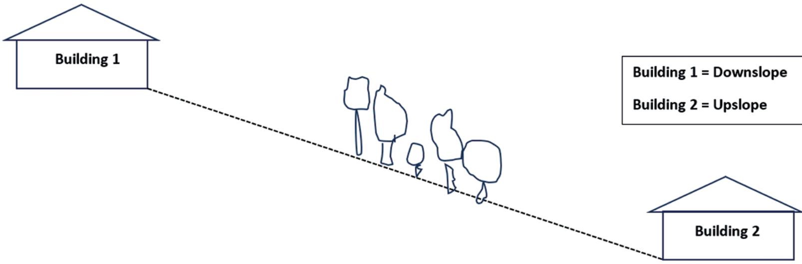
Step 2 in Method 1 involves determining the vegetation classification type(s). Eight different vegetation classifications are used in AS 3959, being: A – Forest; B - Woodland; C – Shrubland; D – Scrub; E – Mallee/Mulga; F – Rainforest; G – Grassland; and H – Tussock/Moorland. Where low threat vegetation occurs (e.g., managed grassland, saline wetlands, public parklands, vineyards, etc.) and non-vegetated areas (e.g., more than 100 m to nearest vegetation, waterways, roads, rocky outcrops, etc.) occur, the BAL is assessed as being BAL—LOW, and the provisions of AS 3959 do not apply.

Step 3 in Method 1 involves determining the distance of the building site from classified vegetation type(s). The distance is a horizontal measurement from the nearest external wall of the building (i.e., it ignores eaves and roof overhangs) to the unmanaged vegetation. The area between the external wall and the unmanaged vegetation may contain vegetation which is not required to be classified.

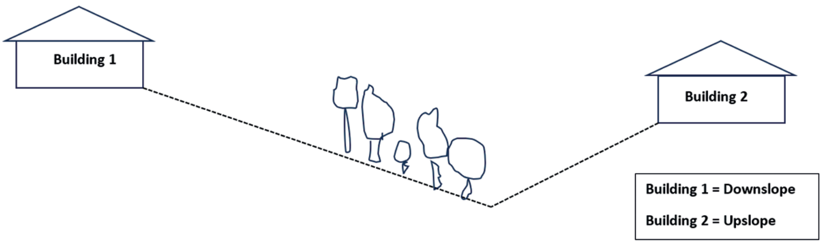
Step 4 in Method 1 involves determining the effective slope of the land under the classified vegetation, i.e., it is not the slope between the building and the classified vegetation, but the slope under the area of vegetation itself. As well as determining the effective slope in degrees from various tables in AS 3959, a determination of whether it is upslope or downslope in relation to the building site is made. In simple terms, upslope occurs where the point of the vegetation nearest the building is lower than the furthest point of the vegetation, and downslope is vice versa, as shown in Figure 96. AS 3959 stipulates that all classified vegetation that is upslope is assumed to be flat land (i.e., an effective slope of 0 degrees) since an approaching fire travels slower down a hill.

Step 5 in Method 1 is to determine the BAL, using tables published in AS 3959 and based on the determination of FDI, classified vegetation type(s), the distance from the site to the nearest classified vegetation, and the effective slope.

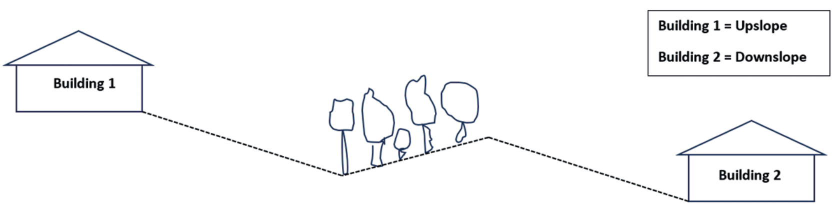
Having established the relevant BAL for the building in question, it is then a case of designing the building in question to comply with the relevant construction sections of AS 3959. Table 29 provides a summary of the BAL descriptions of the bushfire attack and exposure, and the sections in AS 3959 that apply to each BAL.



(a)



(b)



(c)

Figure 96. Illustrative Examples of Effective Upslope and downslope: (a) Building 1 — Downslope, Building 2 - Upslope; (b) Building 1 — Downslope, Building 2 — Upslope; (c) Building 1 — Upslope, Building 2 - Downslope (Adapted from AS 3959 Fig. 2.3 (SA, 2020).

Table 29. BAL Descriptions and Construction Sections in AS 3959 (based on information provided in Table 3.1 of AS 3959 SA, 2020).

BAL	BAL Description	Construction Section(s)
BAL—LOW	Insufficient risk to warrant specific construction requirements	4
BAL—12.5	Ember attack	3 & 5
BAL—19	Increasing ember attack and burning debris ignited by windborne embers together with increasing heat flux	3 & 6
BAL—29	Increasing ember attack and burning debris ignited by windborne embers together with increasing heat flux	3 & 7
BAL—40	Increasing ember attack and burning debris ignited by windborne embers together with increasing heat flux with an increased probability of direct flame contact	3 & 8
BAL—FZ	Direct flame exposure from fire front as well as heat flux and ember attack	3 & 9

Sections 5 to 8 in AS 3959 provide specific construction requirements for BAL—12.5 to BAL—40, respectively. Each of these sections is a mix or prescriptive provisions and 'performance-based' requirements, where for the latter, construction elements must meet a certain level of performance when tested to Australian Standard AS 1530.8.1 (SA, 2018a). Various provisions apply to different elements of construction, such as sub-floor supports, floors, walls, external glazed elements and doors, roofs, verandas and the like, and above-ground utility piping.

AS 1530.8.1 provides methods for determining the performance of external construction elements when exposed to radiant heat, burning embers and burning debris. The radiant heating regime consists of a standard exposure profile for each of the different levels BAL—12.5 to BAL—40, as shown schematically in Figure 97, where there is a rapid heating phase, followed by a constant peak for 120 seconds (2 minutes), and then gradual decay phase, with a total radiant heat exposure period of 600 seconds (10 minutes) (Baker *et al.*, 2020).

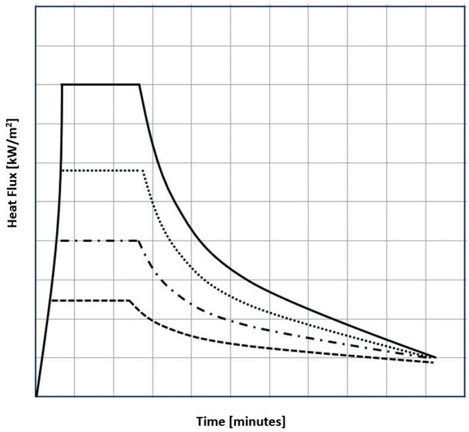


Figure 97. Schematic radiant heat exposure profiles for different BALs (adapted from AS 1530.8.1, Fig. 14.1 (SA, 2018a).

To achieve the applicable radiant heat exposure shown in Figure 97, a vertical specimen holder frame that is used for standard fire resistance testing to Australian Standard AS 1530.4 (SA, 2014), with a steel plate infill, acts as a radiator. To achieve radiant heat exposure to the test specimen of the profile shown in Figure 97, control of the fire resistance furnace heating achieves the initial growth and subsequent steady phases, while the test specimen is moved progressively further away from the radiating steel panel during the final decay phase (Baker *et al.*, 2020).

In AS 1530.8.1, burning ember exposure to vertical walls and the underside of exposed horizontal surfaces (i.e., areas where burning embers cannot accumulate) is treated as a form of piloted ignition and is approximated by a small pilot gas flame that is manually introduced to areas of the test specimen which are exhibiting significant pyrolysis behaviour. Exposure to burning debris and an accumulation of burning embers, on upper surfaces that are horizontal or nearly so, is represented by small timber cribs which are pre--ignited prior to the test procedure commencing (Baker *et al.*, 2020).

In the AS 1530.8.1 test method, the specimen is observed for a period of 60 minutes, and a series of criteria are monitored during that period, as follows:

a) The formation of 3 mm diameter through gaps.
b) Sustained flaming of more than 10 seconds on the non-fire side.
c) Flaming on the fire-exposed side at the end of the 60-minute test period.
d) Radiant heat flux 365 mm from the non-fire side in excess of 15 kW/m^2 from glazed/uninsulated areas of the test specimen.
e) Mean and maximum temperature rises greater than 140 K and 180 K, respectively, on the non-fire side of the test specimen (except for (d) above).
f) Radiant heat flux 250 mm from the fire-exposed side in excess of 3 kW/m^2 between 20 and 60 minutes.
g) Mean and maximum temperatures of the internal faces exceeding 250 °C and 300 °C, respectively, between 20 and 60 minutes.

Section 9 in AS 3959 provides the construction requirements where a building is classified as BAL—FZ and is the most onerous of the construction sections in AS 3959. Where the prescriptive provisions are not adopted, or the setback distance for the building to the classified vegetation is less than 10 m, the relevant elements of construction must meet the specified performance level when tested in accordance with Australian Standard AS 1530.8.2 (SA, 2020b). AS 1530.8.2 provides test methods for determining the performance of external elements of construction when exposed to direct flame impingement from the bushfire fire front (Baker *et al.*, 2020). The 'direct flame impingement' is achieved by subjecting a standard fire resistance test specimen to a standard fire resistance test in accordance with AS 1530.4 (SA, 2014) for a 30-minute period, followed by a 60-minute monitoring period once the test specimen has been removed from the fire resistance furnace, i.e., a total test duration of 90 minutes (Baker *et al.*, 2020). The following performance criteria are monitored during the test:

a) Formation of 3 mm diameter through gaps.
b) Flaming on the fire-exposed face more than 30 minutes after the completion of 30-minute heating phase.
c) Radiant heat flux 365 mm from the non-fire side in excess of 15 kW/m^2 from glazed and uninsulated areas.
d) Mean and maximum temperature rises greater than 140 K and 180 K, respectively, on the non-fire side of the test specimen (except for (c) above).
e) Radiant heat flux 250 mm from the fire-exposed side in excess of 3 kW/m^2 more than 30 minutes after completion of the 30-minute heating phase.
f) Mean and maximum temperatures of internal faces exceeding 250 °C and 300 °C, respectively, more than 30 minutes after completion of 30-minute heating phase.

Method 2 in AS 3959 is a more comprehensive, ten-step, methodology for determining the applicable BAL for a building and follows similar principles to Method 1. The primary difference between the two methods is that as opposed to simply looking up a table as is required in Method 1, Method 2 requires each input (FDI, fuel load, emissivity, flame temperature etc) to be manually entered and the associated complex calculations completed. While more complex, Method 2 enables more detailed consideration of individual site characteristics and can be adapted to consider short fire runs, restricted vegetation geometry, and view factor shielding in urban environments (Penney, *et al.*, 2020). The limits of applicability for Method 2 are that the effective slope under the classified vegetation is no more than 30 degrees downslope or 15 degrees upslope and the slope of the land between the building site and the classified vegetation is no more than 20 degrees, regardless of the slope type (SA, 2020).

Step 1 in Method 2 is to determine the relevant FDI or wind speed. Step 2 involves the determination of the vegetation classification, the fuel loads and the height of the vegetation. Step 3 requires that the effective slope under the classified vegetation be determined. Step 4 involves the determination of the slope of the land between the classified vegetation and the building site. Step 5 is to determine the distance to the classified vegetation from the building site. Step 6 requires the calculation of the flame length. Step 7 requires the determination of the flame width. Step 8 involves the determination of the elevation of the radiation receiver. Step 9 requires the radiant heat flux to be calculated. Step 10 is to then determine the applicable BAL.

Full details of Method 2 are provided in Appendix B of AS 3959 (SA, 2020).

8.2.5. Deemed-to-Satisfy Provisions in NASH Standard NS 300

The version of NASH Standard NS 300 that is referenced in the NCC Volume Two was published in 2021 (NASH, 2021). The Foreword to NS 300 states that "this Standard sets out acceptable construction solutions for residential and low-rise buildings in bushfire prone areas to reduce the risk of ignition from bushfire attack involving embers, radiant heat and direct flame impingement using non--combustible building materials" and that "the details provide in this Standard cover Bushfire Attack Levels BAL-LOW to BAL-FZ as defined in AS 3959". The Foreword also notes that "buildings constructed in accordance with this Standard are intended to provide a protective sheltering envelope during the passage of the bushfire flame front” and that “the Standard is based on achieving ignition resistance through non-combustible construction using conventional building materials and a level of redundancy to provide a high level of performance in extreme bushfire events and an increased probability that unattended buildings will survive such events”.

The scope of NS 300 is the design of steel framed buildings against bushfire attach only, addressing construction methods for roof systems with non-combustible roof cladding, wall systems including windows and doors, floor systems, secondary structures such as carports, pergolas, balconies and decks, and detached garages and sheds. A specific exclusion from this scope is buildings where roof storage is intended.

NS 300 is similar to AS 3959 for BAL—LOW, and BAL—12.5 to BAL—40, in that prescriptive construction solutions are provided, as well as the option of doing performance-based AS 1530.8.1 testing.

The design approach in NS 300 for BAL—FZ differs from AS 3959 and AS 1530.8.2 however (Baker *et al.*, 2020). Appendix A — Development of Bushfire Resistant Structures in NS 300 provides details of one of the major differences between NS 300 and AS 3959/AS 1530.8.2. Whereas the AS 1530.8.2 test method deals with direct flame impingement via a 30-minute standard fire resistance test, NS 300 approximates a moving bushfire flame front as three stages of radiant heat flux (Leonard, 2010), namely:

1. Radiant heating prior to the arrival of the fire front at the building (1800 seconds).
2. A short period of flame immersion for the building (110 seconds).
3. An extended period of decaying radiant exposure as the fire front recedes from the building (910 seconds).

The NS 300 BAL—FZ flame zone exposure profile is depicted in Figure 98 and consists of 47 minutes of radiant heat exposure, including a 110 second flame immersion period, during which time the radiant heat component is likely to be between 140 and 180 kW/m², depending on the flame temperature (Leonard *et al.*, 2012; Nash, 2021)

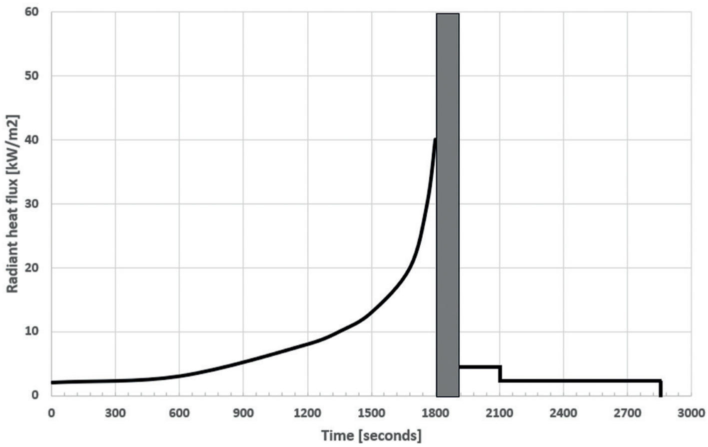


Figure 98. Schematic Flame Zone Exposure profile for BAL—FZ (adapted from Fig. A.1 in NS 300 (NASH, 2021).

A second significant difference between NS 300 and AS 3959 is the function of the building envelope. With AS 3959, the whole exterior building envelope acts as a protective barrier to the bushfire attack, while with NS 300, a non-combustible roof space is part of a strategy to create a controlled space for safe occupancy. This difference is conceptually illustrated in Figure 99, where on the left-hand side the approach for AS 3959 is to utilise the whole external envelope, including the suspended floor system where it exists, while on the right-hand side for NS 300, a safe space is created within the external envelope of the building.

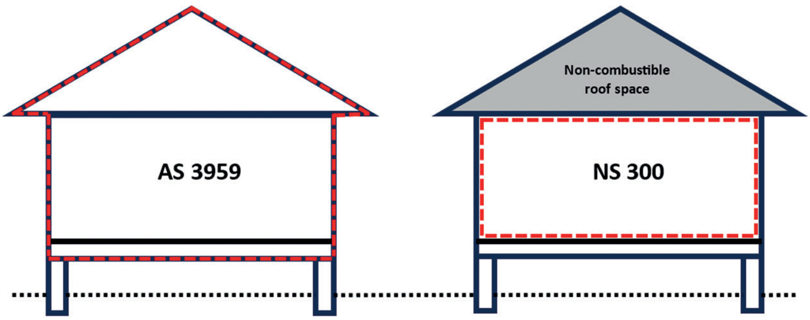


Figure 99. Conceptual Representation of AS 3959 vs. NS 300 Approach to Protect Against Bushfire Attack (adapted from (Leonard, et al., 2015).

8.3. Wildfires in urban-rural dwellings — Insurance as part of the answer?

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8.3.1. The role of insurance: from compensation to damage prevention

We can describe insurance as the contract through which the insurer undertakes, in exchange for compensation (the premium), to cover the risk of an uncertain event (the insured event) that may result in adverse consequences for the insured party, thereby protecting the insured's interest[13]. The way the insurer covers the risk and safeguards the insured's interest is by committing to provide compensation (typically) to the insured in the event of a loss.

From this, it is evident that insurance serves as a means of compensating for losses[14]. Compensation is important not only for its economic and social effects but also for maintaining economic activities (e.g., enabling the repair or replacement of affected property) and preventing impoverishment of those affected.

[13] Main abbreviations: ASF: Portuguese Insurance and Pension Funds Authority; EIOPA: European Insurance and Occupational Pensions Authority; RJCS: Insurance contract act, enacted by Decree-law 72/2008, of 16 April.

[14] On insurance as an instrument for compensation and prevention of damages, Maria Inês De Oliveira Martins, 'Sobre a Discriminação Dos Portadores De Vih/Sida Na Contratação De Seguros De Vida', BFDUC, /2 (2013), 749-800., pp. 242-267. On a broader analysis of the economic effects of absence of compensation, Ecb and Eiopa, 'Policy Options to Reduce the Climate Insurance Protection Gap, Discussion Paper', in Ecb and Eiopa (eds.), (ECB EIOPA, 2023)., pp. 9-14.

Compensation also plays a role in damage prevention. Insurance payouts can facilitate the swift reconstruction of a property, preventing it from deteriorating and being exposed to further risks. It may even enable reconstruction that makes the property more resistant to fire.

Additionally, insurance serves as a tool for risk prevention, encouraging property owners to adopt risk control measures. Insurers are experts in risk analysis and can condition access to insurance or the offer of better terms (broader coverage or more affordable rates) on the adoption of risk control measures ("impact underwriting")[15]. These measures could involve the adoption of risk-mitigating construction techniques and models (e.g., installing double-glazed windows, non-flammable insulation under the roof), self-protection measures (installation of sprinklers, fire-resistant curtains), and managing flammable materials around the house[16].

8.3.2. The Lack of Availability of Insurance Coverage for Urban-Rural Interface Fire Risks

Having identified the interest in insurance protection, it remains to be seen whether such protection is available for the risks under consideration. With this concern in mind, within the scope of collaboration between the Portuguese Association of Insurers and the House Refuge Project, we circulated a questionnaire among participants in the market covering these risks. The results were clear, indicating

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[15] ECB and Eiopa, 'Policy Options to Reduce the Climate Insurance Protection Gap, Discussion Paper'., pp. 18-19.

[16] Deives De Paula and João Paulo C. Rodrigues, 'Relatório No. 6, Melhores PráTicas Construtivas Para MitigaçãO Do Risco De IncêNdio Rural', (Projeto House Refuge, 2023)., pp. 8 and ff; Miguel Almeida, José Góis, and Hadassa Lima, 'AnáLise Da GestãO De CombustíVeis Naturais Na Envolvente Imediata àS HabitaçÕEs Isoladas Em Portugal Continental', in M. Almeida, J. Góis, and H. Lima (eds.), (Projeto House Refuge, 2020)., pp. 19 and ff.

a cautious approach, with the vast majority of respondents (9 out of 14) stating that if a residence is exposed to rural fires, the risk is initially declined, with exceptions considered on a case-by-case basis[17]. With less granularity, the "Dashboard on insurance protection gap for natural catastrophes" prepared by EIOPA and released in December 2022 similarly identifies a protection gap against fire risks concerning Portugal[18].

The situation is unsatisfactory. It is important to diagnose the reasons for this gap and to propose ways to address it.

8.3.3. Reasons for a protection gap and ways to address it

In the questionnaire conducted, we identified issues arising from the supply side of the insurance market. However, the protection gap is also a product of insufficient demand for insurance coverage. A comprehensive empirical analysis of the causes and extent of the gap is lacking. It is nonetheless useful to discuss the matter with the available information.

This analysis may besides be helpful in understanding the issues related to coverage of risks with similar characteristics. I.e., those

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[17] The survey was responded to by a total of 14 insurance companies, which, according to information provided by the Portuguese Insurance Association, represents 93% of the market share in terms of Home Multirisk Insurance premiums in 2020. See Dulce Lopes et al., Relatório No. 4, Resultados Do Questionário Sobre a Situação Atual Do Mercado De Cobertura Seguradora Do Risco De Incêndio Em Habitações Rurais – Práticas E Perceções Presentes (Projeto House Refuge, 2021)., pp. 4 and 15.

[18] See https://www.eiopa.europa.eu/tools-and-data/dashboard-insurance--protection-gap-natural-catastrophes_en. With data regarding December 2022, Eiopa, 'The Dashboard on Insurance Protection Gap for Natural Catastrophes in a Nutshell (Eiopa-22/507)', in Eiopa (ed.), (2022)., pp. 5-7. For a critique of the methodology followed in the Dashboard, see though https://www.insuranceeurope.eu/mediaitem/526fff3d-d83c-45f1-937a-27824b8b50a9/Response%20to%20EIOPA%20consultation%20on%20insurance%20protection%20gap%20dashboard%20for%20natural%20catastrophes.pdf.

involving insured goods of relatively low value, and correspondingly low premiums, which are exposed to catastrophic events.

The Demand Side

a) Insufficient Demand

Insufficient demand for insurance is influenced by both subjective factors related to the perception of the importance of coverage and by material factors regarding its affordability[19].

Among subjective factors, cognitive biases play a role in acquiring less coverage than would be rational. Such biases include the tendency to overvalue current consumption of money over saving, excessive optimism, or an undue fear of regret, leading to the overvaluation of coverage for frequent and less severe losses and undervaluation of coverage for rare and severe losses. The aversion to decisions involving complexity or that confront individuals with topics generating fear or taboos can also come into play[20].

The bias toward acquiring less coverage than what is rational has been diagnosed precisely in the context of coverage for risks related to catastrophic, rare events causing significant losses[21].

These preferences can be driven by cultural factors, resulting in differences in coverage choices between populations. Additionally, some individuals may believe that they won't bear the ultimate

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[19] Eiopa, 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper', in Eiopa (ed.), (2023)., p. 11.

[20] Tom Baker and Peter Siegelman, 'Chapter 19, Behavioral Economics and Insurance Law, the Importance of Equilibrium Analysis', in Eyal Zamir and Doron Teichman (eds.), The Oxford Handbook of Behavioral Economics and the Law (New York: Oxford University Press, 2014), 491-517., pp. 498-502; Colin F. Camerer and Howard Kunreuther, 'Decision Processes for Low Probability Events, Policy Implications', Journal of Policy Analysis and Management, /4 (1989), 565-92., pp. 568 e ss

[21] David Krantz and Howard Kunreuther, 'Goals and Plans in Decision Making', Judgment and Decision Making, /3 (2007), 137-68., pp. 140 and ff.; Eiopa, 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper'., pp. 4 and 20-21.

cost of damages since the state will compensate them, which is an example of moral hazard, leading individuals to be less diligence when they don't bear the full consequences of their actions[22].

On the material side, accessibility to coverage is determined by individuals' purchasing power, influenced by factors such as a country's wealth and wealth distribution. Additionally, factors related to the supply side, like market competitiveness or the feasibility of segmenting insurance for lower-risk properties[23], can affect premium reduction efforts.

b) Possible Responses

b1) Measures to support private autonomy

Biases affecting the assessment of insurance importance can be countered with measures guiding individuals' decisions toward more desirable outcomes. Information campaigns, targeting states, regions, or directly affected individuals, can be effective in raising awareness. For example, requiring disclosure of the fire risk level and associated mitigation costs in property sale advertisements could be beneficial[24]. Implementing nudging techniques[25], such as displaying information on coverage more prominently than other

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[22] EIOPA 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper'., pp. 4 and 21; for what we say next, pp. 17-19 and 12-14. On moral hazard in the insurance contract, Maria Inês De Oliveira Martins, 'Risco Moral E Contrato De Seguro', in António José Avelãs Nunes, Luís Pedro Cunha, and Maria Inês De Oliveira Martins (eds.), Volume De Homenagem Ao Prof. Doutor Aníbal De Almeida (Coimbra: Coimbra Editora, 2012), 637-76., passim.

[23] On the segmentation of the market, see Martins, 'Sobre a Discriminação Dos Portadores De Vih/Sida Na Contratação De Seguros De Vida', pp. 750-754.

[24] EIOPA, 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper'., pp. 5 and 24-26.

[25] For the original concept, Richard H. Thaler and Cass R. Sunstein, Nudge, Improving Decisions About Health, Wealth, and Happiness (New Haven/ London: Yale University Press, 2008)., pp. 6-8; for its limitations, Luca Congiu and Ivan Moscati, 'A Review of Nudges, Definitions, Justifications, Effectiveness', Journal of Economic Surveys, /36 (2022), 188-213., pp. 191-197.

information or bundling fire insurance fire with other financial or insurance products (with owners opting out if they don't want fire risk protection), can help encourage more favourable decisions[26]. However, such measures are limited to the purchasers of houses. Moreover, the effectiveness of nudging measures still remains open to doubt; and combined offerings can increase product complexity[27].

Simplifying the purchasing experience through digitalization and offering price comparison tools can also enhance accessibility. The practice of offering discounts for risk control measures may incentivize responsible property owners[28].

b2) Mandatory Insurance

Beyond voluntary approaches, mandatory insurance requirements can be considered. Effective implementation would involve creating a system of mandatory acceptance of those risks, similar to that of mandatory coverage of automobile insurance[29]. However, the duty to purchase insurance doesn't guarantee that it becomes affordable to the entire affected population. The extent to which premiums can be lowered depends on how much the heightened risks can be

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[26] On information as nudging, Congiu and Moscati, 'A Review of Nudges, Definitions, Justifications, Effectiveness', (, pp. 191-197; Peter Gulborg Hansen, 'The Definition of Nudge and Libertarian Paternalism: Does the Hand Fit the Glove?', European Journal of Risk Regulation, /1 (2016), 155-74., pp. 168-169. Further Thaler and Sunstein, Nudge, Improving Decisions About Health, Wealth, and Happiness., pp. 34-35; Eiopa, 'Measures to Address Demand Side

[27] Congiu and Moscati, 'A Review of Nudges, Definitions, Justifications, Effectiveness', (, p. 200, Michael Hallsworth, "Making Sense of the "Do Nudges Work?" Debate" (https://behavioralscientist.org/making-sense-of-the-do-nudges-work--debate/). Eiopa, 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper'., pp. 16, 22-23

[28] Eiopa, 'Measures to Address Demand Side Aspects of the Natcat Protection Gap, Staff Paper'., pp. 5, 27-30.

[29] Mandatory placement, in accordance with the annual list prepared by ASF, of risks that have been declined by at least three insurers (see Art. 18 of the Act on mandatory motor insurance, Decree-law 291/2007, of 21 August and Norm 9/2006-R, of 24 October 2006, of ASF).

pooled within a larger set of risks. Instead of distributing higher premiums among purchasers of voluntary insurance (which could lead to increased premiums and decreased demand in this segment), it may be more fruitful to address catastrophic risks as a whole. For instance, creating a mandatory coverage system for various uncorrelated risks (earthquakes, forest fires, floods, storms)[30] that could benefit property owners across the entire territory. Nonetheless, some portion of the population may still find premiums unaffordable; the penalties for failing to take out insurance may then raise delicate issues of constitutional law.

The framework of mandatory insurance should incentivize property owners to prevent damage. It should not provide full coverage, and its conditions should be sensitive to the level of risk of each individual property.

b3) Public Financing

Overcoming affordability challenges may require public subsidization of coverage, either through direct premium subsidies, or through tax credits related to premium expenses. Tax credits would only have effect for individuals who exceed minimum income thresholds and have a tax liability.

c) The supply side

c1) Lack of sufficient supply

This may consist of lack of availability of any coverage, even basic, or of its unavailability for high severity risks.

c1a) Lack of reliable parameters for premium calculation

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[30] The pooling of catastrophic risks of different nature (flooding, earthquake, terrorism, rebellion) is the approach followed in Spain by Consorcio de Compensación de Seguros (cfr. https://www.consorseguros.es/web/documents/10184/232010/SEGURO_RREE_2019ES.pdf/86b4dd09-815e-4914-aa0f-f252f457bede)

In the coverage of small and mass risks, such as risks of fire in dwellings, insurers primarily rely on mutualization techniques. Using statistics and estimates, insurers calculate the probable losses that a group of subjects exposed to the same risk will suffer and then divide that value among the insured group. Since not all subjects will be affected by insured events, the premiums paid by those who remain unharmed serve to pay the benefits due to those who suffer losses.

In the current context of climate change, there are not yet good models available for predicting probable losses caused by wildfires[31]. Furthermore, fire risks in the same region may be positively correlated with each other — a fire that affects one property can spread to neighbouring properties — requiring projections to be adjusted with safety margins to account for this added complexity.

This issue may give cause the insurers not to offer cover at all, or to increase the premiums with considerable safety margins — which, in its turn, may reduce demand.

c1b) Poor quality of the risks

The risks at stake are perceived as being of high severity and uncertain probability, thus being of "poor quality" for the insurer. This is attributed to changing climate patterns, to the low resistance of buildings to fire (given the use of poor construction techniques), and to non-compliance with administrative rules, especially regarding fuel management, without proper administrative enforcement.

c1c) Infeasibility of risk selection

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[31] This was pointed out in the context of preparatory meetings for the webinar "The insurance sector and the protection of dwelling houses against wildfires", organizado no âmbito do projeto House Refuge (https://adai.pt/houserefuge/webinar-o-setor-dos-seguros-e-a-protecao-de-habitacoes-contra-incendios-rurais/)

The insurer may counter these trends by seeking to have only low-risk insureds — "good risks" — in its portfolio. This allows them to charge lower premiums, potentially attracting more demand and low-risk demand, who is not willing to pay high premiums.

As mentioned above, it is through risk assessment, conducted at the beginning and during the contract, that the insurer encourages the adoption of best practices and pursues the goal of preventing fire damage. To assess the likelihood of an insured event and the size of the associated loss, the insurer may consider certain factors, whether "dynamic" (e.g., management of flammable materials) or "static" (e.g., location of the house, type of construction).

In a segment where demand is very sensitive to increases in premiums, there is very limited opportunity to absorb these verification costs. Even the least expensive risk assessment methods — those that are done only once and through simple document review (e.g., through photographs, plans, and construction descriptions to verify building characteristics) — are seen by some insurers as excessive for the premiums in the segment.

d) Possible Responses

d1) Technical Improvements

Introducing technical improvements can support an expansion of coverage[32]. First, in the realm of actuarial techniques, with the development of updated models for predicting risks of wildfire. Secondly, in regard of evaluation of individual risks, the introduction of automated techniques may significantly reduce verification costs. This could involve document verification through artificial intelligence with text recognition capabilities or image analysis

[32] As pointed out in Lopes et al., Relatório No. 4, Resultados Do Questionário Sobre a Situação Atual Do Mercado De Cobertura Seguradora Do Risco De Incêndio Em Habitações Rurais – Práticas E Perceções Presentes., pp. 16-17 and in the context mentioned in the previous note.

(including satellite imagery) to assess compliance of flammable materials management measures, for example.

d2) Third-Party Certification

The assessment and certification of individual risks can be placed in the hands of a third party other than the insurer, so that their costs do not impact premiums. Certification could be entrusted to private entities, funded by individual policyholders. It is though doubtful that they will be willing to bear such costs. Alternatively, it could be handled by public entities or subsidized, critically depending yet on the availability of technical and human resources in the public administration or the allocation of financial resources for this purpose.

d3) Parametric Insurance

Parametric insurance contracts are agreements in which the insurer commits to make predetermined payments to policyholders as soon as a certain index is surpassed (e.g., earthquake intensity, rainfall volume, storm strength, fire intensity)[33]. These payments are automatic and independent of whether the policyholder suffers specific damage. Different from a derivative financial instrument, the insurance is only contracted with subjects exposed to risks associated with that index. For example, it is agreed that the policyholder will be entitled to a certain amount if a hurricane with intensity exceeding a certain level occurs within a 50-mile radius of the risk location (e.g., policyholder's facilities). In the case of fire,

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[33] Emmanuel Berthelé, 'Chapter 5. Using Big Data in Insurance', in Marine Corlosquet-Habart and Jacques Janssen (eds.), Big Data for Insurance Companies (ISTE/ Wiley, 2018), 131-61., pp. 145-146; Swiss Re, 'What Is Parametric Insurance?', in Swiss Re (ed.), (2023). (ttps://corporatesolutions.swissre.com/insights/knowledge/what_is_parametric_insurance.html)

only homeowners in the region for which the index is calculated would be covered.

One significant advantage of these insurance products is their simplicity, as they eliminate the need for individual risk assessments and also the claims adjustment process[34]. This greatly accelerates pay-outs, allowing policyholders to quickly obtain funds to repair their damages and reducing premiums by eliminating a significant portion of administrative costs.

However, this product has limitations. Firstly, although it operates in a straightforward manner, it relies on complex calculations associated with the prediction of highly uncertain events[35]. This business has been more developed by insurtech companies than traditional insurers.

The decisive limitation — which is also the central virtue of the product — is that, by design, insurance benefits are not defined by damage suffered by the policyholder. This is problematic when the event does not have the necessary intensity to trigger coverage, despite the policyholder suffering losses. Attempts have been made to mitigate this problem by constructing products with staggered pay-out structures (with progressively larger payments as the exceeded index increases) or multiple payment triggers[36]. However, this increases the complexity of calculations involved.

Therefore, product does not serve as the central axis of coverage. Its role is to complement basic coverage provided by conventional insurance. Furthermore, the fact that the product has not yet had substantial penetration in the national market raises doubts

[34] Jannis Gutbrod and Andreas Göhl, 'Parametrische Risikotransferlösung Für Forderungsausfallrisiken Art, Option Für Alle Unternehmen?', VW, (2023), 100-05., pp. 101, 103-104.

[35] Swiss Re, 'What Is Parametric Insurance?'.

[36] https://corporatesolutions.swissre.com/insights/knowledge/10_myths_about_parametric_insurance.html, myth 1.

about its functioning. The indices governing more conventional parametric insurance products are not influenced by individualized human actions, but the occurrence of a fire above a certain intensity could be caused by the actions of the policyholder or a third party. Therefore, questions arise regarding the applicability of certain aspects of typical insurance regulations, such as the non-coverage of intentional acts (Article 46 of RJCS) or the insurer's subrogation in the policyholder's rights against the tortfeasor (Article 136 of the RJCS). The nature of this product, between insurance and derivative contract, leaves doubts, especially regarding the latter point.

d4) Expanding the Reinsurance Market

Reinsurance is insurance that protects the assets of insurers themselves against the risk of having to make payments due to claims[37]. It is a way to distribute the impact of claims across multiple balance sheets. Obtaining reinsurance is essential for insurers to be willing to accept risks whose outcomes can be unpredictable and result in high claims payments. The traditional reinsurance market (the assets of reinsurers) has limits to its capacity. One way to increase the supply of reinsurance is to place risks outside the insurance market and into the capital markets by issuing securities (e.g., catastrophe bonds) or distributing derivative contracts tied to loss indices (e.g., catastrophe options)[38]. This allows access to financing in the capital market and increases the supply of reinsurance, lowering its cost and thus reducing premiums.

However, it should be noted that financial markets are volatile, and one cannot rely on continuous demand for these instruments.

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[37] Margarida Lima Rego and Diogo Costa Seixas, 'O Contrato De Resseguro', in Margarida Lima Rego (ed.), Temas De Direito Dos Seguros, a Propósito Da Nova Lei Do Contrato De Seguro (2 Ed edn.; Coimbra: Almedina, 2016), 287-326., pp. 287-304.

[38] Specially focusing on cat-bonds, ECB and EIOPA, 'Policy Options to Reduce the Climate Insurance Protection Gap, Discussion Paper'., pp. 20-24

An accumulation of catastrophic events or a context of high interest rates could significantly reduce demand[39].

d5) Public-Private Partnerships

Public-private partnerships in this context refer to the allocation of funds under public administration to cover risks[40]. These can be mechanisms for public reinsurance, protecting the assets of insurers, or mechanisms for public insurance, providing benefits directly to policyholders. Public reinsurance mechanisms may be particularly important by providing last-resort protection in the event of high-impact, low-frequency events. There is even consideration of establishing a European fund for covering high-impact catastrophes related to climate change[41]. Public insurance mechanisms can be illustrated by the insurance of extraordinary risks provided by the Spanish *Consorcio de Compensación de Seguros*, which serves as a mandatory additional coverage for catastrophic risks for those who purchase home insurance[42].

A limitation of these approaches is that they do not condition the level of protection provided on the adoption of risk control measures by each policyholder or country. The architecture of the funds can yet be designed to incentivize prevention by leaving a portion of the damages uncovered and conditioning them on the adoption of preventive measures by individuals or States[43].

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[39] Ibid., p. 21.

[40] Ibid., pp. 25-27.

[41] Ibid., pp. 3-4, 28 and ff.

[42] https://www.consorseguros.es/web/documents/10184/232010/SEGURO_RREE_2019ES.pdf/86b4dd09-815e-4914-aa0f-f252f457bede.

[43] ECB and EIOPA, 'Policy Options to Reduce the Climate Insurance Protection Gap, Discussion Paper'., pp. 3-4, 27. In general, Jonas Knetsch, Le Droit De La Responsabilité Et Les Fonds D'indemnisation, Analyse En Droits Français Et Allemand (Paris: L. G. D. J., 2013)., pp. 359 and ff.

An issue that frequently arises in the context of guarantee funds concerns their financial sustainability. If the funds are called upon to provide coverage on a large scale — due to the occurrence of multiple catastrophic events — this could deplete their resources and trigger the need of additional funding from public authorities.

d6) Land use and construction regulations, enforcement, and coercion

The role of land use and construction regulations will be all the more important when they are appropriate (e.g., imposing suitable building and fuel management requirements) and when their enforcement is effective. Positive incentives, such as subsidizing housing adaptation measures, may be useful[44].

d7) Civil Society

Lastly, the role of civil society, i.e., grassroots organizations of the especially affected communities, should be emphasized. These organizations can play an important role as direct intermediaries with insurers, negotiating group insurance solutions, and organizing processes to verify compliance with risk control requirements.

8.3.4. Conclusions

In spite of the importance of insurance in compensating and preventing damage caused by wildfires in dwellings, insurance coverage remains below the desired level. The gap stems from both a lack of demand and an inadequate supply. Filling this gap seems

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[44] See respectively p Lopes et al., Relatório No. 4, Resultados Do Questionário Sobre a Situação Atual Do Mercado De Cobertura Seguradora Do Risco De Incêndio Em Habitações Rurais – Práticas E Perceções Presentes., p. 16-17 and Ecb and Eiopa, 'Policy Options to Reduce the Climate Insurance Protection Gap, Discussion Paper'., p. 30.

to depend more on a combination of solutions that can change demand perceptions and stimulate supply, involving also the public sector, in its role as financer, provider, and overseer, as well as the affected communities. Risk control will be more effective when supported by an entire ecosystem of administrative interventions, civil society, and the insurance market. Sustainably bearing the cost can only be feasible when they are shared between administrative funds and the insurance market.

8.4. Land-Use Planning in the American Wildland-Urban Interface: Avoidance or Compliance?

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Wildland fires exist in a complex social geography that requires increasing attention to saving lives and assets in the wildland-urban interface. In some places, such as the United States and Australia, the shift in attention to the WUI came about as more people sought to live closer to wildlands. In the United States the WUI challenge is related to uncontrolled population growth.

In southern Europe, on the other hand, the abandonment of the interior has led to more devastating fires near towns and villages. The interior municipalities of Portugal, for example, have seen steady population decline for decades (Tedim *et al.*, 2020). Although coastal areas of Portugal are undergoing WUI growth and experience frequent fires (Viegas *et al.*, 2003; Ascoli *et al.*, 2023), the most devastating fires have been in the interior, an area of steady population decline.

This chapter is about public, private, non-profit and community actors that inform WUI growth in the United States. In the context of integrated fire management, private actors such as homeowners and the insurance industry, as well as community organizations such as fire safe councils and environmental organizations, all participate in these policy choices alongside state agencies (Auer, 2021). Many policies can restrict growth indirectly through measures such as defensible space mandates that increase the cost of development in the WUI. Direct policies to reduce or redirect growth away from the WUI, however, are almost non-existent.

My focus is on the state of California, where losses from fire have been amplified by WUI growth as well as by the presence of larger and more frequent fires under conditions of climate change (State of California, 2022, 6; Scalingi, 2021). There are an estimated two million homes in high fire risk hazard zones in the state. The state added a million homes to the WUI between 1990 and 2010 (Yap *et al.*, 2021). Another 1.2 million homes are expected to be built in areas Cal Fire classifies as high wildfire risk areas, between 2000 and 2050 (Frank, 2022). California on the other hand has the most wide-ranging statewide framework for fire management in the country. This includes the adoption of Firewise compliance in hundreds of communities, the widespread presence of fire safe councils, increasingly granular fire risk mapping, and the presence of a state fire agency that embraces integrated fire management. Yet local policymakers continue to approve sprawling WUI projects across the state (Yap *et al.*, 2021).

Home hardening and defensible space are part of current legislation for the WUI, but these policies have been used by the building industry to promote new growth and to expand the WUI further into wildland areas. Landowners in WUIs sometimes resist regulations intended to make their communities safer, as they look forward to eventually subdividing their own large parcels without adding costly fire-resistant infrastructure (Chase 2015; Mockrin *et al.*, 2020).

To bring WUI policy further into focus, I will look at some local examples from areas impacted by the 2018 Camp Fire. This fire destroyed the town of Paradise (26,000 people) and devastated large swaths of unincorporated Butte County in northern California. It is still at this writing the most costly and deadly wildfire disaster in the state's history. On part of the land this fire passed through, a developer wishes to put a new housing project with almost 3,000 homes on 600 hectares. His claim that he can make this development safe from wildfire is an example of the appropriation of fire safe practices, such as defensible space, in the interest of WUI growth.

Researchers have asked why communities that have burned do not do more to become fire-adapted in the aftermath of this trauma (Alexandre *et al.*, 2015; Kramer *et al.*, 2021; Mockrin *et al.*, 2018; Mockrin *et al.*, 2020; Schumann *et al.*, 2020). Adaptation could include redirecting, slowing or even stopping growth in areas that have burned (Yap *et al.*, 2021; Chapple *et al.*, 2021). Researchers have found that not only do areas build back after fires, but they also often surpass the growth compared to before a fire, suggesting that fires themselves are opportunities for jurisdictions to pursue more growth in the WUI. Fire histories are brushed aside in favour of an emphasis on new “fool-proof” technologies in defensible space and home hardening in the WUI (Yap *et al.*, 2021).

8.4.1. What is the WUI?

Since the 1980s, policy makers and fire experts have used the WUI as a tool to prioritize efforts to control and prevent wildland fires where lives and assets are most at risk (Bento-Gonçalves and Vieira, 2020; Pyne, 1997). There are two main definitions of the WUI used in the United States and elsewhere since the 1980s: the interface and the intermix. The interface exists where settlements and significant stands of wildland vegetation come together. The interface is usually on the edge of cities or towns, and often grows through urban sprawl. The intermix is where very small towns or rural hamlets, or large-lot developments, exist amidst wildland vegetation. New exurban growth in California has seen the appearance of large lot housing developments of one acre or more in wildland areas (Pincetl *et al.*, 2008). The WUI is the fastest growing land-use type in the United States. Almost half of all new homes are built in the WUI and it already contains about one-third of the country’s population (Radeloff *et al.*, 2018).

The California Department of Forestry and Fire Protection (Cal Fire) provides its own calculation for the state's WUI areas to enable application of state laws that address the WUI (Calfire-FRAP, 2019). Figure 100 shows the extent of interface, intermix WUI areas as well as those areas within 1.5 mile from the interface, known as the WUI influence zone. Along the west coast, the conurbations of San Diego, Los Angeles and San Francisco have all experienced destructive WUI fires. Fires regularly move through many smaller communities and towns of the Sierra Nevada foothills, to the east.

Figure 100. WUI in California. Source: Cal Fire.

The WUI is a moving target, always growing even as wildfire threats increase. In the western United States, the WUI has increased in size by 60% since 1970 (Moritz *et al.*, 2014). It is possible that the current definition of the WUI is becoming dated, given the threat of wind-driven fire, climate change, ember cast and urban fuel sources (McGee, McCaffrey and Tedim, 2020; Moritz *et al.*, 2014; Calkin *et al.*, 2014). Researchers and agencies have created much broader definitions of the WUI based on changing assumptions and emerging mapping tools. Most of these recalculations have found that the WUI is larger than assumed and contains areas once excluded from it (Li *et al.*, 2023; Dale and Barrett, 2023). For example, Oregon has a three-part definition of the WUI, which includes interface, intermix and the additional category of "occluded WUI" to capture risk to areas that have little fuel cover but are close enough to vegetation to receive embers during a wildland fire (Oregon State University, 2023). Cal Fire has included a designation called "WUI Influence Zones," as shown in the map above. Recent experiences show that wind and embers, along with fuels from the built environment, can bring fire deep into non-WUI urban areas (Headwaters Economics, 2016). Fire agencies have also been urged to conduct fire modelling that includes human settlements as a fuel source (de Kok, 2020; State of California *et al.*, 2021).

8.4.2. To restrict or not restrict with land use planning?

That so much of California is within the WUI makes it unrealistic to imagine completely disallowing growth there. However, encouraging growth in existing urban areas (infill) or even in established WUI areas is preferable to the WUI "sprawl" that is taking place in the state (Chapple *et al.*, 2021; Pincetl *et al.*, 2008).

The question next addressed is whether fire adaptation masquerades as land-use planning without actually implementing fundamental changes to the location of settlements. Developers claim to be engaging in land-use planning when they design their subdivisions according to fire-informed standards. But they interpret “land-use” as how to build new subdivisions, not where to build them, and they employ defensible space and building code upgrades to advocate for continued WUI sprawl. The planning community itself largely dismisses the possibility of interfering directly in decisions about whether to rebuild burned communities (Pope, 2018). Some who advocate for more land-use planning do not see this as restricting development, but “layering” construction, landscaping, design and insurance rules on land-use in fire-prone areas (Dale and Barrett, 2023, 21). The only non-growth policy mentioned in Headwater Economics’ list of fourteen “land use planning strategies to reduce wildfire risk” is the last one-- the preservation of open space (Headwaters Economics, 2016).

For others, however, land-use planning is about the avoidance of growth in inappropriate spaces Pincetl *et al.*, 2008). The policies available for this interpretation of land use tend to address long-range growth at community or regional scales, such as the general plan. Environmental review of all significant built projects has the power to stop growth in some areas (Yap *et al.*, 2021; Abbott *et al.*, 2023).

8.4.3. Different layers of policy toward land use regulations and the WUI

In the United States, development decisions are left to local jurisdictions (cities, towns and counties), even when development in the WUI can end up costing the whole country billions of dollars in disaster relief (Kramer *et al.*, 2018; Mockrin *et al.*, 2020). That is not to say that there are no federal initiatives about WUI fire management, a point I will return to below.

Fire management is multi-layered process that takes place at many geographic scales and involves actors which are only indirectly involved in land-use decisions. These include firefighting (public, private, volunteer) entities, communities, individual homeowners, and the insurance industry (Moritz *et al.*, 2014). Codes designed to make homes more fire resistant usually apply to new homes only. The voluntary basis of defensible space and home hardening means there is no grand coordinated reworking of the WUI environment. Land-use decisions are delegated to local entities that have little motivation to interfere with growth (Plevel, 1997).

8.4.4. The indirect role of fire agencies on WUI development

At the forefront of WUI policies are fire agencies such as Cal Fire. Local jurisdictions (cities and counties) must comply with Cal Fire rules and standards when conducting long range land-use planning and when writing building codes. This section contemplates how some of these rules can indirectly impact growth in the WUI.

Cal Fire's strategic fire plan of 2018 addresses land-use in WUI areas tangentially (not directly recommending slowing or avoiding growth). The plan promises to provide data to support local land-use decisions that prioritize the protection of life, resources and property, taking into consideration individual owners' responsibilities and objectives (State Board of Forestry and Fire Protection, 2018, 19).

Although Cal Fire doesn't overtly restrict building into the WUI, it is motivated to reduce the cost of defending WUI fires. Cal Fire can affect WUI growth by imposing regulations that raise the cost of housing, such as enhanced road widths and turn radii for all construction. The agency can indicate to the insurance industry where fire risks are highest, thus provoking rate increases or insurance company retreat in some areas.

Cal Fire's State Board of Forestry and Fire Protection is one of several state agencies that create mandatory codes. Recently, its defensible space requirements have become costly enough for builders to complain that California is impeding growth in the WUI (Grijalva *et al.*, 2022). The update of its code in spring of 2023 introduced a set of enhanced requirements such as road widening, paving, and accessibility (California State Board of Forestry and Fire Protection, 2023). Among the most controversial of these changes is the rule that new developments must upgrade the existing adjacent road system. Another key change is restriction on the ridge top building. These areas have been prime targets for development given their desirable views.

If judged by the reaction by the building industry, these changes could have major impacts on the ability of individuals and builders to carve out new areas of the WUI for development. More about these reactions will be addressed below under "defensible space," which is the guiding justification for these restrictions.

8.4.5. Land-use planning or simply preparing for fire?

California is experimenting with several approaches to WUI growth. It has added requirements to the mandatory environmental review of housing developments and upgraded building codes and defensible space requirements. Jurisdictions are required to include, if they are in a WUI, an analysis of fire risk in all long-range planning documents such as the general plan.

Defensible Space Requirements: Cal Fire is responsible for defining and enforcing defensible space in much of California's WUI. Otherwise, for local responsibility areas (usually cities), "State law requires jurisdictions to adopt defensible space ordinances [only] if they have [very high fire severity zones] within their boundaries" (Petek, 2021,11).

However, in California, "there are hundreds of state and local agencies involved in defensible space programs. Without consistent coordination, this can lead to gaps in the delivery of programs in some places and potential duplication in others" (Petek, 2021, 2). For example, Cal Fire passes inspection and compliance on to local jurisdictions. Enforcement can lag as local jurisdictions are only authorized but not required to enforce defensible space requirements. Only 35% of properties in hazardous areas were inspected across California on average in 2019-20. Butte County, the seat of the Camp Fire, had only 20% of its susceptible parcels inspected (Patek, 2021, 14).

A recent change in state law will enforce defensible space during the transfer of property in WUI areas. The law determines that property sellers obtain documentation of an inspection from Cal Fire or from a local agency that verifies this compliance (Patek, 2021, 12). Homeowners can therefore put off defensible space maintenance for years in many jurisdictions.

Building Codes: California is one of only three states in the western United States that has a mandatory building code for WUI areas (Dale and Barrett, 2023, 24). Since 2008, California building codes have been enhanced for WUI areas to include (for new housing) non-flammable roofing and siding, double paned windows, and vent specifications. Critics have argued that fire codes would be more effective if they included requirements and funding for retrofitting homes to current standards (Pincetl *et al.*, 2008).

Some have argued that these codes have been successful in reducing loss in recent major fires (Dale and Barrett, 2023, 24). In the Camp Fire, older homes provided fuel and radiant heat that could ignite newer homes. Although homes built to 2008 standards were destroyed relatively less than older homes, still almost 50% of new homes were destroyed in that fire (Yap *et al.*, 2021).

General Planning: The general plan and accompanying zoning code are the main tools of long-range planning in cities and counties in the United States, and in many other countries. Since 2012, California state law has required the inclusion of wildfire hazards in general plans for jurisdictions that include WUI areas. The requirements include the consideration of fire hazard maps, historical data on wildfires, location and distribution of existing and projected uses of land, and description of all agencies responsible for fire protection in the jurisdiction (de Kok, 2020). Local jurisdictions could decide, based on this information, to steer growth away from WUI areas, but this is a decision that is rarely taken.

Environmental Review: While land-use planning decisions ultimately rest with local jurisdictions, state environmental law in California requires that most development (such as infrastructure projects, subdivisions, or other major construction) undergo detailed environmental review, according to the California Environmental Quality Act (CEQA) of 1970. Draft environmental impact reports are subjected to public disclosure and are vetted by state agencies. Lawsuits often focus on faulty or incomplete reviews of projects.

Fire hazards have been a part of the CEQA hazards guidelines for many years, and have included questions about risk of death, injury or property loss from wildfire. In 2018, additional questions about wildfire were added to the CEQA guidelines (Abbott *et al.*, 2023). WUI development has more recently come under additional scrutiny from the State Attorney General's Office, which published a set of new guidelines for environmental review, including the use of additional fire modelling, consideration of settlement density, the assurance of adequate water sources, and more focus on the hardening of homes (Bonta, 2022).

The Attorney General's Office has joined lawsuits where large WUI projects fall short in their environmental review. This jurisprudence is shaping expectations for careful consideration of large WUI developments, mostly in the direction of more restrictions, but still no one is saying "no" to development in the WUI. The case against the massive Guenoc Valley resort project in California's Lake County was settled by the Attorney General's office, which dropped its objections after winning concessions related to wildfire risk (Callahan, 2023).

Insurance: The insurance industry can be a "game changer" in altering WUI expansion (Wunder *et al.*, 2021). Home sales normally require proof that a buyer can secure insurance, a process that has become increasingly difficult in WUI areas. Industry profits have been eroded as repeated wildfires (and other climate-driven disasters) have led to billions in payouts in California. Insurance disbursements for Camp Fire victims were between $9 and $11 billion (Town of Paradise, 2022; Gabbert, 2022). Major insurance carriers have either pulled or limited new policies in California (Kamisher *et al.*, 2023).

While once very specific to each property, alignment with Firewise (see below) modifications can inform insurance companies whether to work with a community at large. A project in Paradise is seeking ways to keep homeowner insurance available through landscape level changes which explicitly invoke "Wildfire Informed Development Patterns" which model slower growth rates in the town and "[focus] on rebuilding in areas with lower wildfire risk and being intentional with land-use planning" (Chamberlain *et al.*, 2023, 1; Moritz *et al.*, 2022).

8.4.6. Community-based fire management and WUI growth

Local knowledge of fire conditions and risk, acceptance of risk by different actors, and geographically informed risk modelling can inform fire policy at all scales and help prioritize spending (Patrão, 2020; Tedim *et al.*, 2016; Tedim *et al.*, 2021). This section asks how community-based fire management might affect growth in the WUI.

Firewise — This is a national program that rewards communities for efforts at creating defensible space through community collaboration. It has become a reference for defensible space standards throughout the United States. The maximum size of a participating community is 2,500 people. This small scale allows for evaluation of adherence to defensible space and home hardening that local agencies cannot engage in for political or budgetary reasons. In California, there were 600 Firewise communities as of December 2022. Being Firewise compliant can enable funding for community projects such as fuel abatement and can lead to the reduction of insurance premiums (National Fire Protection Association, n.d.). Participating communities must present evidence of compliance every five years. This system can be misconstrued, unfortunately, to mean that certified communities are safe from fire.

Fire Safe Councils — These are 338 non-profit community organizations in California that employ a neighbour-to-neighbour approach to fire resilience in WUI areas. Their statutes include collaborating with firefighting agencies, public utility companies, the insurance industry, environmental groups and with many other entities (California Fire Safe Council, n.d.). Fire Safe Councils focus on preventive measures such as fuel breaks, chipper programs, grazing, home hardening and outreach to vulnerable populations (California Fire Safe Council, n.d.). Although councils sometimes offer inspections for willing homeowners, they are primarily focused on mobilizing homeowners for compliance with defensible space practices. Despite the upbeat message of collaboration, their approach acknowledges the slow, incomplete and ongoing nature of collaboration and the uncertainty of creating WUI environments where people can live without fear (Sturtevant *et al.*, 2008).

Community Wildfire Protection Plan (CWPP) — Since the passage of the federal Healthy Forests Restoration Act of 2003, local jurisdictions have been encouraged to create these plans to target fuel reduction in cities, towns and counties (State of California, 2022; Mockrin *et al.*, 2020). These plans are updated every five years by local jurisdictions and are always signed off by fire authorities. The CWPP limits itself to identifying fuels risk (State of California, 2022) but has no direct jurisdiction over land-use planning (Moritz *et al.*, 2022).

8.4.7. Does community resilience serve WUI growth?

It is hard to imagine effective WUI management without these local actors and initiatives. But reliance on homeowner buy-in can leave gaps in compliance and opens up the question of how to help less privileged communities to live safely in the WUI. Research and policy have sought to identify WUI communities that will suffer greater harm and displacement from wildfires fires (Wigtil *et al.*, 2016; Paveglio *et al.*, 2018).

Setting these concerns aside, the building industry presents the case that the WUI will become “hardened” as new developments replace aging, and less compliant infrastructure and housing. Developers use Firewise and other evidence of good WUI management to justify their own projects. They argue that subdivisions all built at the same time under similar codes are safer than existing communities with their mix of old and new housing.

The building industry's argument depends on the privatization of services by homeowner associations (HOAs) that makes them uniquely able to enforce compliance. Many Firewise Communities in California are indeed HOAs (National Fire Protection Association-NFPA, n.d.). In a letter to the State of California Department of Forest, a coalition of builder interests argued that HOA-run subdivisions should not have to comply with Cal Fire's new regulations regarding road requirements, discussed above (Grijalva et al, 2022).

8.4.8. Resistance: environmental activism

To make areas "safe," massive removal of vegetation, water capture and other changes are seen as environmentally catastrophic by many groups (Radeloff *et al.*, 2018). Citizens, indigenous groups and allied non-profit organizations have confronted the growth machine that feeds expansion of the WUI. Environmental organizations such as the California Native Plant Society, Centre for Biological Diversity and the Sierra Club have partnered with grassroots resistance to stop or slow down major land-use projects in WUIs across California (Frank, 2022).

8.4.9. Is fire resilience a means or an end?

The perspective of fire resiliency as a "package" of deliverable engineering fixes passed off as land-use planning has led the development industry and its allies to pitch growth as safe in the WUI. California's housing shortage has legitimized a pro-growth stance among housing activists, developers, and politicians. Land-use planning, when defined by developers as making adjustments for wildfire, can actually increase development in the WUI by giving the impression that it is safe to build there (Butsic *et al.*, 2014; Moritz *et al.*, 2022).

Fire researchers are unlikely to engage in the same hubris. Their goal is to find a reasonable level of risk to live with fire, not to promise the absence of risk (McWethy *et al.*, 2019). Fire is a wicked problem, intertwined with other unpredictable environmental issues that go far beyond the WUI (Thacker *et al.*, 2023; Wunder *et al.*, 2021). Fire spread dynamics are changing and are not well understood, leading to a cautious stance among most researchers about innovations such as home hardening and defensible space.

The integrated nature of fire resiliency leads to difficult questions about its shared costs and resources. WUI-specific approaches to resilience do not begin to cover all the costs to society of building in those spaces (Jenerette *et al.*, 2022). How much does a water-rich irrigated "resilient" landscape cost to other water users whose wells depend on the same groundwater? Who is responsible for wildfire's externalities, such as when fire spreads toxic smoke for hundreds of miles (Wunder *et al.*, 2021; Scalingi, 2021), when insurance subsidies climb for everyone (Christopher and Gedye, 2023) or when endangered plants are threatened by fuel management (Pincetl *et al.*, 2008)? Perhaps when this broader perspective on risk is understood, people will begin to embrace land-use planning in the WUI as avoidance and not just as compliance.

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Conclusions

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Conclusions

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The increasing frequency and severity of wildfires in the wildland-urban interface across the globe underscore the critical importance of understanding and managing wildfire risk at these areas. The significant economic and sociologic impacts of the recent dramatic fires have highlight the need for continued research and practical application in both operational and policy-making spheres.

As the boundaries between building and natural areas become increasingly blurred, particularly in scenarios of intermix, the WUI has become a focal point for wildfire management. It is within these areas that the most dramatic and severe losses occur during wildfires. Additionally, human activities, which predominantly take place in WUI areas, are the leading cause of ignitions, further emphasizing the need for focused risk management strategies.

One of the key challenges highlighted by recent wildfire events is the incapacity and insufficiency of public civil protection services to address all incidents during very large-scale fires. As climate change and various social factors contribute to the growing frequency and intensity of those extreme wildfires, it becomes evident that wildfire management systems must evolve to include a broader array of actors and approaches. Traditionally, these systems have relied heavily on public civil protection agencies such as firefighters, forest rangers, and military forces, among other players. However, there is a growing recognition that citizens must play an active role in this challenge. Rather than being passive participants, citizens can be crucial in both preventive measures and response actions, helping to safeguard their properties and communities.

While citizens are the most widespread group of actors, their involvement is potentially effective and appropriate at the property and community scales. Therefore, it is crucial that wildfire risk management strategies in WUI areas not only consider the capabilities of public civil protection but also empower citizens as key players in this process. Of course, this also includes leveraging the potential contributions of organizations, businesses, and other entities.

As discussed in chapters 1 and 2, interventions in the WUI can occur at various scales — landscape, community, and property. This book has primarily focused on the property scale, though much of its content is applicable to the community scale and, to some extent, the landscape scale as well. Renowned researchers specializing in WUI fire management at the property scale were invited to contribute their latest findings to this volume. The chapters, while independently written, collectively provided a comprehensive overview of scientific perspectives on WUI fire risk management at the property scale. Each chapter has been curated by its coordinator, who is also its first author, ensuring coherence throughout the chapter. While some redundancy or varying approaches to the same topic may be detected through the book due to the independent nature of the chapters, they follow a logical sequence that allows readers to progress over the book methodically.

The first three chapters served as an introduction to the topic, providing the reader with the necessary context (Chapter 1), understanding the characteristics and challenges of different WUI scenarios (Chapter 2), and basic definitions related to the vulnerability of elements exposed to WUI fires (Chapter 3). Subsequent chapters delve deeper into specific topics, such as the mechanisms by which wildfires affect infrastructure (Chapter 4), and the primary components associated with the property scale: the surroundings of the building — defensible space (Chapter 5), and the use of self-protection systems (Chapter 6). Chapter 7 focuses on modelling the fire behaviour as it approaches to the building, and Chapter 8 discusses policies and regulations, including the potential role of the insurance sector as a key player in wildfire risk management.

These chapters collectively demonstrate that there are multiple, complementary approaches to managing wildfire risk in the WUI. While there is a wealth of solutions available, it is clear that further research and analysis are needed to fully understand and address this complex challenge.

We are confident that this book represents a valuable contribution to the understanding of wildfire risk at the property scale in the WUI, offering insights into the current state of scientific knowledge. Its organization into independent chapters allows readers to explore various perspectives, making it a useful resource for professionals involved in different phases and components of wildfire risk management. Although this book is rooted in scientific research, its relevance extends to a wide range of audiences — from citizens to operational personnel, municipal agents, and anyone with a vested interest in managing wildfire risk in WUI areas at the property scale.

Ultimately, managing wildfire risk at the property scale in the WUI is just one aspect of the broader challenge of wildfire risk management. The true value of this work lies in its ability to integrate various approaches, connect different stakeholders, and bridge the gaps between studies and publications in this field. This holistic perspective is essential for readers as they engage with this book.

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